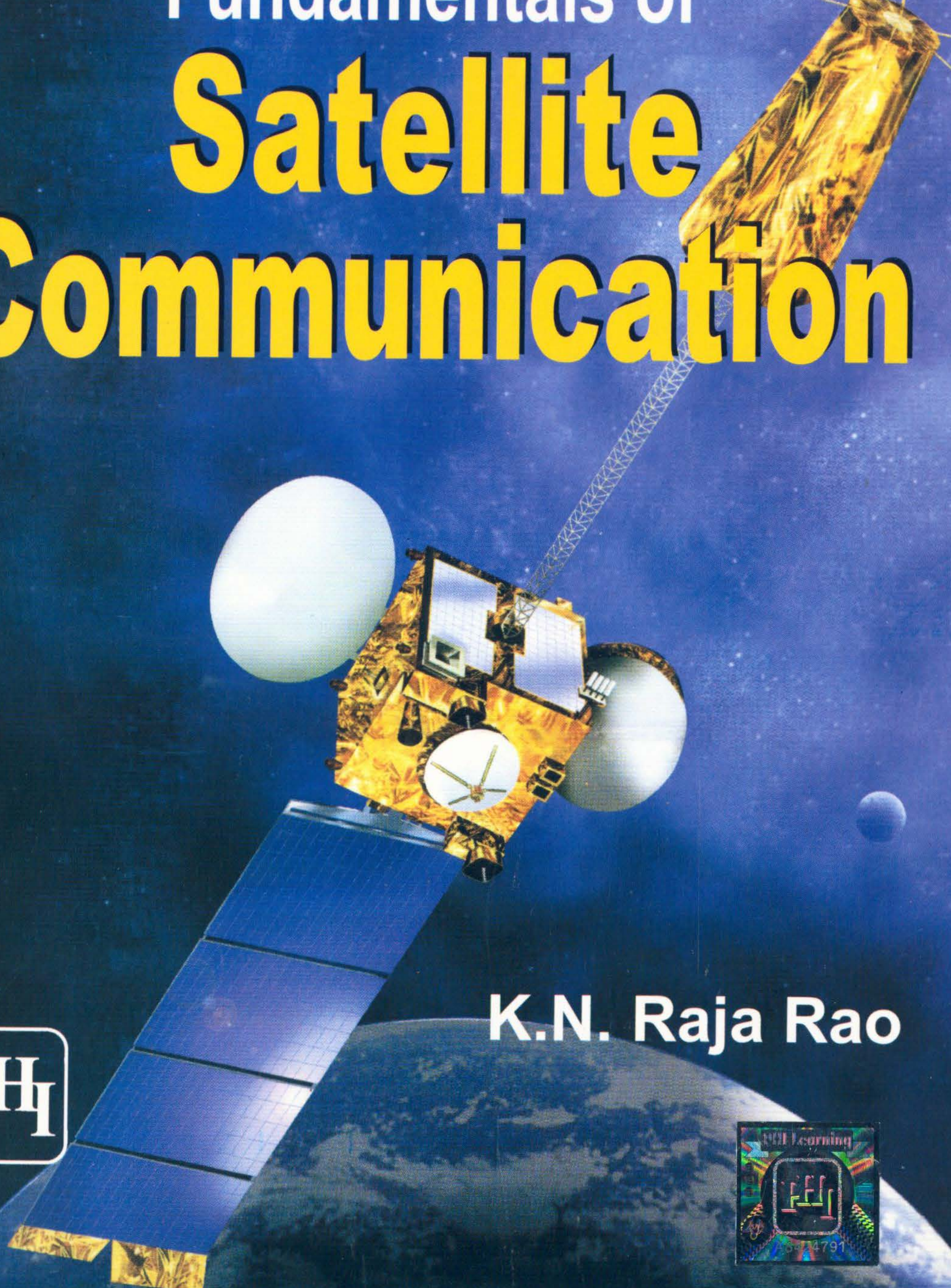
Eastern Economy Edition

Fundamentals of Satellite Communication



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PHI

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FUNDAMENTALS OF SATELLITE COMMUNICATION
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To My Parents

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Preface

One of the important components of a broadband communication system is the satellite link, the other being optical. Satellite communication has become the backbone of long distance communication irrespective of geographical conditions. Satellites have passed the age when their use was restricted to outer space experiments and remote sensing. Today many satellites are multipurpose satellites which are used for communication, meteorological data collection, search and rescue, global positioning systems, mineral and oil exploration etc. Satellite communication has transformed the world into a "global village".

A satellite system represents one of the most sophisticated and intriguing systems to design. Engineers need to consider almost all aspects of applied sciences, engineering and technology. They apply the principles of a variety of scientific disciplines such as physics of materials, sensor technology, virtual instrumentation, communication engineering, automatic control systems, mechanics of structures and so on.

After teaching this subject for nearly a decade I found that there is a need for a structured textbook which would cover the subject comprehensively so as to impart to the reader, full command of the basic concepts and enough of application-oriented knowledge to design satellite links. Though there are a number of books on satellite communications with excellent contents (as referred here in the bibliography) the exact requirement of the students remains to be fully met. The objective of this book is to fulfill their need. The credit therefore goes to my students who prompted me to take up this work. In this book I have tried my best to present the subject in a simple way, yet convey all the important aspects of space and satellite communication. This book is suitable for a one-semester course in space and satellite communication and is written keeping in mind both, undergraduate and postgraduate students. Practising engineers in this field can also refer this book.

This book covers, besides the basic concepts of satellite system; important parameter calculations and design concepts. The emphasis is on geostationary satellites. Beginning with orbiting parameters, the book gradually progresses to the more advanced concepts finally detailing the design of a complete multiple access links.

Chapter 1 not only introduces the subject matter but also gives insight to important definitions that are required to understand the latter chapters. It contains an overview of space and satellite communication and also describes the history of satellite communication as well as the contemporary trends. Chapter 2 is devoted to orbital parameters, launch and control of satellites.

Once the satellite is in orbit it is essential to not only communicate with the satellite but depending on the application also think of the options for carrier and bandwidth requirement. Chapter 3 deals with these aspects as per WARC standards.

Chapter 4 discusses satellite communication link design explaining the concepts for both analog and digital links. Some aspects of link performance improvement are also described at the end of this chapter.

Satellite is a multipurpose and multiuser facility providing multiple access. A conceptual discussion of multiple access techniques has been presented in Chapter 5 wherein link design equations have been clarified.

The sub-systems a satellite requires for its proper working, are addressed in Chapter 6 with stress on power supply.

As against the earlier chapters which generally pertain to geo-stationary satellites, Chapter 7 throws light on the applications of satellites in mobile communication.

It has been the desire of the author that the reader derives the most from the topics covered and therefore, almost every section is succeeded by relevant solved problems.

Since the students who would use this book would be its best critics, their feedback and suggestions, on this book are earnestly solicited. As I found it appropriate to regard the subject from an Indian perspective, instances pertaining to the Indian scenario have been included in most of the chapters.

K.N. RAJA RAO

Acknowledgements

I would like to thank persons and organizations who contributed directly or indirectly in making this project a success.

I feel it a privilege to thank Indian Space Research Organization (ISRO) that permitted me to use their public domain literature which have been included in this book. I am also grateful to my family for the help they gave in entering the text and figures. Thanks are due to all my colleagues who encouraged me in this endeavour.

K.N. RAJA RAO

Nomenclature

M	Additional margin required
h	Altitude or height of satellite
ω_s	Angular velocity
$\alpha_{coupling}$	Antenna coupling loss
η	Antenna efficiency
M_{aj}	Anti jamming margin
A_{eff}	Area of aperture of antenna
A_{iso}	Area of aperture of isotropic antenna
A_z	Azimuth angle
k	Boltzmann's constant
L	Cable loss factor
f	Carrier frequency
C/I	Carrier to interference
C/IM	Carrier to intermodulation
C/N	Carrier to noise
C/N_o	Carrier to noise density
R_b	Channel bit rate
X	Crosstalk
δ_e	Declination of sun
D	Diameter of dish antenna reflector
e	Eccentricity
α	Eclipse angle
ξ_∞	Elevation angle for satellite at infinity
J/S	Figure of merit of anti jamming
ρ	Filter roll off
Δf	Frequency deviation
g_o	Gravitational coefficient
G	Gravitational force
B_{if}	IF bandwidth
G_{if}	IF amplifier gain

B_{io}	Input back-off
α_{ion}	Ionosphere loss
λ_{AE}	Latitude of earth station
l	Loading factor
λ_E	Longitude of ES
λ_s	Longitude of satellite
L	Loss factor
M	Mass of primary body
m	Mass of satellite
f_{max}	Maximum signal frequency
G_m	Mixer gain
T_m	Mixer noise temperature
F	Noise figure/noise factor
P_n	Noise power
ξ	Normal elevation angle
N	Number of channels
B_{oo}	Output back-off
α_p	Path loss
t_e	Period of eclipse
G_{rf}	R.F. amplifier gain
T_{rf}	R.F. amplifier noise temperature
d	Radius of orbit or distance of satellite
r_e	Radius of earth
α_{rain}	Rain attenuation
h_r	Rain height
P_r	Received power
G_r	Receiving antenna gain
G/T	Receiving earth station figure of
f_s	Sample long frequency
G_{sat}	Satellite gain
a	Semi major axis
b	Semi minor axis
W	Signal bandwidth
S/N	Signal to noise
d_s	Slant range
Ω_α	Solid angle of main lobe of antenna
Ω_s	Solid angle of sun R

1 An Overview of Space and Satellite

1.1 INTRODUCTION

Space segment is a very strong and effective communication media. The developed countries took full advantage of the outer space which has never been a private property of any nation to park communication satellites during sixties. During sixties, the fibre optic communication was still in the infant stages and hence satellites looked very attractive due to their capabilities of handling large bandwidths. In spite of fast growth in fiber technology, satellite communication remains a blue-eyed kid of countries having difficult terrains, high mountainous regions, oceans, etc. where it is difficult to run optic fiber cables. Another advantage, which has made space communication the ultimate, is its capability to broadcast (Multi-point, multi-user capability) and the way a satellite can be designed for the multipurpose activities. This capability of satellite has come very handy, particularly for the developing countries. The growing demand and the urge for the space exploration has made the satellite launch and design a big business.

Thanks to Arthur C. Clarke, a fiction writer who envisaged the importance of satellite in 1945. Though the distance communication has been there since centuries, space communication has come to stay as the main means of distance communication particularly in unapproachable regions of the globe from the last two decades or so. One could classify satellites as nodes (active or passive) for the space communication.

Let us see, what the terms space and satellite mean in the present context?

1.2 SOME BASIC DEFINITIONS

Space

Space can be defined as *a place free from obstacles.* In common man's language, we define space as altitude at which an aircraft cannot fly due to the lack of aerodynamic force. The Outer Space Act 1986 was introduced to ensure that the governments of various countries have no claim of sovereignty over the space or the moon. In the UN treaty on 'Exploration and use of Outer Space' including the moon and other celestial bodies in space may not be subject to any claim of national sovereignty. Most of the members of UN involved in space activities and ITU have signed this treaty.

We can classify space into:

(a) Air space
(b) Outer space
(c) Deep space

Air space. Region below 100 km from the earth's surface.

Outer space. This is also called **cosmic space** and falls between 100 km and 42,000 km. In this region, aerodynamic lift is ineffective and is taken over by the centrifugal force.

Deep space. Regions beyond 42,000 km fall in this category which is not in use for the communication satellites.

Satellite

Satellite can be defined as *a heavy object which goes around another object in space due to the effect of mutual gravitational forces.* The path followed by the orbiting body may be as per the, Kepler's laws of orbiting bodies. During the seventeenth century, Kepler had predicted that the path followed by the satellite of mass m around a primary body of mass M in space will be an ellipse. The body centre mass M of the primary body should coincide with one of the foci of the ellipse. In such a case, eccentricity would exist and the angular velocity of the revolving body will change. The Kepler's laws are dealt in more detail in Chapter 2.

Types of Satellites

The satellites can be classified into two categories:

1. Active satellites
2. Passive satellites

Active satellites. Active satellites are used not only for linking but also for processing and transmitting signals. This type of linkage is called **Bend pipe technology** where frequency translation and power amplification take place. Some active satellites also use 'Regenerative technology' in which demodulation, processing, frequency translation, switching and power amplification are carried out. The block used for this purpose is called **transponder**. All communication satellites are active satellites of one or the other kind.

Passive satellites. Passive satellites do not have any on-board processing and are just used to link two stations through space. In the process, there is loss of power. These are not very useful for regular communication or sensing applications.

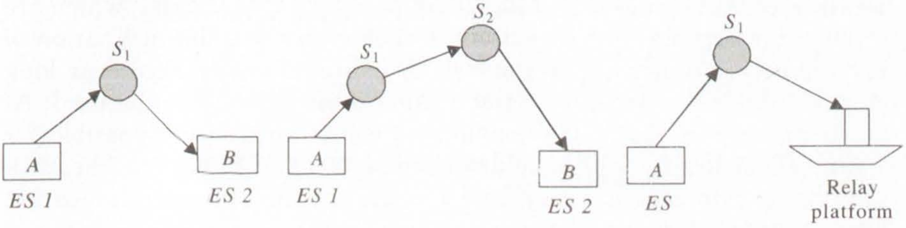
Satellite Systems

Broadly, there are three types of satellite systems:

Ground to ground. In this an earth station A sends signals to the satellite, which after processing retransmits to another earth station B, as shown in Figure 1.1(a).

Ground cross link ground. If the earth stations are situated such that they are not in the line of sight of a common satellite, it becomes essential that the help of another satellite is taken. The link between the two satellites in space is such that the signal from the earth station A goes to satellite S_1 and the satellite S_1 sends the processed signal to another satellite S_2 which in turn retransmits the processed signal to the earth station B, as shown in Figure 1.1(b).

Ground to relay platform. An earth station can send signals to the satellite, which can be further retransmitted from the satellite to several other relay platforms, and the data can be utilized. Even the direct reception could be considered under this category, as shown in Figure 1.1(c).



(a) Ground to ground (b) Ground cross link ground (c) Ground to relay platform

Figure 1.1 Satellite systems.

Satellite Orbit

Whether the satellite is natural like the moon or artificial like the one launched by man, they revolve round the planet as per the Kepler's laws in space. The path in which satellite goes round the primary body or the mother body is called **orbit path** and the distance from the centre of the primary body to the satellite is called **orbit radius**. The height of the satellite from the surface of the earth is called **altitude**.

In case of eccentric orbits, the radius varies while in circular orbits, it is constant. If we consider the earth as a primary body then the satellite can be classified in terms of altitude as follows:

***Low earth orbit* (LEO).** Satellites that orbit below an altitude of around 1000 km is called **low earth orbit satellites**. Satellites at such low heights are useful for mobile communication but a number of such satellites are required for the continuous communication between a user and satellite. The height being low, the transmitter power required is small and hand held transreceivers can be used. However, the main disadvantage in such orbits is that the life of the satellite is limited because of the fuel requirement. The rotation period of such satellite is about 1 hour 30 min while they remain insight for a quarter hour from a particular earth station.

***Intermediate circular orbit* (ICO).** In the altitudes lying between 2,000 km to 10,000 km, there is excessive radiation and the satellite cannot be kept in these altitudes. This is called **Van Allen belt** and the satellites have to be below this belt or above this belt. Satellites above this belt are said to be in the *intermediate circular orbit* (ICO). Satellites in this orbit are better than in LEO as far as the life and coverage area are concerned. Hence, the number of satellites required is less than that in LEO. This orbit is being visualized as the ultimate for global communication such as telephone, e-mail, fax, etc. For the continuous communication, earth stations have to be used for switching. In this orbit, the rotation period of satellites is 5 to 12 hours and the line of sight visibility period is 3 hours.

***Highly eccentric orbit* (HEO).** These orbits are also called as **Molniya orbits** and are used for communication by countries, which are in the polar regions such as Russia, Uzbekistan, etc. The inclination of such orbits is around 63°. However, for continuous coverage over long hours, a number of satellites in the same orbit path are to be used. At the inclination of about 63°, continuous communication is possible for about eight hours for orbit heights above 20,000 km. Therefore, theoretically three satellites are required for the continuous communication throughout the 24 hours.

***Geosynchronous earth orbit* (GEO).** Any satellite above 36,000 km *orbiting* at an angular velocity equal to the angular velocity of *revolution* of earth around its polar axis is called **geosynchronous**. Though the orbit height for these satellites is very high still these are very useful for communication. A special case of geosynchronous is the geostationary orbit. When the satellite is in the equatorial plane and is geosynchronous, the satellite is said to be in the **geostationary orbit**, i.e. the satellite will look to be stationary when seen from any point on the earth. These orbits are not useful for places in the polar regions because there is a visibility limitation discussed in Chapter 2. At this height, the coverage area is limited to less than 80% of the earth's surface excluding countries lying in the polar regions.

Features of Geostationary Satellites

Advantages

1. Tracking equipment is avoided.
2. Earth stations remain at constant distance and line of sight from the satellite.
3. Because of larger coverage area, a number of earth stations can access the satellite.
4. Small number of satellites can provide global coverage.
5. Quality of service is same for the rural and urban areas.
6. Almost no doppler shift.
7. Cost effective services.

Disadvantages

1. Earth stations in latitudes greater than 81.5° in northern and southern Hemisphere cannot access the satellite.
2. Received signal strength is weak because of large distance.
3. Time delays of send-receive more than 270 milliseconds.
4. More powerful launching vehicles required.
5. High free space loss.
6. Finite number of satellites can be parked as parking longitudes are fixed.

1.3 BRIEF HISTORY

In view of the enormous advantages of satellites, many countries tried to launch their own satellites initially on experimental basis, but now it is a profitable proposition and is widely used for commercial communications and military applications. Looking back over the years, one finds the development in this field has been quite significant and speedy.

1945: Theoretical studies carried out by Clarke proving that a satellite orbiting in an equatorial orbit at a radius of 42,242 km would look as if the satellite is stationary. He also proved that three such satellites spaced at 120° apart in space could cover the whole world.

1957: Sputnik-I was launched by USSR.

1958: SCORE (Signal communication by orbiting relay equipment) was launched by USA. This satellite was used to record messages sent uplink on a carrier of 150 MHz and on request was received back at 60 wpm on a carrier of 132 MHz. The lifetime of this satellite was about 35 days.

1960: First communication satellites ECHO-I and II were launched as floating balloons. These were passive satellites.

1962: Bell laboratories launched TELSTAR-I. It was a real time broadband active satellite with on-board transponders. It was a LEO satellite with 50 MHz bandwidth and a uplink frequency of 6.389 GHz and downlink frequency of 4.169 GHz.

1963: First geostationary satellite as visualized by Clarke in 1945 called **SYNCOM** (Synchronous communication satellite) was launched jointly by NASA and defence department of US. It had uplink of 7 GHz and downlink of 1 GHz. This used FM/PSK transponders and served for two years.

1965: First communication satellite INTELSAT-I, also called **early bird**, developed by **In**ternational **tel**ecommunication **sat**ellite organization was launched. This was a joint venture of Europe and USA. It had two 25 MHz bandwidth transponders. The 6.301 GHz centre frequency transponder was used by Europe and the 6.390 GHz centre frequency transponder was used by USA. The corresponding downlinks being 4.081 GHz and 4.161 GHz, respectively. This satellite was active till 1969.

1970's: About fourteen INTELSAT series 3 and 4 satellites were launched for weather forcasting and communication.

1980's: About fifteen INTELSAT series 5 and 6 were launched for T.V. transmission, satellite switched multiple access, weather forcasting, etc. First generation Arabsat activities also started.

1990's: INTELSAT series 7 and 8 in Ku band were launched. Arabsat-2 and 3 series as well as Asia-sat first commercial Chinese launch took place.

2000: Third generation Arabsat and INTELSAT 9 series have started.

Subsequently a number of INTELSAT satellites have been parked in space during the years 1966, 1968, 1971, 1981, 1983, 1986 and onwards.

From 1976 onwards, many countries have launched their own satellites for communication applications. It was in 1980's that most of the countries realized the potential of the satellite communication and spent huge sums from their annual budget on space and satellite research.

Indian Scenario

The space program in India has come a long way from early 60's when experiments were conducted with the help of American satellite ATS-6 to indigenously designed INSAT series of satellites by the Indian space research organization (ISRO) under Government of India. Indian space research organization (ISRO), initiated a number of programs and initiated studies in this direction as early as 1962. Aryabhatta was the first step towards indiginization. This satellite was launched on April 19,

1975. The space application studies were started side by side with the help of NASA's ATS-6 (application technology satellite) during 1975–76. This program was popularly known as **SITE program**. This covered limited areas, covering 2400 villages in the states of Andhra Pradesh, Karnataka, Madhya Pradesh, Orissa, Bihar and Rajasthan. Later on in 1977–79, with the help of Franco German, SYMPHONIE, **STEP** program was launched. The then post and telegraph department gained useful experience from this program.

In 1979 remote sensing experiments were conducted using Bhaskara-I. Meanwhile Arian series of launch vehicles were developed by European space agency and they offered to send an Indian satellite free of cost. On 18th June, 1981 APPLE (Arian passenger payload experiment) satellite was launched. This was the first geosynchronous satellite. This helped ISRO, Department of telecommunication, Indian space application centre, Vikram Sarabhai space centre, etc. to carry out the space application experiments that they had taken during the STEP program.

With all these experiences and studies carried out on the different socio-economic application aspects, ISRO decided to have a multipurpose satellite instead of dedicated satellite. This was the first of its kind in the world and was called **INSAT** (Indian national satellite). INSAT-I was the first generation satellite with a weight of 1200 kg in the transfer orbit and 650 kg in the geostationary orbit. The average electrical power required was about 1000 W, mainly provided by a solar panel of about 11 sq. m.

Since then a number of such INSAT satellites have been launched. The INSAT series is multipurpose satellite catering to the needs of Department of space, Department of telecommunications, Indian meteorological department, All India Radio, Doordarshan (T.V. broadcasting agency under ministry of information) and now is also shared by private operators.

INSAT system has virtually revolutionized the long distance voice communication and television broadcasting in India. With INSAT-2 having five T.V. channels, it is a boon for long distance coverage from South-east Asia to Middle East in the areas of education, entertainment, sports, etc. Other than communication, INSAT is serving many applications, some of which are highlighted below:

- National informatics centre network (NICNET) is an interactive data communication network. It has helped in socio-economic growth. Customized master earth stations support thousands of remote duplex small earth stations. The master station is located in the country's capital (New Delhi) with a host computer and connected to all district head quarters through INSAT.
- Satellite based rural telegraph network (SBRTN) is a low cost digital messaging network operating in TDM/TDMA mode. It uses C-band. All rural telegraph terminals (RTT) are connected through a master HUB.

- Radio broadcast of message and DATA for the benefit of subscribers to this service. All the PTI (Press Trust of India) bureaus are connected through the INSAT network.
- Meteorological data transmission, standard time and frequency is another service provided by INSAT.
- In some INSATs there is an automatic remote DATA collection service called **Data Collection Platform (DCP)**. It supports 406 MHz, search and rescue beacons. It also has the disaster warning system, which has been highly useful in coastal and north-eastern areas.

Milestones of Indian Space Programs

1962: Indian national committee for space research (INCOSPAR) formed by the Department of atomic energy and work on establishing Thumba equatorial rocket launching station (TERLS) started.

1963: First sounding rocket launched from TERLS on Nov. 21st.

1965: Space science and technology centre (SSTC) established in Thumba.

1967: Satellite telecommunication earth station set up at Ahmedabad.

1968: TERLS dedicated to United Nations on Feb. 2nd.

1969: ISRO formed under Department of atomic energy on Aug. 15th.

1972: Space commission and department of space set up. ISRO brought under DOS on June 1st.

1972–76: Air-borne remote sensing experiments.

1975: ISRO became government organization on April 1st. First Indian satellite, Aryabhatta launched on April 19th.

1975–76: Satellite instructional television experiment conducted.

1977: Satellite telecommunication experiments project carried out.

1979: Bhaskara-I, an experimental satellite for earth observation launched on 7th of June. First experimental launch of sunsynchronous launch vehicle-3 (SLV-3) for Rohini technology payload.

1980: Second experimental launch of SLV-3. Rohini satellite successfully placed in orbit on July 18th.

1981: With the help of first developmental SLV-3. RS-D1 placed in orbit May 31st. Apple, an experimental geostationary communication satellite successfully launched on June 19th. Bhaskara-II launched.

1982: INSAT-1A launched on April 10th. Deactivated on Sept. 6th.

1983: Second developmental SLV-3 launched. RS-D2 placed in orbit on April 17th. INSAT-1B, launched on Aug. 30th.

1987: First developmental ASLV launched on March 24th with SROSS-1 satellite on-board. Satellite could not be placed in orbit.

1988: Launch of first operational Indian remote sensing satellite, IRS-1A on March 17th. Second developmental launch of ASLV with SROSS-2 on-board on July 13th.

1990: INSAT-1D launched on June 12th.

1991: Launch of second operational remote sensing satellite, IRS-1B on August 29th.

1992: Third developmental launch of ASLV with SROSS-C on-board on May 20th. Satellite placed in orbit. INSAT 2A, the first satellite of the indigenously built second generation INSAT series, launched on July 10th.

1993: INSAT-2B, second satellite in INSAT-2 series launched on July 23rd. First developmental launch of PSLV with IRS-1E on-board on Sept. 20th. Satellite could not be placed in orbit.

1994: Fourth developmental launch of ASLV with SROSS-C2 on-board on May 4th. Satellite placed in orbit. Second developmental launch of PSLV with IRS-P2 on-board on Oct. 15th. Satellite successfully placed in polar sunsynchronous orbit.

1995: INSAT-2C, the third satellite in INSAT-2 series, launched on Dec. 7th. Launch of third operational IRS, IRS-1C on December 28th.

1996: Third developmental launch of PSLV with IRS-P3 on-board on Mar 21st. Satellite placed in polar sunsynchronous orbit.

1997: INSAT-2D, the fourth satellite in INSAT series, launched on June 4th. Becomes inoperable on October 4th, ARABSAT-1C, since renamed INSAT-2DT, was acquired in November 1997 to partly augment the INSAT system. First operational launch of PSLV with IRS-1D on-board on Sept. 29th. IRS-1D satellite was placed in orbit.

1998: INSAT system capacity augmented with the readiness of INSAT-2DT acquired from ARABSAT.

1999: INSAT-2E, the latest in multipurpose INSAT-2 series, launched by Ariane from Kourou French Guyana on April 3rd. IRS-P4 (OCEANSAT) launched by Polar satellite launch vehicle (PSLV-C2) along with Korean KITSAT-3 and German DLR-TUBSAT from Sriharikota on May 26th.

2000: Geosynchronous launch vehicle launched from SHAR centre. INSAT-3B weighting 2070 kg and GSAT-1 launched.

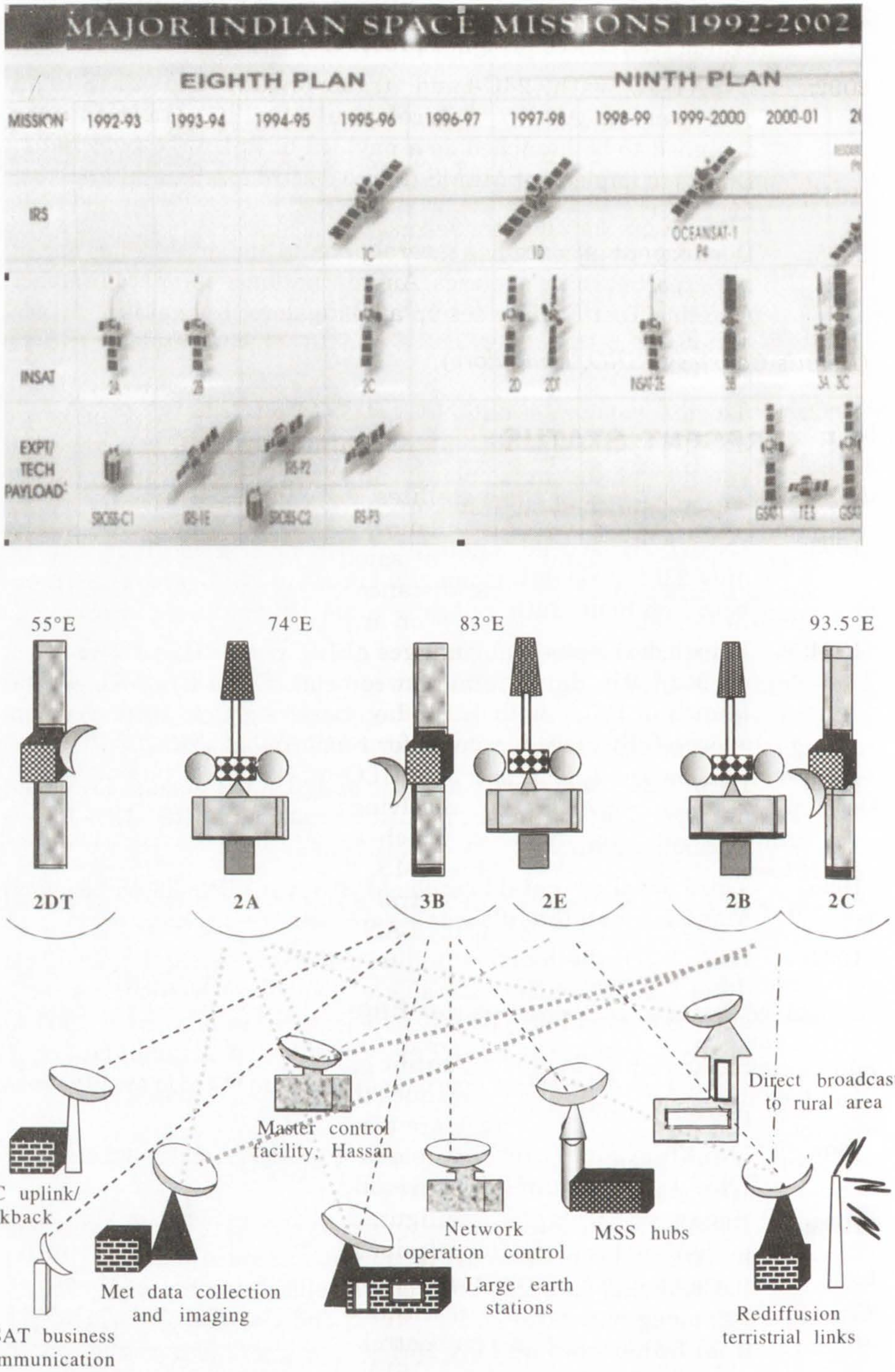


Figure 1.2 Indian space programmes.

2001: Technology experiment satellite designed and developed to evaluate advanced designed procedures.

2002: INSAT-3C with 24C-band transponders and Z, S-band transponder. Also a meterological satellite METSAT was designed to be launched as a payload of PSLV-C4 from India. Efforts to implement MEMS (Micro electro mechanical systems) for ST&C.

2003: Department of space has several patents and qualified as one of the export earning agencies. An international standard compact Antenna Test Facility set-up at Bangalore, Karnataka.

(Details Courtesy ISRO, Bangalore)

1.5 PRESENT STATUS

From 1960s, the man made satellites have taken long strides in communication, navigation, surveillance, weather prediction, explorations, etc. The major applications of satellite are their usefulness in telecommunication such as long distance telephony, radio link, data communication, television transmission and so on. When a country uses satellites, it has a number of advantages over terrestrial networks.

Point to point communication between countries using INTELSAT or Molniya are things of the past. Today more than 100 countries are taking advantage of satellite systems for numerous applications for the welfare of the mankind. The concept of GLOBAL VILLAGE has emerged because thousands of satellites are revolving round the earth. Today there are satellites in space segment, which are dedicated meteorological satellites like TIROS, WMO, ATS, GMS, ETC. Earth resource investigating satellites that use Multi spectral scanner (MSS) transmit data about water, soil and vegetation like LANDSAT.

Effect of Space Technology on Engineering

Apart from communication and scientific explorations, satellite research and technology has created new avenues in most of the engineering and technological fields, some of which are discussed here.

Spacecraft designs have put in new thoughts and developments under aerodynamics. The computing resources have been augmented to simulate flows over complex configurations. In the area of flight mechanics, steering and trajectory design, dynamic analysis for various separation systems have been carried out. Important activities carried out during recent year include the realization of on-board hardware and finalization of software modules for control, digital autopilot software and inertial guidance systems. In India GSLV-D1 flight, system is a classic example. Telemetry, tracking and telecommand (TTC) packages have also been realized. A video imaging system is being developed for monitoring on-board events like stage separations, strap-on separation and heat shield separation during launch vehicle missions.

Communication network, base-band for geomobile applications, satellite switched network, microwave photonics for spacecrafts, GPS simulator, spacecraft control system, development of microprocessor system, fault tolerant system, precision fault tolerant system, etc. are in progress. Advent of satellite communication has opened new gates in electro-optics and sensors such as multi spectral microwave radiometers, very high resolution radiometers (VHRR), charge coupled device cameras scatter meter, altimeters, optic gyros, miniature earth sensors and pyro-electric earth detectors.

Composites are on the top priority list of many of the space agencies. The need for newer materials that are light weight, heat resistant, environment friendly, flexible but sturdy, have good dielectric properties has brought a new dimension in this area. Realizations of all systems like nozzles, motor cases and igniter motor cases of solid motors for launch vehicles have been developed. Composite subsystems including antenna reflector and CFRP support structure for Multifrequency scanning microwave radiometer (MSMR) payload have been realized. Design and fabrication of titanium lined kevlar/epoxy pressurant tanks, divergent assemblies of nozzles for air breathing propulsion test modules have been fabricated. Composite elements like solar panel substrates, yokes, antenna reflectors and pultruded elements have been developed.

Apart from communication and networking, satellite has been effectively used for space sciences applications and research. Some of the areas where satellites have been already extensively used are astronomy and astrophysics, study of planetary atmospheres, study of Leonid showers, solar system studies, laser physics, and quantum optics as well as earth sciences. Training and development communication channel provides one-way video and two-way audio teleconferencing network for interactive training and education. Open universities can use these facilities. These facilities can also be used for rural development, computer connectivity, telehealth and telemedicine services. Space research and science has brought many new materials for day to day use of common man.

1.6 FUTURE TRENDS

Why Use Satellite for Communication?

1. Active satellites are usually wide band in nature. Each transponder is capable of accommodating several channels.
2. The cost of sending messages to long distances is equal to that via radio-links for small distances. Thus, satellites are

economical for long distance communication, cutting down the maintenance cost drastically.

3. Satellite transmission is not restricted by geographical conditions. They are particularly useful where cable networks have not yet been established or where terrains and oceans make places inaccessible.
4. Communication between two points is possible in a satellite as long as the two earth stations fall within a given view angle of satellite antenna.
5. Unlike in case of terrestrial network we can use carrier to send a number of message signals, cutting the cost of equipment.
6. Satellites serve small and large towns alike with identical standard of service and hence help in the development of country as a whole. The communication is distance insensitive and even costs less.
7. In addition, the communication satellites can be used for other services also like education, data collection, meteorology, search and rescue work.

One problem that makes satellite unsuitable for some applications is the time taken for a signal to travel to satellite and return to earth station (delay). Any message will take about 650 ms for hear and reply; hence, the speed of transmission reduces.

The only competitor to space communication is the fibreoptic communication. Countries in which good cable networks have already been established, fiberoptic communication may help, but in countries which are developing or are underdeveloped and where there are lots of hilly regions and terrains the only answer to reliable and economic communication is satellite communication. It has not only revolutionized long distance communication but also is assisting in timely help during natural disaster warning and rescue operations.

With the advent of satellite communication, centralized satellite database may be available which will help global development. As such a scenario can emerge only if the relevant standards are set up overcoming the regional differences for the upliftment of mankind. Global positioning satellites for navigational applications and astronomical studies will be quite helpful.

Other trends are maritime mobile satellite services, aeronautical mobile satellite services and land mobile satellite services. In these services, LEO satellites are quite useful. Organizations working in this area being, International maritime satellite organization (INMARSAT), International civil aviation organization (ICAO), American mobile satellite corporation (AMSC) and so on. Another area where LEO satellites can be effectively used is the cellular phones; a typical example is the Iridium project. Apart from the geostationery satellites' achievements, the low earth orbit satellites (LEO) would be very helpful in linking rural and isolated villages. This is because the earth station requirements for these satellites are very less, as they orbit at a perigee of 700 to 1500 km.

The future predictions show that there could be a three-tier system in space.

1. Low altitude constellation (LAC)
2. Semisynchronous constellation (SC)
3. Geosynchronous constellation (GSC)

Applications

LAC: Mobile voices, global-paging, low altitude earth observatories.

SC: Precision ranging signals for radio navigation, disaster detection, communication relay.

GSC: GPS transponder links, weather observatories, precision global time synchronization.

It is envisaged that the satellite communication will move towards personal communication with space switching and direct broadcast, rather than just being a repeater. Improvements in the higher frequency (microwave) technology will also improve the Bandwidth capabilities. Thrust now would be, therefore, towards laser communication link through satellite. It is for the member countries of the International telecommunication union (ITU) to solve some upcoming problems like limited parking place, space debris, interference, national security problems, etc. What is worrying is the ever-increasing man made space debris and their ever-increasing concentration that will take place during the 21st century.

Spacecraft Cluster in Space

With the crowding in the geostationary orbit (GSO), it is inevitable that a cluster of satellites will have to be located and maintained in a given longitudinal slot. Though the satellites are not connected physically, they would lie within the beamwidth of the earth station antenna thereby increasing the capacity multi-fold as far as the user is concerned. From the mission control point of view, the station keeping of this cluster is much more difficult than that of an individual satellite. Coordinated station keeping (SK) strategies have to be evolved using proven computer simulations and then adopted for operations. Inter-satellite ranging will help in preserving the required minimum separation between the satellites.

SUMMARY

In this chapter we have learnt the basic definitions of space and satellite. Satellite links and orbits were also classified. The road map of satellites was also discussed with emphasis on Indian space and satellite projects. The advantages of satellite communication were also brought out with comments on future trends.

REVIEW QUESTIONS

1. Define the terms space and satellite.
2. What is the dependence of space on altitude?
3. Explain different satellite links and show how satellite helps in extending the coverage.
4. What are the advantages of geosynchronous satellites?
5. In what way satellite has an edge in communication compared to other methods?
6. What is the need of satellite communication in the modern world?

2 Orbit, Launch and Control

2.1 INTRODUCTION

In this chapter we will define important parameters of orbiting satellites, derive certain relations and see factors that affect the orbit. We will also study typical launching procedures and the control of satellite from central earth station. In the end of the chapter typical structure of satellite will also be seen.

2.2 SATELLITES IN ORBIT

In the beginning of the 17th century, it was Kepler who predicted the motion of two bodies in space by the observations he made. Later on these laws were proved by Newton. Since it was Kepler's work that assisted the modern day scientists to predict and design the orbiting satellites, the laws are still known as **Kepler's laws** or **Kepler's principles** of orbiting bodies. He predicted that when the two bodies are in space uninfluenced by aerodynamic lift and other disturbances they are acted upon by mutual gravitation.

Some Important Definitions

In this section let us study some important definitions and understand important terms that would be used in subsequent discussions.

Orbit. When a body A revolves around another body B, body A is said to be orbiting around body B. Body A is called the **satellite** of body B. B can be termed as **primary body** or mother body.

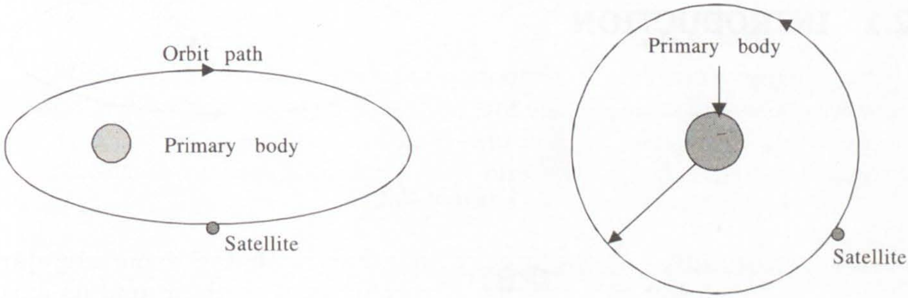
Orbit path. The path followed by an orbiting body is called **path of orbit**. Depending on the shape of the path the satellite follows, orbit path is further categorized as elliptical or circular orbit.

Elliptical orbit. Every satellite revolves with a certain angular velocity ω around the primary body. If ω varies the path tends to become elliptical (discussed later in this chapter). There are certain disadvantages of elliptical orbit which are discussed hereinafter:

1. Velocity of satellite changes depending on the orbit path parameters.
2. As the distance varies power received also varies.

Circular orbit. When angular velocity ω remains constant the path of orbit is circular. For communication/broadcast satellites, circular orbit is preferred, as power requirement remains constant.

Radius of orbit. In a circular orbit the primary body lies at the centre of the circular path and the satellite on the circumference of the circle. Hence the radius of this circle is called **radius of orbit**. [See Figure 2.1(b)] Evidently elliptical orbit has variable radius.



(a) Elliptical orbit (b) Circular orbit

Figure 2.1 Radius of orbit.

Orbit plane. The plane in which the satellite orbits is called the **plane of orbit.** A man made satellite can lie in any of the following planes depending on the application:

Polar plane. It is the plane assumed to be cut along the poles of the earth. If one sees this plane as a section from east or west it looks to be a circle of radius r_e (where r_e is radius of earth). [See Figure 2.2(a)].

Equatorial plane. It is the plane assumed to be cut along the equator. If one sees this section from poles it looks to be a circle of radius r_e. A satellite revolving in this plane is called **equatorial satellite**. A special case of a satellite orbiting in this plane is the geostationary satellite. [See Figure 2.2(b)]

Inclined plane. The plane of orbit, which is at an angle to both polar plane and equatorial plane, is called **inclined plane.** [See Figure 2.2(c)]

Prograde. When a man made satellite orbits in the same direction as the direction of revolution of earth, the orbit is called **prograde orbit**. Launching of the satellite is necessarily in prograde orbit. [See Figure 2.2(d)]

Retrograde. When a man made satellite orbits in the opposite direction than that of the direction of revolution of earth, the orbit is called **retrograde orbit**. [See Figure 2.2(d)]

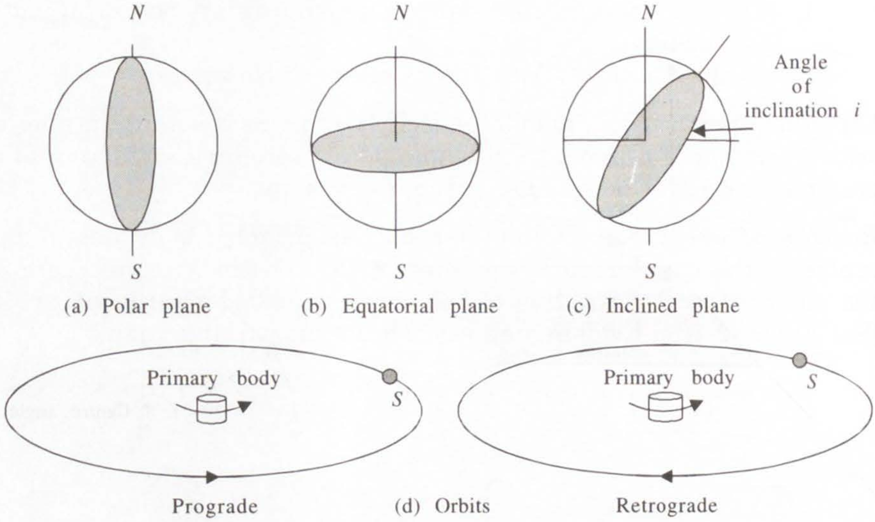


Figure 2.2

Geosynchronous. A satellite which moves with the same angular velocity (in the orbit path) as that of revolution of earth around its axis of rotation (pitch axis), is called **geosynchronous**. A geosynchronous satellite has an orbit period of 24 hours.

Geostationary orbit. A satellite which is geosynchronous in the equatorial plane and additionally has prograde circular orbit, is said to be **geostationary**. The minimum radius of orbit to achieve this condition is 42000 km.

Sub-satellite point. The imaginary point S' on the earth's surface created by a normal drawn from the centre of the satellite to the centre of the earth is called **sub-satellite point**. [Refer Figure 2.4]

Azimuth. The angle made eastward from a geographic north by an earth station to satellite along the horizontal plane is called **azimuth angle.** As the sub-satellite point is directly below the satellite on the horizontal plane, azimuth is also the angle from earth station eastward to sub-satellite point. [See Figure 2.3]

Elevation angle. The angle subtended by an antenna looking at the satellite from the horizontal plane in the vertical direction is called the **elevation angle**. It is also called **earth-satellite angle**. [See Figure 2.3]

Look angle. The angle subtended and determined by azimuth and elevation angle.

Slant range. The line of sight distance from a particular point on the earth to satellite is called **slant range**.

Height of satellite. It is the height h or altitude of satellite from the

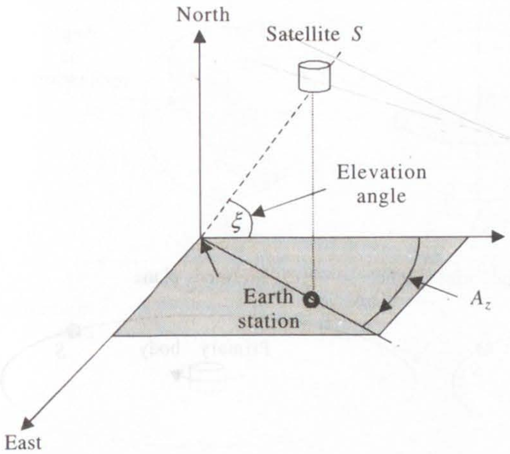


Figure 2.3

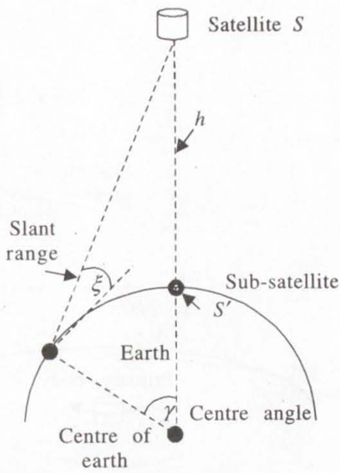


Figure 2.4

sub-satellite point on the surface of earth to satellite. In an **elliptical orbit** this varies. Radius of orbit is the sum of height and the radius of earth, $(r_e + h)$.

Ascending node. During each orbit a satellite crosses the equatorial plane twice, once while going from south to north and once travelling from north to south. The point of intersection of orbit path with the equatorial plane while travelling from south to north is called **ascending node**. The ascending node is specified by the right ascension Ω. [See Figure 2.5]

Descending node. The point of intersection of orbit path with the equatorial plane while travelling from north to south is called **descending node**. [See Figure 2.5]

Perigee. In an elliptical orbit the distance of satellite from primary body varies, hence a point in orbit when satellite is nearest to the earth or primary body is called **perigee**. The perigee depends on the eccentricity and is equal to $a(1 - e)$, where a is the major axis of the ellipsoid and e is the eccentricity.

Apogee. It is a point in orbit when the satellite is farthest from the earth. The apogee height is given by $a(1 + e)$. Note, in case of circular orbit apogee and perigee coincide as e is zero.

Inclination. The angle between orbital plane and earth's equatorial plane is called **angle of inclination**. [Refer Figure 2.5]

Satellite axes. The satellite being in space, to keep the spacecraft in proper position it is necessary to define the axes that control the spacecraft. The three axes of control are roll, pitch and yaw.

Roll. The tangent along the orbit path is called the **roll axis** which is

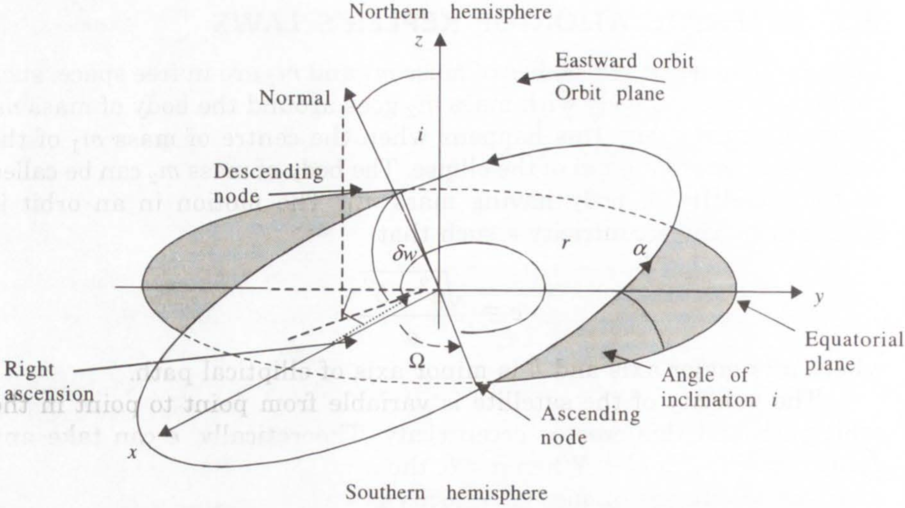


Figure 2.5

shown in Figure 2.6. Around the roll axis the satellite can either tilt towards north or south. A tilt towards north is said to be **positive roll** while a tilt towards south is called **negative roll**.

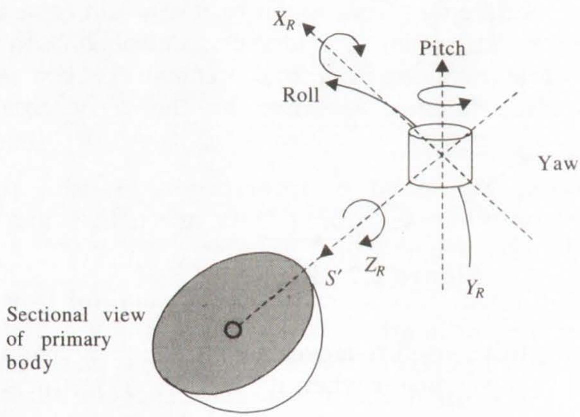


Figure 2.6

Pitch. The axis of satellite perpendicular to the orbit path is called **pitch axis** as exhibited in Figure 2.6. A satellite rotates around the pitch axis. The pitch rotation can be either eastwards called **positive pitch** or westwards called **negative pitch**. Earth's pitch axis is polar axis.

Yaw. The third axis of satellite is the axis, which is directed towards the centre of the earth along this axis the satellite can either rotate clockwise or anticlockwise hence it is called **yawing** [Refer Figure 2.6]. A clockwise rotation is positive yaw and anticlockwise rotation is negative yaw.

2.3 INTERPRETATION OF KEPLER'S LAWS

Law 1. Whenever two bodies of mass m_1 and m_2 are in free space, such that $m_1 >> m_2$, the body with mass m_2 goes around the body of mass m_1 in an elliptical orbit. This happens when the centre of mass m_1 of the body lies at one of the foci of the ellipse. The body of mass m_2 can be called as the **satellite** of body having mass m_1. The motion in an orbit is governed by the eccentricity e such that

$$e = \frac{\sqrt{a^2 - b^2}}{a}$$

where a is major axis and b is minor axis of elliptical path.

The velocity of the satellite is variable from point to point in the orbit path and this creates eccentricity. Theoretically, e can take any value between 0 and 1. When $a = b$, the orbit is circular and there is no eccentricity (change of angular velocity is zero).

Law 2. If the satellite travels from X to Y in an arc distance S_1 in one second during its orbit and during the same period travels arc of distance S_2 (X' to Y') then the area covered under OXY is equal to area covered under $OX'Y'$, as shown in Figure 2.7.

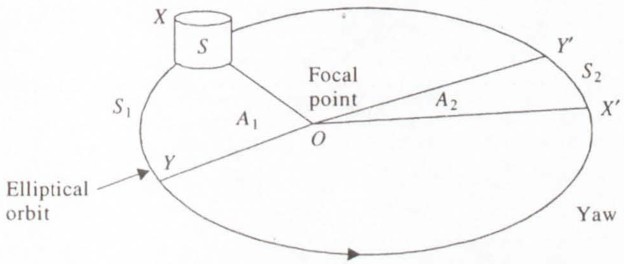


Figure 2.7 Kepler's law.

That means as the satellite moves away from the earth its velocity decreases, while it moves faster when it is nearer to the primary body.

Law 3. If the period of orbit of satellite is t_0 and the mean distance between the primary body and satellite is d_0, then square of the periodic time of orbit is proportional to the cubic distance. Such that

$$t_0^2 = ad_0^3$$

where a is called **orbital constant** or **Kepler's constant**.

Satellites in Circular Orbits

Most of the satellites used for communication purpose move in circular orbit and are preferred to be parked in geostationary orbit. If the satellite is in any other orbit the relative velocity between earth station and the satellites will not be zero and more than one satellite will be required for uninterrupted communication. Think of what would happen if every country depends on satellites not in geostationary orbits? Therefore, our main interest would be to study satellites in circular orbit in the equatorial plane, moving in space, free from aerodynamic lift or any influence of external torques.

Let M be the mass of earth and m be the mass of satellite. If the satellite is moving with an angular velocity ω under the influence of earth's gravitation G and its own gravitation, the satellite would go into circular orbit provided it satisfies the conditions derived hereunder. [Refer Figure 2.8]

For an orbit height of h or orbit radius $(r_e + h)$, the velocity of satellite would be

$$v_s = \omega(r_e + h)$$

where r_e is the radius of earth.

If the satellite has to orbit stably, then the centrifugal force that tries to take away the satellite should be equal to the centripetal force with which the satellite is attracted towards the earth.

If F_1 is the force acting upon by satellite due to its own mass m and velocity v, the satellite tends to pull away from earth, such that

$$F_1 = \frac{mv^2}{d} = \frac{mv_s^2}{r_e + h} = \frac{m\omega^2(r_e + h)^2}{r_e + h}$$

$$F_1 = m(2\pi/T)^2\ (r_e + h) \tag{2.1}$$

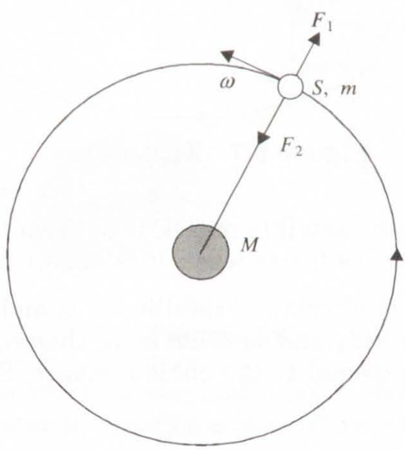


Figure 2.8 Orbit parameters calculation.

On the other hand, F_2, the force that attracts the satellite towards earth is given by

$$F_2 = \frac{GMm}{d^2} = \frac{GMm}{(r_e + h)^2} \tag{2.2}$$

In equilibrium the centrifugal force should be equal to the centripetal force, for example, if a stone tied to a string is made to orbit by rotating the hand holding it, the stone will go round and round till the force acting on it due to motion of hand is equal to the inertial force that is trying to take the stone away. In conclusion,

$$F_1 = F_2$$

$$\therefore \quad \frac{m(2\pi)^2\,(r_e + h)}{T^2} = \frac{GMm}{(r_e + h)^2} \qquad 2.3$$

If any one of the forces increases or decreases, the stone no longer remains in orbit. For example, if the motion of hand disturbs or reduces, the stone will fall on the head or on the other hand if the string breaks F_1 becomes very large and F_2 tends to zero making the stone fly away.

Rearranging Eq. (2.3), the time of orbit would be

$$T_s^2 = \frac{4\pi^2\,(r_e + h)^3}{g_0} \qquad 2.4a$$

$$T_s = \frac{2\pi}{\sqrt{g_0}}(r_e + h)^{3/2} \qquad 2.4b$$

where $g_0 = GM$ called the **gravitational coefficient** or **Kepler's coefficient**.

For earth, $G = 6.672 \times 10^{-11}$ newton metre/kg^2 and $M = 5.97 \times 10^{24}$ kg. Therefore,

$$g_0 = 3.9861 \times 10^5 \text{ km}^3/\text{s}^2$$

Is it not the same as predicted by Kepler in his third law?

i.e.

$$t_0^2 = ad_0^3$$

$$\text{where } a = \frac{2\pi}{\sqrt{g_0}}$$

Equation (2.4b) indicates that, as the radius of orbit increases, the time of the orbit also increases.

Now, let us find the velocity of satellite. Substituting $v_s = \omega(r_e + h) = (2\pi/T)(r_e + h)$, we get

$$v_s = \sqrt{\frac{GM}{(r_e + h)}} = \sqrt{\frac{g_0}{(r_e + h)}} \qquad 2.5$$

This shows with the increase in orbit radius the velocity of the satellite decreases as predicted by Kepler in his second law.

For such a satellite to look stationary in geostationary orbit, it is necessary that the relative velocity between the orbiting satellite and orbiting earth (earth orbits round the sun) should be zero. That means, at sub-satellite point S' the velocity of the satellite and earth should be same, i.e., 7.905364 km/s and as the satellite goes farther away from the earth the velocity should correspondingly decrease. Also if the satellite has to be geosynchronous, the time taken for one full orbit should be 24 hrs. The solar day of 24 hrs does not give exact calculations as both sun and earth are moving objects, therefore, sidereal day referred to fixed stars is used for better accuracy in orbiting satellites. A sidereal day is of 23 hrs 56 mins and 4 seconds which is 0.9972 times the solar day.

Additionally for the satellite to orbit in space, it should also revolve round its pitch axis like a top to create necessary gyroscopic stiffness. Imagine a revolving top, when this top attains a certain angular velocity, it revolves around its pitch axis stably without falling and at higher speeds even leaves the surface. This is possible because of the stiffness it attains due to high angular velocity. But as the velocity decreases the top tends to wobble. This is analogous to a revolving satellite.

Example 2.1

A satellite is orbiting in a geosynchronous orbit of radius 41500 km. Find the velocity and time of orbit. What will be the change in velocity if the radius reduces to 36000 km. If $g_0 = 398600.5$ km^3/s^2.

Solution

Given:

The gravitational coefficient $g_0 = 398600.5$ km^3/s^2

Radius of orbit = 41500 km

Since

$$v_s = \sqrt{\frac{g_0}{(r_e + h)}} = \sqrt{\frac{398600.5}{41500}} = 3.099 \text{ km/s}$$

and

$$\text{Period of orbit } T_s = \frac{2\pi d^{3/2}}{\sqrt{g_0}} = \frac{2\pi(41500)^{3/2}}{\sqrt{398600.5}} = 84136.26 \text{ s}$$

For $(r_e + h) = 36000$ km

$$v_s = \sqrt{\frac{g_0}{(r_e + h)}} = \sqrt{\frac{398600.5}{36000}} = 3.3274 \text{ km/s}$$

Thus,

Increase in velocity = 3.3274 – 3.099 = 0.2284 km/s

Ans.

Some important parameters of circular orbit geosynchronous satellite are given in Table 2.1

Table 2.1 Parameters of Circular Orbit Geosynchronous Satellite

Quantity	*Equation*	*At sub-satellite point*	*At geostationary orbit*	*Units*
Velocity	$v_s = \sqrt{\frac{g_0}{(r_e + h)}}$	7.905364	3.074689	km/s
Orbit period	$T_s = \frac{2\pi d^{3/2}}{\sqrt{g_0}}$	5069.347	86164.091	s
Angular velocity	$\omega_s = \frac{\sqrt{g_0}}{d^{3/2}}$	0.001239	72.9211×10^{-6}	rad/s
Acceleration	$a = \frac{g_0}{d^2}$	9.79×10^{-3}	0.22×10^{-3}	km/s^2

Practical Problems in Space and Orbit Perturbations

As a first approximation, we have assumed that only mutual gravitational forces of the two bodies in space (earth and satellite) act upon the orbiting satellite in space. The orbit described so far is Keplerian orbit. However, the Keplerian orbit is ideal in the sense that it assumes that the earth is a uniform spherical mass and that the only force acting is the centrifugal force, resulting from satellite motion balancing the gravitational pull of the earth.

In actual practice it is not true because any satellite in space is also acted upon by torque due to other external as well as internal forces.

External torques

1. Gravitational effect of other planetary bodies like sun, moon and other heavenly bodies.
2. Non-spherical earth.
3. Atmospheric drag (only in low orbits).
4. Aerodynamic forces (only in low orbits).
5. Solar pressure on the solar cell panel.
6. Magnetic forces acting on the satellite due to earth's magnetic fields.

As is seen above, the gravitational force on the satellite is given by

$$F = \frac{g_0 m}{d^2} \tag{2.6}$$

The earth's polar diameter is about 42 km shorter than the equatorial and also the earth is not spherical but oblate spheroid, as shown in Figure 2.9. This causes variation in *F*. As an example INSAT 2A is parked at 74° east but due to anomalies in the centripetal force it

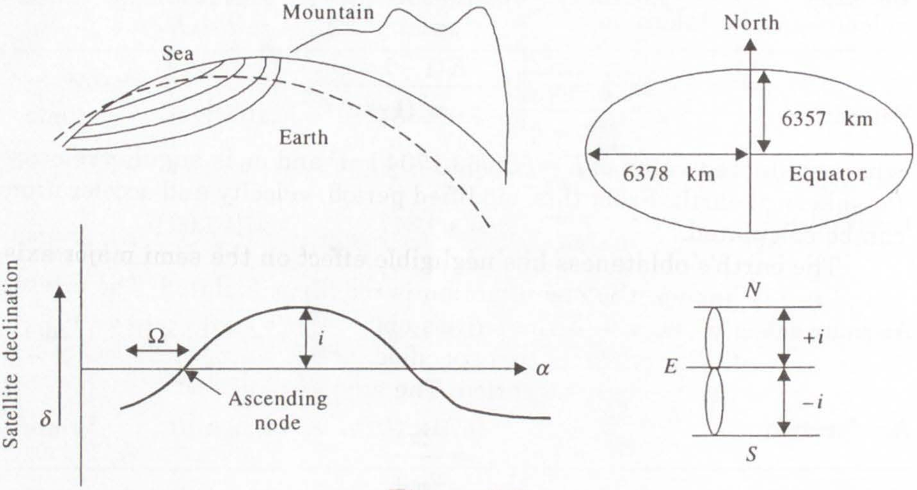


Figure 2.9

drifts from its place and needs correction and control. We also find that the gravitational effect of sun, moon and atmospheric drag are quite significant depending on the position of the satellite. The gravitational pulls of sun and moon have negligible effect on LEO satellites but they do affect satellites in the geostationary orbit, therefore, there is no ideal geostationary satellite in practice. Atmospheric drag, on the other hand, has negligible effect on geostationary satellites but does affect low orbiting earth satellites below about 1000 km. The effect on the equatorial plane orbiting satellite (perfect geostationary) is negligible due to earth's oblateness but as soon as the satellite attains an inclination due to lunar and solar perturbations the earth starts influencing the satellite. Due to these gravitational forces the satellite tends to incline and the pitch axis tilts (an essential requirement of the geostationary orbit is that inclination should be zero) that means that a geostationary satellite tends to become geo-asynchronous. The net result is that the satellite oscillates in the north-south direction as it moves forward in its orbit path forming a figure of eight over the day. This oscillation is called **north-south oscillation**. In order to limit this inclination and hence oscillations within ±0.75° to ±1.00° over a year, orbit control thruster motors have to be used. The ground-tracking antenna practically moves north-south only, as the east-west oscillation which is twice a day for geostationary satellites, is negligible. Also the earth's ellipticity causes the satellite to drift eastward as it moves along the orbit. The most stable geostationary satellites are 79° east and 252.4° east.

From Figure 2.5, $i = 90 - \delta_w = \cos^{-1} W_z$, where W_z is the Z axis component of orbit normal.

The angular velocity of a geostationary satellite, $\omega_s = \sqrt{g_0/d^3}$ will be affected by the above factors. Studies by individuals and different agencies have shown and are accepted by designers that modified value of angular velocity can be taken as:

$$\omega_{\text{mod}} = \omega_0 \left[1 + \frac{K(1 - 1.5 \sin^2 i)}{a^2(1 - e^2)^{3/2}} \right] \qquad 2.7$$

where evaluated value of $K = 66{,}063.1704$ km^2 and ω_0 is angular velocity for spherical earth. From this, modified period, velocity and acceleration can be calculated.

The earth's oblateness has negligible effect on the semi major axis a and if a is known, the mean motion is readily calculated. The orbital period taking into account the earth's oblateness is termed as **anomalistic period.** The mean motion specified in the NASA bulletins is the reciprocal of the anomalistic period. The anomalistic period is

$$t_A = \frac{2\pi}{\omega_{\text{mod}}} \qquad 2.8$$

where ω_{mod} is in radians per second.

If ω_{mod} is known, one can solve Eq. (2.7) for a by finding the root of the equation, keeping in mind that ω_0 is also a function of a.

Oblateness of the earth also produces regression of nodes and rotation of apsides.

As discussed earlier the nodes are supposed to be on the intersection of orbit path and equatorial plane but during orbit the line joining the nodes rotates about the centre of earth and due to oblateness shifts the positions of ascending and descending nodes. This makes the nodes look to slide along the equator and is called **regression of nodes**. The word *regression* is used because if the orbit is prograde the nodes slide eastward and if retrograde westward, exactly opposite to the direction of motion of satellite. This depends on the inclination of plane of orbit.

The line of apsides is defined as the *line joining the perigee and apogee in an elliptical orbit*. Due to oblateness the circular orbit tends to become elliptical and apsides exist. Thus, the orbital parameters change, this causes the line of apsides to rotate. The detail calculations can be referred to in reference.

For satellites in the low earth orbit (below 1000 km), the effect of atmospheric drag is significant and it tries to slow down the satellite. This causes change in eccentricity and position of apogee changes during every successive revolution. This results in change of major axis and is approximately given by

$$a_{\text{mod}} = a_0 \left(\frac{\omega_0}{\omega_0 + \omega_0' (t - t_0)} \right)^{2/3} \qquad 2.9$$

The solar pressure is another aspect to be considered while designing the shape and architecture of the satellite. Since the satellite is in an environment almost free of all forces, the sunrays (which essentially consist of photons) when fall normally on the solar panel, exerts a typical force of 4.63×10^{-6} newton/m^2 or 95.5 lbs/ft^2. This is quite enormous in space particularly in case of geosynchronous orbits where the sunrays always fall normal to the solar panels. Even though this seems to be minute, they are sufficient to tilt the satellite in space. To compensate for such forces solar sails or compensating panels are necessary.

The magnitude of the earth's magnetic field on satellite, in geostationary orbits is around 0.1×10^{-6} tesla and is not sufficient to disturb the geostationary orbit but is definitely important in lower earth orbits. INSAT's disturbance torque due to all the above effects is estimated to be around 3.6×10^{-5} Nm. Though this is very small it has significant effect on spacecraft in space.

The radio visibility of the satellite from a ground station depends on the angular separation between the station and the sub-satellite point (SSP) and on the altitude of the satellite. The SSP latitude oscillates with a maximum value equal to the inclination of the orbit at the frequency of orbital revolution. For near-earth satellites, the SSP longitude varies over all the values and hence visibility from a given ground station occurs for short durations (typically 10 to 15 minutes) a few times in a day. On the other hand for a geostationary satellite, there is little relative motion between the earth and the satellite and the visibility is continuous. This distinction has obviously an impact on the control centre operations.

Influence of internal torque

The internal torque that influences the spacecraft are:

1. Thruster misalignment
2. Fuel movement in spacecraft

Ideally the thruster is used to control the north-south axis of the satellite and the force that acts due to this should pass through the centre of mass of the satellite but if there is any minute misalignment, it will produce a torque that may change the stability of the satellite.

Fuel movement is another important factor as the satellite rotates around its own axis, the liquid hydrazine inside churns and produces a rotational torque, which may change the attitude and orbit of satellite. This is further discussed in Section 3.3.

Position of Satellite Above Earth

The position and parking place of satellite is decided by the following factors:

1. The elevation angle at which the satellite is seen from the earth station.
2. The azimuth angle which the earth station makes along the local horizontal plane from the north to east.
3. The time of occurrence of solar eclipse.

The satellite is in space and if one imagines to be sitting in the satellite and observes he would find that the location depends on the coordinates of the three axes [Refer Figure 2.10]. The angle at which the earth station is visible, is called **look angle**.

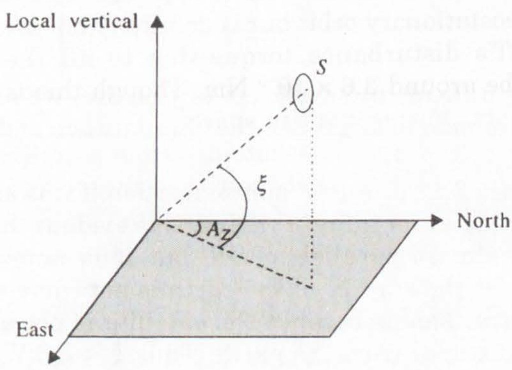


Figure 2.10

Let us assume that a satellite S is in space at the height h from sub-satellite point S', the distance of satellite is $(r_e + h)$. Let the earth station be located at a particular latitude and longitude at point E on the earth's surface. Thus, if a tangent to the surface of the earth is drawn at E and E-S are joined, the angle subtended is called the **elevation angle** (in fact if an antenna is placed at E pointing towards the satellite, the pencil beam of EM waves would subtend an angle of ξ with the earth's surface).

From Figure 2.11 if a perpendicular is dropped onto OS to fall at A

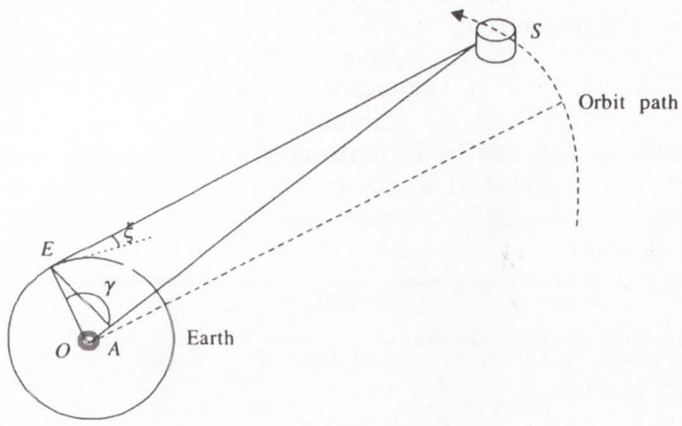


Figure 2.11

then triangle OAE is a right angled triangle and so also triangle EAS, so that

$$ES^2 = EA^2 + AS^2$$
$$= (OE^2 - OA^2) + (OS - OA)^2$$

But $OA = r_e \cos \gamma$, $OE = r_e$ and $OS = r_e + h$

$$\therefore \quad d_s^2 = [(r_e)^2 - (r_e \cos \gamma)^2] + [(r_e + h) - r_e \cos \gamma]^2$$

Let $(r_e + h) = d$, radius of orbit

$$\therefore \quad d_s = d\left[1 + \left(\frac{r_e}{d}\right)^2 - \frac{2r_e}{d}\cos \gamma\right]^{1/2} \qquad 2.10$$

Since it is difficult to measure γ in practice, we should be able to express the expression in terms of either ξ or latitude and longitude of the earth station.

From Figure 2.11 as a first approximation if it is assumed that the satellite is orbiting at an infinite radius, it is evident that $\gamma = (90° - \xi_\infty)$ because ES is almost parallel to OS, but it is noteworthy that the elevation angle at the surface of the earth is not same as it would have been at its centre. This is because the satellite is not at infinity but at a much lesser distance from the earth. Thus $\xi < \xi_\infty$. With the result, a geostationary satellite is not visible from poles and countries in the polar region; like Russia cannot take advantage of geostationary condition.

Example 2.2

A hypothetical satellite is orbiting at a distance of 68400 km. The earth station antenna makes a vertical angle of 30° for a LOS communication with this satellite. Calculate slant range for this case using first approximation?

Solution

From first approximation,

$$\varepsilon_\infty = \varepsilon = 30°$$
$$\therefore \gamma = 90 - 30 = 60°$$

Then

Slant range $d_s = 68400[1 + (6378/68400)^2 - 2(6378/68400) \times \cos 60°]^{1/2}$
$= 65444.51$ km

Ans.

Always, $d_s < d$

From Figure 2.12, we have

$$\tan \xi = \frac{AS}{EA}$$

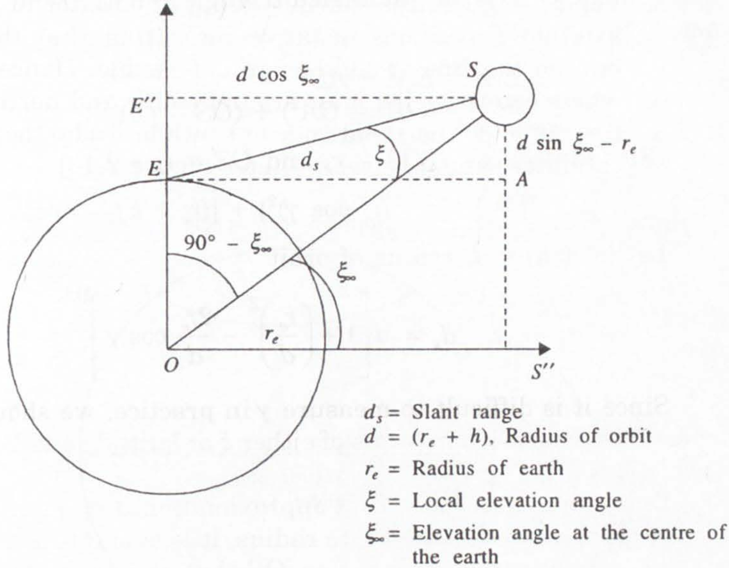


Figure 2.12

$$= \frac{d \sin \xi_\infty - r_e}{d \cos \xi_\infty} = \frac{\sin \xi_\infty - \frac{r_e}{d}}{\cos \xi_\infty} \qquad 2.11$$

This gives the relation between ξ_∞ and ξ. Typical calculated results are shown in Table 2.2.

Table 2.2 Calculated Results

ξ_∞ (in degrees)	ξ (in degrees)	*Parallax error* (in degrees)
0.0	–9.5278	9.5278
10.0	0.3374	9.6625
30.0	20.9748	9.0252
50.0	42.9422	7.0578
70.0	66.0996	3.9024
90.0	90.0000	0.0000

The difference between ξ and ξ_∞ is called **parallax error**. On calculating ξ for every ξ_∞ (see Table 2.2) from the above expression for geostationary satellite at 38000 km and earth's radius of 6378 km two things are evident:

1. The parallax error reduces and becomes zero at zenith as the satellite is directly above the earth station.

2. For $\xi_{\infty} = 0$, i.e., the satellite being at equator in geostationary satellite ξ becomes negative indicating that the satellite is beyond the line of sight or is not visible. Hence, at latitudes where countries lie on or around south and north pole regions (i.e. 80° to 90° north latitude or south latitude) the geostationary satellites cannot be seen. [Refer Figure 2.13]

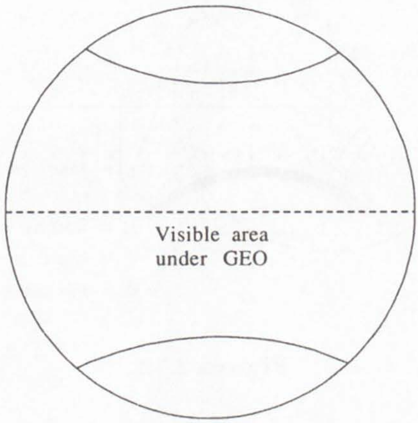


Figure 2.13

In these regions, therefore, satellites in inclined or polar orbits are used. But as they are not relatively stationary with respect to the earth station more than one satellite are required, depending on the required duration of communication and the satellite orbital constants.

In most of the geostationary satellites the usable latitude is taken as 70° for satisfactory communication.

2.4 SATELLITE VISIBILITY

Is a satellite visible from any earth station for any satellite altitude? We will now discuss two important aspects as a part of this discussion:

1. The satellite visibility angle for minimum elevation
2. The minimum elevation angle and area of coverage

Any geostationary satellite has an arc of visibility which can also be called **area of coverage or footprint**. This depends upon the height of satellite, elevation angle and the position of earth station.

Consider Figure 2.14 and applying sine rule to $\triangle OES$ or to triangle *OES*, we get

$$\frac{\sin[90° - (\gamma + \xi)]}{r_e} = \frac{\sin(90° + \xi)}{r_e + h} = \frac{\sin \gamma}{d_s} \qquad 2.12$$

$$\therefore \quad \sin(90° + \xi) = \frac{(h + r_e)}{d_s} \sin\gamma = \cos\xi \qquad 2.13$$

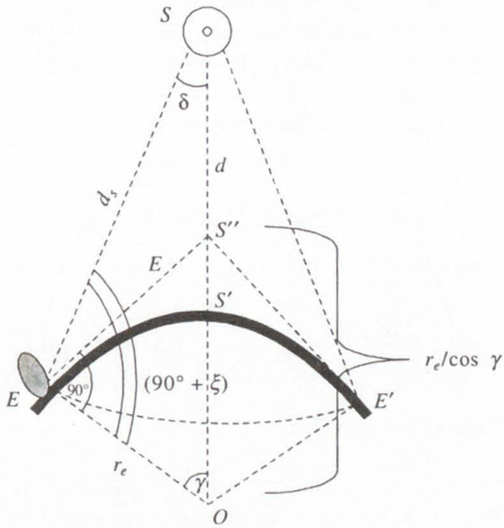


Figure 2.14

In triangle *EOS*, let us assume that $90° - (\gamma + \xi) = \delta$
Also from Eq. (2.12) and Eq. (2.13), we get

$$\sin\delta = \frac{r_e}{r_e + h} \cos\xi \qquad 2.14$$

Also, the minimum height of visibility is given by

$$d \geq r_e/\cos\gamma \qquad 2.15$$

Though Eq. (2.14) is satisfied even for $\xi = 0$, but this never happens in practice because then noise due to earth's reflections will be excessive. Hence most of the times ξ is kept more than 5°. Also the value of r_e is not constant at every point around the globe and depends upon the latitude of the earth station. Thus, Eq. (2.14) can be rewritten as:

$$\sin\delta = \frac{r_e}{r_e + h} \sin(90° + 5°) \qquad \text{(for minimum elevation angle)} \quad 2.16$$

The minimum height of satellite $h_{\min}$ is given as:

$$h_{\min} = r_e\left(1 - \frac{\sin^2\lambda_E}{298.26}\right) \qquad 2.17$$

where λ_E is longitude of earth station.

This value of δ gives the visibility angle from any earth station with minimum allowable elevation angle depending upon the locations of the earth station on the earth's surface.

Example 2.3

Calculate the slant range of a geostationary satellite orbiting at 42200 km from an earth station making an elevation angle of 25°. Also find the viewing angle of the satellite.

Solution

Given:

$$d = 42200 \text{ km}$$

Let us assume the radius of earth to be 6378 km.

Now,

$$\gamma = \cos^{-1}\left[\frac{r_e \cos \xi}{d}\right] - \xi = \cos^{-1}\left(\frac{6378 \cos 25}{42200}\right) - 25 = 57.12°$$

The slant range therefore will be

$$d_s = d\left[1+\left(\frac{r_e}{d}\right)^2 - \frac{2r_e}{d}\cos\gamma\right]^{\frac{1}{2}} = 42200\left[1+\left(\frac{6378}{42200}\right)^2 - \frac{2\times 6378}{42200}\cos 57.12\right]^{\frac{1}{2}}$$

$= 39135.637$ km

Viewing angle δ is given by

$$\sin \delta = \frac{r_e}{r_e + h} \cos \xi = \frac{6378}{42200} \cos 25 = 0.1369$$

$\therefore \quad \delta = 7.872°$

Ans.

Calculation of ξ can be carried out if the longitude and latitude of the earth station and the longitude of the geostationary satellite is known (latitude of geostationary satellite is zero?) using the equation:

$$\xi = \tan^{-1}\left[\frac{\cos \lambda_{AE} \cos \lambda - 0.151}{\sqrt{1-\cos^2 \lambda_{AE} \cos \lambda}}\right] \qquad 2.18$$

where λ_{AE} is the earth station's latitude

and

$$\lambda = \lambda_E - \lambda_s$$

the difference between the longitudes of the earth station and satellite.

Thus substituting different values of λ_{AE} and λ, it is found that if the latitude of earth station is greater than $\pm 81.3°$ the satellite will go below horizon, indicating that the satellite is out of sight.

$$A_{z(\text{cal})} = \tan^{-1}\left[\frac{\tan\lambda}{\sin\lambda_{AE}}\right] \tag{2.19}$$

The value of azimuth angle depends upon the relative positions of satellite (sub-satellite point on the earth) and earth station. Figures 2.15(a) and 2.15(b) show the actual values of azimuth for all the four quadrants.

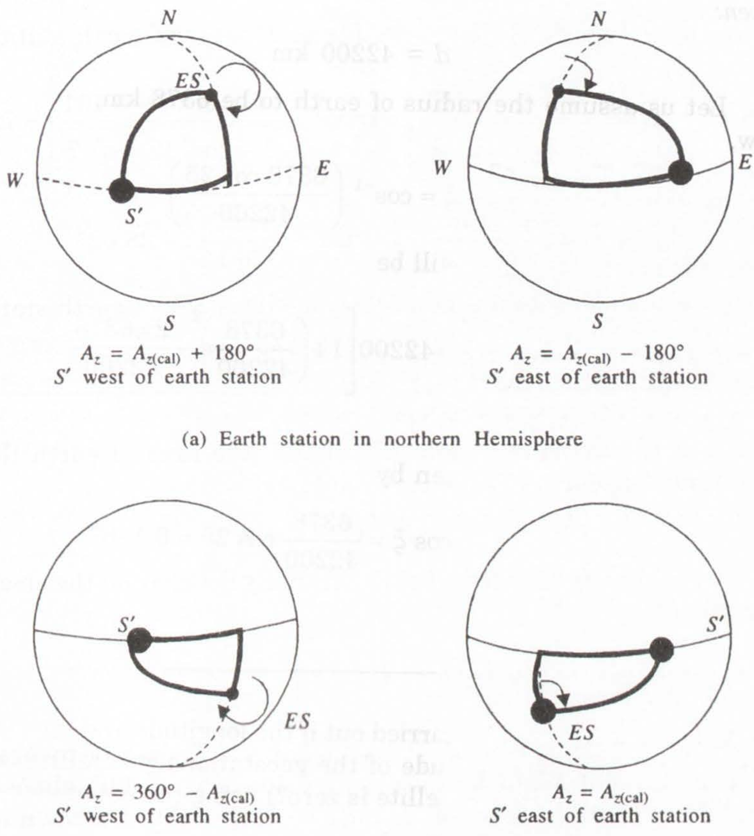


Figure 2.15 Calculation of actual azimuth.

The minimum height of visibility is given by as shown earlier

$$d \geq r_e/\cos\gamma \tag{2.20}$$

Continuing with the discussion, let us now find the area a satellite is able to cover from a given altitude. It is very clear from Figure 2.7 that the area of coverage depends both on the height of the satellite as well as the angle δ made by the satellite. In other words if we assume that the satellite antenna has a beam width not less than δ then the coverage by

Example 2.4

An earth station is located at a longitude of 76° east and latitude of 13° north while the satellite is at 83° east. Calculate the elevation and azimuth requirement of a transmitting antenna.

Solution

From the data given

$\lambda = \lambda_E - \lambda_s = 76 - 83 = -7$ or satellite is 7° west of earth station.

$$\xi = \tan^{-1}\left[\frac{\cos\lambda_{AE}\cos\lambda - 0.151}{\sqrt{1-\cos^2\lambda_{AE}\cos^2\lambda}}\right] = \tan^{-1}\left[\frac{\cos 13\cos 7 - 0.151}{\sqrt{1-\cos^2 13\cos^2 7}}\right] = 72.86°$$

$$A_{z(\text{cal})} = \tan^{-1}\left[\frac{\tan\lambda}{\sin\lambda_{AE}}\right] = \tan^{-1}\left[\frac{\tan 7}{\sin 13}\right] = 28.62°$$

Since the sub-satellite point (sat. itself) is SW of earth station

$$A_z = A_{z(\text{cal})} + 180° = 208.62°$$

satellite will be maximum. From Figure 2.7, the area of earth that is covered assuming earth is spherical would be

$$A_{\text{cov}} = (2\pi r_e)^{2\cdot}(1 - \cos\gamma) \qquad 2.21$$

We have already seen from Eq. (2.12) that γ depends on the elevation angle ξ such that

$$\gamma = \cos^{-1}\left[\frac{r_e\cos\xi}{d}\right] - \xi \qquad 2.22$$

From Eq. (2.21), it is evident that when $\gamma = 0$, area of coverage is zero or a single point. While for maximum value of γ, i.e., 90°, almost half the area of earth will be covered. But, this is impossible as shown in the previous discussion due to limitation on ξ. Therefore, practically more than two satellites are necessary to cover the whole of earth. Plausibly three satellites 120° apart are sufficient as shown in Figure 2.16(a).

Taking the percentage coverage, it can be shown

$$\frac{A_{\text{cov}}}{4\pi r_e^2} = \frac{2\pi r_e^2\,(1-\cos\gamma)}{4\pi r_e^2} = 0.5(1-\cos\gamma) \qquad 2.23$$

where $4\pi r_e^2$ is total area of earth's surface, in this expression γ is always less than 90°.

Hence the coverage area is always less than 50% of half the globe.

A plot of approximate number of satellites required versus altitude is plotted in Figure 2.16(b).

Also from Figure 2.14 in order that the satellite should be visible from earth station E, the satellite should not be at a height below S'' or in other words

$$d \geq CS''$$

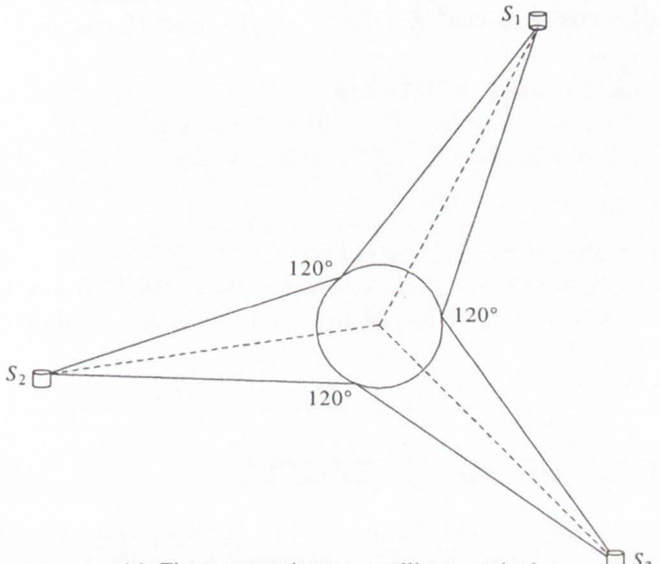
where

$$d = r_e + h$$

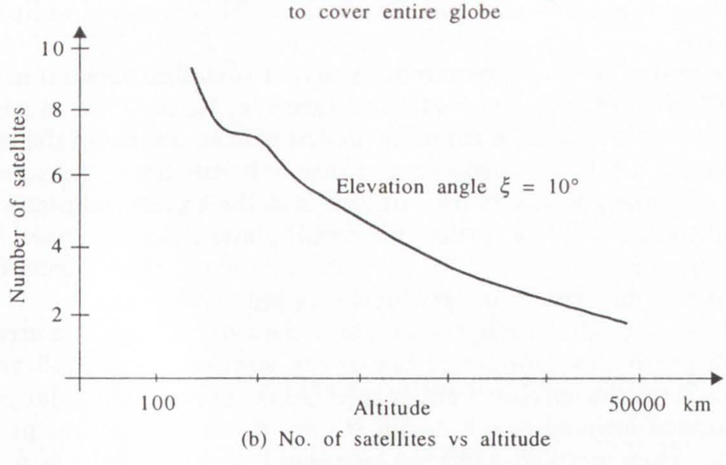
From triangle ECS''

$$d \geq r_e/\cos \gamma \tag{2.24}$$

$$\gamma \leq \cos^{-1} r_e/d \text{ (for a given height of the satellite)}$$



(a) Three geostationary satellites required to cover entire globe



(b) No. of satellites vs altitude

Figure 2.16

EXAMPLE 2.5

A LEO satellite is at 1000 km from the sub-satellite point on the earth. Determine the angular velocity and time of orbit, assuming ideal orbiting conditions. If this satellite has to scan from 20° south-east to 40° north-east. Estimate the number of satellites required for communi-cation throughout 24 hours.

Solution

Given:

$h = 1000$ km

Then

$$d = r_e + h$$
$$= 6378 + 1000 = 7378 \text{ km}$$
$$v = \sqrt{g_0/d} = \sqrt{(3.98 \times 10^5/7378)} = 7.344 \text{ km/s}$$
$$\omega = v/d = 7.344/7378 = 9.95 \times 10^{-4} \text{ rad/s}$$

Time of orbit to cover 360° is:

$T_0 = 2\pi/\omega = 2\pi/1.2 \times 10^{-4} = 6311.67$ s

$\therefore$ Time to cover 60° = (6311.67/360) × 60 = 1051.95 s = 17.53 min

No. of satellites required for 24 hrs or 1440 min = 1440/17.53

= 82 to 83 satellites

Ans.

2.5 EFFECT OF SOLAR ECLIPSE

All satellites in space have to undergo a period during which its solar power system is eclipsed by the shadow of the earth, that is, when the earth comes between the sun and the satellite. This is called **eclipse of the satellite**.

The period of eclipse varies from satellite to satellite depending upon the type of orbit and its longitude and latitude. In the case of geostationary satellites, which have the same period of orbit as that of the period of revolution of earth, this problem is acute only during equinox period. This is because the geostationary satellite is in the equatorial plane. It is known that the sun will be in the equatorial plane twice in a year. That is, around 21st of March and 23rd of September every year during these dates night and day are equal and hence called **equinoxes**.

On these days the earth, the sun and the satellite are in a straight line during particular hours and hence the sunrays do not fall on the solar panel. Since the satellites major payload is supported by solar power the communication may break down. It can, therefore, neither pick up instructions from ground stations nor send signals. This is a very dangerous state and hence sufficient backup battery system has to be provided at least for telemetry, tracking and command (T, T & C) if not for payload.

Let us calculate the duration during which a satellite may be under eclipse. To start with let us assume:

1. The rays are not affected by environment around the earth and sunrays are parallel beams of photons.
2. The eclipse occurs only on equinox day when the satellite is completely eclipsed as shown in Figure 2.17.
3. Eclipse starts at S_s as the satellite moves in the orbit path; this situation will exist up to S_e, the end of eclipse. Let the angle subtended from S_s to S_e be α, **the angle of eclipse.**

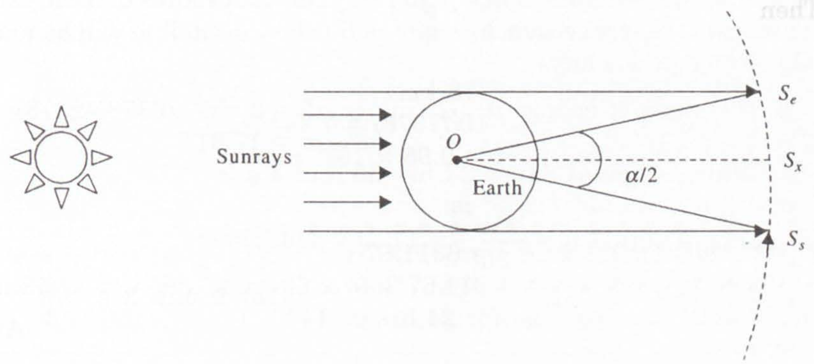


Figure 2.17 Satellite under eclipse on equinox day.

From triangle S_xOS_e, as the radius of orbit is very large arc S_xS_e can be considered as a straight line, hence

$$\frac{S_eS_x}{OS_e} = \frac{r_e}{d} = \sin\frac{\alpha}{2}$$

Thus,

$$\text{angle of eclipse } \alpha = 2\sin^{-1}\frac{r_e}{d} \qquad 2.25$$

where $d = r_e + h$.

Since we know the time of orbiting of a geostationary satellite is same as that of earth (geosynchronous), i.e., 24 hours, we can calculate the duration of eclipse t_e as follows:

$$t_e = \frac{\text{Orbit period}}{360} \times \alpha \qquad 2.26$$

From Eqs. (2.25) and (2.26), we find that

1. Eclipse angle depends on the height of satellite.
2. The duration of eclipse increases as height of satellite increases.

EXAMPLE 2.6

If a satellite is at a height of 36000 km and orbiting in equatorial plane, comment whether the satellite will be under eclipse on equinox days and find the duration of eclipse.

Solution

Given:

h = 36000 km if radius of earth is taken as 6378 km

Then

Radius of orbit $d = r_e + h = 6378 + 36000 = 42378$ km

Since the satellite is in equatorial plane and radius of orbit 42378 km which is nearly geosynchronous radius hence satellite will be under eclipse on equinox days.

The angle of eclipse $\alpha = 2 \sin^{-1} (r_e/d) = 2 \sin^{-1} (6378/42378) = 17.31°$

Taking sidereal day = 23 hrs 56 min 4 s

$$\text{Eclipse period } t_e = \frac{86164}{360} \times 17.31 = 4143.05 \text{ s}$$

$$= 1 \text{ hr } 9 \text{ min } 3 \text{ s}$$

Ans.

In the above discussion, we have assumed that the rays are parallel and eclipse occurs only on the equinoxes days. But this is not true because of the following factors:

1. The sunrays have variable inclination. [(Refer Figure 2.18(b)]
2. The sun has its own path of motion.
3. The surface of earth is not plane but spherical.
4. The atmosphere surrounding the earth has variable refractive indices as altitude increases.

Figure 2.18(a) shows the effect on eclipse due to inclined rays. Actually, one would observe an umbra region (total eclipse) and penumbra region (partial eclipse).

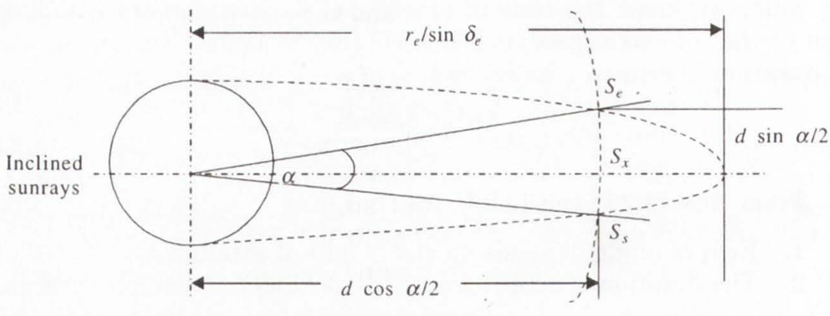


Figure 2.18(a)

If we say that the rays are bent and inclined and the umbra region having total eclipse is only considered as in Figure 2.18(a), the region under eclipse is elliptical. For this ellipse the semi-minor axis is the earth's radius r_e while the semi-major axis is due to sun's declination δ_e and is $r_e/\sin \delta_e$. Figure 2.18(a) shows that eclipse can occur only if

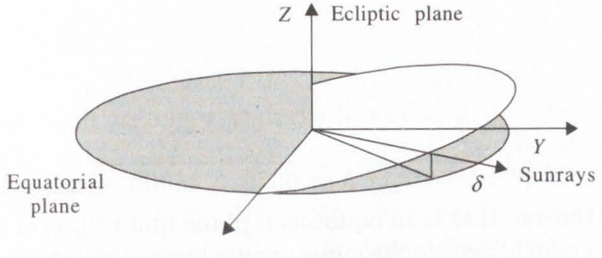


Figure 2.18(b)

$r_e/\sin \delta_e$ is greater than radius of orbit of satellite. This shows that suns declination is inversely proportional to the orbit radius. Using equation of ellipse, we have

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

$$\left(\frac{d \cos \dfrac{\alpha}{2}}{\dfrac{r_e}{\sin \delta e}}\right)^2 + \left(\frac{d \sin \dfrac{a}{2}}{r_e}\right)^2 = 1$$

$$\cos^2 \frac{\alpha}{2} \sin^2 \delta_e + \sin^2 \frac{\alpha}{2} = \frac{r_e^2}{d^2}$$

$$\therefore \quad \frac{a}{2} = \cos^{-1} \sqrt{\frac{1 - \dfrac{r_e^2}{d^2}}{\cos^2 \delta_e}} \qquad 2.27$$

Two things are to be noted from the above derivation, one the declination of sun varies with the radius of orbit and the other, angle of eclipse also varies with the radius of orbit.

Also it is seen that if the radius of orbit is greater than the semi-major axis, there will be no eclipse at all, but this may not be practicable. If the graph of duration of eclipse and number of days is plotted, it is seen from Figure 2.18(b) that the eclipse of more than one hour exists almost for about 30 days, theoretically, but since δ_e is variable, the eclipse usually does not exist for more than 50 to 52 days while duration of eclipse goes on reducing drastically around equinox days. A typical plot in

Figure 2.19 depicts this. This plot will change depending on parking place.

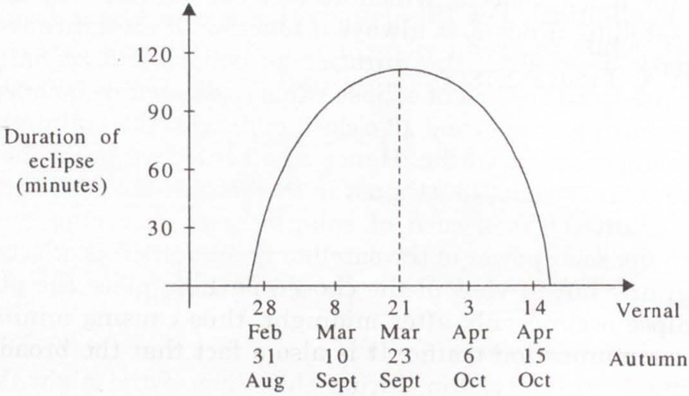


Figure 2.19 Graph showing duration of eclipse for $\delta_e = 8.3°$.

EXAMPLE 2.7

Calculate the duration of eclipse for a geostationary satellite orbiting at 42378 km and the declination of sunrays is 2.6°. For this declination what should be the radius of orbit so that no eclipse will ever occur?

Solution

Given:

$$d = 42378 \text{ km}$$
$$\delta_e = 2.6°$$

Then

$$\alpha = 2 \cos^{-1} (\sqrt{(1 - r_e^2/d^2)}/\cos \delta_e)$$
$$= 2 \cos^{-1} (\sqrt{(1 - (6378/42378)^2}/\cos 2.6)$$
$$= 16.51°$$

Now,

$$\text{Eclipse period } t_e = \text{Orbit period}/360 \times \alpha$$
$$= 86164/360 \times 16.51$$
$$= 3953.58 \text{ s}$$
$$= 1 \text{ hr } 5 \text{ min } 53.58 \text{ s}$$

Comparing this with the earlier result of Example 2.6 without δ the eclipse time is reduced.

From Figure 2.18(a), for no eclipse to occur, radius of orbit $d > r_e/\sin \delta_e$.

Substituting

$$d > 6378/\sin 2.6$$
$$> 140599.203 \text{ km}$$ **Ans.**

which is not practicable for communication satellites using present day technology.

Choice of Parking Place

This is one of the major aspects, which decides the time of eclipse of a geostationary satellite. Since δ_e is always a function of the latitude and longitude of parked satellite, the duration of eclipse cannot only be minimized but the starting time of eclipse can be adjusted in such a way that the eclipse only occurs beyond 12 o'clock midnight, thus minimizing its effect on communication traffic. Hence satellites have been allotted a parking place from 72° east to 94° east in the geostationary orbit. The parking place allotted takes care of solar eclipse occurring during equinoxes when the solar power of the satellite is shut off. This affects the communication link but in view of the chosen parking place the power is shut off (eclipse occurs) only after midnight, thus causing minimum hindrance to communication traffic. It is also a fact that the broadcast and voice channels are very thin during this time of the night. With advanced technology it has been possible to provide sufficient battery backup for the satellite to work satisfactorily during eclipse period also.

The other aspect, which has to be taken into account, is the stability of satellite in orbit. It has been seen in previous section that due to ellipticity of earth the gravitational attraction is more towards the equatorial bulge rather than towards the centre of the earth. This leads to varying accelerations at different longitudes.

Visibility Considerations

The radio visibility of the satellite from a ground station depends on the angular separation between the station and the Sub-satellite point (SSP) and on the altitude of the satellite. The SSP latitude oscillates with a maximum value equal to the inclination of the orbit at the frequency of orbital revolution. For near-earth satellites, the SSP longitude varies over all values and hence visibility from a given ground station occurs for short durations (typically 10 to 15 minutes) a few times in a day. On the other hand for a geostationary satellite, there is little relative motion between the earth and the satellite and the visibility is continuous. This distinction has obviously an impact on the control centre operations.

2.6 SATELLITE STRUCTURE

Satellites in space could be of two types:

1. Passive
2. Active

Passive satellites do not have any processing circuits within it but just may act as a reflector to deviate the uplink radio frequency waves to another desired direction. Evidently such satellites would be useful only if the height of satellite is small, the signal is very strong and bandwidth is limited.

All the satellites in space, whether for communication applications, data collection applications or surveillance, have to be active satellites of one sort or the other. These satellites may be designated to have a *pipeline* structure for communication purposes. A pipeline structure means that the modulated signal flows from earth station to satellite, is processed in the satellite and then is returned to another or same earth station/ stations. A satellite can also be termed as a **star network**. A satellite is having numerous systems, parts and mechanical structures. It will not be possible to cover all these in detail but effort is made to understand the basic structure. Active satellites can be broadly divided into three sections:

1. The system bus section
2. The payload section
3. The power supplies section

The system section is the heart of the satellite. Any blockage or breakdown of any sort in this section makes the satellite dead and the central control station will fail to track and control the satellite. The main parts of the system bus are telemetry circuits, sensors and associated processors, momentum wheels, thruster motors, command analysis and execute circuits. In brief this section takes care of attitude control, orbit control, telemetry, tracking and command (T, T & C) of the spacecraft.

The payload section can be defined as *that section which provides monetary returns to the launch agency or parent organization*. The launch agency sells the utilization time to the user at a certain rate to recover the expenses incurred to design, fabricate, launch and maintain the satellite. It consists of low noise amplifiers to amplify uplink signals, band pass filters to separate the signals, frequency converter/converters, amplifiers, multiplexers and power amplifiers before retransmitting the signals. Payloads are specifically used for communication and data collection and retransmission. In some cases it also works as a link exchange and performs switching.

Most of the earlier satellites were having a bandwidth (BW) of 250 MHz. The present trend is to have satellite effective BW as large as possible. A general block of a satellite input, transponder and output signal processing system is shown in Figure 2.20. The uplink and down-link frequencies are kept different as common antennas are used.

All communication satellites are multiple access type and hence one of the multiple access techniques has to be adopted such as TDMA, FDMA or CDMA. Either zone beam or spot beam antenna is used for larger coverage or point-to-point coverage, respectively. The input is filtered and passed through low noise receiver working in redundancy. Two such sets are used so that if one fails the other should keep the transponder active.

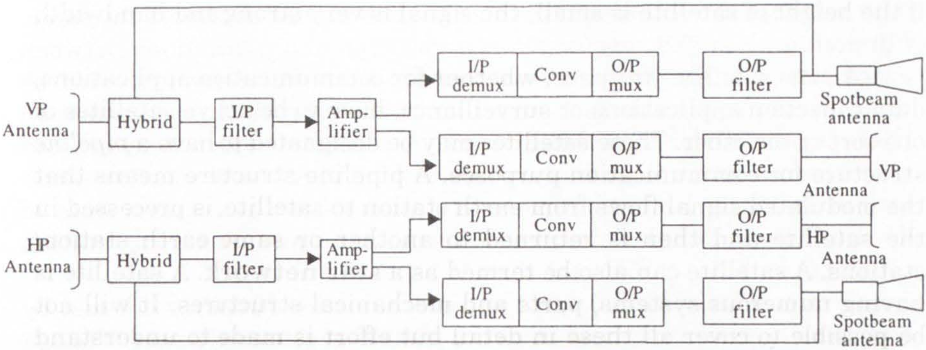


Figure 2.20 Typical satellite input, transponder and output configuration.

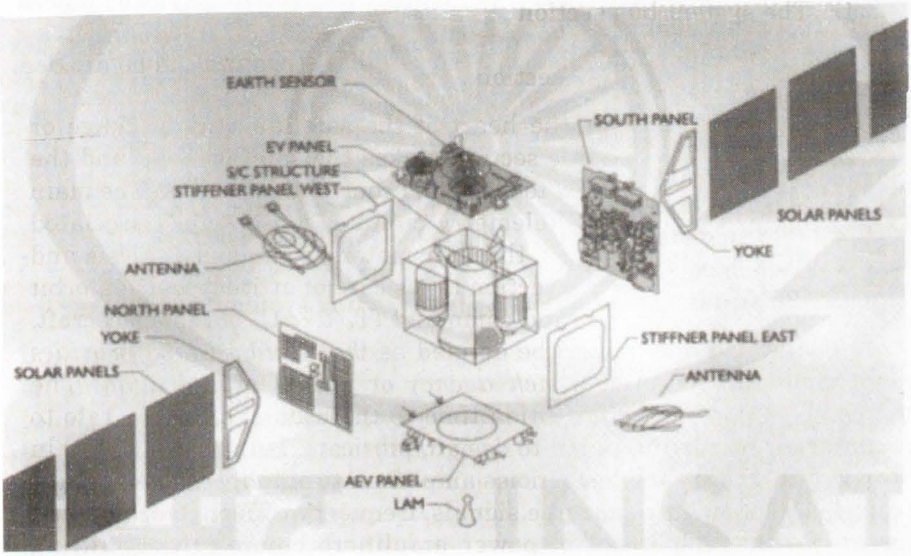


Figure 2.21 INSAT 3. (Courtesy Indian Space Research Organization)

Earlier satellites used wideband transponders with bandwidths of 250 MHz. This drove high power TWTA to non-linear region and hence performance was not satisfactory. Present satellites use a number of transponders with limited bandwidth. But the effective BW is still large. Each transponder can have 36, 40 or 74 MHz bandwidth; this also helps in multiple accesses. 6/4 GHz satellites usually carry 24 active transponders. A set of multiple accesses, transponder has a guard band of 4 MHz, in case of 36 MHz bandwidth transponders.

Satellite systems could be one of the three types:

1. Repeater system
2. Broadcast mode and asymmetrical system
3. Communication or database of two and three-dimension

The requirements of earth stations in all these cases may slightly vary whereas the satellite system as a whole would be almost the same. For example, in the case of repeater system communications between earth stations that would act as primary exchange networks could be there while the satellite may be a node connecting all these together. In the broadcast mode the satellite would again be a repeater but its antenna would transmit to a large zone, where DBS or VSAT (very small aperture terminals) could be used to receive the signals. The requirements of design hence would depend upon the data and receiving station capabilities.

Power supply for most of the communication satellites are met by solar panels generating from 500 W to 2500 W of electrical power. Though the efficiency of these cells are very poor but they are economical and reliable in the long run. Backup rechargeable batteries are provided to partial extent. Back-up batteries are usually avoided for payloads unless and until absolutely necessary.

For designing and modelling, the satellite structure can be divided into following categories:

1. Mechanical support
2. Sensing and control circuitry
3. Thermal shield and conduction
4. Transponders and associated electronics
5. Antennae
6. Solar panels and associated supporting systems

As the satellite undergoes several extreme vibrations, heat and environmental conditions, mechanical structure of the satellite is extremely important. Outer and inner body insulation, design and choice of materials of moving parts is most important. The structure must be designed to sustain the tests, transportation, launch, apogee and perigee firings, antennae and solar panel deployment jerks. The balancing of the load is another important area for good stability and attitude. Size of launch vehicle also plays an important role in designing the outer shell. The types of materials for support and fixtures play an important part due to overall weight constraints. Most of the satellites have deployable antenna and solar panels support structure, which have hinges and autolocks. These are folded so that the satellite can easily fit onto the launch vehicle and opened in stages once the satellite is separated from the launch vehicle. The payload and associated systems are generally supported by a single structure in the middle of the spacecraft. These are covered by thermal louvers to protect the electronic circuitry. Below this are placed propulsion tanks rigidly mounted. These contain fuel like monomethyl hydrazine, pressurant like helium, oxidizer like nitrogen tetraoxide, etc. The lowest compartment contains thruster motors.

Software tools are nowadays extensively used to design and analyze the mechanical structures with single or multiple degrees of freedom. Computer models are generally generated defining material properties like modulus of elasticity, stiffness, thermal properties to get optimum design of mechanical components like struts, shells, rings, etc. Some examples of commonly used materials for components are beryllium composites for struts and shells, graphite-epoxy and aluminium boron composites for panels and rings.

Sensors and telemetry instruments are generally mounted at the top portion of the spacecraft. The types of sensors used depend on the bench-marks with respect to which tracking and alignments are performed.

As the satellites particularly geostationary are in space where there is no air to cool the dissipating components and all the heat has to be transferred by conduction through solids and radiated to space. The temperature of satellite also rises because of solar radiations and heat dissipation of power devices.

Effect of solar radiation. On one hand solar energy is the source of main power supply to the satellites on the other hand it also creates several problems during and after the launch.

- Solar flares create radio-fade outs.
- Solar cells need shielding and coating as unwanted wavelengths of high energy radiations may damage the cells.
- The earth absorbs 47% of solar energy while 37% of energy is reflected back into space. This energy is known as **albedo**. The remaining 19% is absorbed by atmosphere but the exact percentage depends on many factors like cloudy conditions, water vapour concentration, gases and so on.

To achieve proper dissipation and protect the parts and components the outer shell/body and internal circuits have to be carefully designed. The spacecraft when launched and orbiting through the ionosphere, results in collision with charged particles which results in accumulation of charges on the outer surface resulting in arcing. To overcome this problem, appropriate conductive path and grounding is necessary. As a typical example the Indian remote sensing satellite used stiffened aluminium and aluminium honeycomb panels for mounting. Passive thermal control was achieved using heat resistant paints, MLI blankets, OSRs and on/off temperature controllers connected to heaters.

2.7 TELEMETRY TRACKING AND COMMAND (T, T & C)

In the case of biotelemetry, a patient's health is kept under count, scrutiny and maintained, similarly telemetry, tracking and command takes care of the health and attitude of satellite in space. T, T & C is a closed loop communication and control system. Telemetry does the job of acquiring the different data, such as, health of the battery, temperature at different points in the satellite, power consumption by each sub-unit, pressure ranges, etc. within the spacecraft using sensors. The sensed parameters are multiplexed, converted into digital data and sent to the earth station over an appropriate carrier. Tracking helps the Satellite control earth station (SCES) to keep track of the satellite using on-board sensors and transponders. The measured data can be used to control the attitude, altitude, orbit path, parking place and the look angle. This control is achieved by commands that are sent by the control earth station either in manual mode, auto mode or program track mode.

For all this, RF carriers are necessary and appropriate modulation techniques have to be used depending on the type of information. The telemetry data essentially is a downlink RF signal sending the real-time sensed parameters to the SCEC. Tracking is both downlink and uplink signals while command is an uplink RF signal. Some of the points, which should be kept in mind while choosing the RF carrier for T, T & C are:

1. The frequency chosen should be such that during transfer orbit phase, help should be available to control the satellite through other satellite/satellites already in orbit as well as different earth stations spread over in and outside the country. These should be able to communicate with the launched satellite to control its orbit path, altitude and attitude.
2. Generally C-band is preferred by most of the countries because of reliable propagation.
3. The beam width shall be kept as narrow as possible. Higher the frequency narrower could be the beam.
4. The signal to noise ratio should be sufficiently high for error free tracking and command.
5. Should be less prone to fading.

For telemetry the base band is built by converting the analogue signals available at the output of sensors from transducers to PCM/PSK signals after signal conditioning. The word format typically is 8-bits sent at about one kilobits per second. The telemetry frame consists of typically 128 words/frame. The frame identification can be of 4-bit length. The arrangement and structure of frame is similar to any other digital data frame, which is discussed in Chapter 4 in detail. The telemetry section has a main or master unit and number of remote units.

T, T & C subsystem is configured to serve the requirement of spacecraft telemetry, tracking and command during all the phase of the mission. The T, T & C subsystem operates in C-band whose frequency lies between 4 to 6 GHz. C band is preferred because of the fact that the losses are minimum. Telecommand subsystem provides ground control link and enables the transmission of command information spacecraft. The uplink commands get executed immediately. The baseband signals from the receivers are fed to the decoders directly. The system has the capability of decoding simple on/off pulses and level commands routing data to the subsystem. The telecommand specifications are:

1.	I/P signal modulation		PCM/FSK
2.	Command bit rate	:	100 bauds
3.	Command word length	:	32 bits
4.	Command frame length	:	56 bits
5.	FSK tone frequency	:	3.125 kHz – '0' 5.555 kHz – '1'
6.	Information length	:	16 bits
7.	Mode address	:	6 bits
8.	Mode selection	:	2 bits
9.	Decoder address	:	2 bits
10.	Satellite address	:	5 bits
11.	Start bit	:	1 bit.

Command Word Format

1	2 3 4 5 6	7 8	9 10	11 12 13 14 15 16	17 to 32
Start bit	Satellite addres	Decoder address	Mode	Mode address	MSB LSB command information

A T, T & C receiver has a demodulator and a series of amplifiers. The T, T & C *Rx* receives the modulated command signals from the ground stations. The commands are demodulated and amplified so that the final commands output is in binary form. This is the baseband signal. Baseband signals form the input to the telecommand system. The telecommand system has the decoder and number of output lines, which are connected to different subsystems in the satellite. The baseband signals are decoded and a particular output line is activated whenever a command is sent.

The telecommand basically is PCM/FSK and takes the help of dedicated microcontrollers. The command word length is typically 32 bits sent at a very low bit rate of 100 bits/sec, as it has to activate electro-mechanical/pneumatic mechanisms in the spacecraft. The overall frame consists of satellite address which may be 5 bits or more with information of 16 bits. In addition decoder address, mode address and selection are also transmitted. This would result in a command frame length of 56 or more bits.

Every frame is repeated at least 4 times for error free operations. In the satellite the repetitive commands are stored and compared before execution. The command bit is about 5 ms duration.

The T, T & C systems should be fully foolproof, for this purpose they have to be properly packaged and should have sufficient redundancy. These systems are specially protected against space plasma, which causes electrostatic discharge. Thus, they are sealed in a *faraday cage*. Care is always taken to subtract the delays caused in circuits and demodulation during ranging.

Surface mount devices using ASIC and FPGA are common, this not only provides maximum reliability but also flexibility in design. Infact in space technology it is a well-known fact that hybrid microcircuits (HMCS) provide higher package purity and improved reliability. Micro electro-mechanical systems (MEMS) are finding favour with the designers. Figures 2.22 and 2.23 show the typical T, T & C as well as electrical power block.

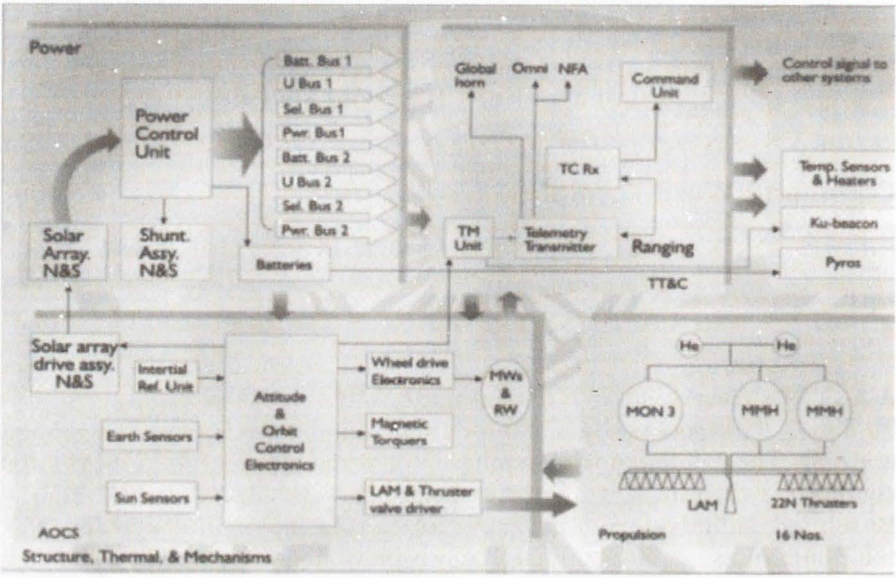


Figure 2.22 INSAT 3B satellite house keeping and power bus block. (Courtesy ISRO, India)

Typical specifications of T, T & C

Uplink frequency	6419.32	MHz
Downlink	4197.504	MHz
Transmitter power	0.5 to 3.5	W
Antenna gain in transfer orbit	–10	dB
Antenna gain in permanent orbit	17	dB
Modulation telemetry (Downlink)	PSK/PM	
Modulation telecommand (Uplink)	FSK/FM	
Sensitivity of satellite	–105	dBm
Bandwidth requirement	1.5	MHz
Antenna pointing accuracy in pitch	+/– 0.2	degrees
Antenna pointing accuracy in yaw	+/– 0.4	degrees

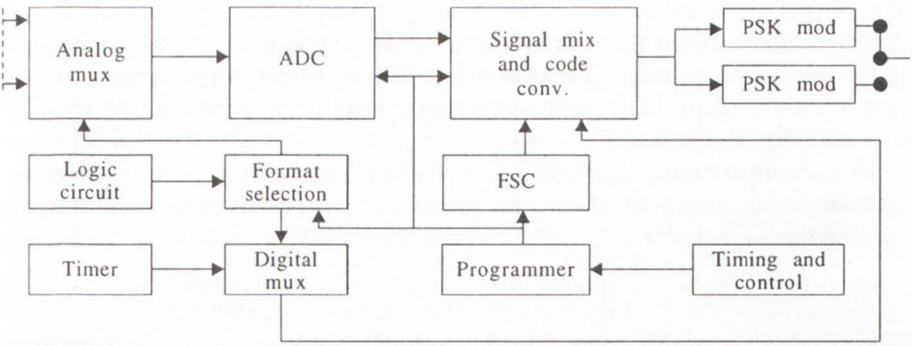


Figure 2.23(a) Telemetry system.

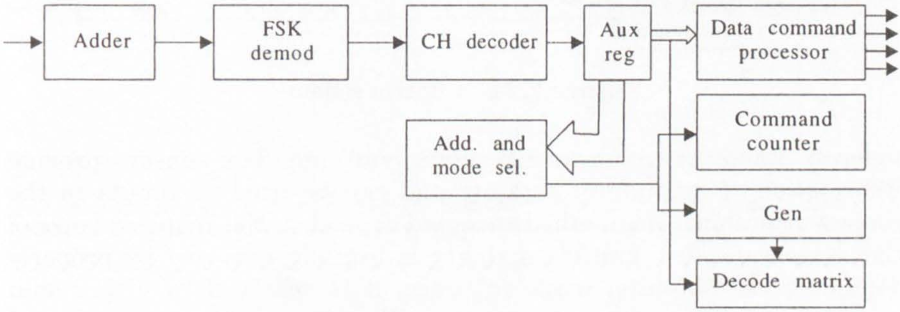


Figure 2.23(b) Telecommand block.

Estimation of Drift Rate

Especially in the context of satellite clusters, it is important to determine the east-west coupling which arises during the North-south station keeping (NSSK). As it is difficult to predict this component, one generally estimates this based on the post-maneuver tracking data and the estimation can take several hours by the conventional methods. It is important to develop new techniques by which the longitudinal drift rate is estimated to the necessary accuracy in a much shorter time-span so that the corrective actions can be initiated early enough. A fairly good assessment of the drift rate is found feasible from the thruster time telemetry data. Such a system is implemented in INSAT control facility

Attitude Control

Attitude of a spacecraft is the exact orientation of the craft in space with respect to three constants, that is, azimuth, elevation and its rotation acceleration. In order that a communication satellite is able to reassign and relay the signals from e rth stations, it is necessary that the position or attitude of satellite is kept within the allowable limits of 3×10^{-4} per sec. The main reasons for the change of parking position of satellite is the disturbance torques from different sources like solar pressure, thruster misalignments, gravity effects of other bodies in space and interaction of spacecrafts residual magnetic dipole with earth's magnetic field (already discussed in Section 2.3).

In order to control the attitude, a closed loop sensing and correction system is necessary as shown in Figure 2.24. To achieve proper control, a number of sensors are used aboard the satellite which are oriented

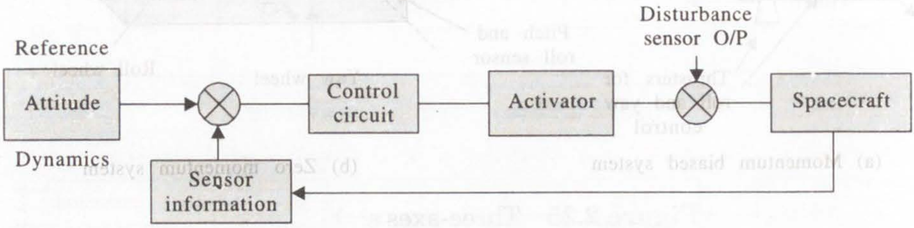


Figure 2.24 Control scheme.

towards stable benchmarks like stars, sun, etc. The sensors provide information of attitude of satellite and can be used as inputs to the correcting system. The methods adopted depend on the shape and size of the spacecraft. The attitude stability is initially provided by properly designing the satellite, while in space, it is achieved by either spin stabilization or three axes stabilization. What is meant by initial design? We have already stated earlier that solar radiation pressure tries to push the satellite if the structure is imbalanced, the order of such pressures is typically of the order of 4.63×10^{-14} N/m. Geostationary satellites are almost parked at a place where no gravitational forces influence and any object would virtually float, hence even the minute push is sufficient to take away the satellite from its fixed orbit. In case of some of the INSAT series satellites, the solar panels are hanging below the satellite and a disturbance torque of 3.6×10^{-14} N/m acts on them with the result that the satellite can tilt. To overcome this, a balancing solar sail is mounted on the top position of the satellite.

In order to stabilize using spin techniques different type of sensors are used. The sensors used depend upon the type of stabilization, orbital parameters to be corrected and required accuracy.

Any spacecraft is governed using three axes—yaw, roll and pitch. In order to control the attitude in space, the satellite has to be properly oriented using momentum wheels and thruster motors in these three axes. The two major methods used are:

1. Three-axes stabilization
2. Spin stabilization

Figure 2.25 shows the arrangement of pitch stabilization and three-axes stabilization. It is seen that the momentum wheels are mounted

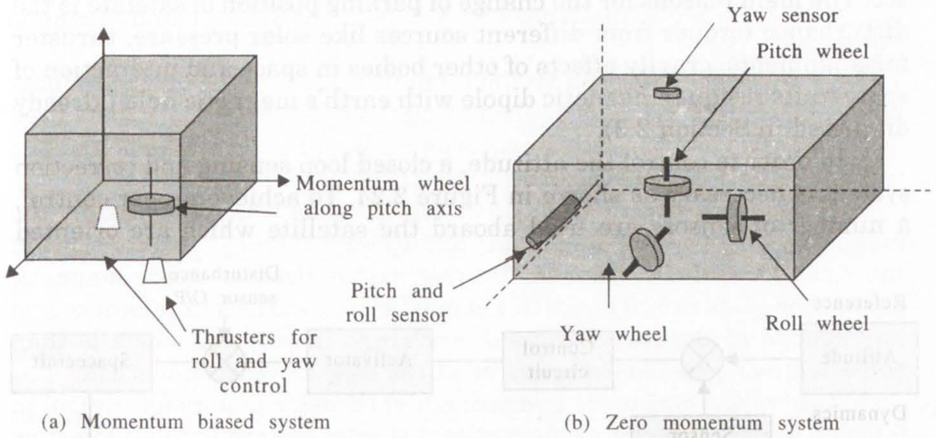


Figure 2.25 Three-axes stabilization.

along the axes. The wheels are rotated at a certain angular velocity to provide required inertia to achieve gyroscopic stiffness and attitude. Any change in attitude is taken care of changing the speed of the wheels and if need be by firing thruster motors. The pitch and yaw sensors provide the required data for control circuit to provide required correction.

Three-axes Stabilization

Though the spacecraft is represented and kept gyroscopically stiff along the pitch axis the attitude dynamics depends upon rotation and acceleration. Hence relative motions and transformation of coordinates is important in the attitude control. One can see that as the satellite goes round in orbit the roll and yaw axes change their relative position every quarter of a cycle in orbit. Thus, three-axes control is virtually converted into two-axes control as in the case of INSAT 2. Thus, it is only required to sense either roll error or yaw error directly and control the other indirectly. Since in communication satellites, roll errors have impact on onboard antennae-pointing accuracy hence roll is sensed directly and yaw controlled indirectly. The three-axes stabilization is achieved either by a momentum wheel along the pitch axis, called **momentum biased system** or by a reaction wheel along each of the three-axes pitch, roll and yaw, this is called a **zero-momentum system**. Both these set-ups are shown in Figure 2.25.

As can be seen from Figure 2.25(a) the momentum wheel by its rotation provides required gyroscopic stiffness while two thrusters that can control the craft's roll and yaw achieve the control. For this only one sensor is sufficient. The yaw error is detected and every six hours it is converted into roll error, which can be used for correction. In zero momentum, three sensors are required as shown in Figure 2.25(b) and the control of wheels is independently done using Whecon and Magnetic torque methods.

In the case of Whecon method, impulse sensing the error produces bits and a control torque is applied along the roll axis by control jets fired by the bit. The bits basically work as on-off signals to control jets, the bits being produced by sensing magnitude of the error rate.

Magnetic torque method is not very good as it is influenced by the magnetic field of the earth and any disturbance thereby. Two coils one in the roll axis and the other in the yaw axis is used to create magnetic dipole along this axis. The earth's magnetic field works as a reference and any change in the flux is sensed by change in current, which is then corrected using thruster motors as in the case of Whecon method.

Most of the crafts use hydrazine fuel thruster motors for control in which a certain amount of mass of fuel is released out with an effective velocity v_t so that the satellite of mass m experiences a velocity changed dv such that

$$m \cdot dv = -v_t \, dm$$

where dm is the mass of fuel released.

The fuel is released out for a small duration depending on the impulse bit of the error control electronic circuit. The typical time is 200 to 230 s, thus the impulse is given by

$$I_{sp} = v_t / g$$

where g is satellite gravitation opposition.

The mass of fuel required to be injected out is given by

$$dm = -\frac{mdv}{gI_{sp}}$$

For a three-axes stabilized satellites like INTELSAT and INSAT, thrusters are fired several times everyday for the purpose of unloading the disturbance angular momentum stored in the momentum wheels. The propellant requirement for this purpose is comparable to what is required for longitude drift control thrusters located in the opposite faces of the satellite. It is possible to control the drift rate, furthermore, an experiment was carried out on INSAT 1D located at 74° east, to partially counteract the force due to solar radiation pressure by switching between the redundant thrusters twice everyday. This experiment has demonstrated the possibility of an effective reduction in the perturbation due to solar radiation pressure, which is primarily responsible for the eccentricity evolution, thereby allowing the sub-satellite longitude to be controller within allowable limits.

Spin Stabilization

Spin stabilization is the method in which the whole satellite is rotated to achieve gyroscopic stiffness; in this case the satellite can be linked to a revolving top. As long as the top has correct pitch, roll and yaw orientation, it spins vertically at a single point, any disturbance in one of the directions makes the top to move away or wobble. A similar situation occurs to spacecrafts in space. Satellites are generally designed to spin around the axis of maximum momentum of inertia.

As communication satellites have antenna/antennae that should always be oriented towards the earth, it is not possible to have this type of stabilization but still some satellites like INTELSAT IV did use this technique with modifications. In this method the satellite body is divided into two parts, one, the rotor that creates gyroscopic stiffness, while the other, a despun platform over which communication antennae are mounted. This is called **split body stabilization** and is shown in Figure 2.26.

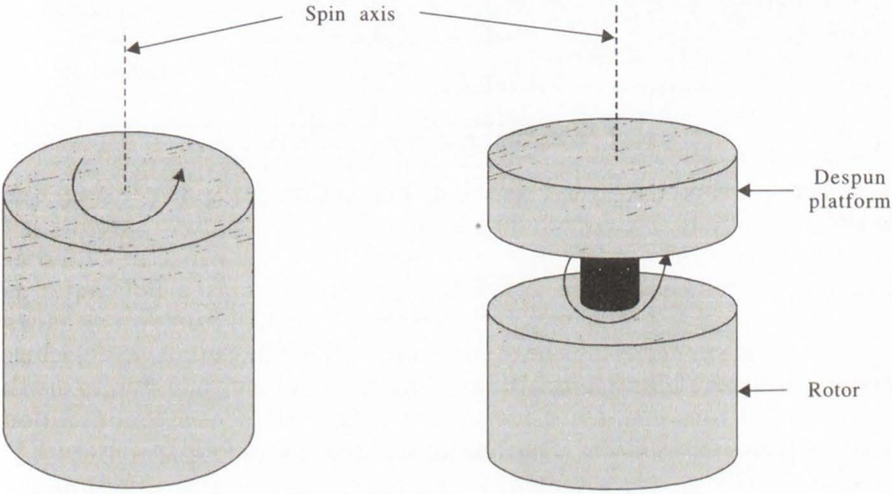


Figure 2.26 Spin stabilization.

The main problem that a designer has to face in such a stabilization is the motion of liquid fuel which forms almost one third the weight of the satellite. This fuel is required for apogee motors and other thrusters. As spinning takes place, this liquid churns inside and disturbs the stability of inertia axis. The other problem is, this disturbance varies depending upon the age of the satellite, since quality of liquid fuel reduces with age of satellite.

Sensing the Attitude

The selection of sensors depends on some of the primary factors such as construction details of the satellite, type of stabilizations used, orbit plane of the satellite and duration as well as time of sensing.

The most common type of sensors used are the sun (see Figure 2.27) and the earth sensors. The sun is easy to detect as it is a small bright point but unfortunately at times the earth, the sun and the satellite fall in the same line and, thus the sun goes out of the view. The sun sensors are generally solar cells placed or positioned in such a way that sunlight falls on it through a meridianal or inclined slit. In many geostationary satellites, two perpendicular slits are used to detect different angles. Two solar cells are used below each of the slits.

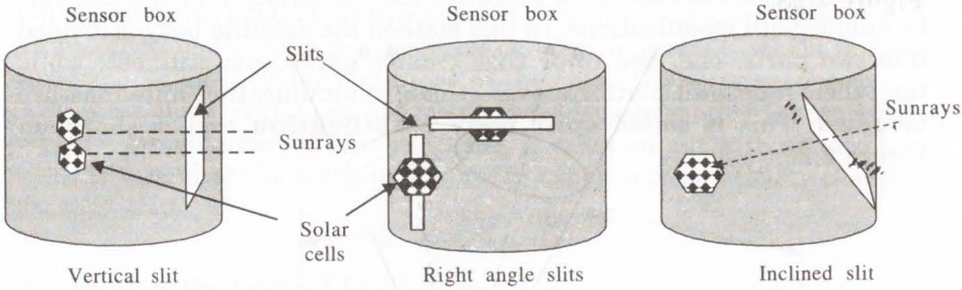


Figure 2.27 Sun sensors.

Though earth is a good reference marker for attitude sensing, due to the atmosphere, the infrared radiations from the earth to satellite get disturbed. This infrared radiation is generally in the range of 14 μm or 15 μm, which is passed through a germanium lens onto a Bolometer as the earth is scanned. The earth sensors are also called **horizon sensors** since an image of earth falls onto the sensor, which has multiple detectors to determine the alignment. All measurements of attitude due to earth sensors are determined along the yaw axis. An earth sensor configuration may consist of two sensors like the sun sensors with a field of view of 1.1° to 1.2°.

RF radiations from earth and other sources can also be used to find the attitude of satellite. A single reflector with two identical antennae (preferably horn) can be used. The outputs of the two antennae determine the attitude of the body on which it is mounted. With proper alignment for a single source of RF signal, the outputs can be made equal and any difference would give error in attitude. For sensing roll and pitch, RF sources from earth are picked by a single antenna and their relative amplitude determine the satellite attitude.

Earth's magnetic field is also used to determine the orientation of satellites using a magnetometer. Tri-axial magnetometer is a good method of determining the orientation of satellite axis with respect to the geomagnetic field.

In addition to these, bright stars are also sometimes used as sharp reference points. Since these are not easy to locate and require very sensitive sensor transducers with higher amplification requirement, these are not frequently used in geostationary satellite.

As an example, the attitude of Aryabhatta was determined using tri-axial magnetometer, these gave the direction of the satellite axis with respect to the geomagnetic field, which was measured as an angle between the spin axis and geomagnetic field vector. In addition the solar sensors gave the angle between sun's normal, on the satellite and satellite axis vector. This technique is called the **dual cone technique** in which the spin axis is common to both the cones, thus the angles of earth sensed locus and sun sensed locus determine the attitude. This is shown in Figure 2.28.

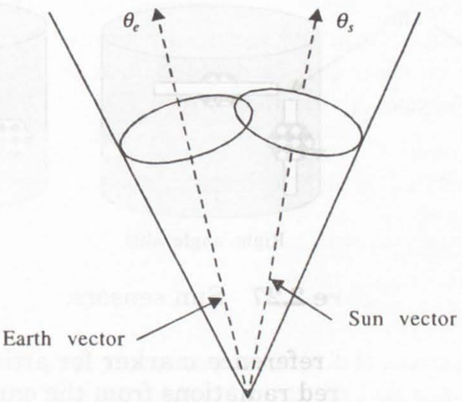


Figure 2.28 Dual cone sensing.

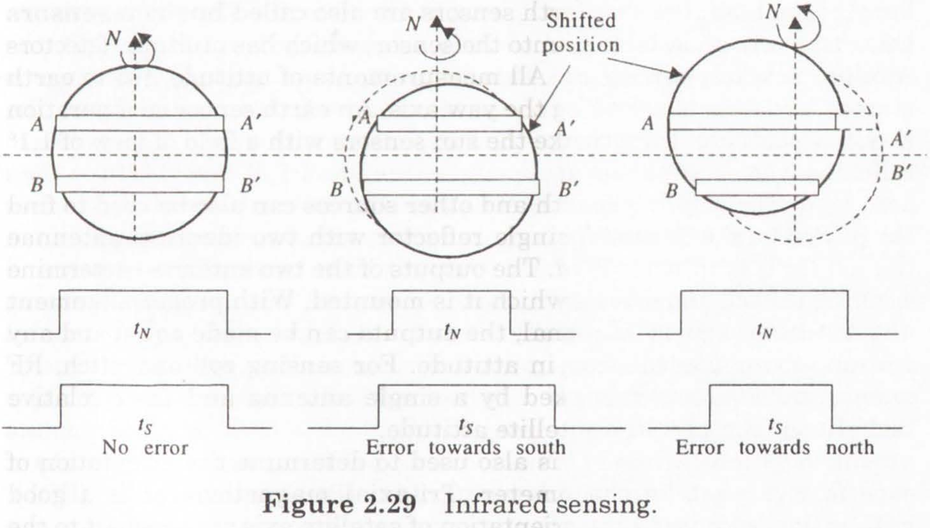


Figure 2.29 Infrared sensing.

In the case of geostationary satellite like INTELSAT and INSAT, *N-S* control using infrared sun sensor is common which is shown in Figure 2.29. When the satellite is properly placed at its assigned attitude the sensors provide equal pulsewidth or equal number of pulses from *A* to *A′* and *B* to *B′*. But when there is an error, pulsewidth (or number of pulses) AA' is not equal to BB'. This provides an error signal over the telemetry, which is then corrected using the appropriate telecommand to thruster motors.

Mission Control for Communication Satellites

In any satellite mission there are broadly three segments, namely, the space segment, mission control segment and user segment. The space segment consists of the payload and the bus subsystems, the mission control segment provides the facility for controlling the satellite and the user segment is composed of the services provided by the satellite.

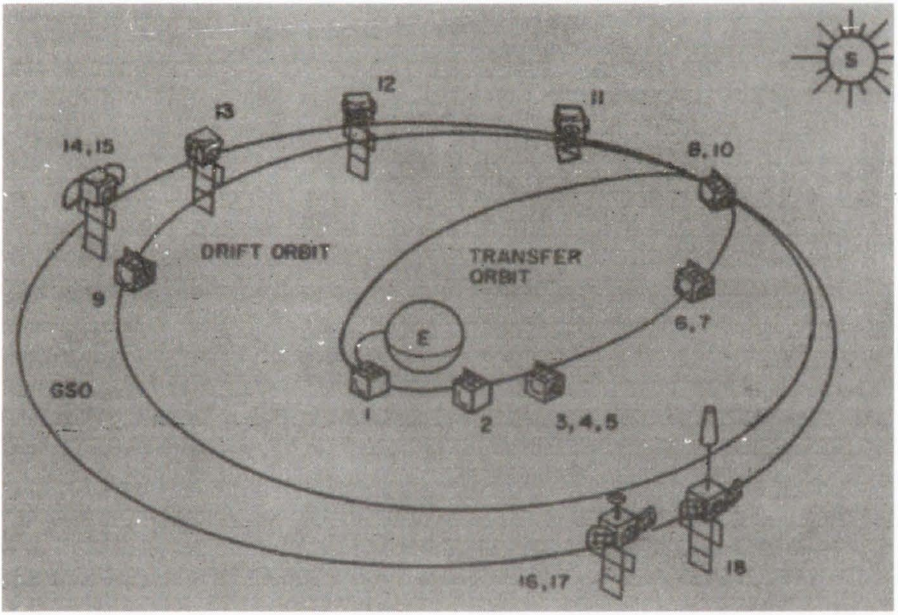
Any satellite mission can be divided into several phases. In most missions, the phases can be divided into:

1. Testing phase
2. Launch and early orbit phase
3. Initial phase
4. Payload checkout phase
5. Satellite in-orbit phase
6. End-of-life phase

In the first phase, the satellite subsystems are rigorously tested against space standards. Satellite undergoes simulated launching, telemetry, control, power and environment tests. After passing all these tests, it is enclosed and transported to the launch pad. During the launching phase, the satellite is attached to launch vehicle as piggyback. Once the vehicle is launched (details are discussed in Section 2.7), the satellite is taken to a certain altitude, control and tracking procedure is started and this is called **early orbit phase**. During initial phase the satellite attitude, firing thruster motors control orbit path, antennae are unfolded, the solar panels are commissioned and T, T and C is fully then activated. The satellite reaches its allocated parking place and stabilizes the payload are activated for tests and adjusting of the finer points. When the satellite is in orbit it is necessary to keep track of the health and working of each and every subsystem. Apart from this the station keeping and attitude control is another important activity of ground control station. Error control from central control station by firing thruster motors and adjusting momentum wheel speeds on regular basis is a major task. In the communication front keeping track of back-off requirements during multiple accesses and avoiding jamming are also important aspects. Every satellite has beginning of life (BOL) and end of life (EOL) EOL is the estimate by the designers indicating how long the satellite can be kept under control which depends mainly on the fuel and the backup batteries. The EOL may extend during actual orbit. Hence as the EOL approaches, the management of resources plays an important role. The telemetry data immensely helps during EOL. The time planning and parking of new satellites depend on these factors.

2.8 SATELLITE LAUNCH

A geostationary satellite undergoes three orbit phases during launch. The satellite can be launched using geosynchronous satellite launch vehicle (GSLV) in case of geosynchronous satellites, Polar satellite launch vehicle (PSLV) in case of inclined or polar orbit satellites. The launch vehicles can be classified into expendable type or reusable type. The expendable type of vehicles like Ariane, Delta etc. take the satellite up to a certain altitude in space and leaves it to spin and proceed. The vehicle itself gets destroyed in space. These vehicles may carry more than one satellite for launching to reduce the launch cost. The satellite is placed inside the vehicle and hence this is one of the factors that decides the size of satellite shell. In case of reusable vehicle like Space shuttle, the satellite is piggyback on the vehicle. The vehicle returns to the earth after leaving the satellite at a certain altitude in space. The launch vehicle is launched in prograde orbit with a skip velocity to cross earth's atmosphere and gravitational pull. Figure 2.30 shows different stages from the time of launching to final parking.



1. Injection
2. Sun ACQ
3. AOS Hassan
4. E.V. Face earth ACQ
5. Gyro calibration
6. North face earth ACQ
7. LAMATT, change
8. AMF 1
9. To sun pointing mode
10. AMF 2, AMF 3
11. Solar array deploy west face sun ACQ
12. Solar array tracking
13. Earth ACQ, wheels L mode
14. ANT deployment (West)
15. ANT deployment (East) 12 hours later
16. Sail deployment
17. Wheels V mode
18. GSO configuration

Figure 2.30 Typical launch progress from time of launch. (Courtesy ISRO, India)

The launch vehicle is a complex system consisting of propulsion systems, auto piloting, aerodynamic structure, interactive steering subsystem, etc. Navigation and guidance of launch vehicle are important to take the satellite to require altitude, orbit path and provide essential kinematics condition. All this is achieved by not only proper mechanical design but also software control. There are several simulation tools used for the purpose like NISA, MARC, NASTRAN and COSMOS. The launch vehicles have onboard computers which take care of self-check, executing error recovery, interfacing with ground station checkouts, navigation, sensor failure detection, guidance with algorithms that execute attitude and thruster commands. Auto piloting takes care of attitude error computation, generates equivalent commands, stabilizes the vehicle in the trajectory.

The four stages are:

1. Circular low earth orbit
2. Hohmann elliptical transfer orbit
3. Intermediate drift orbit
4. Circular geostationary orbit

In case of INSAT 2A, Ariane IV carried the satellite while Ariane V carried INSAT 3B. The launches took place from French Guyana in South America. The launch vehicle takes the satellite in low orbit and injects the satellite into transfer orbit. The satellite is injected into desired three-axes stabilized mode to obtain gyro condition due to a series of commands given by launch vehicle to carry out pyro firing. Thus, the acquired or tracked satellite is already in stabilized gyroscopic stiffness mode. In case of INSAT 2, nineteen minutes after the launch, the satellite is placed into transfer orbit with a perigee of 200 km and an apogee of 35976 km while in case of INSAT 3 these were set at 560 km and 35865 km, respectively. In case of INTELSAT, the orbit has an initial inclination varying from 6° to 8°. At the time of launch, the T, T and C circuits are kept on so that the satellite acquisition by the ground station can be easily carried out. The spacecraft is in radio visibility of different assisting stations, as the satellite is not geostationary initially. Sometimes it may be necessary to take the help of existing spacecraft for tracking. For example in the case of INSAT during the orbit raising phase, a global network of stations located at Perth (Australia), Fucino (Italy) and Lake Cowichan (Canada) are linked to central control station at Hassan (India). Once the satellite reaches the apogee after 24 to 26 hours of launch, the **Apogee kick motor** (AKM) which contains liquid fuel, hence also called **Liquid apogee motor** (LAM) is fired for long duration at two or three stages to take the satellite to intermediate orbit. When the first time AKM is fired for about 60 minutes the satellite attains 61 to 62% of the required geosynchronous velocity. The second apogee motor firing is typically planned after additional two orbits and spacecraft attains required angular velocity and acceleration for geosynchronization. This orbit will keep the satellite in line of sight of the central control station for more than 20 hours and hence enabling the deployment of solar panels. This would require further stabilization and attitude control through the control of momentum/reaction wheels. Further the antennae and transponders are turned on. The satellite enters into stabilized geostationary orbit after a month or two during which detailed checkout tests are carried out before the satellite becomes operational.

For a communication satellite in geostationary orbit, INTELSAT, COMSAT and INSAT being typical examples, the transfer orbit phase is the early orbit phase. The initial phase includes activities such as deployment of solar array, antenna and other structures. The orbit checkout involves, orbit transfer operations involving firing of a large thruster and deployment of payload.

Once a satellite is placed in its assigned orbit, there are several regular activities which are to be performed such as:

1. Orbit maintenance
2. Attitude maintenance
3. Thermal management
4. Power management
5. Battery maintenance
6. Payload operations
7. Software requirement

Some of these operations are routine in nature whereas some others are scheduled as and when required. A few of these operations could be automated and carried out without a need for an active involvement from the control centre. This type of automation is particularly useful for near-earth satellites which do not have a continuous visibility from a given earth station.

To control the satellite we need to obtain as much information about the satellite subsystems as possible. This is provided through the telemetry subsystems. Telemetry provides information about analog parameters such as voltages, currents, temperatures, and digital parameters such as status of equipment and command confirmation. The different parameters are sampled, multiplexed and brought out as a digital bit stream. This is modulated appropriately for transmission using a radio frequency carrier. By analyzing the telemetry data, it is possible to know the health of the satellite in real time. By incorporating appropriate alarms in the computerized processing of telemetry data, it is possible to take immediate and effective actions.

The command system provides access to the satellite in terms of the capability to switch on/off equipment as well as for transmitting data to different subsystems. This link is vital to carry out control operations on an orbiting satellite.

The tracking is the function by which the ground station continuously keeps its antenna pointed in the direction of the satellite.

The look angles of the antenna are a valuable input for determining the orbit of the satellite and its position. During orbit determination as an additional input, it is possible to determine the instantaneous slant range to the satellite by sending an appropriate tone and measuring the two-way travel time.

Orbit Maintenance

A satellite in a geostationary orbit is assigned a nominal longitude, which is referred to as its orbital slot. Strictly speaking, the satellite will not be geostationary because additional forces acting on it will change the shape of the orbit, affect the orientation of the orbital plane and alter the sub-satellite longitude. These changes can be compensated by orbit maneuvers performed by activating thruster motors onboard the satellite at suitable times for calculated durations. These are called **station-keeping maneuvers**. The majority of the propellants carried on the satellite are earmarked for station-keeping maneuvers and its non-availability would mark the end of the operational life of the satellite.

Attitude Maintenance

Attitude maintenance of a satellite depends on the type of stabilization used. For three-axes stabilized satellites, the attitude control function is under the onboard computer control. Using the attitude information provided by the onboard sensors, the control system initiates the actuators such as momentum wheels, magnetic torques and thruster motors. Depending on the requirements of attitude control in different phases of the mission (transfer orbit ejection, acquisition mode and station keeping) different modes of control of the attitude are used. There are parameters of this subsystem, which need to be properly reselected periodically by ground commands. For example, if sun/moon is predicted to fall into the sensor field of view, proper action needs to be taken.

Thermal Management

It is essential to maintain the temperature of different subsystems well within their operating limits. Because of the equipment the temperature of the components tends to vary. The thermal control is simpler in the case of spin-stabilized satellite compared to a three-axes stabilized satellite. In the latter case, we have a diurnal cycle as well as seasonal variations. By switching the heaters on/off at appropriate times of the day and year, the thermal control is achieved. This is in addition to the care taken during thermal design using blankets, reflectors, paints, etc.

Power Management

For a satellite in the geosynchronous orbit, the solar array power generation varies due to sun's declination, variation in solar constants and solar cell degradation. The worst case power generated would be in the summer solstice season at the end of life. The power system is sized to provide a positive margin even under this worst condition. In contrast, for remote sensing satellites, the power demand is not uniform and generally peaks during the payload operations. Normally, the fraction of time, the payload operated is small and hence it is possible to share the peak power demand by the solar array and the battery.

Battery Maintenance

Peak power demands during normal days as well as during eclipse support have to be taken care of. For a satellite in a geostationary orbit, eclipse occurs for about 45 days around the equinoxes. Care is taken that the eclipse of satellite occurs at a local time of near midnight. Prior to the eclipse season, battery needs to be reconditioned which is done by discharging the battery at a very low level and recharging the same.

Payload Operations

Normally for the communication payloads once they are switched on for the on-orbit checkouts, there may not be a requirement to turn them off except as part of the eclipse load management plan. However, depending on the way the transponder is being utilized, there may be the requirements for changing the attenuator settings which have to be commanded from ground.

Software Requirement

The mission control centre software generally falls into two categories namely, Real time software (RTS) which monitors the satellite health and issues the commands for its control, and Analysis and planning software (APS) which carries out detailed computations. RTS also includes the software for the device drivers for interfacing with the base-band equipment such as range processor. It includes functions such as data base management, event recording and critical alarm monitoring. APS provides support for the orbit related events, intrusion of sun/moon in the sensor field of view and lunar shadowing. One of the important tasks of the APS is the planning for the station-keeping maneuvers.

The INSAT mission is controlled from the Master control facility (MCF), located near Hassan, Karnataka. MCF is the control centre for INSAT satellites both during the launch and orbital operations period. It performs ranging, telemetry reception and analysis, command transmission and orbit determination functions. In order to ensure highly reliable functioning during critical phases of the mission, the facility is equipped with fully redundant systems for all the above requirements. The Master control facility consists of:

1. Satellite control earth stations (SCES)
2. Satellite control centre (SCC)
3. Uninterrupted power supply (UPS) consisting of an electrical substation, diesel-generating sets, power converters and inverters, batteries and associated control equipment.

Satellite control earth station (SCES). The location and size of the SCES depends upon the controls to be achieved, for example, in India presently there are four satellite control earth stations. These are equipped with fully steerable 14 m diameter antenna, with axially symmetric parabolic reflector. C-band transmit and receive chains, test equipment and remote control consoles for the antenna and the electronic equipment. The antenna can be driven in azimuth and elevation by servo systems, which can operate, in four distinct modes:

1. Manual
2. Autotrack
3. Program track
4. Slew

In the manual mode, the antenna can be pointed to any single set by an operator at the control console. In autotrack mode, the antenna automatically tracks the satellites. The pointing direction in this mode is derived from the deviations in signal strength received from the satellite. In program track mode, the computer provides the azimuth and elevation angles and the servo system follows this inputs. In the slew mode, the antenna can be driven at a constant speed from the thumb wheel on the control console. All the operations of the drive system are controlled from a console situated at the satellite control centre (SCC). Typically a C-band receive system operates at 3.7 – 4.2 GHz band. The G/T specification of the system is 31.7 dB/deg K at 4 GHz at 5° elevation angles.

The receive chain consists of uncooled parametric amplifiers, alongwith down converters and Intermediate frequency (IF) circuitry for telemetry reception and ranging. A test down converter is provided to enable monitoring of participating earth stations in the INSAT network. The C-band transmit system consists of 10 m to 14 m antenna with transit capability for simultaneous transmission of two carriers with an effective isotropic radiated power of 85.0 dBW per carrier in the 5855 to 6425 MHz band. This is accomplished by the provision of two transmit chains each having a 3 kW High power amplifier (HPA).

For the sake of redundancy, there are three up converters and three HPAs. In addition to the local control of all the units at SCEs, remote control of all the units at SCEs, is provided by means of a control and monitor console located in the SCC.

A test translation system, a satellite T, T and C simulator and a satellite communication simulator are provided that permit testing of transmit and receive chains and interface with SCC equipment.

Satellite Control Centre (SCC). SCC is the control point for all decision making, monitoring and control for the launch and on-orbit operations. SCC performs the following functions:

1. Command and ranging
2. Telemetry and ranging reception
3. Data recording
4. Real-time data analysis and display
5. Timing
6. Control and display consoles
7. Spacecraft payload checkout
8. VHRR quick-look display, etc.

The command and ranging transmission equipment generates command messages and ranging tones, which modulate a 70 MHz carrier. The command and ranging transmission equipment consists of four command generators, four FM modulators, four ranging units and a phase modulator. The inputs and outputs of all the units appear on patch panels can be patched to any of the earth stations. The telemetry and ranging reception subsystem provides for the reception and processing of telemetry and downlink ranging signals from the satellite. The subsystem consists of eight telemetry/ranging receivers, twelve PCM systems, the PCM word displays and the ranging units.

The orbit determination, maneuver planning, and real-time data analysis and display functions are provided by the computer based subsystems, plotters, magnetic disc units, magnetic tape units, and graphic terminals.

Two analog tape recorders and four strip chart recorders provide the data recording function. The timing subsystem provides a timing reference for labelling all satellite activities processed and recorded at SCC. The timing subsystem consists of a standard time radio receiver with associated antenna time code generators and displays.

The SCC control console and two satellite status panels provide the control and display functions. The SCC control console is the focal point for real time monitoring and control of the satellite. It consists of four ANK/CRT terminals and SCC and SCES status panels and a time display. Dedicated consoles are provided for the on-orbit operations of spacecraft.

The test equipment consists of TV monitor and other on-orbit test equipment. The TV pattern generator generates a TV test pattern for transmission to satellite to enable measurement of deterioration of the signal on reception through the MCF loop. The on-orbit communication test equipment provides instrumentation to generate uplink signals to measure frequency and power levels for any uplink and downlink. VHRR test equipment consists of a digital processor, quick look display facility and a hard copy facility.

2.9 EMERGING TRENDS IN MISSION CONTROL

With the steady growth in the number and complexity of satellites, there is an ever-increasing need for reliable and efficient mission operations. The tremendous advance in the area of personal computers and workstations has made it possible to provide the spacecraft controllers with the required environment to carry out their tasks effectively. These workstations allow multi-colour graphic displays, helping in presentation of the most relevant information for satellite control. Need to control different satellites from the same controlling station has made access to information and its presentation to be of minimum complexity and unambiguous. While trying to introduce new technology, compatibility must exist with the previously adopted and proven techniques. Vast improvement in communication/networking facilities has made it possible to provide an access to the centralized satellite based database via dial-up telephone lines to the authorized analysts. Such a scenario will obviously call for improved data security.

Standardization

In the coming years, there will be an increasing emphasis on adopting relevant standards in data handling. The packet telemetry standards will allow the subsystem analysts to access the data concerning the particular subsystem more easily. It will also be possible to vary the frequency of data sampling onboard as per the requirements of the user. The packet telemetry standards provide for error-control coding to guard against communication link impairments. Packet standards are also evolved for telecommand with the associated possibility of distributed spacecraft control. Presently, for the purpose of orbit a global network of stations is being used which transfer tracking data over the communication lines. It is possible that with the availability of data relay satellites with onboard DSP chips may reduce the dependence on such a network.

For the successful mission operations, the spacecraft controllers play a vital role. It is important to design proper Man machine interface (MMI) to ensure flawless operations. MMI should provide a user-friendly environment for the controllers to generate commands, to monitor the telemetry and to provide contingency support. Multiplayer architecture should be used in the mission control software specialist as part of the operation team and complex computer jargon is to be chosen based on contingency handling, which might occur quite unexpectedly. All the operations have to be carried out as per well defined and documented procedures. It is a good practice to have a weekly operation plan which can include inputs from the flight dynamics group regarding orbital events like sensor intrusion, sun outages, maneuvers and earth/moon shadowed. Based on this plan a step-by-step schedule for daily operations must be generated, validated and authorized for operations. Any departure from the schedule has to be authorized by operations directives generated by responsible subsystem engineers. The controllers should generate a detailed log of their activities that has to be reviewed by the higher management on a daily basis. Whenever an anomaly occurs a separate report/analysis has to be generated and archived.

Better Information Flow

For efficient satellite control, it is essential to provide the controllers with the most relevant information. With the possibility of development of better transducers onboard, critical parameters such as propellant balance, RF output of transmitter, received input signal strength, battery cell pressures, etc. may become feasible to be telemetered. Generation of a comprehensive database of all the faults/deviations/anomalies observed during the life cycle of the equipment serves as an important diagnostic tool. If nearly identical health process schemes are adopted for pre- and post-launch phases; it is easy to integrate the ground test data for the use in the on-orbit phase.

The availability of powerful spacecraft simulators has further made mission controllers in understanding the response of the satellite. Since the satellite systems are complex, and most of the malfunctions may be encountered in the early phase of the mission, it is a common practice to involve the spacecraft subsystems designers in this crucial phase of mission operations.

Trend Analysis

One of the important activities of mission control is to analyze the spacecraft telemetry for detecting abnormal behaviour and identifying the cause of the anomaly. The huge amount of telemetry data, which gets collected and archived, must be systematically analyzed to bring out various underlying patterns. The term trend analysis generally refers to processing a segment of data covering a relatively large span of time and extracting performance degradation, ageing effects, etc.

Several techniques of statistical data analysis can be used for analyzing the large volumes of numerical data. For example, the techniques of time series analysis to segregate secular, cyclic and long-term periodic behaviours can be quite useful. Detection of trends is usually rendered difficult because of the presence of high frequency variations. These unwanted components termed as **noise** have to be removed to bring out the underlying trend. For example, to plot the attitude disturbance torque profile over a day from the wheel speed data, it is required to pass it through a smoothing filter. These filters are easily realizable for operation on digital data.

Mission Planning

One of the major activities of mission analysis is to arrive at a suitable Sequence of events (SOE) for the various operations required throughout the mission. This process is usually carried out in several stages; in the first stage, the overall sequencing of the activities is arrived at and subsequently detailed command schedules are prepared. Several considerations such as safety of the satellite, network visibility, orbital geometries, etc. are to be considered. A well designed sequence should be set out in a modular form so as to allow relocation of a block of commands as and when necessary. It is possible to transfer some of the activities presently being carried out by the spacecraft. However, in all cases the ground segment should retain the master role. When present limits are crossed, automatic corrective action can be initiated by the satellite, especially in configuring the satellite into a safe mode, safe from the point of view of propellant consumption, power generation and thermal environment. Even when the ground control system is in the loop, it is possible to provide an automatic transmission of a set of authorized commands from the mission control centre whenever corrective actions are time-critical. Features like periodic checkon the satellite can be easily automated. With the use of digital devices onboard, there is an ever-increasing possibility of Single event upset (SEU), i.e., a change of state in one bit. SEU may be caused by the penetration of a high-energy particle on exposure to cosmic rays or due to solar flares. A possible effect of SEU is to disrupt the ordinary execution of the processor software code. Periodic automated checks can detect the occurrence of SEU and alert the operator for corrective action.

Software Development and Usage

The mission control software is becoming increasingly complex day by day. In order to validate and accept the same, sophisticated software engineering techniques and tools have to be used right from the requirements definition stage. The software has to undergo rigorous testing and should conform to the quality assurance standards that are required for space technology. Time tested, reliable and repeatability are important factor. Onboard, embedded and user-friendly software are being developed for self-test and auto control. The use of software in space technology and operations has crossed Moore's law limits.

Inclined Orbit Operations

In the last few years most of the communication satellite agencies have been advocating stoppage of inclination control maneuvers for extending the useful life of a satellite. On the one hand this calls for tracking ground antennae and on the other it requires restoration of the spacecraft beam pointing by attitude bias commanding. Such a scheme has been already experimented at INSAT MCF for INSAT 1B satellite. The impact of inclined orbit operations on mission control is the requirement for frequency commanding to change the attitude biases, and this can perhaps be automated.

Expert Systems

In the near future knowledge-based systems will be used for satellite control operations. These expert systems can reduce the strain on the operator significantly as it will reduce the monotonous work of analyzing huge quantities of data. The expert system can be designed to keep track of the subsystem health and provide processing information to the controller. Expert system can be of immense help to the mission personnel, whenever complicated command sequences are to be executed within a time frame. Another area of expert system application will be mission-planning to solve complex scheduling problems associated with the satellite missions. Considerable research and developmental work is going on in the area of artificial intelligence and neural network to achieve the mission control. What was a fiction will definitely become a reality in near future!

SUMMARY

In this chapter we tried to familiarize with different definitions and terminologies that are used in satellite in space. We also learnt about the orbiting parameters that affect the orbit and orbit path. These discussions showed that the higher the altitudes the satellite orbits at the lesser its velocity and acceleration; and more the time it takes to complete an orbit. This helps in choosing proper radius of orbit for geostationary satellites and we arrived at a conclusion that a geosynchronous satellite should be at around 42,100 km radius or an altitude of 36000 km. We also studied visibility aspects like minimum altitude, solar eclipse affect and parking aspects. In order to satisfy the requirements of telemetry tracking and control, brief idea of satellite structure and launching was also discussed. Finally some concepts and trends of mission control were also spelt out from the data collected from different agencies working in these fields.

REVIEW QUESTIONS

1. Define the following and explain:
   (i) Satellite orbit
   (ii) Satellite axes
   (iii) Gyroscopic stiffness
   (iv) Earth station look angles
2. What is the difference between a geosynchronous and a geo-stationary satellite?
3. Define the following with respect to a satellite:
   (i) Eccentricity
   (ii) Axes
   (iii) Sub-satellite point
   (iv) Ascending node
4. Distinguish between synchronous, subsynchronous and non-subsynchronous types of satellites.
5. Define Kepler's laws of orbiting bodies and derive an equation to show that the third law is true for any orbiting satellite.
6. What is slant range and what is its importance in satellite communication?
7. What do you mean by eclipse in case of a geostationary satellite and when does it occur?
8. Explain the effect of solar eclipse on the performance of a geostationary satellite. In what way it is related to fixing the parking place of a satellite?
9. (i) Explain the need for satellite communication.
   (ii) What are the different types of satellite orbits? Discuss their merits and demerits.
   (iii) A low orbiting satellite has an 8-hour prograde orbit. How long during each orbit will an earth station be able to communicate with it above an elevation angle of 15?
10. Explain how attitude and orbit control is achieved from an earth station?
11. What are the methods used to achieve stability of satellites in orbit?
12. What are the torques that affect the position of a geostationary satellite?
13. Describe the steps involved in launching a satellite.
14. Why T, T and C are necessary for a satellite system?

PROBLEMS

1. The mass of earth being 5.9733×10^{24} kg and gravitational force 6.673×10^{-20} km^3/kg s^2, calculate gravitational constant g_0. If the exact radius of orbit is to be 42164.57 km, calculate the velocity, angular velocity, orbit period and acceleration of the satellite.

   (**Ans.:** 398600 km^3/s^2, 3.07 km/s, 72.92×10^{-6} rad/s, 23 hrs 56 min 4.09 s, 0.2242×10^{-3} km/s^2)

2. If a satellite has an orbiting time of 23 hrs 56 min, calculate the orbiting distance (radius of orbit). Assume suitable data if required.

   (**Ans.:** 42160 km)

3. The longitude and latitude of an earth station are 76°E and 13°N. Find the azimuth and elevation from this station to ASIASAT situated at 105°E.

   (**Ans.:** A_z = 247.75°, ξ = 53.12°)

4. A satellite is orbiting at 28300 km apogee with an eccentricity of 0.3. What is the perigee distance and average orbiting period. Assume $g_\sigma = 3.98 \times 10^5$ km^3/s^2.

   (**Ans.:** 15238.46 km, 31965.08 s)

5. A satellite is orbiting round the earth at 42124 km. The earth station is looking at this satellite at an elevation angle of 35°. Calculate the slant range. Make suitable assumptions and give reasons for making such an assumption.

   (**Hint:** Take ξ_∞, **Ans.:** 35773.56 km)

6. Determine the slant range from an earth station situated at 20°E and 10°N from a geostationary satellite parked at 70°E. The height of satellite from sub-satellite point is 36348 km.

   (**Ans.:** ξ = 31.7642°)

7. A satellite receives sunrays at 7°6′ and the duration of eclipse is 56 min. Calculate:
   (i) Radius of orbit
   (ii) Height of satellite

   (**Ans.:** 36460.599 km, 30082.599 km)

8. A satellite is orbiting in the geostationary orbit at a radius 42100 km. If the sunrays are falling at a declination of 0.8, what will be the eclipse time on the autumn equinox day.

9. A geostationary satellite is in eclipse for a period of 47 min; calculate the eclipse angle and the declination angle of sunrays.

   (**Ans.:** α = 11.782°, δ = 6.42°)

10. A geostationary satellite is orbiting at 42000 km. If the radius of orbit of earth is 6385 km and sun's declination is 7°15′, calculate the duration of eclipse. Also calculate the starting time of eclipse if the satellite longitude is 83°E.

    (**Ans.:** 9.8°, 2360.7 s, 23 hrs 30 min 43.38 s)

3 Choice of Carrier

3.1 INTRODUCTION

A need to have a common technical standard throughout the world for proper telecommunication network resulted in the formation of **International telecommunication union (ITU)** in 1864 with twenty member countries. In 1990 the membership increased beyond 230 countries. This became important as there was growing demand of parking place and new orbit demands by member countries. This led to the formation of many space regulations and frequency coordinates.

To avoid chaos and prescribe standards the administration of space communication and telecommunication regulation and coordination are done under the three regional administrative radio conferences.

3.2 CONTROLLING AGENCIES

Space service is defined depending upon the services, the type of processing and applications. The selection of suitable frequency bands, orbit type and orbital position is the foremost prerequisite for a successful satellite system and its operation. There are several ITU administration bodies that take care of such coordination as shown in Figure 3.1.

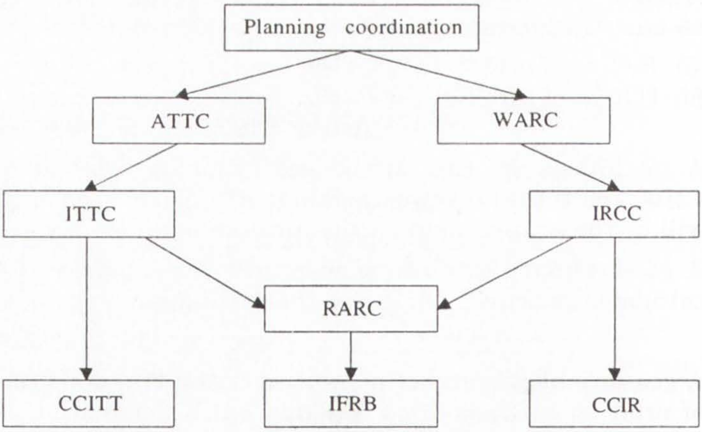


Figure 3.1 Organizational chart.

International telecommunication union (ITU) member countries are advised about frequency usage, parking space and coordination, power permitted to be transmitted, mass of satellites, cost effectiveness, etc.

World administrative radio conference (WARC) meets once in twenty years to review the development of space communication and telecommunication. WARC is made up of the following three regional administrative radio conferences:

1. **ATTC.** Administrative telegraph and telephone conference takes care of terrestrial networks in the regions.
2. **ITTC.** International telegraph and telephone conference scrutinizes the recommendations and recommendations of CCITT are finally published.
3. **IRCC.** International radio consultative conference scrutinizes the recommendations of CCIR and finally publishes the recommendations.

Consultative committee on international telegraph and telephone (CCITT) services provides the standards and data rate for different services which are approved for the member countries.

International frequency registration board (IFRB) takes care of and scrutinizes the advance publication report of countries and finally allocates the usable carrier frequencies and data rates.

Consultative committee of international radio communication decides the general standard adopted in radio communication and publishes the recommendations from time to time under the banner of ITU.

3.3 FREQUENCY COORDINATION

Requirements

The sharing of resources depends upon the type of service whether fixed satellite service or mobile satellite service. The communication satellites must conform to certain procedures laid down by the ITU regulations, some of which are:

1. Maximum allowable interference in the communication channels
2. Different interference paths and their avoidance
3. The minimum C/T of the power spectrum and the type of modulation involved
4. Total transmission losses
5. Frequency planning

All these are necessary since number of satellites have been stationed or are going to be stationed in the geostationary, inclined or even polar orbit. This results in certain restrictions on Effective isotropic radiated power (EIRP), antenna gain, beamwidth and amount of power flux density available at space and arriving at earth station.

ITU has mainly specified Articles 8, 11, 12 and 13 as radio regulation to be followed in satellite and terrestrial networks. This facilitates allocation of common frequency bands and their effective use by member countries. The frequency bands allocated for the satellite services used by communication satellites and the choice of frequency bands depends on:

1. System considerations
2. Organization level frequency planning
3. Orbit frequency planning and coordination

System considerations. Appendices of ITU radio regulation lists number of parameters like system design consideration and resulting information which have to be dealt with by the member countries. The most important is the uplink and downlink power spectral density whose off-axis EIRP should not interfere with terrestrial communication links operating at the same frequency as the adjacent satellite links. The design of antenna and its radiation pattern is also important. From frequency coordination point of view, the antenna pattern should be away from such terrestrial links.

Earth station system noise temperature, equivalent satellites link noise temperature and transmitter gain are the important parameters to be submitted as Advance publication information (API) to ITU. Bandwidth requirement depends on class of station and nature of service. Typical calculation procedures have been performed and explained in Chapter 4 and Chapter 5. These are also indicated as standard calculations in CCIR reports 792 and 871.

The satellite characteristics to be submitted to the bureau for planned satellite networks are explained below. The planned satellite networks are:

1. The Broadcasting-satellite service (BSS), downlink space stations under the provisions of Appendix S30
2. The Fixed-satellite service (FSS), under Appendix S30A and under Appendix S30B.

Organization level frequency planning. Currently graphical representations of antenna gain contour and service area diagrams for geostationary satellites and diagrams of space station antenna gain in the direction of the geostationary orbit and for geostationary satellites need to be submitted to WRC.

The World radio communication conference 2000 (WRC–2000) assigned 10 assignments/channels to countries in region 1 and 12 assignments/channels to countries in region 3 in both the downlink and feeder-link. Taking into account the time required to process the networks, the bureau will not be in a position to publish the circular letter required in resolve 2 of Resolution 53 (Rev. WRC–2000) until a few years. Therefore, the coordination requirements associated with the relevant assignments in the plans should be submitted well in advance.

Orbit frequency planning and coordination. The API of the planned satellite should be sent to IFR in advance for approval. This should also contain the time required to build the satellite, date of commissioning, validity period, orbital coordinate required, launch schedule, frequency assignment, etc.

For coordination of geostationary satellites, the minimum separation between the satellites have to be maintained according to radio regulations R2616. The longitudinal tolerances presently is ± 0.1° for all GSO satellites. The visible arc of satellite should be such that the satellite is visible from most of the places of the nation of origin depending upon application.

In spite of large visible arc, service arc may be much smaller as only a selected area would receive large field strength for satisfactory reception as shown in Figure 3.2. The area of coverage is called footprint and circumference of this as end of coverage (EOC).

For India, visual arc is 70° to 95°E typically for INSAT.

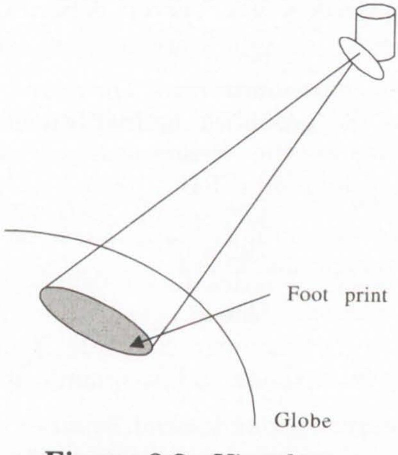


Figure 3.2 Visual arc.

Frequency Planning

The ranges of frequencies, which lie in the electromagnetic spectrum, are generally categorized as radio frequencies, since these have to carry the intelligence. The planning and choice of these frequencies depend on the base-band frequencies of interest or bandwidth of the baseband. The main services, which are currently categorized by the International body, are: (Refer: ITU radio regulation 8 revised by WARC)

1. Amateur satellites

2. Broadcast satellites
3. Earth exploration satellites
4. Fixed satellites
5. Inter or cross link satellites
6. Mobile satellites
7. Radio determination satellites
8. Radio location satellites
9. Radio navigational satellites
10. Space operations
11. Space research
12. Standard frequency and time signal satellites

The minimum radio frequency used for these services have to be essentially one which can penetrate the ionosphere, undergo minimum losses and propagation absorption and handle the required base-band. In case of amateur satellites, generally 1260–1270 MHz band is allocated. The fixed satellite services have the frequency band lying between 4500–4800 MHz, 6725–7025 MHz, 10.7–10.95 GHz, 11.2–11.45 GHz and 12.75–13.25 GHz as per the recommendations. These allotments are based on the requirements of national space application system and their geographical and temporal conditions.

Different services have been given different status. These are essential for sharing the following frequencies if required:

1. *Primary frequency allocation.* These are the frequency bands which are totally protected against interference from all other transmissions. In the visible arc no frequency sharing or reallocation is done by IFRB.

2. *Secondary frequency allocation.* These do not enjoy any sort of protection and can be shared.

3. *Footnote allocation.* The status of these frequency bands can be changed depending upon their use from time to time. They can be primary at times and secondary at other times.

In addition the frequency coordination between satellite-earth station and terrestrial station requires detailed study. This involves not only national but International coordination with least interference. ITU regulation under Articles 27 and 28 gives such technical specifications and guidelines. The three regions for such frequency allocation are guided by Regional administrative radio conference (RARC), which are:

Region I: Europe, USSR, Africa and Mongolia
Region II: Asia and Pacific region like Australia, India, Pakistan, New Zealand, etc.
Region III: USA, Canada and neighbouring countries

In addition each of these regions and the countries individually have their own national allocation tables controlled by their space agencies or commissions under the scrutiny of WARC for final allocations. All allocations are scrutinized by IFRB. All planning have to be done five years in advance or at least two years in advance with an advance publication to the world body. This is essential in order that all the countries in the region or elsewhere come to know about the frequency allocation and send their objections about particular frequency bands (if any) within one year of such publications. The different frequency allocations are given in Table 3.1 as per 1992 publication.

Table 3.1 Frequency Allocation

Band (MHz)	*Allocation*	*Region*	*Service*
401–403	Secondary (E-S)	I, II, III	Earth exploration satellites
620–790	Secondary (S-E) footnote	I, II, III	Fixed mobile and terrestrial broadcasting satellites
1215–1300	Secondary (S-E)		Earth exploration satellites, radio location
1260–1270	Footnote (E-S)	I, II, III	Amateur satellites
1400–1429	Primary	I, II, III	Space operations and research
1525–1530	Primary (S-E)	I, II, III	Maritime mobile non-speech low-bit rate data communications
1530–1544	Primary (S-E)	I, II, III	Maritime distress and safety system
1545–1559	Primary (S-E)	I, II, III	Direct terrestrial station-aircraft or aircraft links
16100–16260	Primary (E-S)	Except Sweden and Cuba	Aeronautical mobile satellite (R)
1634.5–1645.5	Secondary (E-S)		Land mobile
1646.5–1656.5	Primary (E-S)		Aeronautical mobile satellite (R)
1656.5–1660.5	Primary (E-S)		Land mobile
2025–2110	Primary (E-S and S-S)		Non-GEO links
2200–2290	Primary (S-E and S-S)		Earth exploration satellites
2310–2360	Primary	2, 3 USA and India	Digital audio broadcast
2400–2450	Footnote	I and II	

(Continued)

2500–2690	Primary (S-E)	II and III national and regional	DRS fixed satellite community reception
2640–2655	Secondary	I, II, III	Passive
2655–2690	Primary (E-S)	II and III national and regional	Fixed satellites
2535–2655	Primary (S-E)	II national and regional systems	Fixed satellites
2655–2690	Primary (E-S)	II and III national and regional systems	Fixed satellites
3400–3410	Footnote	II and III only, subject to not causing interference	Amateur satellites
900–6200		Lower band II/III and upper band I	Shared with fixed and mobile
4200–4400	Secondary		(passive) without protection from radio-altimeters
5650–5670	Footnote (E-S)	Subject to not causing interference	Amateur satellites
5725–6725	Primary (E-S)	I, II, III	Fixed satellites
7025–7075	Primary (E-S)	I, II, III	Fixed satellites
7250–7750	Primary (S-E)	I, II, III	Fixed satellites
7900–8400	Primary (E-S)	I, II, III	Fixed satellites
9975–10025	Secondary	II, III	For weather radars
10100–10300	Primary (S-E)	I, II, III	Geostationary meteorological satellites
10450–10500	Secondary	I, II, III	Amateur satellites
10950–11200	Primary (S-E)	I, II, III	Fixed satellites
11200–11700	Primary (S-E)	I, II, III	Fixed satellites
11700–12200	Primary	Limited to national and subregional systems Region 1	Broadcasting satellites
12200–12700	Primary (S-E)	National and subregional Region 3	Limited to community reception
13750–14000	Primary (E-S)	I, II	Limited power

(Continued)

14000–14800	Primary (E-S)	Countries outside Europe	Broadcasting satellite feeders
17300–18100	Primary (E-S)	Region III	Fixed satellite for broadcasting satellite feeders
18600–18800	Primary	Region II	Allowing links to mobiles
19300–19700	Secondary (E-S)	II	Future: public land mobile telecommunication systems
22500–23000	Primary (S-E) Passive	I, II, III	Space research, earth exploration
27500–30000	Secondary (S-E)	I, II, III	Uplink power control beacons, earth exploration
41000–43000	Primary (S-E)	I, II, III	Broadcasting, fixed, mobile
47000–47200	Primary	I, II, III	Amateur satellites
50000–58000	Primary	I, II, III	Earth exploration
84000–86000	Primary	I, II, III	Space research, radio astronomy, earth exploration satellites

The following abbreviations denote:

E-S : Earth to satellite
S-E : Satellite to earth

Article 11 of the ITU radio regulations addresses satellite networks and coordination of satellite and terrestrial links sharing the same carrier frequencies. This article indicates

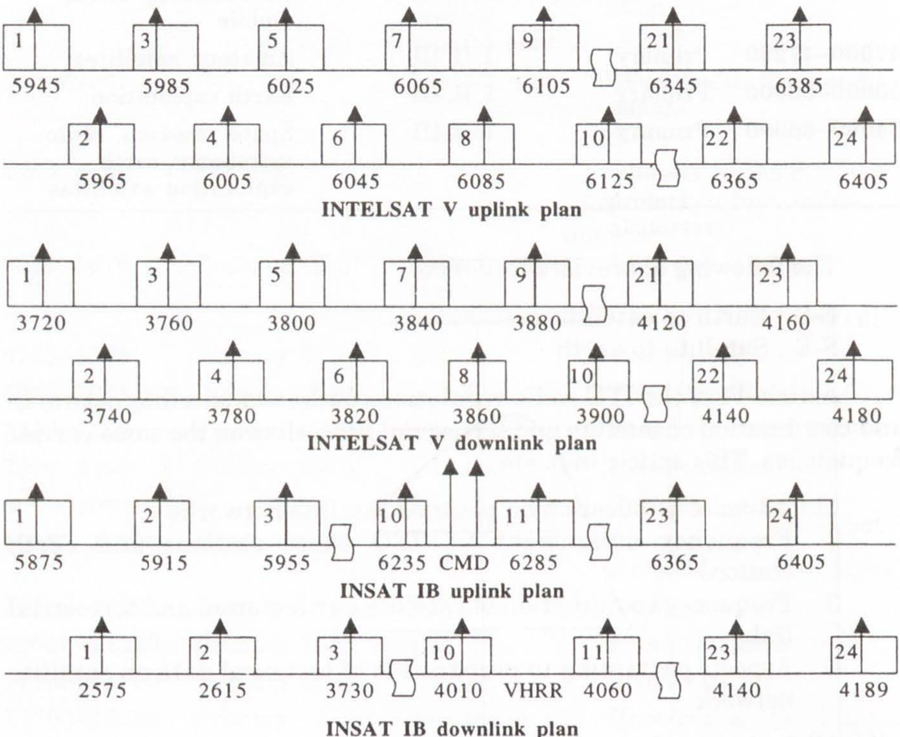
1. Advance publication on planned satellite networks
2. Frequency assignment to GEO space stations and earth stations
3. Frequency coordination of satellite earth station and terrestrial link
4. Aspects pertaining to preparation of technical data on satellite network

All frequency allotment activities have to undergo project implementation phases consisting of:

1. *Study phase.* This phase involves preparation of guidelines and policy matters pertaining to transponder frequency utilization, intended services, surveying of frequency bands in use and preparation of API.

2. *Pre-operational phase.* Registration of satellite network with IFRB, final orbit frequency planning, review of services and any additions to be conveyed.
3. *Operational phase.* Registering and sending intimations to other satellite network agencies, assisting agencies and requesting other members to cooperate in proper and successful operation.
4. *Organizational phase.* Training of technical personnel in orbit frequency planning, attending ITU and CCIR meetings, help in study and planning of new services and projects.

During the period of approval of the project, the agency/organization will side-by-side carry out the design of earth station and satellite. Figure 3.3 shows the frequency plan of INTELSAT V and INSAT IB.



(Frequency is in MHz)

Figure 3.3

Structure of the Near Earth Space

Atmosphere, troposphere and ionosphere affect the propagation, the position, and constructional aspects of a satellite. The main characteristics that have to be considered during design are composition, temperature, pressure and density of these layers as they not only affect the solar radiations and gravitation but also get affected during day, night and seasons.

The atmosphere extends approximately up to 200 km. The concentration of gases varies with altitude. 50% of the mass being in the lower 5 km, 49% in the next 25 km, 1% beyond 30 km and above 100 km is negligible. Atmosphere consists of gases which are exhibited in Table 3.2. The variation of temperature with altitude is illustrated in Figure 3.4.

Table 3.2 Contents of Atmosphere

Gas	*Content*
Nitrogen	78%
Oxygen	21%
Argon	1%
Carbon dioxide	300 ppm
Methane	1 ppm
Ozone	0.5 ppm
Helium	18 ppm
Neon	5 ppm
Hydrogen	0.5 ppm
Potassium	1 ppm

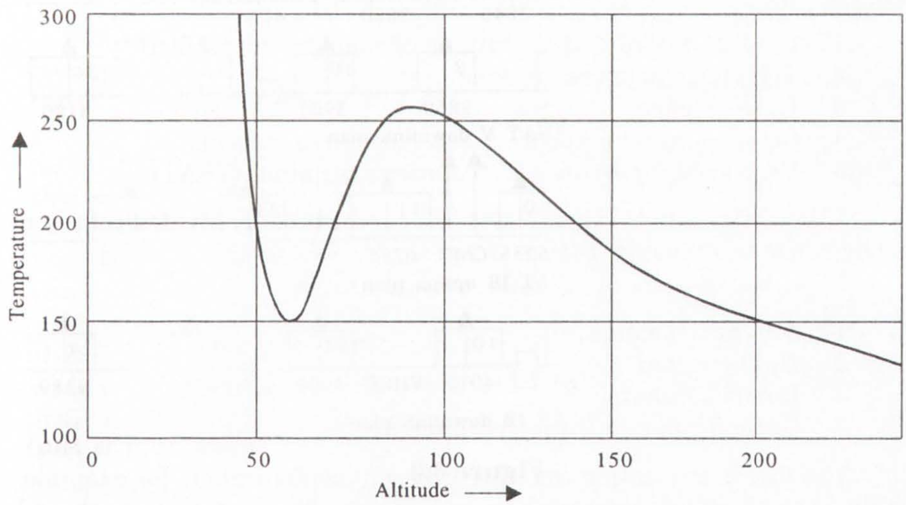


Figure 3.4

The first 16 km is the troposphere, the next 50 km is the stratosphere which has the bulk of ozone. From 50 to 90 km is the mesosphere. The temperature at the surface of the earth is more as the sunrays heat up the earth's surface but as altitude increases the temperature reduces as shown in Figure 3.4 (Effect of these is discussed in Link Analysis, Chapter 4). Beyond 90 km of altitude, the temperature raises rapidly up to 200 km becoming isothermal as 400 km is approached. The temperature indicated here are not exact temperatures or altitude as the temperature depends on many real-time effects and cannot be calculated. For all designs and predictions statistical probability have to be used. Also, the air in the first 100 km is having almost constant characteristics and constituents and hence this region is also called as **homogeneous region**. But this layer contains ozone and water vapours, which undergo changes as sunrays fall and cause thermal gradient. Above 100 km the changes occur drastically in chemical composition.

In space applications the knowledge of the above factors is absolutely necessary as it affects the propagation, noise characteristics, launching characteristics, life of satellite (particularly LEO) and so on. Several models are available for the designers, depending upon the type of orbit. These models are out of scope of this book but can be read in the references mentioned.

3.4 EARTH STATION TECHNOLOGY

The complexity of the earth station depends on the type of signals it has to handle. An earth station required to control a satellite is quite different from a cable operator. The earth stations can, therefore, be broadly divided into:

1. Central control earth stations or master control facility
2. Telephone network stations
3. Large capacity stations
4. Small relay or entertainment type earth stations
5. Very small aperture earth stations terminal (VSAT)

The configuration of earth stations can be broadly divided into four subsystems as shown in Figure 3.5.

Basic subsystems of an earth station are:

1. Antenna systems
2. Uplink chain
3. Downlink chain
4. Ground communication equipment

The first earth station can have different configuration, for example, in the case of a TV transmitter there is no receiver section as such and it just transmits the signal spectrum generated by the studio whereas in the case of a telephone network the hub station transmits as well as receives the modulated carriers. Similarly a satellite control station also receives telemetry signals and transmits the control commands.

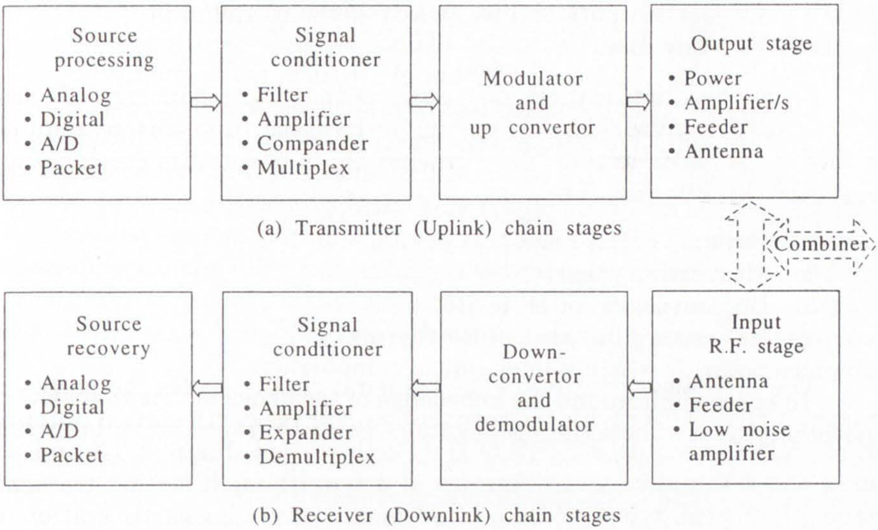


Figure 3.5 Sub-systems of earth station.

The design of earth station depends on:

1. Application
2. Intermediatory processing
3. EIRP required
4. Back-off requirements

Consider the case of a telephone network application; it is meaningless and uneconomical to transmit every call on a separate carrier. Hence the subscriber channels are multiplexed in groups, super groups, master groups, etc. to build a base band. This base band is then amplified, modulated, power amplified, filtered and fed to the antenna whereas in the case of a satellite control station the process is more complicated and requires complex subsystems. This is necessary because any error or tracking calculations are time and space dependent. The computers in the control station have not only to calculate the error or changes but also calculate the corrective action to be taken in split of milliseconds, the data thus generated has to be put in a frame that contains the header giving coded information about the destination, source and error check information. This frame of digital symbols is then modulated power-amplified and transmitted. The corrective action taken at the satellite has to be checked at the control station and hence loop back has to be created to receive the new telemetry, ranging information for further processing.

Earth stations can, therefore, be classified on the basis of services provided such as:

1. Two-way TV telephony and data
2. Two-way TV
3. TV receiver only

4. TV receiver only and two-way telephony and data
5. Two-way data

From the classification, it is obvious that the technology of earth station will vary considerably on the performance and service requirements of the earth station. The transmit chain of satellite earth station performs the following functions:

1. Building of base band
2. Modulation of carrier
3. Up conversion of IF to RF
4. Power amplification of RF carrier

The final power output of the transmit chain decides the stages in transmit chain along with the transmit gain of the earth station antenna to provide the required EIRP of the earth station. Figures 3.5 and 3.6 show the schematic block diagrams of a typical earth station transmit chain. Different types of base-band signal that the earth station is required to handle could be TV, multiplexed telephone channels, number of small carriers in SCPC, radio networking channels, data, etc. After the base-band signals modulate the IF, the carrier is up converted to the RF in the up converter and then amplified to the desired output by the high power amplifier.

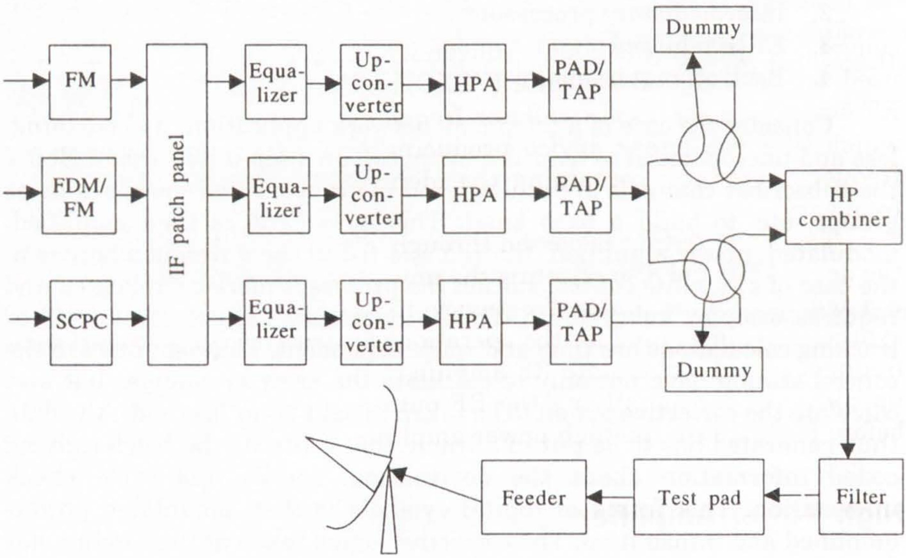


Figure 3.6 Transmit chain of a large earth station.

Up Converter

The up converter consists of the following major subcircuits:

1. IF amplifier

2. Mixer
3. Local oscillator
4. RF power amplifier

Usually the IF is 70 MHz. However higher frequencies from 140 MHz to 400 MHz can also be used as the intermediate frequencies. This depends on modulating carrier and available technology.

The schematic diagram of a typical up converter is shown in Figure 3.7. The up converter can be either single conversion or double conversion type. In the double conversion scheme, two mixer stages are used, one uses crystal oscillator (VCXO) and the other *LC* oscillator. The RF signal and the local oscillator frequencies are mixed in the mixer, which is a non-linear device producing the higher and lower order frequency products containing the identical information of the input frequency.

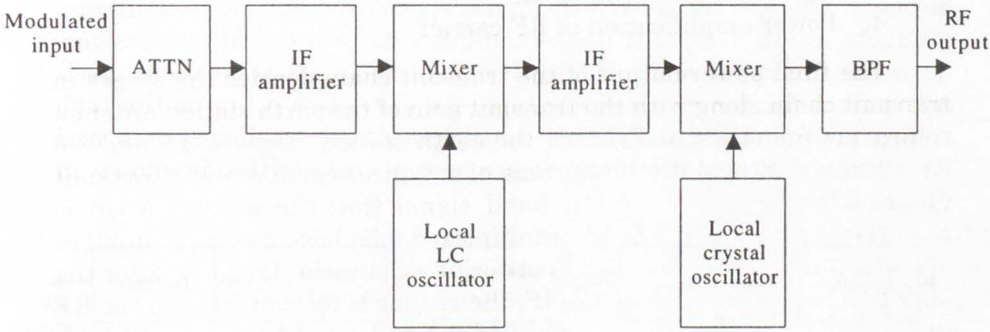


Figure 3.7 Typical up converter.

The mixer output is passed through a band pass filter for selecting the desired RF and also rejecting the unwanted LO frequency. Instead of a fixed crystal oscillator frequency in the LO chain, a frequency synthesizer can be used for the operation of the up converter over a wide frequency band. Solid state RF amplifiers are used at the output of the up converter for amplifying the RF output power to the desired level before feeding it to the high power amplifier.

High Power Amplifier

Depending upon the power output/EIRP requirement of the earth station, the high power amplifier (HPA) can be one of the following types:

1. Travelling wave tube amplifier (TWTA)
2. Klystron amplifier
3. Solid state power amplifier (SSPA)

At C-band frequency range, Travelling wave tube amplifiers (TWTA) and Klystron amplifiers are used as HPA for power output of 50 W to 3 kW. The advantage of TWTA over the Klystron power amplifiers is the wide instantaneous bandwidth of a TWTA.

High power TWTA can offer instantaneous bandwidth of approximately 10% change of 40 dB gain. The Klystron power amplifiers are usually tunable over the entire transmit frequency range with the desired instantaneous channel bandwidth which is usually 40 MHz.

The gain, bandwidth and the power output are the major specification requirements of the high power amplifiers. There are however, other secondary requirements, e.g. third order intermodulation products, group delay and phase non-linearity, AM to PM conversions, harmonics contents, etc., which the HPAs of each station must meet. Apart from the power amplifier tube, the HPA also contains the high voltage power supply, and various control circuits, air-cooling system, and RF circuitry. Schematic block diagram of a typical HPA is shown in Figure 3.8.

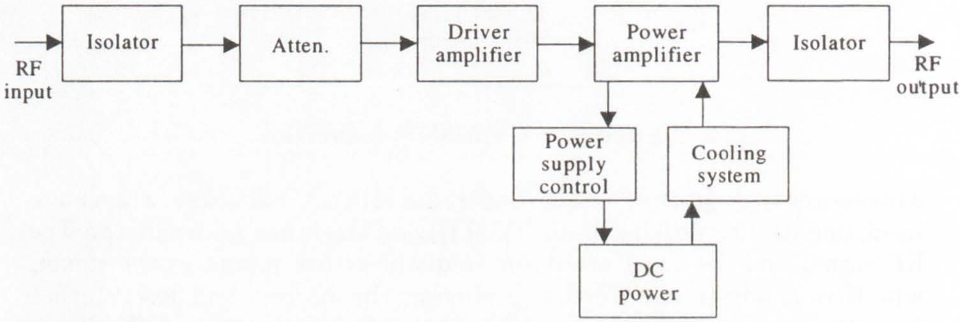


Figure 3.8 Block of typical high power amplifier.

With the advancement of GaAs field effect transistor (FET) devices at microwave frequencies, Solid State Power Amplifiers (SSPAs) of 20 to 25 watt are now available at 6 GHz frequency range for use in earth stations. Most of the C-band VSAT type small terminals use SSPAs in the final power amplifier, which makes the terminals compact, reliable and easy to operate. These VSATs are able to handle low-bit rate data or a single digital/analog voice channel.

Receive Chain

The receive chain of satellite earth station performs the following functions:

1. Amplification of the weak received carrier
2. Down conversion of the RF to IF
3. Extraction of the base-band signal, after demodulation

The earth station receive system is characterized by the figure of merit defined by G/T where the G is the receive antenna gain and T is the system noise temperature. Figure 3.9 shows the schematic block diagram of the receive chain of the earth station which consists of:

1. Low noise amplifiers (LNA)
2. Down converter
3. IF amplifier
4. Demodulator

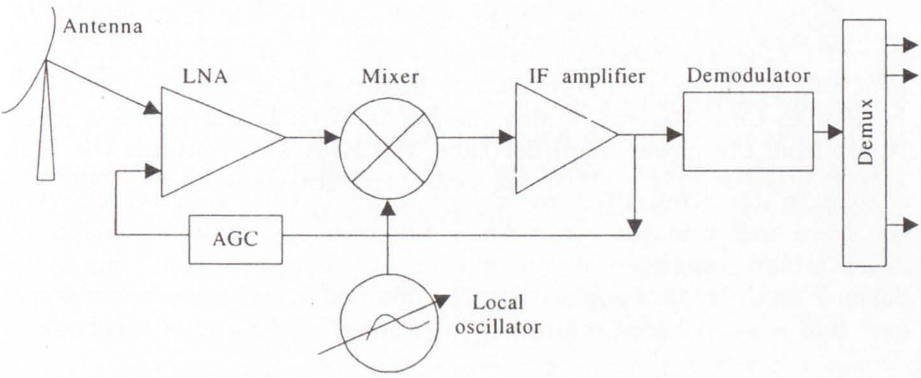


Figure 3.9 Block diagram of the receive chain of the earth station.

Low noise amplifier. The low noise amplifiers used in satellite communication earth stations are of the following types:

1. Parametric amplifier
2. FET amplifier
3. HEMT amplifier
4. Bipolar amplifier

Both cooled and uncooled parametric amplifiers were used in the first- and second-generation earth stations in the sixties and seventies. However, with the advancement in semiconductor technology and monolithic RF integrated circuits (MIC), semiconductor LNAs are frequently being used. For low noise and good S/N performance, the LNA characteristics play an important role and are discussed in the next chapter. LNAs should not have noise temperature exceeding 35° K. Heterodyning is a usual feature of any communication receive chain to get required selectivity and ease of detection apart from other benefits like BW requirement and stability criterion. AGC are used to control these requirements along with linear operation. Mixer stages helps in heterodyning and down converting the uplink frequency to allotted intermediate frequency spectrum. Demodulator and demultiplexer design depends on the type of signal and modulation which will be discussed in Chapter 4. All satellite receiving stations including cable operators use low noise block converters (LNBC) at the antenna to increase CNR. [See Figure 3.10]

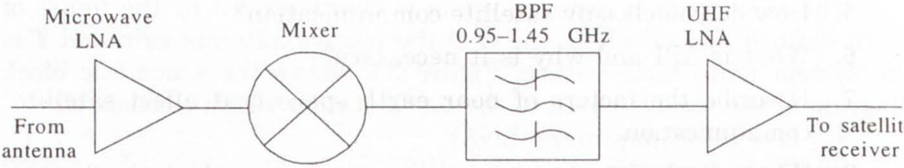


Figure 3.10 Low noise block converter.

Many a time double heterodyning may be preferred from stability point of view. IF amplifiers are frequency selective and provide required voltage gain and spectrum selectivity to keep carrier to intermodulation within the prescribed limits. In case of TV broadcast, it is necessary to again modulate the video and audio signal as per CCIR/FCC/SECAM standards. In addition other subsystems like power supply, antenna steering systems and filters are also required. In case of digital receivers the front end remains same while the recovery portion consists of descrambler, expander, demultiplexer and decoder. The complexity depends on the type of application. The detailed discussion is out of scope here and is available in references mentioned at the end of this book.

SUMMARY

In this chapter emphasis was given to study the different organizations that control the activities of space communication. It was also seen how frequency bands are allotted for different applications and regions. The tables showed the uplink and downlink frequency coordination. Different satellite applications were also listed and discussed. Lastly, we briefly discussed the earth station configuration. The detailed discussions are covered in latter chapters.

REVIEW QUESTIONS

1. Why is it necessary to have a control on the space communication?
2. Describe the hierarchical set-up of the controlling agencies in telecommunication?
3. What is the need to have International telecommunication union (ITU)?
4. What are the different requirements that are looked into to decide the carrier frequency in satellite communication?
5. How do you classify satellite communication?

5. How do you classify satellite communication?
6. What is API and why is it necessary?
7. Describe the factors of near earth space that affect satellite communication.
8. What are the important components of an earth station?
9. What are the different components of a satellite receiver front end?
10. Describe the working of a typical high power amplifier used at the output of earth station.
11. How is it possible to select a particular downlink frequency in a receive chain?
13. What is the need of an LNBC?

4 Link Concepts

4.1 INTRODUCTION

In order to design the earth station as well as satellite subsystems, it is essential to know the characteristics of the propagating path and different losses/absorption that the EM wave undergoes. The designer should also know the minimum signal to noise requirement in order to get good reception or error free data. The analysis depends on several factors that are discussed in this chapter. These discussions are the basis of multiple access analysis.

4.2 SATELLITE LINK ATTRIBUTES

In this section we will see what are the attributes on which a satellite link depends. Any satellite link has an uplink (from transmitting earth station to satellite), the repeater (satellite), the downlink (satellite to earth station or platform) and the receiver (earth station itself). Satellite communication without exception uses frequency modulation for analog signal transmission and invariably frequency or phase variation of carrier in case of digital stream. Any communication engineer is aware that amplitude modulation or amplitude variation characteristic of carrier with respect to amplitude of signal cannot be preferred in satellite communication because of the following reasons:

1. Larger propagation paths involved
2. External noise sensitivity of AM compared to other modulation techniques
3. Carrier frequencies involved
4. Carrier to noise ratio requirement at the receiver

Lot of detailed literature is available in most of the communication books (some are listed in the reference list) on the above aspects for the reader to refer to and hence it is avoided here.

The overall link performance depends on the distance the EM wave has to travel over several mediums. The characteristics of the medium play an important role in deciding the overall performance of the link. We will study the effect of fading from time to time depending on time of the day and atmospheric conditions as was discussed in Chapter 3. Noise is another important attribute which degrades the link performance, it could be external noise or the system noise itself. The carrier to noise density plays an important role in the reception or recovery of a signal be it a analog or digital source. These aspects have been discussed in detail in the succeeding sections.

4.3 SATELLITE LINK ANALYSIS

It has been seen in Chapter 3 the choice of frequency depends upon the type of source and bandwidth of the earth station handling the sources. In addition it also depends upon the losses it may undergo during transmission. In fact if the carrier frequency is below VHF range, the EM wave will never cross the ionosphere. Geosynchronous satellites are above the earth much beyond ionosphere and the satellites are in the line of sight of earth station antenna. As the EM wave propagates it undergoes the following losses:

1. Path loss α_p
2. Losses in troposphere/atmosphere α_a: due to scattering and absorption and due to precipitation like rainfall and fog
3. Losses in ionosphere α_i, e.g. Faraday rotation
4. Losses in the antenna system α_{ant}
5. Miscellaneous losses in linking systems α_l

Path Loss

Path loss is the attenuation of signal that occurs as the EM wave travels from earth station to the satellite and vice versa. This is the major loss in any satellite link. In order to calculate path loss it is essential that one should know the slant range of the satellite from the earth station antenna, the power output of the transmitter, the frequency of the carrier and the directive gains of the transmitting and receiving antenna.

If we assume transmitting antenna to be omnidirectional then the output power of the transmitter will get distributed all around. We can compare it with a point source at the centre of a ball, where the source will distribute all the power equally within this ball in all directions. Thus if P_t watts is the transmitted power then at a distance d_s the power received at point S would be

$$P_r = \frac{P_t}{4\pi d_s^2} \qquad 4.1$$

where d_s is the slant range. [See Figure 4.1]

If a hypothetical case is taken when the antenna is 100% efficient, this is also called as **power flux density** and represented in watts /unit area.

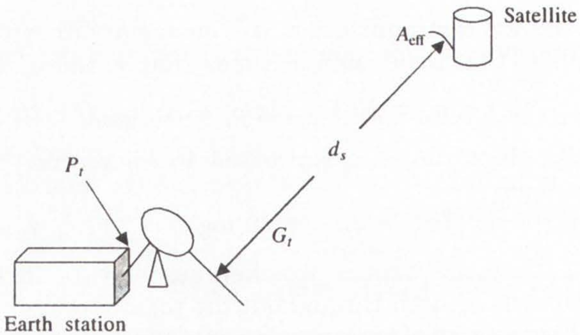


Figure 4.1

Now, if the transmitted power is concentrated in one direction instead of being omnidirectional as shown in Figure 4.1 the output power P_o is concentrated by G_t—where G_t is called the **directive gain** of the directive antenna e.g. an antenna with a parabolic reflector. The gain G_t is defined as the ratio of the effective aperture that captures or radiates the EM waves to a fictitious isotropic antenna which radiates in all the directions, thus

$$G_t = \frac{A_{\text{eff}}}{A_{\text{iso}}}$$

An isotropic antenna has an effective aperture $\lambda^2/4\pi$.

The received flux density at the satellite is:

$$\varphi_o = \frac{G_t P_t}{4\pi d_s^2} \text{ while } P_o = \frac{A_{\text{eff}} P_t}{4\pi d_s^2} \qquad 4.2$$

The product $P_t G_t$ is called the effective isotropic radiated power (EIRP).

The received power at the satellite in case of an isotropic receiving antenna is, therefore,

$$P_r = P_t \frac{\frac{\lambda^2}{4\pi}}{4\pi d_s^2} \qquad 4.3a$$

In this equation $[P_t/P_r]$ is defined as path loss α_p and λ is the wavelength of the carrier such that

$$\lambda = c/f_c$$

where f_c is the carrier frequency and c being the velocity of EM wave which is 3.33 km/s.

Therefore,

$$\alpha_p = \left(\frac{4\pi d_s}{\lambda}\right)^2 = \left(\frac{4\pi d_s f_c}{c}\right)^2 \qquad 4.3$$

In satellite communication, it is customary to express all quantities in decibels so that the design becomes simple, therefore,

$$10 \log \alpha_p = 20 \log [4\pi/c] + 20 \log f_c + 20 \log d_s$$

If the slant range is expressed in kilometres and frequency in gigahertz then

$$[\alpha_p] = 92.4 + 20 \log f_c + 20 \log d_s \qquad 4.4$$

Note that the square bracket quantity is in decibel and this convention will be used throughout the text.

If G_t is the gain of transmitting antenna defined in terms of effective apertures of the directive antenna with respect to an imaginary isotropic antenna, then

$$G_t = \frac{A_{\text{eff}}}{A_{\text{iso}}}$$

$$= \frac{A_{\text{eff}}}{\frac{\lambda^2}{4\pi}}$$

This is the maximum gain and many a time called **isotropic power gain.** Thus, the received power of equation 4.3a will be modified to

$$P_r = G_t P_t \frac{\frac{\lambda^2}{4\pi}}{4\pi d_s^2} \qquad 4.5$$

Similarly, if the receiving antenna at the satellite has an effective aperture A_{reff} then we can calculate the gain of this antenna also so that the received power at the satellite would be

$$P_r = (A_{\text{reff}}/A_{\text{iso}})_r \; G_t P_t / 4\pi d_s^2$$

$$= G_r G_t P_t \; (\lambda^2/4\pi)/4\pi d_s^2$$

$$\alpha_p = \frac{P_t}{P_r} = \frac{(4\pi d_s)^2}{G_t G_r (\lambda)^2} = \frac{(4\pi d_s f_c)^2}{(c)^2 G_t G_r} \qquad 4.6$$

Therefore, the path loss in decibels would be

$$[\alpha_p] = 20 \log (4\pi/c) + 20 \log f_c + 20 \log d_s - 10 \log G_r - 10 \log G_t$$

As shown above, substituting 20 log $(4\pi/c)$ with a calculated constant, we get

$$[\alpha_p] = 92.4 + 20 \log f_c + 20 \log d_s - 10 \log G_r - 10 \log G_t \qquad 4.7$$

This shows that the path loss is directly proportional to the carrier frequency and slant range while inversely proportional to antenna gains. The values of antenna gain depend on the type of reflector used. In most of the earth stations, parabolic dish are used and so also in spacecrafts. [See Figure 4.2]

The input power required at the satellite to produce saturation of amplifier (TWT or SSP) at a transponder is called **saturation flux density**, φ_m. As discussed earlier

$$\varphi_m = \frac{G P_t}{4\pi d_s^2} = \frac{\text{EIRP}}{4\pi d_s^2}$$

where EIRP is the effective isotropic radiated power, the power that an hypothetic isotropic antenna would have radiated with a total generated power of GP_t.

In terms of decibels

$$[\varphi_m] = [\text{EIRP}] - [\alpha_p] - 20 \log (c/f) - 10 \log (1/4\pi)$$

$$(\because\ [\alpha_p] = 20 \log (4\pi d_s f/c))$$

In the case of parabolic dish, the aperture being a circle with diameter D.

$$A_{\text{eff}} = \pi D^2/4$$

So that directive gain $G = A_{\text{eff}}/A_{\text{iso}}$

$$= \frac{(\pi D^2/4)}{(\lambda^2/4\pi)}$$

Therefore,

$$G = \left(\frac{\pi D f_c}{c}\right)^2 \tag{4.8}$$

and in decibels

$$[G] = 20 \log (\pi/c) + 20 \log f + 20 \log D \tag{4.9a}$$

Usually in satellite communication, carrier frequency is in gigahertz and the diameter of antenna in metres so that $20 \log (\pi/c) = 20.4$ dB and, therefore,

$$[G] = 20.4 + 20 \log f + 20 \log D \tag{4.9b}$$

Note that this equation holds good provided:

1. All the EM waves within the aperture are captured.
2. All captured EM waves are reflected and absorbed by the feeder.
3. The captured EM signal is converted to electrical energy.

But if one sees the radiation pattern [Figures 4.2(c) and 4.2(d)] of an antenna it has a main lobe and in addition a number of side lobes. Also the entire received signal or that generated by the transmitter does not get converted to electrical signal in the case of receiving antenna and EM waves in the case of the transmitting antenna with the result the efficiency of the antenna is poor. If η_a is the efficiency of antenna system

$$G = \eta_a \left(\frac{\pi D f_c}{c}\right)^2 \tag{4.10a}$$

In decibels, we can calculate this gain

$$[G] = 10 \log \eta_a + 20 \log [\pi/c] + 20 \log D + 20 \log f_c \qquad 4.10b$$

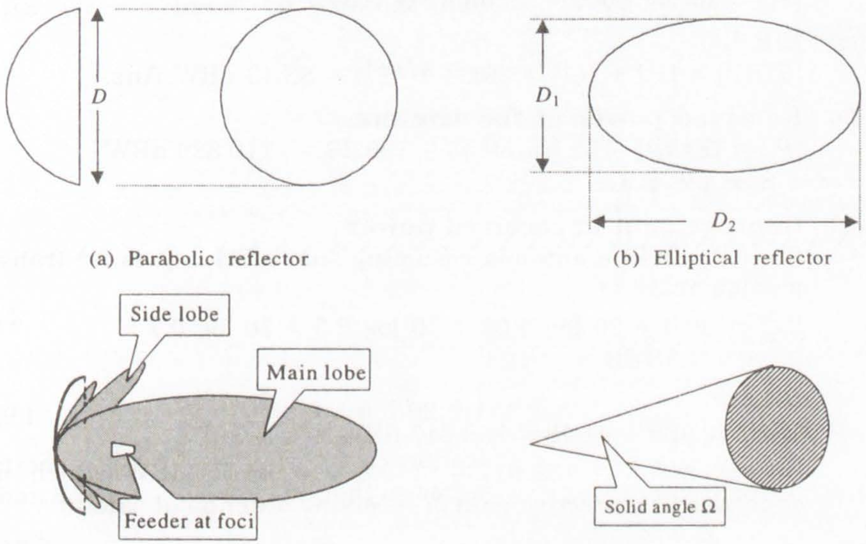
The value of η_a is invariably between 0.65 to 0.75, while constant 20 log $[\pi/c]$ is 20.4 dB for D in meters and f in GHz.

In case of elliptical reflector antenna,

$$A_{eff} = \pi \left[\frac{D_1}{2}\right]\left[\frac{D_2}{2}\right]$$

where D_1 and D_2 are minor and major axis, respectively.

There are many new types of antenna which have been used in satellite communication and are discussed in Chapter 6, such as, cassegrain, patch and arrays.



(a) Parabolic reflector (b) Elliptical reflector

(c) Main lobe and side lobes (d) Conical cross-section of main lobe

Figure 4.2 Types of reflector and radiation pattern of parabolic reflector.

EXAMPLE 4.1

An earth station transmits at 5.62 GHz from an antenna of 6 m. The transmitter generates an output of 8 kW. The satellite is 39920 km from the earth station. The efficiency of transmitting antenna being 0.7. Calculate:

(i) Path loss
(ii) Transmitting antenna gain
(iii) Transmitter power in dBW
(iv) EIRP
(v) Received power at the satellite
(vi) Improvement in received power if the satellite uses a parabolic dish of 2.5 m.

(Continued)

Solution

(i) **Path loss**

The path loss at a slant range of 39920 km will be:

$[\alpha_p] = 92.4 + 20 \log f_c + 20 \log d_s$ dB

$= 92.4 + 20 \log 5.62 + 20 \log 39920$ dB

$= 199.26$ dB **Ans.**

(ii) **Transmitting antenna gain**

The gain of the transmitting antenna is:

$[G_t] = 20.4 + 20 \log f_c + 20 \log D + 10 \log \eta$

$= 20.4 + 20 \log 5.62 + 20 \log 6 + 10 \log 0.7$

$= 49.4$ dB **Ans.**

(iii) **Transmitter power in dBW**

$[P_t] = 10 \log 8000 = 39.03$ dBW **Ans.**

(iv) **EIRP**

$[\text{EIRP}] = [P_t] + [G_t] = 39.03 + 49.4 = 88.43$ dBW **Ans.**

(v) **Received power at the satellite**

$[P_r] = [\text{EIRP}] - [\alpha_p] = 88.43 - 199.26 = -110.829$ dBW

$= 8.26$ pW **Ans.**

(vi) **Improvement in received power**

Gain of satellite antenna assuming sum efficiency as for transmitting antenna

$[G_r] = 20.4 + 20 \log 5.62 + 20 \log 2.5 + 10 \log 0.7$

$= 41.78$ dB

Hence,

$P_r = 110.829 + 41.78 = 152.617$ dBW

Improvement $= 152.617 - 110.829 = 41.78$ dBW which is equivalent to directive gain of receiving antenna at satellite.

Ans.

Losses in Troposphere and Atmosphere

The EM wave travels through troposphere and atmosphere along a path depending on the elevation angle of the transmitting antenna. Smaller the elevation angle longer is the path it travels. Troposphere is the region extending from the surface of the earth up to a height of 8 to 10 km at the equator; it slightly varies as we go towards poles. The major absorption of microwave signals occurs in this region due to absorption of EM waves by rain, fog, hail, snow, gases (like oxygen, nitrogen, etc. Composition of atmosphere was discussed in Chapter 3). The water molecules absorb the radiated power as the diameter of raindrops approach even fraction of wavelength. (See Figures 4.3 and 4.4)

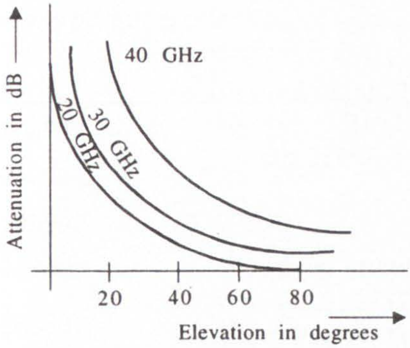


Figure 4.3 Rain attenuation

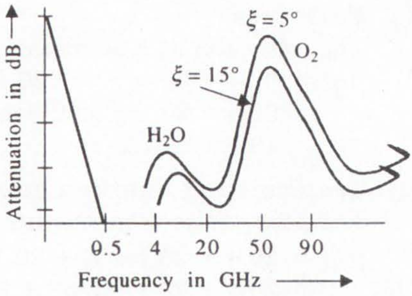


Figure 4.4 Atmospheric absorption

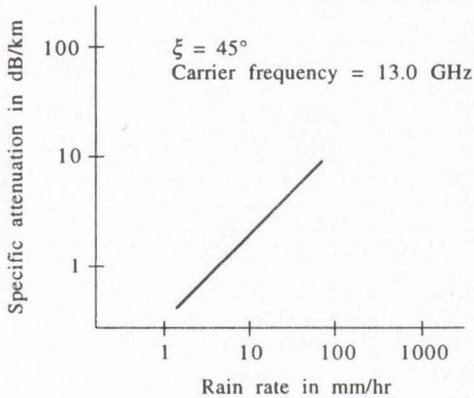


Figure 4.5 Specific attenuation plot. (Courtesy ISRO)

Specific attenuation and rain rate are related by power relation given by

$$\alpha_a = aR^b \tag{4.11}$$

where a and b are parameters which depend on temperature, water droplet size distribution, frequency and polarization. R being the rain rate in mm/hour and α is given in dB/km. It is economical to design a reliable satellite communication link in the frequency band of 12/14 GHz and 20/30 GHz range as these do not suffer much due to these absorptions, λ being higher than the raindrop size. Some computations carried out in the 12/14 GHz band is shown in Figure 4.5, also calculated values of the coefficients using standard equations as shown in Tables 4.1 and 4.2. The equations are:

$$a = 4.21 \times 10^{-5} f^{2.42} \quad \text{(for } 2.9 \le f \le 54 \text{ GHz)} \tag{4.12}$$

$$b = 1.41 f^{-0.0779} \quad \text{(for } 8.5 \le f \le 25 \text{ GHz)} \tag{4.13}$$

Table 4.1 Showing Values of Coefficients Computed Using the Equation

Frequency in GHz	*Elevation angle* ξ	a	b
12.0	0	0.03091	1.07506
	30	0.03060	1.06999
	45	0.03031	1.06467
	90	0.2973	1.05316
13.0	0	0.03847	1.06393
	30	0.03813	1.05767
	45	0.03787	1.05106
	90	0.03118	1.03668
13.4	0	0.04171	1.05987
	30	0.04145	1.05122
	45	0.04121	1.04200
	90	0.04179	1.02162

Table 4.2 Calculated Values of Coefficient at $\xi = 90°$ for Different Carrier Frequencies

Frequency in GHz	a	b
1	0.00015	0.95
4	0.0008	1.17
6	0.0025	1.28
10	0.0125	1.18
15	0.0357	1.12

Rain rates above 100 mm/hr is called heavy rain, between 25 and 99 mm/hr medium, 12 to 24 mm/hr light rain, 2 to 23 mm/hr light rain and below 2mm/hr drizzle. The link during medium and heavy rains are affected badly and hence tropical regions have poor links.

Such calculations which are compounded attenuation may not be helpful sometimes where the variation of rain rate is large over a period of time. In such cases probability graphs or tables may be used for design of reliable communication links depending upon the application. One such graph is shown in Figure 4.6.

It is seen from this graph that beyond 8 GHz the reliable availability of the link goes on reducing. In such probability graphs a term called **outage time** is defined, which is the percentage of time the attenuation

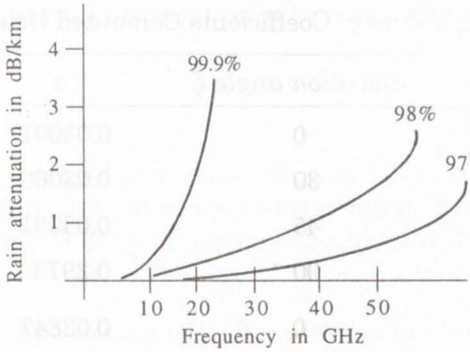


Figure 4.6 Probability graph.

α exceeds a given value. $1 - P[\alpha]$ is the % availability of the link where attenuation is less than the specified maximum value of α_a.

Modelling Rain Absorption

A handy method of calculating the rain loss is by modelling for rain losses knowing the path length of EM waves in rain. This can be calculated from the elevation angle as shown in Figure 4.7. If L_r is the path length, H_r rain height, and H_e is the height of the antenna above sea level, then

$$L_r = \frac{H_r - H_e}{\sin \xi} \tag{4.14}$$

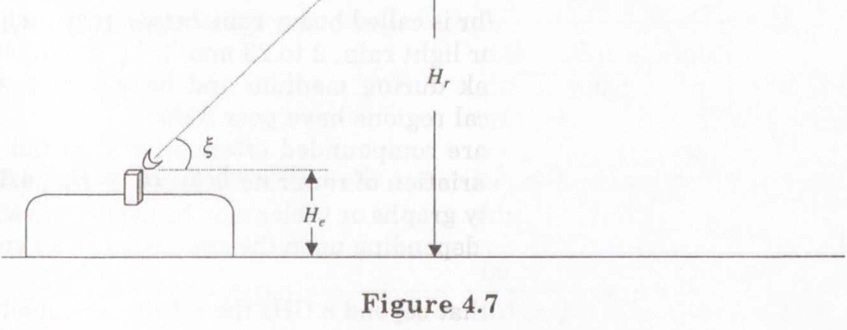


Figure 4.7

Two popular models used by the designers in Europe, USA, Asia and other regions are:

1. SAM model
2. CCIR model

SAM model. In this model H_i is the isothermal height where clouds are supposed to form as the temperature approaches 0°C. It is interesting to note that the rainfall rate depends on the heights H_r and H_i such that

$$H_r = H_i \qquad 4.15$$

where H_r is the cloud height, when $R \leq 10$ mm/hr and

$$H_r = H_i + \log_{10} [R/10] \quad (\text{for } R > 10 \text{ mm/hr}) \qquad 4.16$$

where isothermal height depends on the latitude of earth station. Such that

$$H_i = 7.8 - 0.1\ (\lambda_{AE}) \text{ for } \lambda_{AE} > 30°$$

In this method attenuation due to rain follows the relation:

$$\alpha = aR^b L_r \qquad \text{for } R \leq 10 \text{ mm/hr} \qquad 4.17\text{a}$$

$$\alpha = aR^b \left\{ \frac{1 - \exp\left[-\gamma b \left(\ln \frac{R}{10} L\right) \cos \xi\right]}{\gamma b \left(\ln \frac{R}{10} \cos \xi\right)} \right\} (\text{for } R \geq 10 \text{ mm/hr}) \qquad 4.17\text{b}$$

where $\gamma = 1/22$.

CCIR model. For the calculation of attenuation CCIR has recommended a model defining the attenuation for a probable reliable link of 99.9% of time in which the attenuation is given by

$$\alpha[0.01] = a\{R_p\}^b\ L_r r_p \qquad 4.18$$

where R_p is probable rain rate, r_p is a reduction constant depending on probability. Now,

$$L_r = \frac{2(H_r - H_o)}{\left[\frac{\sin^2 \xi + 2(H_r - H_o)}{8500}\right]^{1/2} + \sin \xi} \quad (\text{for } \xi \text{ less than } 10°) \qquad 4.19$$

$$= \frac{(H_r - H_o)}{\sin \xi} \quad (\text{for } \xi \text{ greater than } 10°) \text{ where } H_o = H_e \qquad 4.20$$

and

$$r_p = \frac{90}{90 + 4L_r \cos \xi} \text{ for } p = 0.01\%$$

EXAMPLE 4.2

Calculate the rain attenuation if an earth station is at a latitude of 35° and the transmission takes place on a carrier of 6.21 GHz. The link has to be designed for a failure not exceeding 0.01% of the time at a rain rate of 15 mm/hr. The elevation of earth station antenna is 35°.

Solution

In SAM model

Given

Latitude $\lambda_{AE} = 35°$
Carrier frequency $f = 6.21$ GHz
Rain rate $R = 15$ mm/hr

From equations (4.12) and (4.13)
$a = 3.49 \times 10^{-3}$
$b = 1.22$

The isothermal height is:

$$\begin{aligned} H_i &= 7.8 - 0.1\,\lambda_{AE} \\ &= 7.8 - 0.1\,(35° \times \pi/180) \\ &= 7.7389 \text{ km} \approx 7.74 \text{ km} \end{aligned}$$

$$\alpha = aR^b \left\{ \frac{1 - \exp - \left[\gamma b \left(\ln \dfrac{R}{10} L_r \right) \cos \xi \right]}{\gamma b \left(\ln \dfrac{R}{10} L_r \right) \cos \xi} \right\} \quad \text{(for } R \geq 10 \text{ mm/hr)}$$

The rain height is:

$$\begin{aligned} H_r &= H_i + \log (R/10) \\ &= 7.74 + \log (15/10) \\ &= 7.916 \text{ km} \end{aligned}$$

The rain length is:

$$\begin{aligned} L_r &= \frac{(H_r - H_e)}{\sin \xi} \qquad \text{Assuming } H_e \approx 0 \\ &= (7.916 - 0)/\sin 35° \\ &= 13.8 \text{ km} \end{aligned}$$

In CCIR model

The rain height is:

$$\begin{aligned} h_r &= 5.1 - 2.15 \log \left[1 + 10^{(\lambda_{AE} - 27)/25} \right] \\ &= 4.0468 \text{ km} \end{aligned}$$

(Continued)

The rain length is:

$$L_r = \frac{H_r - H_e}{\sin \xi}$$
$$= (4.0468 - 0)/\sin 35°$$
$$= 7.0554 \text{ km}$$

The absolute attenuation is:

$$A(0.01) = aR_p^b \times L_r\gamma_p$$
$$= 0.0937 \times (7.0554) \times 90/90 + 4(7.0554) \cos 35°$$
$$= 0.526 \text{ dB}$$

It is also possible to calculate the field strength F if rain absorption α and rain length L_r are known, such that

$$F = 10^{-\alpha L/20}$$

while rms voltage $$E_{rms} = \frac{173\sqrt{P_t G_t}}{L_r} \quad 4.21$$

Variation of refractivity in the troposphere tends to bend the EM wave. The refractive property of the troposphere is given by

$$N = (n - 1) \times 10^6$$

where N is refractivity and n the refractive index.

The CCIR standard value of N at sea level is defined as N_o and is equal to $289N$ units. N decreases as height increases and follows a relation:

$$N_s = 289^{-0.136}\ h$$

where h is the altitude of satellite.

Due to this the modified distance will depend on ΔN_s, the change in refractive index.

At higher heights atmospheric absorption is caused due to molecules and gases present like oxygen, nitrogen, water etc. At elevations below 5° the tropospheric path of propagation is so long that turbulence in troposphere may cause rapid change in amplitude and phase called **scintillation.** These exist for small durations only.

Multiple path fading is another big problem for ξ less than 5°, if the atmosphere is clear of all pollution such fading can be drastically reduced. In troposphere such fading are caused both due to polarization rotation and scattering. A linearly polarized wave tends to become elliptical and hence the receiving antenna constructed to pick up linearly polarized signals is unable to pick all the received signals.

Two types of fading occur when EM waves travel through troposphere:

1. Short term fading or fast fading
2. Long term fading or slow fading.

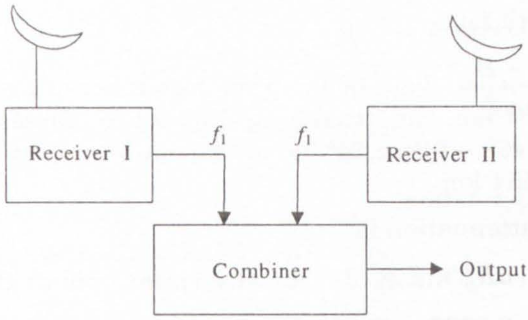


Figure 4.8 Space diversity.

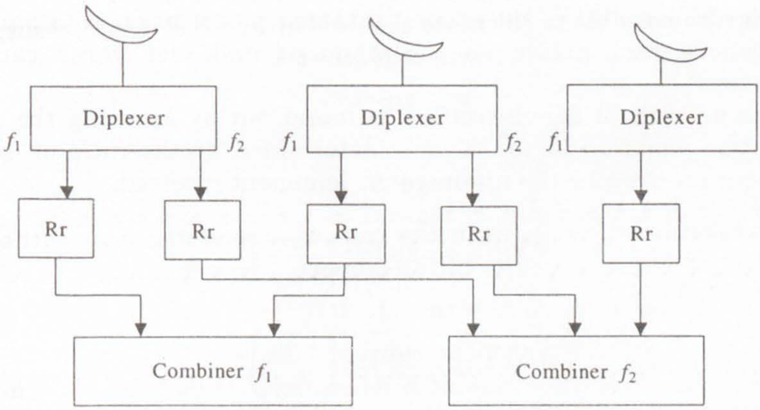


Figure 4.9 Frequency diversity.

Fast fading occurs due to sudden changes in atmospheric conditions. This causes the signal strength to fall down below threshold. Such situations can be overcome by using diversity reception. Diversity reception can be achieved using:

(i) Space diversity
(ii) Frequency diversity

In case of space diversity, a number of antennae spread over a vast area pick up the signal and the signals so received are analyzed for the best C/N and combined or taken individually to get the final reproduced signal as shown in Figure 4.8. Whereas in case of frequency diversity, the same base band is transmitted over different carriers and picked by different antennae at the same sight and the best signals are selected and combined for the best reception or detection, as shown in Figure 4.9.

Ionospheric Losses

Ionosphere, which lies above 60 km from the surface of the earth contains charged ions. When the travelling EM wave passes through the ionosphere region, losses occur due to two main reasons:

1. Faraday rotation
2. Scintillation

Other losses could be due to absorption, phase dispersion and scattering.

Faraday rotation is more prominent below X-band (i.e. below 7 GHz). The amount of polarization rotation depends on the frequency of the wave. If there are two linearly polarized waves transmitted one Vertically and other Horizontally, these may undergo polarization rotation and H-component may arrive as V-component and vice versa causing interference.

The amount of depolarization is found out by knowing the cross polarization isolation factor. This is determined by the ratio of Actual component received by the interference imponent received.

$$(XPI)_V = 20 \log \left(\frac{V'_{VC}}{V_{HX}} \right) \tag{4.22a}$$

$$(XPI)_H = 20 \log \left(\frac{V'_{HC}}{V_{VX}} \right) \tag{4.22b}$$

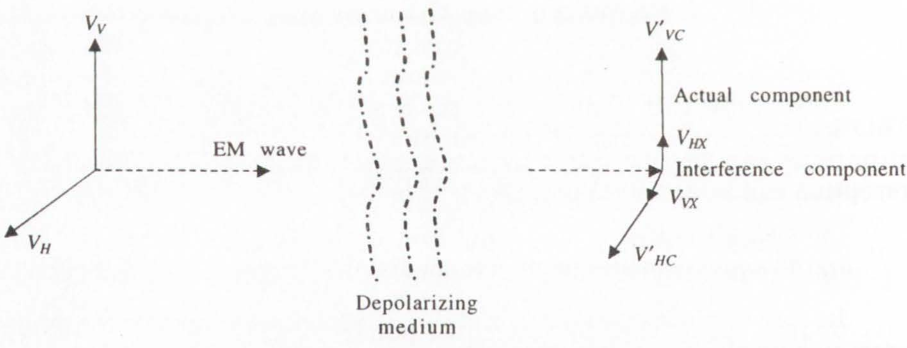


Figure 4.10 Satellite systems.

Polarization rotation angle is frequency dependent and is given by

$$\phi = \frac{(2.36 \times 10^4)}{f^2} L_i N_e B \cos \theta$$

where L_i is the path length of EM wave in ionosphere, N_e is electron density, B is geomagnetic flux density and θ is the angle made by the propagating EM wave with respect to the geomagnetic line.

Due to the irregularities in the upper part of the ionosphere, there occurs sudden turbulence after the local sunset. Such changes are frequent around the spring and the equinoxes. These changes are significant in countries near the equator. Due to these changes scintillation losses occur in the EM wave that travel through the ionosphere during this small period. These cause short-term fading.

Antenna Misalignment Loss

The on-axis peak gain G_m of the antenna is effective when the transmitting and receiving antennas are exactly aligned in the line of sight. A misalignment loss occurs when the two antennas are not in line and the pointing vector of the transmitting antenna does not coincide with the position vector of the receiving antenna. This can happen when the position of the feeder is not properly aligned. In the geostationary scenario the displacement in the elevation or azimuth or both transmitting/receiving antennas may be the major reason. In the case of satellite the change in position or attitude could cause misalignment.

In order to minimize these losses, a closed loop tracking system is used, which senses the field strength and moves the antenna in elevation and azimuth. The tracking methods adopted are **monopolar, conical and hill climb**. Of late antenna arrays being used, **adaptive tracking and pointing** are being suggested. In the case of monopolar type separate receivers detect the change in the strengths due to displacement in elevation and azimuth and the error signal controls the stepper motor or the synchro. In the conical technique, the main beam is made to electronically rotate within a cone of 1 to 1.5 minutes around the main axis. If there is no change in the signal strength the antenna is supposed to be aligned or else the error generated corrects the elevation and azimuth. In the Hill climb method the beam is moved step by step either by changing the position of the antenna physically or moving the beam electronically. The maximum strength indicates the aligned position and a relative reduction in the field strength gives the error. The monopolar and hill climb suffer from fading and the cause of change in signal strength cannot be distinguished immediately. These days at the satellite and some ground stations antenna arrays are being suggested where DSP techniques can be used to control the pointing errors.

The pointing loss depends on the aperture of the reflector and the position of the feed with respect to the received pointing vector. As there is a pointing error or misalignment, the field distribution plane at the focal point changes. It is therefore necessary to arrive at this change and the direction in which this change has occurred. A separate collector feed is used for this purpose whose output is connected to error detection circuitry. These operate at a higher mode compared to normal horn feeds and extract the beacon signals. It is a general practice to install a beacon on board the satellite which transmits signals at intervals for alignment correction.

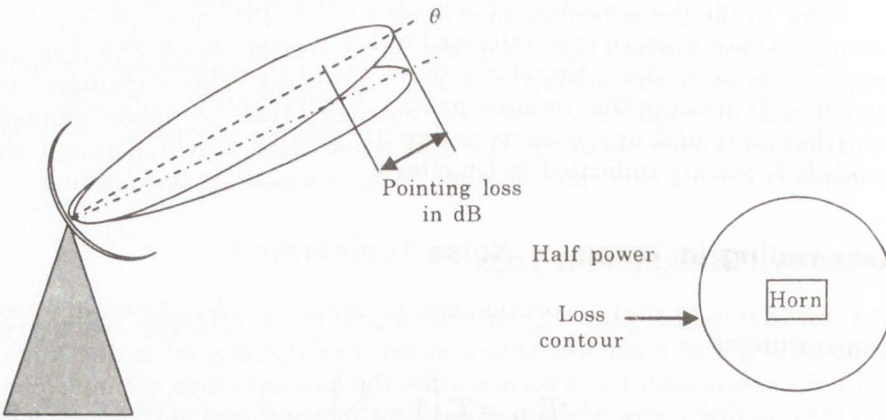


Figure 4.11 Pointing loss.

As discussed above the antenna pointing loss can be determined knowing the beam position which is a function of the off-axis angle θ and the aperture of the antenna. It has been well known that for a uniform aperture antenna the gain distribution can be found using first order Bessels' function and is given by:

$$G(u,\ \theta) = \lambda \left| \frac{J_1(u)}{u} \right|^2 \quad \text{where } u = \frac{\pi D}{\lambda} \sin\theta$$

For the uniform aperture paraboloid half power beam width means $G(u,\theta) = 1/2$. Normally the off-axis should be within the half power beamwidth. Typically, pointing loss may vary between 0.1 dB to 1 dB.

4.4 CONCEPT OF NOISE TEMPERATURE

Most of the losses occurring in the satellite link can be calculated in terms of noise temperatures. As we know that when a signal contains noise the *S*/*N* ratio indicates the quality of the received signal. The different sources of noise in satellite communication are:

1. Radiation from sun
2. Radiation from moon
3. Cosmic radiations
4. Reflection from earth
5. Rain absorption
6. Vegetation absorption
7. System noise

The first four sources can be reduced by proper design of the antenna. When sun rays directly fall into the parabolic dish it feeds R.F. noise into the feeder reducing the *S*/*N* ratio drastically and making detection of signal impossible. This is called **sun outage**. To avoid such a condition care must be taken to avoid reflector directly beaming into the sun. The earth stations, therefore, should erect the receiving antennae carefully. By making the antenna pattern highly directive and avoiding side lobes stray pick ups, such as multipath, picking of reflections can be avoided. These are indicated in Chapter 6.

Rain Fading in Terms of Noise Temperature

The fading due to rain absorption can be represented in terms of noise temperature as

$$T_{\text{rain}} = T_o\left(1 - \frac{1}{\alpha_r}\right) \qquad 4.23$$

where T_0 is the physical temperature of antenna that picks up the transmitted signal and α_r the probability of rain attenuation as calculated under Section 4.2. $T_{\text{rain}} = T_o\,(1 - e^{-\alpha}\,\text{dB}/4.34)$. During clear sky the value of T_0 is between 270 to 290° K. α is the average absorption during the specified percentage of the time as calculated in Section 4.2.

EXAMPLE 4.3

If the rain absorption is 0.5 dB over 0.1% of the time over a year. Find the rain absorption temperature.

Solution

Rain attenuation as ratio = $10^{0.05} = 1.122$

Rain absorption temperature would be

$$T_{\text{rain}} = 290\left(1 - \frac{1}{1.122}\right)$$

$$= 290 \times 0.108 = 31.53\text{ K} \quad \textbf{Ans.}$$

If one wants to directly substitute the value of α in dB then

$$\begin{aligned} T_{\text{rain}} &= T_a\,(1 - e^{-\alpha/4.34}) \\ &= 290\,(1 - e^{-0.5/4.34}) \\ &= 290\,[1 - 0.8911] \\ &= 31.55\text{ K} \quad \textbf{Ans.} \end{aligned}$$

Noise Temperature in General

Any communication receiver particularly analog is a heterodyne receiver, having an antenna connected to the R.F. amplifier through a cable. The R.F. amplifier output is down converted to intermediate frequency using a mixer. The signal is further amplified depending upon the requirements. This is not only true in the case of an earth station but also for satellite. The concept of noise temperature can thus be applied in general to any receiving system and for all types of absorptions and noise pickups. Though satellite system antenna is directional it does contain some side lobes which picks up noise from the earth and atmosphere.

In fact if we consider that the input of the receiver is a noise free signal the receiver by itself produces thermal noise due to the different active and passive components. These being thermal, noise is produced due to random motion of molecules due to flow of current, this is called White (Johnson) noise. The details of these are available in most of communication texts.

The noise voltage produced depends upon resistance and temperature and is given by

$$V_n = \sqrt{kTR} \qquad 4.24$$

where k is the Boltzmann's constant 0.38×10^{-23} W/K or –228.6 dBW/°K, T is the temperature in degree kelvin, R is the resistance of the device at that temperature.

If the source and load resistances are matched and if we assume maximum transfer of noise power then the equivalent noise power would be

$$P_n = \frac{V_n^2}{R} = \frac{kTR}{R} \qquad 4.25$$

$$P_n = kT \qquad 4.26$$

This is called Noise spectral density. Since the amount of noise will be band limited by the receiver bandwidth, hence, the noise power is

$$P_n = kT\Delta f \qquad 4.27$$

Sometimes Δf is also called **noise bandwidth** though strictly it is the bandwidth of system or measuring device.

If we assume that the gain of the receiving system is G_r then we can represent the system as an ideal noise free system with a noise of P_n at the input resulting in an output noise of

$$P_n G_r = kT\Delta f G_r$$

Since the selectivity of heterodyne receiver is decided by the IF stage, we get $\Delta f = B_{if}$, where B_{if} is the IF amplifier's bandwidth.

Noise Models

While modelling it is assumed that the receiver blocks are noise free with gains as specified. The noise introduced by the block is taken as input in addition to noise coming from the preceding stage. This is shown in Figure 4.12.

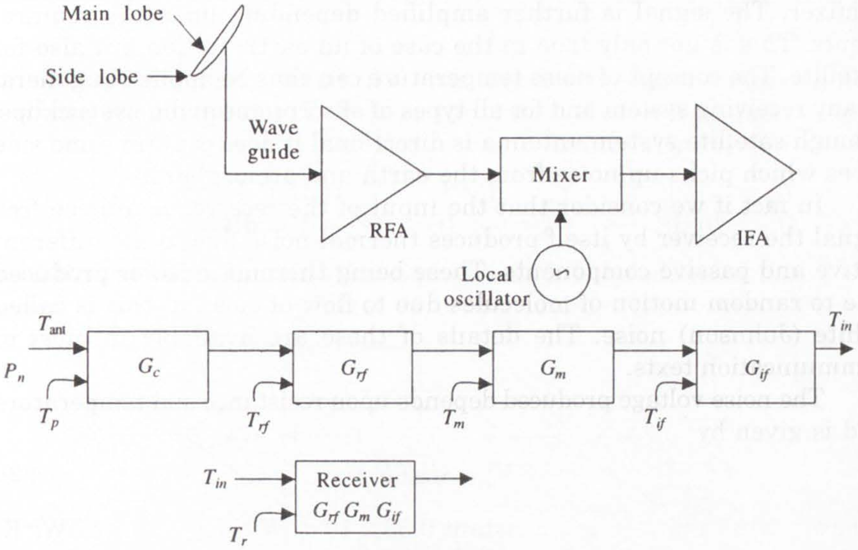


Figure 4.12 Noise models.

Thus,

$$\text{input noise } T_{in} = T_{\text{ant}}G_c + T_{p_n}$$

where G_c (gain of cable) < 1.

The total output noise power is given by

$$\begin{aligned} P_n &= \{(T_{in} + T_{rf})\ G_{rf}G_mG_{if} + T_mG_mG_{if} + T_{if}G_{if}\}\ k\Delta f \\ &= T_sG_{rf}G_mG_{if}\ k\Delta f \end{aligned} \qquad 4.28$$

Thus, the equivalent system noise temperature is

$$T_s = T_{in} + T_{rf} + \frac{T_m}{G_{rf}} + \frac{T_{if}}{G_{rf}G_m} \qquad 4.29$$

If the gains G_{rf}, G_m, and G_{if} are substantially large and T_m/G_{rf}, $T_{if}/G_{rm}G_m$, substantially smaller than the term $T_{in} + T_{rf}$ then the system equivalent noise temperature is given as:

$$T_s \approx T_{in} + T_{rf}$$

This shows that the noise introduced and amplified in the receiver is mainly due to T_{in} and T_{rf} and they should be minimized. This necessitates use of low noise r.f. amplifier (LNA) at the input of receiver.

Example 4.4

In a satellite receiving system, shown in figure, the input equivalent noise temperature to R.F. antenna is 20 K. The receiving system has following characteristics:

$T_{rf} = 15°$ K $\quad T_m = 40°$ K $\quad T_{if} = 150°$ K

$G_{rf} = 20$ dB $\quad G_m = -2$ dB $\quad G_{if} = 100$ dB

Calculate the system noise temperature and noise power produced by this receiver, if receiver BW is 10 MHz?

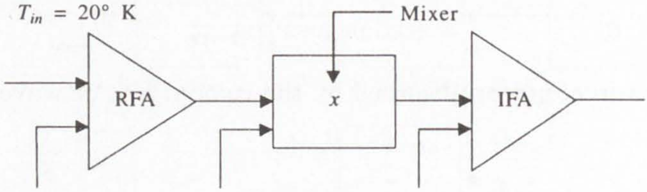


Figure 4.13

T_{rf} = 15° K $\quad T_m$ = 40° K $\quad T_{if}$ = 150° K

G_{rf} = 20 dB $\quad G_m$ = −2dB $\quad G_{if}$ = 100 dB

Solution

Given

$G_{rf} = 20 \text{ dB} \equiv 100 \qquad G_m = -2 \text{ dB} \equiv 0.63$

System noise temperature

$T_s = (T_{in} + T_{rf}) + T_m/G_{rf} + T_{if}/G_m \times G_{rf}$

$= (20 + 15) + 40/100 + 150/100 \times 0.63$

$= 37.78°$K

In decibels

$T_s = 10 \log 37.78$

$= 15.77$ dB°K **Ans.**

Received noise power

$[P_n] = [K] + [T_s] + [BW]$ $(P_n = kT\Delta f)$

where $k = 1.38 \times 10^{-23}$ Joules/K $\equiv -228.6$ dB $= 228.6$ dBW/K

$= -228.6 + 15.77 + 70 = -142.83$ dBW

Ans.

Reducing the Noise Introduction in a Receiving System

We know that T_{in} is due to noise picked up by the side lobes of the antenna mainly and a part due to main lobe. This noise is due to

1. Heating up of earth and corresponding radiations due to this
2. Cosmic radiations
3. Noise in lossy networks like couplers, coaxial cables or waveguides.

In order to reduce the noise pickup by antenna, the antenna should be highly directional with no side lobes [ideal condition]. The main lobe should have a very narrow beam width. Transmission lines or wave-guides, which connect antenna to receiver, are lossy networks and produce noise themselves in addition to reducing the strength of the signal. The loss is defined either as loss factor or insertion loss

$$\text{Loss factor } L = \frac{P_i}{P_o}$$

and

$$\text{Insertion loss } \rho = \frac{P_o}{P_i}$$

The ratio of power absorbed by the coaxial line or waveguide is

$$\frac{P_i - P_o}{P_i} = 1 - \frac{P_o}{P_i} = 1 - \frac{1}{L} = 1 - \rho \qquad 4.30$$

Noise in a Network

Consider the network shown in Figure 4.14. If there is perfect matching

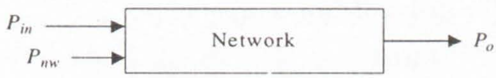


Figure 4.14

between input and output then input power is equal to output power so that

$$P_{in} + P_{nw} = P_o$$

$$\rho K T_x \Delta f + P_{nw} = K T_x \Delta f$$

where P_{nw} is noise generated in the lossy network.

Now,

$$P_{nw} = K T_x \Delta f \,[1 - \rho]$$

$$K T_{nw} \Delta f = K T_x \Delta f \,[1 - \rho]$$

Therefore,

$$T_{nw} = T_x[1 - \rho] = T_x[1 - 1/L]$$

If the lossy line is assumed to be noise free with its equivalent noise temperature assumed to be at the input then equivalent noise temperature is given by

$$T_{nwi} = L T_{nw}$$
$$= L T_x(1 - \rho)$$

If T_x is the absolute temperature of network represented as T_o then

$$T_{nwi} = T_o[L - 1] \qquad 4.31$$

Generally T_o is taken as 29°K for most of the design.

This noise will be substantially large in satellite communication. Considering Figure 4.15 let the antenna noise temperature be T_{ant} and R.F. amplifier noise temperature be T_{rf}.

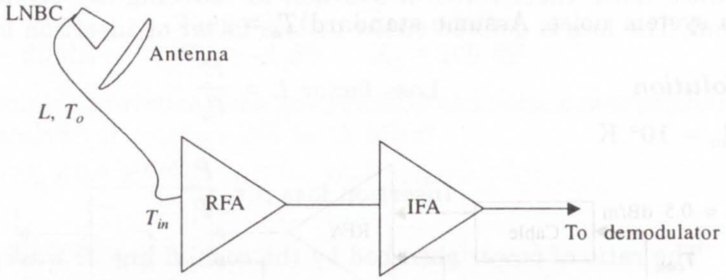


Figure 4.15 Satellite receiving front-end.

The noise power density generated by these two will be

$$P_n = K\,[T_{ant} + T_{rf}] \text{ W/Hz}$$

This is fed to the cable having a loss factor of L so that the input noise to cable will consist of two components

1. $K\,[T_{ant} + T_{rf}]$ and
2. Cable noise itself.

Thus, the noise at input of cable will be

$$KT_{in} = K\frac{(T_{ant} + T_{rf})}{L}G_{rf} + KT_o\,[L-1]$$

Therefore, total system noise will be

$$KT_s\frac{G_{rf}G_mG_{if}}{L} = KT_{in}G_mG_{if} + KT_mG_mG_{if} + KT_{if}G_{if}$$

$$T_s = \frac{T_{in}L}{G_{rf}} + \frac{T_mL}{G_{rf}} + \frac{T_{if}L}{G_{rf}G_m}$$

$$= [T_{ant} + T_{rf}] + T_o\,[L-1] + \frac{T_mL}{G_{rf}} + \frac{T_{if}L}{G_{rf}G_m} \quad 4.32$$

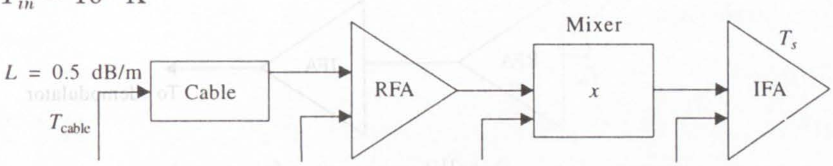
This will substantially reduce the noise effect due to lossy transmission network if the R.F. amplifier or/and frequency converter is connected very near to the antenna or atop the antenna. For this purpose Low noise block converters (LNBC) are used. Another remedy for reducing noise is keeping T_{rf} as small as possible. This can be done by using LNA or LNC made of parametric amplifiers or GaAs FETs.

EXAMPLE 4.5

If in the previous problem the receiver is connected through a 10 m cable to an antenna, feeding an overall equivalent noise temperature of 10°K to the cable with a loss factor of 0.5 dB/m. Calculate the change in system noise: Assume standard T_o = 290°K.

Solution

T_{in} = 10° K



Total cable loss, L_{total} = 0.5 × 10 = 5 dB ≡ 3.16 ratio loss

Assume T_o = 290°K as per discussion.

$$\begin{aligned} T_{cable} &= (L - 1) \times T_o \\ &= (3.16 - 1) \times 290 \\ &= 627.1°K \end{aligned}$$

System noise temperature is given as:

$$\begin{aligned} T_s &= (10 + 627) + (3.16) \times 15 + (3.16) \times 40/100 + (3.16) \times 50/100 \times 0.63 \\ &= 693.18 \text{ K} \\ &= 28.4 \text{ dB° K} \end{aligned}$$

This section of the problem shows that by introducing a cable between antenna and receiver, the overall noise temperature will drastically increase.

Ans.

Model Using Noise Figure

Noise figure is the figure of merit of a receiver indicating the signal to noise ratio at the input of the receiver with respect to signal to noise ratio at the output of the receiver. Many a times the receiver specifications are given in terms of noise figure which has to be interpreted in terms of noise temperature.

If T_o is the source noise at room temperature, the input noise power density = KT_o. Let amplifier temperature is T_A then

$$GK(T_o + T_A) = FGKT_o \qquad 4.33$$

or

$$GKT_A = FGKT_o - GKT_o$$

$$T_A = [F - 1]\ T_o \qquad 4.34$$

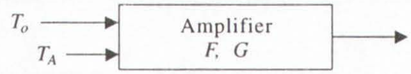


Figure 4.16 Conversion of noise figure to noise temperature.

EXAMPLE 4.6

A receiving system, shown in Figure 4.16, has antenna noise temperature 60° K and receiver noise figure 9 dB. Find the system noise temperature.

Solution

Given

$F = 9 \text{ dB} \equiv 7.94$

From previous discussion, we get

$$\begin{aligned} T_s &= T_{ant} + T_o(F - 1) \\ &= 60 + 290\ (7.94 - 1) \\ &= 2072.6° \text{ K} = 33.165 \text{ dB K} \end{aligned}$$

Carrier to Noise Ratio and *G/T* of a Receiving System

We have seen that the transmitted signal [carrier] undergoes a path attenuation and absorptions before reaching the antenna, both at the satellite and receiving earth station. In addition we have also seen that the noise is introduced both at the antenna and receiving system. The net result is that the performance of the communication link not only depends upon the modulated carrier power but also the amount of noise introduced in the path before the signal is detected. It is a common practice to represent the system performance by a factor called **carrier to noise ratio**, which may be an essential parameter in the selection of the stages. The carrier is the noise free input received by the demodulator of the receiver while the noise is the amount of noise received by the demodulator.

Thus,

$$C = P_r G_r$$

where P_r is received power after attenuation and absorption

$$N = P_n G_r = KT\Delta f G_r$$

It, therefore, becomes essential to define quality factor, carrier to noise ratio of a system to design a receiving system.

C/N = Carrier power at the output/Noise power at the output
= Carrier power at input to demodulator/Noise power at the input of demodulator

Higher the C/N, better is the reception. Therefore, substituting the values of C and N, we get

$$\frac{C}{N} = \frac{P_r G_r}{KT\Delta f G_r}$$

$$= \frac{P_r}{KT\Delta f} \qquad 4.35$$

We know from previous discussions

$$[C] = [\text{EIRP}] - [\text{LOSSES}] + [G_r]$$

and

$$N = KT_s B_{rf} \text{ or } [N] = [K] + [T_s] + [B_{rf}]$$

where B_{rf} is the receiver bandwidth. Therefore,

$$[C/N] = [\text{EIRP}] - [\text{LOSSES}] + [G_r] - [K] - [T_{sys}] - [B_{if}] \text{ dB}$$

Note: All values here are in decibels.

This can be re-written as

$$[C/N] = [\text{EIRP}] - [\text{LOSSES}] + [G_r/T_{sys}] - [K] - [B_{if}] \qquad 4.36$$

From Eq. (4.36),

$$\frac{C}{N} \propto \frac{G_r}{T_{sys}}$$

That is C/N ratio will be high if G_r/T_{sys}, which is the quality factor or figure of merit of a receiving system, is high. In fact G/T ratio is an important specification of a receiver or satellite and is very useful in satellite link design.

Some typical G/T ratios are:

1. G/T of INSAT transponder is –11 dB/°K
2. G/T of INTELSAT transponder is –17.6 dB/°K
3. Earth station for telephone is 40 dB/°K

As is seen the G/T of satellite receiving systems are poor and the earth station antenna and front end should take care of the required G/T for minimum S/N requirement.

Example 4.7

A satellite orbiting at 38000 km transmits signal at 11.7 GHz. The output power of the satellite transmitter is 250 mW fed to an antenna of directive gain 18.9 dB. The earth station antenna being 4 m dish with efficiency 60%. Find the G/T ratio of the earth station of bandwidth 36 MHz if C/N = 40 dB.

(Continued)

Solution

Given

$$P_t = 250 \text{ mW} \equiv -6.02 \text{ dBW} \qquad K = -228.6 \text{ dBJ/°K}$$

We know from the previous discussion,

$$[C/N] = [\text{EIRP}] - [\text{LOSSES}] + [G_r/T_{sys}] - [K] - [B_{if}]$$

Therefore,

$$[G_r/T_{sys}] = [C/N] - ([\text{EIRP}] - [\text{LOSSES}] - [K] - [B_{if}])$$

$$\text{EIRP} = -6.02 + 18.9 = 12.88 \text{ dBW}$$

$$G_{rant} = 22.4 + 20 \log 11.7 + 20 \log 4 + 10 \log 0.6$$
$$= 22.4 + 21.36 + 12.04 - 2.22 = 53.58 \text{ dB}$$

$$\text{LOSSES} = 92.4 + 20 \log 38000 + 20 \log 11.7 - 10 \log G_{rant}$$
$$= 92.4 + 91.59 + 21.36 - 53.58 = 151.77 \text{ dB}$$

$$B_{if} = 10 \log 36 \times 10^6 = 75.56 \text{ dBHz}$$

$$\therefore \; [G_r/T_{sys}] = 40 - 12.88 + 151.77 - 228.6 + 75.56 = 25.85 \text{ dB/°K}$$

Ans.

4.5 ANALOG LINK DESIGN

Bandwidth Calculations

As seen above the noise in a system is dependent on the bandwidth of filters or I.F. amplifiers. The reproduction of original information from the demodulated received R.F. signal depends on the signal to noise (S/N) ratio, hence it is essential to link the link design with this factor. The satellite link is used both for analog signals like speech, video etc., and digital signals like digitized speech, telegraphy, telemetry, data transfer, etc. Thus, it is essential to calculate the bandwidth requirement of satellite transponders as well as earth stations with respect to the corresponding information being handled. Analog signals could be single source, single channel per carrier (SCPC) with frequency modulation (FM) or multiple sources multiplexed, Multiple channel per carrier (MCPC) with FDM/FM. The digital signals could typically comprise of TDM/FSK/FM or PCM/TDM/DM/FM or TDM/PSK, etc.

Modulation in Analog Signals

There are three basic modulation schemes to carry analog signals. These are: amplitude modulation, frequency modulation and phase modulation.

Some of the important factors that govern the choice of carrier and modulation scheme from a designer's point of view are listed below:

1. *Noise consideration:* In satellite applications the EM wave has to travel long distances as discussed earlier resulting in losses, polarization rotation and absorption, resulting in low power at the receiver.
2. *Signal to noise ratio:* Apart from the noise introduced during propagation the receiving systems themselves introduce noise resulting in low signal to noise ratio and hence unsatisfactory detection of information.
3. Low level modulation can be used in FM and subsequent sections can be class-C, hence more efficient transmitter.
4. As the slant range is high, beamwidth should be as small as possible to avoid spillage. This requires higher carrier frequency and smaller antenna.
5. AM modulation index is smaller while FM mostly greater than 1 (2 to 5 is quite normal) and output power is proportional to square of the modulation index.
6. In AM maximum power is wasted as carrier power while all the transmitter power is transmitted as FM power.
7. Co-channel and adjacent channel interference is less in FM.

These considerations and indirect modulation in which PM is converted into FM has made frequency modulation as standard technique in space communication.

We are aware that in frequency modulation the frequency deviation is directly proportional to instantaneous amplitude of modulating voltage such that

$$V(t) = A \cos \left[\omega_{ct} + \frac{\Delta\omega}{\omega_{\text{mod}}} \sin \omega_m t \right] \tag{4.37}$$

Such a signal has infinite bandwidth since the only solution is using Bessel functions. It can be band limited as per Carson's rule for sufficiently good response to

$$B_{if} = 2f_{\text{mod}}\,(m + 1) \tag{4.38}$$

where B_{if} is the intermediate frequency amplifier bandwidth (the selectivity of any heterodyne communication receiver is fixed by its intermediate frequency amplifier bandwidth and its roll off).

The modulation index for a single tone modulating signal of frequency f_{mod} is given by

$$m = \frac{\Delta f}{f_{\text{mod}}}$$

where Δf is the frequency deviation of FM signal.

For FM broadcast of the commercial type $\Delta f = \pm 75$ kHz for maximum modulating frequency of 15 kHz. In such a case

$$M = \frac{\Delta f}{f_{\max}}$$

called **modulating factor**, where $f_{\max}$ in maximum modulating frequency.

Hence

$$B_{if} = 2f_{\text{mod}}\left(\frac{\Delta f}{f_{\text{mod}}} + 1\right)$$

$$= 2\,(\Delta f + f_{\text{mod}}) \qquad 4.39a$$

or when M is considered

$$B_{if} = 2(\Delta f + f_{\max}) \qquad 4.39b$$

Carson's rule is a widely used method of estimating the bandwidth and m is kept between 2 and 10. Some designers prefer to take the bandwidth

$$B_{if} = 2[\Delta f + 2f_{\max}] \qquad 4.40$$

Frequency Division Multiplexing

There are many applications where the bandwidth of modulated signal is much less than the transponder bandwidth. In such cases a single carrier can carry number of signals by building a Base band consisting of frequency converted information signals. This is called **frequency division multiplexing.** A scheme of such a communication system for transmission of N voice signals is shown in Figure 4.17. A number of analog source, are handled as FDM/FM signals. The communication information could be 120 Hz telegraph, 300 Hz to 3.4 KHz speech, 30 Hz to 15 KHz broadcast, 48 KHz data or 0 to 5 MHz video.

From the Figure 4.17 if we assume a voice channel to have a frequency range of 300 Hz to 3400 Hz and the oscillator frequency of mixer 20 KHz then the output will be

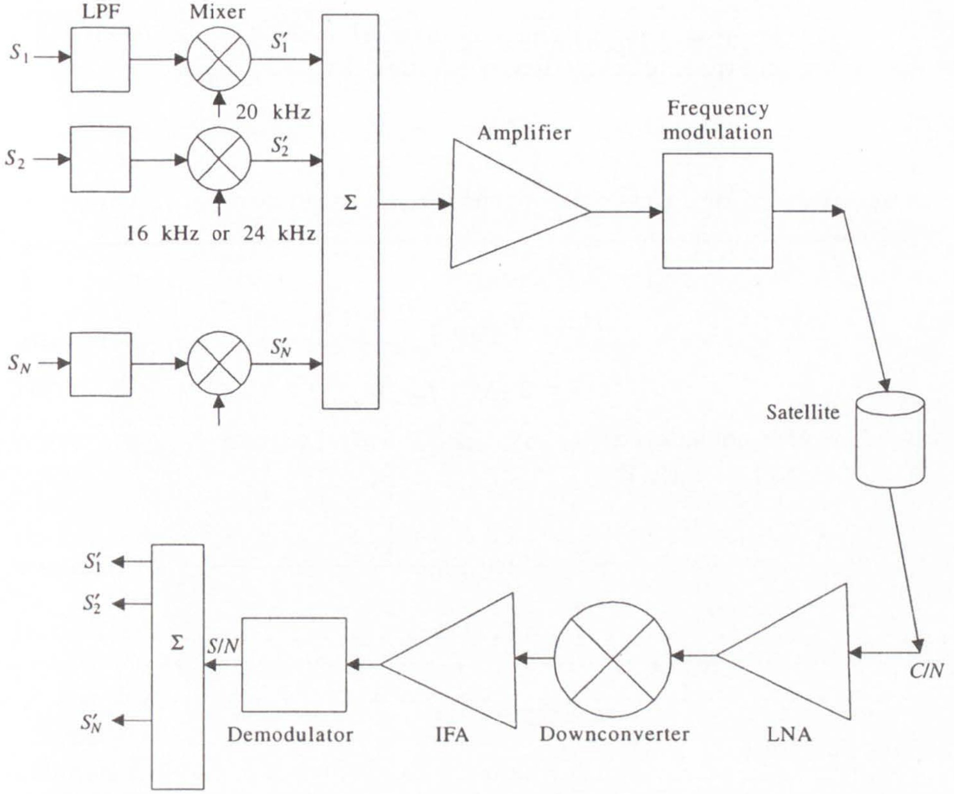
20000 + 300 = **20300 Hz** to 20000 + 3400 = **23400 Hz** (upper band)

or

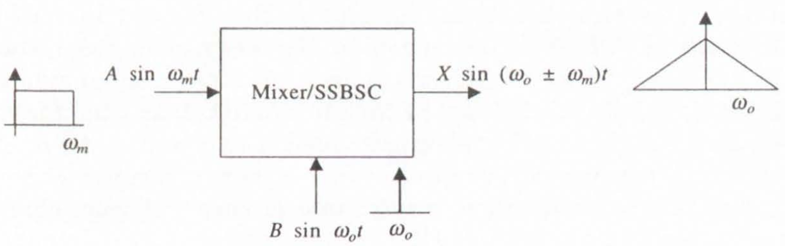
20000 – 300 = **19700 Hz** to 20000 – 3400 = **16600 Hz** (lower band)

One of the above can be used for multiplexing with other sources. Note that the choice of oscillator frequency depends on:

1. The sideband chosen at the output (upper or lower).
2. The number of channels to be multiplexed.
3. The guard band required between the highest signal frequency and lowest multiplexed spectrum frequency.
4. The signal to noise ratio requirement.



(a) Frequency division multiplexing scheme using satellite relay.



(b) Simple converter scheme.

Figure 4.17 FDM.

CCITT has specified certain standards for frequency multiplexing. Voice is considered as an example here. The value of loading factor l depends on the number of multiplexed channels N. The formation of multiplexing groups as per CCITT is divided into standard groups defined as:

1. Basic group consisting of 12 voice channels.
2. Super group consisting of 5 basic groups or 60 voice channels.

3. Master group consisting of 5 super groups or 300 voice channels which is exhibited in Figure 4.18.
4. Super master group consisting of 5 master groups.

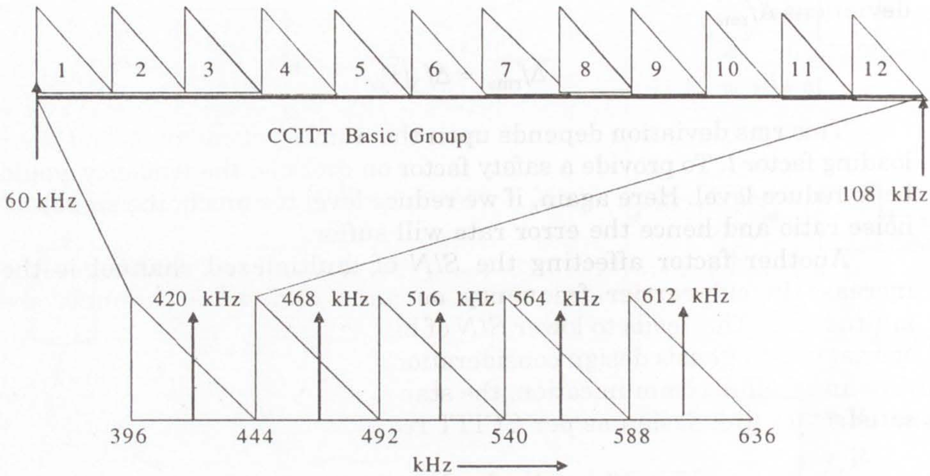


Figure 4.17 CCITT super group.

Line Frequency and Pilots

The band of frequencies that the multiplexer applies to the line, whether the line is a radio link, coaxial cable or open wire, is called the **line frequency**. This also represents the carrier for transmitting the base band. Standard CCITT base bands consist of super master groups, which could be made up of lower sidebands of super groups or upper sidebands of super groups. Pilot frequencies in the group are transmitted for signal level regulation and fault alarm. Pilot frequencies are assigned within the transmitted super master groups as well as super groups. These are located in the guard band region to avoid interference with voice channels. The recommended pilots are:

84.140 kHz at –25 dBm and 84.080 kHz at –20 dBm

Loading in Multichannel Base Band

In a FDM system consisting of duplex conversation many subscribers may be talking simultaneously, this is called **loading a carrier**. The power level P_m depends on the number of channels active and their characteristics at any time, hence the average base band power level decides the multiplexing loading factor. Two things may happen during transmission, one input level due to simultaneous usage may be too high causing inter-modulation noise and cross talk or the level may be too low (very few conversations) causing low S/N ratio. Also the signal level in each conversation may be different and hence mean or average is to be considered. In multichannel case of FDM/FM links since number of signals are multiplexed it is a common practice to consider the rms deviations Δf_{rms}.

$$\Delta f_{\text{rms}} = \Delta f \sqrt{P_m}$$

This rms deviation depends upon the number of channels and their loading factor l. To provide a safety factor on overload the tendency would be to reduce level. Here again, if we reduce level too much, the signal-to-noise ratio and hence the error rate will suffer.

Another factor affecting the S/N of multiplexed channel is the increase in sub-carrier frequency as more and more channels are multiplexed. This leads to lower S/N of higher band sources this requires special pre-emphasis design considerations.

In satellite communication, the standard loading equations used for satisfactory link design as per CCITT recommendations are:

$$20 \log l = -15 + 10 \log N \quad \text{for } N > 240 \text{ channels} \tag{4.41}$$

$$20 \log l = -1 + 4 \log N \quad \text{for } N \text{ between 12 and 240 channels} \tag{4.42}$$

where l is the loading factor and is defined as the ratio of the multichannel equivalent power to the test tone level of 0 dBm.

To calculate the bandwidth since peak deviation is required and the bandwidth is affected by power, sub-carrier, activity and number of multiplexed channels, we have to use a correction factor, also called **peaking factor** g. Defined as the ratio of peak voltage to the rms voltage for a given number of active channels. Remember that at a time not all the N channels are active. Such that

$$\Delta f_{\text{peak}} = g(l\Delta f_{\text{rms}})$$

where peaking factor $g = 3.16$ for $N > 24$ corresponding to 10 dB

$= 6.5$ for $N < 24$ corresponding to 18.5 dB

Hence, as per Carson's rule for FDM/FM, we have

$$\text{Transmitted bandwidth} = 2(gl\Delta f_{\text{rms}} + f_{\text{max}}) \tag{4.43a}$$

For good selectivity receiver the intermediate frequency amplifier should also have the same bandwidth as in 4.43a.

Hence

$$B_{if} = 2(gl\Delta f_{\text{rms}} + f_{\text{max}}) \tag{4.43b}$$

The CCITT standard rms deviation is tabulated in Table 4.3.

Table 4.3 CCITT Standard rms Deviation

No. of channels N	*rms deviation* Δf_{rms} (kHz)
12 & 24	35
60	50
120	50/100
300, 600, 960	200
1260, 1800, 2700	140

Use of the loading formula of this section may permit the use of several data or telegraph channels without serious consequence. But if any wide use is to be made of the system for data-telegraph-facsimile (constant amplitude), then other loading criteria must be used. For typical constant-amplitude signals, traditional (CCITT) transmit levels, as seen at the input of the channel modulator of FDM carrier equipment, are:

1. Data: –13 dBm
2. Signaling: –20 dBm
3. Composite telegraph: –8.7 dBm

For a FDM system with 75% speech loading and 25% data loading with more than 240 channels (total), the rms power could be

$$P_{rms} = -11 + 10 \log N \tag{4.44}$$

Provided certain number of channels remain idle to avoid overloading.

Example 4.8

In a satellite system, it is proposed to transmit 1800 telephone channels through the satellite transponder. Determine the BW requirement of the transponder? Peaking factor being 10 dB. The starting frequency of FDM group is 10 kHz.

Solution

Number of channels, $N = 1800$

$\therefore \Delta f_{rms} = 140$ kHz from Table 4.3

$20 \log l = -15 + 10 \log N$ for $N > 240$

$l = 7.544$

$20 \log g = 10$

$g = 3.16$

(Continued)

$f_{TOP} = f_{initial} + N \times f_{max}$ where f_{max} is maximum signal frequency

$= (10 \text{ kHz}) + 1800\ (4 \text{ kHz})$

$= 7210 \text{ kHz}$

$\text{BW} = 2(g \times l \times \Delta f_{rms} + f_{TOP})$

$= 2[3.16 \times 7.544 \times 140 + 7210]$

$= 21.09 \text{ MHz (for } f_{max} = 4 \text{ kHz)}$

$= 18.93 \text{ MHz (for } f_{max} = 3.4 \text{ kHz)}$ **Ans.**

Voice Activity Factor

Speech on multichannel systems has a low duty cycle or activity factor. Even when a telephone conversation is going on, the channel remains idle during pauses and takeovers hence activity factor is less than unity. Certain signals transmitted over multi-channel equipment have an activity factor of 1. This means that they are transmitted continuously with fixed time frames. Speech is characterized by large variations in amplitude, ranging from 30 dB to 50 dB. We often use the VU (volume unit) to measure speech levels. The average power measured in dBm of a typical single subscriber talking is

$$P_{dBm} = V_{VU} - 1.4 \qquad 4.45a$$

Empirically, the peak power is about 18.6 dB higher than the average power for a typical conversation. This means that FDM carrier equipment must be operated at a low average power to withstand voice peaks to avoid overloading and distortion. These can be related to an activity factor T_a, which is defined in terms of demodulated speech envelope that exceeds some threshold. If the threshold is about 20 dB below the average power, the activity dependence on threshold is fairly weak. Thus, the average speech power can now be rewritten in relation to the activity factor as:

$$P_{dBm} = V_{VU} + 10 \log T_a \qquad 4.45b$$

If $T_a = 0.725$, the results will be the same for the equation relating VU to dBm. Now, if two conversations at different frequency segments are going on on the same equipment, but independent of the first conversation, the system average power will increase by 3 dB. Thus, if we have N subscribers simultaneously talking, each on a different frequency segment, the average power developed will be

$$P_{dBm} = V_{VU} - 1.4 + 10 \log N \qquad 4.45c$$

where P_{dBm} is the power developed across the frequency band occupied by all subscribers. Empirically, it has been found that the peak factor of many subscribers talking over a multichannel analog system reaches the characteristics of random noise peaks when the number of conversations N, exceeds 64. When $N = 2$, the peaking factor is 18 dB; when $N = 10$, it is 16 dB; when $N = 50$, it is 14 dB; and so on. The traditional figure for activity factor accepted by the CCITT is 0.25.

Energy Dispersal

In FM it is well known that the deviation depends upon the amplitude of the intelligence (voice, video, etc.), larger the amplitude larger the spectrum occupation of the band by the modulated signal. Thus, the overall power of the transmitter is spread throughout the bandwidth and the average spectral power density given by watts/Hz is low. But in the absence of any source/intelligence there is no deviation and the power is concentrated in the carrier. The unmodulated carrier should not be allowed which may not only cause interference but may exceed permitted limit of the receiver. This, therefore, becomes a source of interference particularly in case of downlinks. To overcome this problem the spectral power density under unmodulated case should be controlled by some method. This method of controlling the power is called **energy dispersal**.

To achieve this, deliberate spectrum spreading is carried out by introducing a symmetrical triangular wave from 20 to 150 Hz. Transmitting earth stations prefer 60 Hz or 50 Hz (power line frequency) as modulating frequency as these are also compatible with video field frequencies to keep the interference within the prescribed limits specified by ITU. At the receiving station (satellite or terrestrial) this can be easily filtered out. In case of FDM/FM links the amplitude of dispersal signal can be dynamically changed depending on the activity. Usually the peak deviations due to dispersal signals are restricted to 2 MHz. The allowable flux density varies from –160 dBW/m^2 to –100 dBW/m^2.

The overall uplink design is shown in Table 4.4 and power loads at different stages in Figure 4.19.

Table 4.4 Uplink Budget

	Particulars	*Earth station*		*Units*
1.	Power at input of antenna	P_{ant}		dBW
2.	Antenna gain	G_{tant}	(+)	dB
3.	EIRP	1 + 2	(=)	dBW
		Earth to satellite link		
4.	Free space path loss	α_p	(–)	dB
5.	Other losses	α_o	(–)	dB
6.	Total losses	α (4 + 5)		dB
7.	Received power	3–6	(=)	dBW
		Satellite		

(*Continued*)

Table 4.4 Uplink Budget (*contd.*)

	Particulars	*Earth station*		*Units*
8.	a. Satellite antenna gain	G_{sant}	(+)	dB
	b. Satellite G/T ratio		(+)	dB/°K
9.	$\left(\frac{C}{T}\right)_{up}$	7 + 8	(=)	dBW/K
10.	Boltzmann constant	(–)(–228.6)	(+)	dBW/K/Hz
11.	Bandwidth	Hz	(–)	dBHz
	Net $\left(\frac{C}{N}\right)_{up}$ up at output of satellite	9–10–11	(=)	dB

4.6 DIGITAL LINK DESIGN

Digital Signals

Digital signals are sequential binary data with some pulsewidth of a bit of data. This depends on the transmission rate. The three methods used to transmit digital signals are:

1. NRZ—Non-return zero
2. RZ—Return zero
3. Bi-phase or Manchester code

In the case of NRZ the binary values are changing between H_i and L_o values without ever remaining at ground potential. There are two types of NRZ waveforms—unipolar and bipolar. In case of unipolar the H_i and L_o values are either always above '0' volts or below '0' volts. While in the case of Bipolar the binary values are both above (+ve potential) and below (–ve potential), the zero reference. The bit time T_b is the time during which a single bit data is either high or low. Thus, pulsewidth $T_p = T_b$. Where T_b is the bit period.

In the case of Return zero after every bit of data the signal returns to zero. So that the pulsewidth is:

$$T_p = \frac{1}{2} T_b \tag{4.46}$$

In the case of Manchester code the edges are sensed. When the transmission is L_o to H_i, the bit is taken as a H_i bit and vice versa. While T_b is 50% of time of L_o level and 50% of time of H_i level.

So that

$$T_p = T_b$$

Figure 4.19 Typical link power levels.

In all these codes when alternate H_i and L_o signals are transmitted. We get maximum variation or maximum bandwidth. Thus,

$$BW = \frac{1}{T_p} \tag{4.47}$$

Hence for higher rate of transmission BW increases drastically. To reduce the bandwidth sometimes multilevel (combining the bits and assigning different levels to these combinations) encoding is used.

Let us assume that we have 8 bit coding in which the word or symbol, as shown in Figure 4.20 is generated. Under normal transmission the bandwidth requirement of this would be

$$\mathrm{BW} = \frac{1}{T_b} \qquad 4.48$$

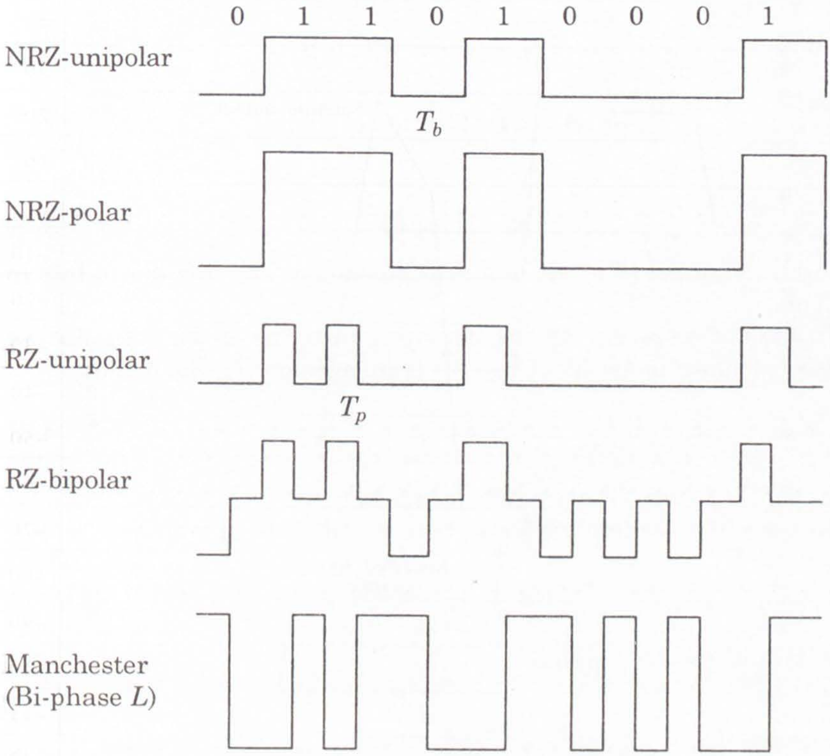


Figure 4.20 Digital waveforms

If the same signal is now represented in four levels instead of two levels, i.e.

1 1 ··· +3 V
1 0 ··· +1 V
0 1 ··· −1 V
0 0 ··· −3 V

We find that the signal waveform is changed which is shown in Figure 4.21. Hence T_b changes to T_{symbol} so that

$$BW = \frac{1}{T_{\text{symbol}}} \qquad 4.49$$

$$= \frac{1}{mT_b}$$

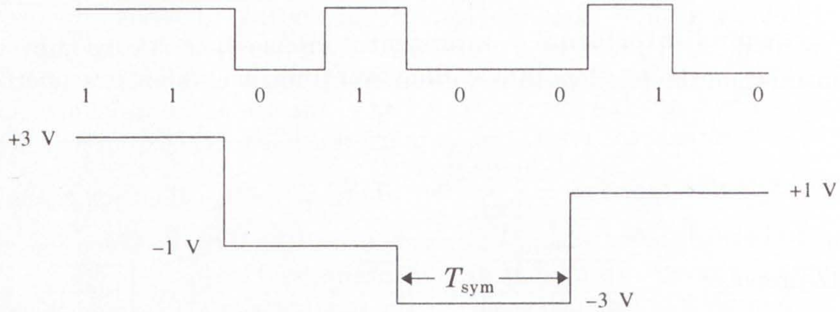


Figure 4.21 Multilevel signal.

where

$$m = \log_2 M \tag{4.50}$$

M being the number of levels and m representing the number of bits in a symbol.

Instead of representing or calculating in terms of time of pulse we can also calculate in terms of rate of transmission R_b. Such that

$$R_b = \frac{1}{T_b} \tag{4.51}$$

So that $BW = R_b$ under normal transmission.

But many designers prefer to take a full cycle in which

$$BW = \frac{1}{2T_b} = \frac{R_b}{2}$$

and in case of m-array signal

$$R_{\text{symbol}} = \frac{R_b}{m}$$

Corresponding bandwidth is given by

$$BW = \frac{1}{2T_{\text{symbol}}} = \frac{R_{\text{symbol}}}{2} \tag{4.52}$$

Effect on Bandwidth Due to Distortion in Received Binary Signal

It is a well-known fact that the received pulses are never of the same shape as they were transmitted but are converted to sine curves due to the inductances and capacitors of transmission lines. The effect of this is not very severe when alternating 1's and 0's are transmitted, but in case there is a tendency of production of damped oscillations at the tail ends and unless the sampling at the receiving end is perfectly timed the possibility is wrong interpretation of data or what is called as

intersymbol interference. Intersymbol interference is caused by the time response of the waveform spilling over from one symbol into another. This may be caused by the ringing effect at the tail of the waveform. One method to control the intersymbol interference is to use signal waveform defined by sine function $\frac{\text{Sin}\,(2\pi B_o t)}{(2\pi B_o t)}$ where $B_o = 1/T_b$ called the **Nyquist bandwidth**. This method gives erroneous results if the receiver does not sample the received signal at proper intervals.

In order to avoid such problems the received signal is passed through a gradually changing frequency response rather than abrupt. This is interpreted as a raised cosine response with a flat portion and a roll off by using a filter. This response is characterized by a Roll off factor ρ.

$\rho = 1 - (f_1/B_o)$ for $\rho = 0$, $f_1 = B_o$ which corresponds to Eq. (4.51) with raised cosine, and the

$$\text{Bandwidth} = \frac{(1 + \rho)R_{\text{symbol}}}{2} \qquad 4.53$$

Note ρ has a minimum value 0 and maximum value 1.

Thus, when $\rho = 0$, the required system bandwidth is that of ideal rectangular filter also called as **Nyquist filter**. Figure 4.22 shows sampling points in receiver.

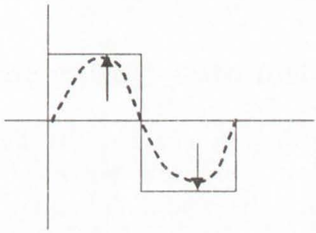


Figure 4.22 Sampling points.

Digital Modulation

Like analog signals the digital stream is to be carried by a carrier for long distance communication. The basic modulation techniques are analogous to analog modulation but called **Amplitude shift keying** (ASK), **Frequency shift keying** (FSK) and **Phase shift keying** (PSK). Keying here stands for the binary information, which is high or low. For example, in the case of ASK if an H_i is fed to the modulator, carrier appears at the output while if it is L_o no carrier appears.

In FSK the binary envelop can be kept constant varying the frequency for an H_i and an L_o, similar to FM. The modulated carrier $V_c(t)$ is of the form:

$$V_c(t) = A \cos\,[\omega_c t + \Delta\omega \textstyle\int m(t)\, dt + \varphi]$$

where $m(t)$ is H_i or L_o. Also A depends on peak amplitude, ω_c the carrier angular frequency, $\Delta\omega$ the deviation and φ the change in phase. Note that $m(t)$ depends upon the digital waveforms as discussed earlier. The carrier spectra and hence the bandwidth requirement depends on the deviation, larger the deviation more is the separation between carriers representing H_i and L_o. This is shown in Figure 4.23. Evidently larger deviation increases the bandwidth. This is due to two reasons:

1. The main lobe itself is wider.
2. The digital pulses having sharp falls (leading and trailing) cause spectral tails.

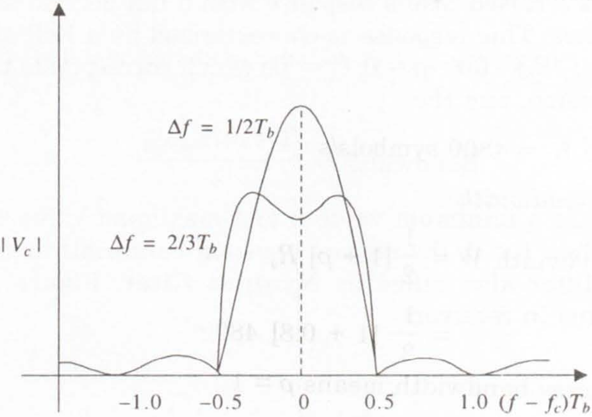


Figure 4.23 FSK spectra.

These can be overcome by shaping the digital stream by passing through raised cosine filters purposely and avoid sharp changes in levels.

In the case of BPSK, the modulated equation is given by

$$V_c(t) = A \cos [\omega_c t + (\pi/2)\{1 - m(t)\} + \varphi]$$

which yields on expansion

$$V_c(t) = Am(t) \cos (\omega_c t + \varphi)$$

Thus the BPSK carrier is identical to ASK, hence similar to ASK, PSK modulated signal also has double sideband, and

$$W = (1 + \rho) R_s \tag{4.54}$$

In the case of analog voice channel signal converted into PCM using an A/D converter with a sampling of $2f_{\max}$ [where $f_{\max}$ is the maximum voice or analog signal frequency]. In such circuits each sample is converted to equivalent digital data of n bits depending upon the A/D converter resulting in N levels of information such that $n = \log_2 N$. Therefore, the corresponding system bandwidth is given by

$$W_{\text{pcm}} = [\log_2 N] \frac{R_s}{2} \tag{4.55}$$

EXAMPLE 4.9

(a) Find the system bandwidth required for a base band digital transmission train having a data rate of 4800 bits/s if the system consists of raised cosine spectrum with (i), $\rho = 0.8$ (ii) efficient excess bandwidth.

(b) If in part (a) the signal is M level signal with $M = 4$, calculate the reduction in bandwidth.

(c) If analog signal of $f_{\max} = 5$ kHz is converted into 8 bit PCM, what is the bandwidth requirement?

Solution

Given:

Symbol rate $R_s = 4800$ symbols/s

(a) *System bandwidth*

(i) Bandwidth $W = \frac{1}{2}[1 + \rho]\, R_s$

$$= \frac{1}{2}[1 + 0.8]\, 4800 = 4320 \text{ Hz}$$

(ii) Excess bandwidth means $\rho = 1$

Hence bandwidth $W = \frac{1}{2}[1 + \rho]\, R_s$

$$= 4800 \text{ Hz}$$

(b) *Reduction in bandwidth*

Since $M = 4$, the number of bits for coding are $M = 2^n$ or $n = 2$. This results in a reduction of symbols and hence symbol rate

$$R_s = \frac{4800}{2}$$

$$= 2400 \text{ symbols/s}$$

Thus, reduction in bandwidth $W = 4800 - 2400 = 2400$ Hz

(c) *Bandwidth requirement*

Sampling rate = 2 × 5000 = 10000 samples/s

$$W = [\log_2 N]\, \frac{R_s}{2} \quad \text{since } \log_2 N = n$$

$$= \frac{1}{2}[8]\, 10000$$

$$= 40 \text{ kHz} \quad \textbf{Ans.}$$

Pulse-code Modulation Signal

Sampling. To transmit analog signals as data, the analog signals have first to be sampled and held at that level till the ADC converts this level to equivalent digital code. Consider the sampling theorem defined by Nyquist, which states that for good reproduction of a sampled analog signal the minimum rate of sampling should be twice the maximum signal frequency.

To avoid repetition overlap, repetitive frequency

$$F = (f_s - f_m) - f_m > 0$$

This equation justifies the above statement.

If we now sample the standard CCITT voice, (300–3400 Hz), at a rate of 8000 samples per second, we will have complied with the Nyquist sampling rate. That means a sample is taken every 125 μs. Similarly a broadcast analog signal of maximum frequency 15 kHz can have sampling rate of 30,000 samples per second. Samples would be taken at 1/30,000 s intervals, or at 33.3 μs. This process of sampling and converting to digital code is called **pulse code modulation** or simply **PCM**.

Practical PCM systems involve time division multiplexing similar to frequency division multiplexing in analog channels. Sampling in these cases does not involve just one voice channel but several. In practice, one samples 24 voice channels in sequence, and another samples 30 channels. The result of the multiple sampling is a pulse amplitude modulation (PAM) wave. A simplified PAM wave is shown in Figure 4.24 which is single sinusoid. A simplified diagram of the processing involved to derive a multiplexed PAM wave is shown in Figure 4.24.

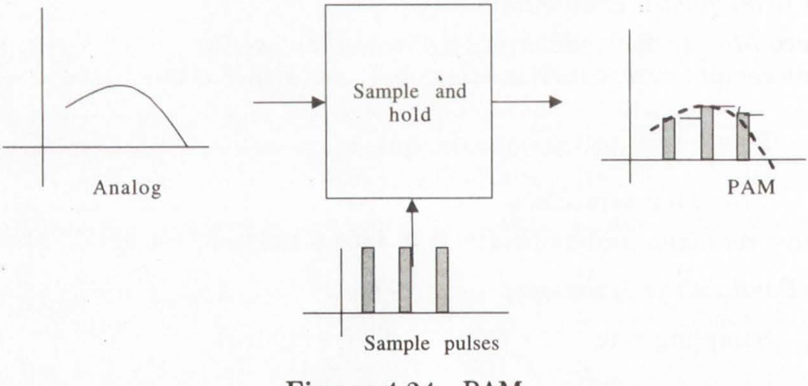


Figure 4.24 PAM.

If the nominal 4 kHz voice channel must be sampled at 8 kHz and a group of 24 such voice channels are to be sampled sequentially to interleave them, forming a PAM multiplexed wave, gating could do this. The gate should be open for 5.2 μs for each voice channel to be sampled successively from channels 1 through 24 as shown in Figure 4.25. This full sequence must repeat after every 125 μs. We call this 125 μs period a *frame* and inside this frame all 24 channels are successively sampled once. The transmitted signal being sequential, to recover the sample, synchronization is essential to identify respective 8 bit samples for proper reconstruction. The actual frame structure is dealt later in this chapter.

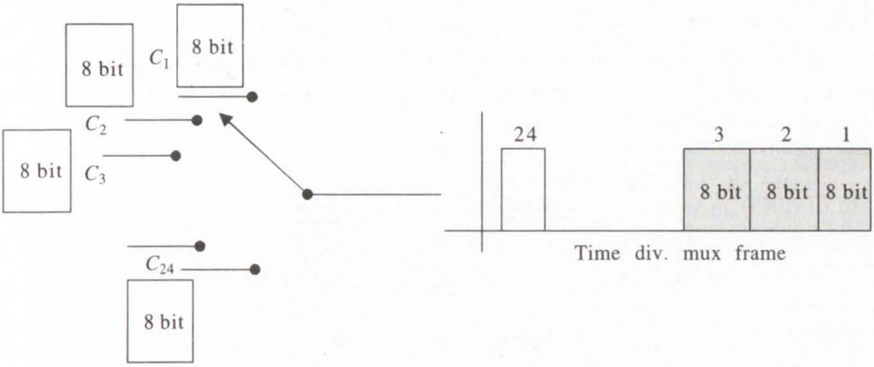


Figure 4.25 125 μs TDM frame.

Quantization. It would appear that the next step in the process of forming a PCM serial bit stream would be to assign a binary code to each sample as it is presented to the coder. The code lengths, or coding level depends upon the representation required for processing. For instance, a binary code with four discrete elements (a four-level code) could code 2^4 separate and distinct codes or 16 characters. Similarly an ASCII is basically a seven-bit code allowing 128 discrete levels ($2^7 = 128$). An eight-level code would yield 256 possibilities.

Quantizing distortion. Quantizing distortion has been defined as *the difference between the signal waveform as presented to the PCM multiplex codec and its equivalent quantized value.* For a linear codec with n binary digits per sample, the ratio of the full-load sine wave power to quantizing distortion power (S/D) is given by

$$\frac{S}{D} = 6n + 1.8 \text{ dB}$$

If we had a 7-bit word and uniform quantizing, S/D would be 43.8 dB. Each binary digit added to the PCM code word increases the S/D values range in the order of 33–38 dB, depending largely on the levels of the conversation.

4.7 CALCULATION OF SIGNAL TO NOISE RATIO

In order that the detected signal is meaningful it is necessary that SNR at the output of the demodulator is above a threshold level both in the case of analog as well as digital transmission. In this section we will see how we can achieve this condition.

FM Received Signal

As seen in the Figure 4.26, the received signal has a certain C/N ratio as discussed in Sec. 4.4, which is passed through receiver front end (cable/wave guide, R.F. amplifier, Mixer, I.F. amplifier) as depicted by Eq. (4.56). The FM signal with this C/N ratio when passed through the demodulator gives a S/N of received signal. Let us now see how to arrive at this S/N for an FM signal.

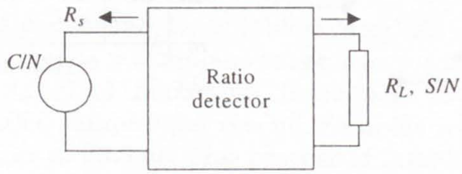


Figure 4.26 FM demodulator.

The carrier power at the output of the intermediate amplifier (input of the demodulator) is given by

$$C = \left(\frac{E_c}{\sqrt{2}}\right)^2 \frac{1}{2R}$$

where E_c is the peak carrier (FM limited) amplitude and $R = R_s = R_L$, under matched condition.

Therefore,

$$C = \frac{E_c^2}{4R}$$

and

Noise power $N = KT_sB_{if}$

The input carrier to noise ratio of the modulated carrier is:

$$\frac{C}{N} = \frac{E_c^2}{4R} \times \frac{1}{KT_sB_{if}} \quad 4.56$$

Unfortunately the output of the demodulator has random noise output and, therefore, to determine the noise power would be quite tedious. To simplify the calculations we will assume one cycle of sinusoid of noise. The phase change of this noise depends on the change in noise amplitude and peak carrier amplitude such that

$$\phi_n = \left(\frac{\Delta v_n}{E_c}\right) \sin \omega_n t \quad 4.57$$

From the FM Eq. (4.37)

$$V(t) = E_c \cos\left[w_n t + \frac{\Delta v_n}{E_c} \sin \omega_n t\right]$$

where

$$\frac{\Delta v_n}{E_c} = M, \text{ the modulation factor}$$

The corresponding equivalent noise frequency is given by

$$(f_n)_{\text{eq}} = \frac{1}{2\pi}\frac{d\Phi_n}{dt}$$

$$= \frac{\omega_n}{2\pi}\frac{\Delta v_n}{E_c} \cos \omega_n t$$

$$= f_n \frac{\Delta v_n}{E_c} \cos \omega_n t \qquad 4.58$$

The maximum frequency or peak deviation will be when $\cos \omega_n t = 1$. Therefore,

$$(f_n)_{\text{peak}} = f_n \frac{\Delta v_n}{E_c} \qquad 4.59$$

In FM, power is proportional to square of deviation, hence noise power is given as:

$$\begin{aligned} dp_n &\propto df_n^2 \\ dp_n &= A\, df_n^2 \end{aligned} \qquad 4.60$$

where A is a constant of proportionality. Differentiating Eq. 4.59 and substituting in Eq. 4.60, we get

$$dp_n = A \frac{f_n^2}{E_c^2} \times \Delta v_n^2$$

$$= A \frac{f_n^2}{E_c^2} \times 4KT_s R df_n$$

Noise power at the output of the Detector having a filter bandwidth W would be

$$P_n = 2\int_0^W dp_n = 2\int_0^W \frac{Af_n^2}{E_c^2} \times 4KT_s R df_n$$

Note: 2 here indicates deviation on both sides of the carrier. Now,

$$P_n = 2 \times \frac{4(AKT_s R)}{3E_C^2}[f_n^3]_0^W \times \frac{B_{if}}{B_{if}}$$

$$= \frac{2}{3} A \times \frac{N}{C} \times \frac{W^3}{B_{if}} \tag{4.61}$$

Signal power $P_s = A\Delta f^2$

Hence signal to noise ratio of the demodulated signal is given by

$$\frac{P_s}{P_n} = \frac{S}{N} = \frac{A\Delta f^2}{\frac{2}{3} A \times \frac{N}{C} \times \frac{W^3}{B_{if}}}$$

$$= \frac{3}{2} \times \frac{C}{N} \times \frac{B_{if}}{W^3} \times \Delta f^2$$

$$= 1.5 \times \frac{C}{N} \times \frac{B_{if}}{W}\left[\frac{\Delta f}{W}\right]^2 \tag{4.62}$$

Detector gain or processing gain, K_{det} is defined as:

$$K_{\text{det}} = \frac{\left(\frac{S}{N}\right)}{\left(\frac{C}{N}\right)} \tag{4.63}$$

From Eq. (4.62)

$$K_{\text{det}} = 1.5\left(\frac{B_{if}}{W}\right)\left(\frac{\Delta f}{W}\right)^2 \tag{4.64}$$

where W is $f_{\max}$ of signal frequency.

In FDM the equation is modified to

$$K_{\text{det}} = \left(\frac{B_{if}}{f_{\max}}\right)\left(\frac{\Delta f_{\text{rms}}}{f_{\text{FDM top}}}\right)^2 \tag{4.65}$$

In terms of decibels, Eq. (4.63) can be re-written as:

$$\left[\frac{S}{N}\right] = \left[\frac{C}{N}\right] + [K_{\text{det}}] \tag{4.66}$$

Two factors that affect the S/N ratio in FM transmission are:

1. The noise produced by the high frequency circuits. No amount of filtering can remove such noise and hence the amplitude of signal beyond 1 kHz is increased. This is called **pre-emphasis**

and is provided by passive peaking circuits. As per EIAA standards these circuits should have a time constant of 75 μs. This provides an overall S/N improvement of 2.5 dB (refer any communication text).

2. In FDM it is found that certain channels are attenuated more than the others also the receiving transducer (handset) affects the signal quality. Hence it becomes necessary to take care of these and perform Psophometric weighing. During the analysis it is customary to use single tone sinusoidal signals but in actual use any system has to deal with multifrequency continuously variable signals. This therefore requires a correction called **weighing factor**. Weighing factor is defined as the amount of degradation caused in the SNR due multitone signals over an ideal single tone reference. Typically the reference frequency used is 800 Hz in telephoney where bandwidth of 3400 Hz is considered. Generally such weighing factors vary from 3.6 to 4 dB.

Hence Eq. 4.66 can be modified to

$$\left[\frac{S}{N}\right] = \left[\frac{C}{N}\right] + [K_{\text{det}}] + [P] + [W] \qquad 4.67$$

where P and W are pre-emphasis and weighing factors, respectively.

In analog link design standard minimum SNR are defined by the CCITT for different sources. To achieve these the system design should satisfy the required C/N, as different losses during the propagation and noise degrades the signal.

Modification in TV Broadcasting

Though in the above problem the usual derived equations have been used it is to be noted that the composite video signal consists of peak-to-peak luminance resulting in a higher S/N. Also in case of Direct broadcast reception the transmitted power is at least 10 dB more than usual outputs of communication satellites. This is necessary to facilitate users to use smaller antenna.

In case of sinusoidal signals the peak-to-peak power is 2 times the rms value, but luminance signal is 1/2 times the composite video resulting in net S/N of:

$$= 1.5 \times \frac{C}{N} \times \frac{B_{if}(2\Delta f)^2}{W^3}$$

$$= 6 \times \frac{C}{N} \times \frac{B_{if}}{W^3} \times (\Delta f)^2 = 6 \times \frac{C}{N} \times \frac{B_{if}}{f_m} \times \left(\frac{\Delta f}{f_m}\right)^2 \qquad 4.68$$

EXAMPLE 4.10

A video signal has a deviation of 12 MHz and a video bandwidth of 5.5 MHz. The emphasis improvement is 1.3 dB and weighing improvement is 1.12 dB. Calculate:

(a) Bandwidth requirement of receiver using Carson's rule.

(b) Signal to noise power ratio, given $\frac{C}{N}$ = 22 dB.

(c) Video signal to noise ratio.

Solution

(a) *Bandwidth requirement*

The bandwidth requirement is defined by intermediate frequency amplifiers.

$$\begin{aligned} B_{if} &= 2(\Delta f + f_m) \\ &= 2(12 + 5.5) \\ &= 35 \text{ MHz} \\ &= 75.44 \text{ dBHz} \quad \textbf{Ans.} \end{aligned}$$

(b) *Signal to noise ratio*

Processing gain is given by

$$\begin{aligned} K_R &= 1.5 \frac{B_{if}(\Delta f)^2}{W^3} \\ &= \frac{1.5 \times 35 \times 10^6 \times (12 \times 10^6)^2}{(5.5 \times 10^6)^3} \\ &= 45.43 \equiv 16.574 \text{ dB} \end{aligned}$$

Hence

$$\begin{aligned} \left[\frac{S}{N}\right] &= [22] + [16.574] + [1.3] + [1.12] \\ &= 40.99 \text{ dB} \quad \textbf{Ans.} \end{aligned}$$

(c) *Video signal to noise ratio*

The $\frac{S}{N}$ voltage ratio = $\frac{\text{Peak to peak voltage}}{\text{R.M.S. noise voltage}}$ under matched conditions

$$\begin{aligned} \left(\frac{S}{N}\right)_v^2 &= 1.5 \frac{C}{N}\frac{B_{if}}{W^3}(2\Delta f)^2 \\ &= 10 \log 1.5 + 10 \log \frac{C}{N} + 10 \log \frac{B_{if}}{W} + 20 \log \frac{2\Delta f}{W} \\ &= 1.76 + 22 + 8.03 + 12.79 \\ &= 44.586 \text{ dB} \equiv 28.75 \times 10^3 \quad \textbf{Ans.} \end{aligned}$$

Calculation of SNR in Digital Domain

As seen in the previous sections, the bandwidth depends upon the type of modulation in digital signals, hence the signal to noise ratio evidently should depend on the same. In satellite communication generally FSK, PSK or BPSK are used. Hence in this section we will deal with PCM channel based SNR calculations. Before we go for the calculation of SNR let us see what are the different types of noise that occur in digital domain. In analog signals noise is unwanted amplitude whereas in digital it is the unwanted symbol. We can, therefore, categorize noise as:

1. Quantizing error or Quantizing noise
2. Overload distortion
3. Intersymbol interference (ISI)
4. Filter mismatch

The first step in generation of a digital signal is to take samples of analog and quantify the levels into codes. This is done using any type of analog to digital converter. In the Quantizing process it is not possible to convert every point of the analog signal to digital and, therefore, the samples are taken at discrete levels of Δ volts. This results in Quantizing error because the A to D converter has invariably an error of $\pm\frac{1}{2}LSB$ or $\pm\frac{1}{2}\Delta S$. But in actual practice, depending upon the ADC, the Quantizing error varies randomly between $-\Delta/2 \le q_e \le \Delta/2$.

Thus, the average power of Quantizing noise is:

$$P_q = \frac{1}{\Delta_s}\int_{-\frac{\Delta s}{2}}^{+\frac{\Delta s}{2}} q_e^2 \, dq$$

$$= \frac{1}{\Delta_s}\left[\frac{q_e^3}{3}\right]_{-\frac{\Delta s}{2}}^{\frac{\Delta s}{2}} = \frac{1}{3\Delta_s}\left[\frac{\Delta_s^3}{8} + \frac{\Delta_s^3}{8}\right]$$

$$= \frac{\Delta_s^3}{12\Delta_s} = \frac{\Delta_s^2}{12} \qquad 4.69$$

If Δ_s is smaller, P_q will be still smaller.

Every quantizer has a dynamic range and if the input exceeds this it causes overload distortion. The overload level i.e. peak-to-peak signal should be less than overload level. Hence to avoid any error the analog input should be well within the dynamic limit.

Intersymbol interference or noise is basically caused at the receiver because of higher bandwidth of channel or filter (remember no filter is ideal). This causes overlapping of oscillatory tails. In order to reduce the

ISI, the filter spectrum should be band limited to R_b where

$$R_b = \frac{1}{T_b} \text{ in case of BPSK}$$

and

$$\frac{R_b}{2} \text{ bits/s} = R_s \text{ (in case of QPSK)}$$

(since two bits are combined to give quadrature phase states). To achieve this full cosine roll-off filters are preferred.

Unlike in the case of analog transmission the carrier power depends on an H_i or an L_o transmitted. Moreover most commonly encountered noise has a flat response resulting in a noise power spectral density (joules-watts/Hz), denoted by N_o. Hence the filter characteristic (bandwidth) will determine the total power. Similarly if we consider bit by bit received power then the average bit energy (joules) E_b can be calculated from average received power P_r such that

$$E_b = P_r T_b = C \cdot T_b$$

or

$$E_s = C \cdot T_s = \frac{C}{R_s}$$

where subscript s stands for symbol.

Now,

$$N_o = \frac{N}{B}$$

Therefore,

$$\frac{E_s}{N_o} = \frac{C}{R_s} \times \frac{B}{N} \text{ (for optimum filter } R_s = B)$$

Such that,

$$\frac{E_s}{N_o} = \frac{C}{N} \qquad 4.70$$

This is an important relation for design.

The received digital signal's figure of merit is defined by BER (Bit error rate) or EP (error probability).

In case of BPSK $BER = SER$ where SER stands for symbol error rate.

In case two bits are combined to form a symbol like in QPSK.

$$BER = \frac{1}{2} \times \frac{SER}{1 - 2^{-N_b}} \qquad 4.71$$

where n_b is number of bits per symbol and for QPSK $n_b = 2$

$$BER = \frac{1}{2} \frac{SER}{(1 - 2^{-2})} = 1.5\ SER \qquad 4.72$$

The probability of a receiver making an erroneous detection is given by

$$BER = \frac{1}{2} erfc \sqrt{\frac{E_s}{N_o}} \qquad \text{for matched filter conditions}$$

erfc being complementary error function, which can be found from *erfc* table.

For BPSK,

$$BER = \frac{1}{2} erfc \sqrt{\frac{E_b}{N_o}} \tag{4.73}$$

From the above discussions for QPSK

$$\left[\frac{E_s}{N_o}\right] = \frac{C}{N} \cdot \frac{B_{\text{QPSK}}}{R_s} = \frac{C}{N} \times \frac{2B}{NR_b}$$

and

$$BER = \frac{1}{2} erfc \sqrt{\frac{2B}{R_b} \cdot \frac{C}{N}} \tag{4.74}$$

In the case of BPSK

$$\frac{E_s}{N_o} = \frac{E_b}{N_o} = \frac{C}{N} \cdot \frac{B}{R_o}$$

Resulting in a BER of

$$BER = \frac{1}{2} erfc \sqrt{\frac{B}{R_o} \cdot \frac{C}{N}} \tag{4.75}$$

when $\frac{E_b}{N_o}$ > 6.5 dB for NRZ which is generally the case in satellite communication

$$BER = \frac{e^{\frac{-E_b}{N_o}}}{\sqrt{4\pi \frac{E_b}{N_o}}} \tag{4.76}$$

Channel Efficient Modulation

Due to more and more demand of channels in the digital domain, increase in bandwidth, power conservation and high channel efficiency is required, satellite communication have started using M-ray PSK (M = 8, 16, ..., etc.) and amplitude phase keying modulation techniques. These techniques require more complex earth stations but the signal degradation can be controlled. Figure 4.27 shows a high speed 8-PSK modulator. In this system a high speed 120 Mbps signal is transmitted. In this scheme the serial data at a rate of R_b is converted into three $R_b/3$ parallel streams, which are phase shifted using IF phase shifters. These are then multiplexed and passed through analog filter. The output is band limited to $R_b/3$.

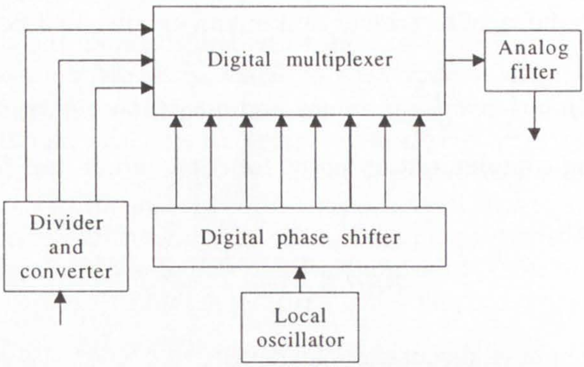
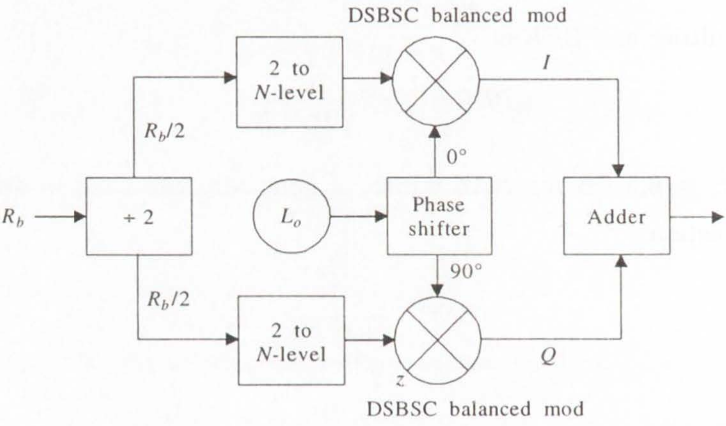


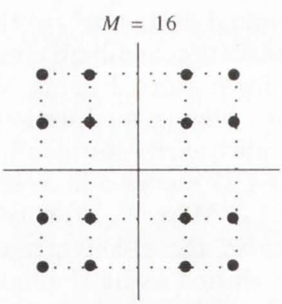
Figure 4.27 High speed 8-PSK modulator.

From the phasor or signal space diagram it is clear that all the states have same amplitude but only phase shifted. Thus even if the amplifiers in the satellite go to saturation it does not degrade the signal. This helps in a better SNR. During demodulation a reverse process is followed. For phase reference a PLL is used which locks with the pilot.

QAM is another highly spectral efficient technique which uses M-ary codes. It can be combined with PSK to achieve better results. One such system is shown in Figure 4.28.



(a) Modulator



(b) Constellation

Figure 4.28 QAM.

The incoming digital stream is divided into $R_b/2$ and converted into N levels having a symbol rate of $R_b/2n$ symbols per second, where $N = 2^n$. This modulates the in phase and quadrature carriers to produce PAM signals which when added gives rise to the signal state space diagram as shown in Figure 4.28(b).

The scope of this book does not allow us to go into the details of all digital modulation techniques but for reference some comparison as to the variation of E_b/N_o to achieve a BER of 10^{-4} is given in Table 4.5 and also the earth station cost complexity is shown in Figure 4.29.

Table 4.5 E_b/N_o Comparison

Modulation	*Remarks*	E_b/N_o
FSK-non-coherent	Ideal	12.4–12.6
	Data/IF BW (0.8)	11.8
	Fading channel	20
MSK	Ideal	9.4
	Data/IF BW (1.8)	10.4
	Fading channel	17
BPSK	Ideal	8.4
	Data/IF BW (0.8)	9.4
	Fading channel	14
DPSK	Ideal	9.3
	Data/IF BW (0.8)	10.6
	Fading channel	17
QPSK	Ideal	8.4
	Data/IF BW (1.8)	9.9
	Fading channel	13.5
M-ary PSK	Ideal	11.8–16.2
	Data/IF BW (2.6–2.9)	12.8–17.2
	Fading channel	16.5–21
M-ary QAM	Ideal	12.4
	Data/IF BW (3.0)	13.4
	Fading channel	18

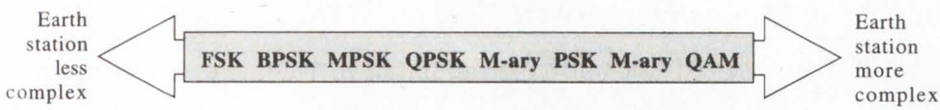


Figure 4.29 Earth station complexity for different modulations.

EXAMPLE 4.11

Calculate the effective bandwidth required to transmit a 16-ary QAM stream if the source rate is 50 Mbps.

Solution

Given

$$R_b = 50 \text{ Mbps}$$

Therefore, it is split to $R_b/2 = 50/2 = 25$ Mbps

Since $M = 16$ each coordinate will have 4 levels resulting in $25/\log_2 4 = 12.5$ symbols/s.

The modulator is DSBSC so the total transmitted

BW = 12.5 MHz **Ans.**

Calculation of SNR in Digital Receivers

Here we will consider two aspects:

1. Noise added due to quantization
2. Noise due to channel

As has been discussed earlier, the quantizer itself creates error and hence affects the SNR of digital stream. As seen in Eq. (4.69) the noise power is given by $\frac{\Delta_s^2}{12}$. If there are n bits in a code then the total quantizing levels will be $Q = 2^n$, hence the signal to quantization noise ratio is given by

$$\frac{S}{N_q} = \frac{\frac{(Q\Delta_s)^2}{12}}{\frac{\Delta_s^2}{12}} = Q^2 \qquad 4.77$$

Just to give an indication of how S/N varies, let us consider an analog signal having a peak amplitude V volts. In which case the rms signal to quantizing noise voltage ratio will be

$$\frac{\frac{V}{\sqrt{2}}}{\frac{\Delta V_n}{\sqrt{12}}} = \frac{\frac{V}{\sqrt{2}}}{\frac{V}{(Q-1)}\Big/\sqrt{12}} = 2.449\,(Q-1)$$

The normalized calculation is tabulated in Table 4.6.

Table 4.6 Normalized Calculation of Signal to Quantization Noise

No. of bits	*Quantizing levels*	*rms signal to quantization noise*		*Normalized distortion*
		Ratio	*Decibels*	
4	16	36.735	31.30	0.0625
6	128	311.023	49.85	7.8125×10^{-3}
8	256	624.495	55.91	3.906×10^{-3}
12	16384	40124.416	92.06	6.1035×10^{-5}

It is seen from the table more the number of levels smaller the step size and hence the distortion. When the signal is received in the receiver it contains error due to ISI and channel distortion resulting in a net BER. Therefore, the overall signal to noise ratio is given by:

$$\frac{S}{N} = \frac{Q^2}{1 + 4Q^2\,(BER)}$$

EXAMPLE 4.12

In a digital transmission $\frac{E_b}{N_o}$ = 11 dB for a polar NRZ transmission over BPSK. The system uses 8 bits per level. Calculate the *S/N* ratio in decibels.

Solution

Assuming matched filtering, the following steps can be followed:

Given:

$$\frac{E_b}{N_o} = 11 \text{ dB}$$

$$\equiv 12.59 \text{ in ratio}$$

$$Q = 2^8 = 256$$

Since $E_b/N_o > 6.5$ dB

$$BER = \frac{e^{-12.59}}{\sqrt{4\pi \times 12.59}} = 3 \times 10^{-7}$$

$$\frac{S}{N} = \frac{Q^2}{1 + 4Q^2\ BER} = \frac{(256)^2}{1 + 4(256)^2 \times 3 \times 10^{-7}}$$

$$= 60.75 \times 10^3$$

$= 47.83$ dB **Ans.**

Improving Signal to Noise Ratio

When linear quantization is done it is found that for larger amplitudes the signal to noise deteriorates, this can be overcome by using non-uniform quantization. For smaller amplitudes linear quantization can be done while for larger amplitudes non-linear, this is called **companding**. At the receiver a reverse process has to carry out to get the data. A simple scheme is shown in Figure 4.30. There is an added advantage that

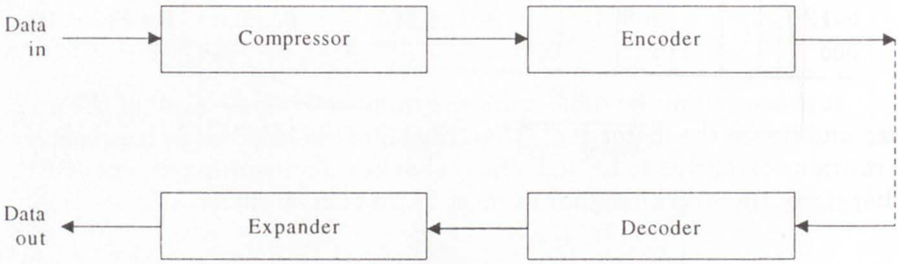


Figure 4.30 Non-uniform PCM.

weaker signals [$v(t) << \pm V$] will be quantized with more levels than stronger signals. Take the case of telephone where two subscribers are talking one with feeble voice and the other with loud; in case of uniform quantization the received signal in the former case will have a volume, which will be difficult to hear while in the latter case too loud.

A compression curve that is quite easy to implement is the logarithmic characteristic which was firstly suggested by Catter-mole. It relates the output and input by two equations:

1. The linear portion from $-1/A$ to $1/A$ (taking only the first quadrant from 0 to $1/A$).
2. The non-linear portion from $1/A$ to 1.

It is evident because it is not logical to use logarithmic scale for small amplitudes. If we calculate the quantizing noise from the combined linear and non-linear characteristic following the indicated characteristics of Figure 4.31(b), we get the output step size

$$\Delta y = \frac{A\Delta x}{1 + \ln A}$$

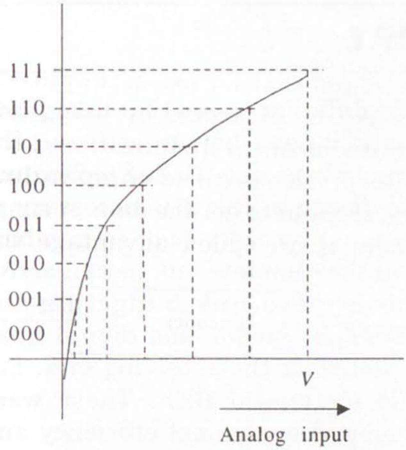
and

$$\Delta y = \frac{1}{1 + \ln A}\frac{\Delta x}{x}$$

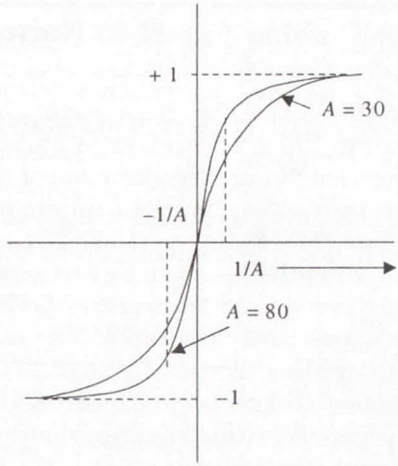
where Δx is sampled input step.

Also

$$\Delta y = \frac{V_{\max}}{2^n} = \frac{2}{2^n}$$



(a) Compander characteristic



(b) Logarithmic encoding characteristic

Figure 4.31 Non-uniform encoding characteristics.

The mean square quantizing noise will be

$$(V_n)^2_{\text{lin}} = \frac{(\Delta x)^2}{12} = \frac{(1+\ln A)^2}{12A^2}\Delta y^2 = \frac{(1+\ln A)^2}{12A^2}\left(\frac{2}{2^n}\right)^2 = \frac{(1+\ln A)^2}{3A^2Q^2}$$

in the linear region, while

$$(V_n)^2_{\log} = \frac{(1+\ln A)^2}{3Q^2}x^{-2} \text{ (In logarithmic region)}$$

Example 4.13

Calculate the effect on quantization noise with increase in linear portion of the companding characteristic.

Solution

Let $A = 100$ so that $1/A = 0.01$ meaning smaller linear region
The mean square quantization noise will be

$$\text{Quantization noise} = \frac{(1+\ln A)^2}{3A^2Q^2} = \frac{31.418}{3\times 10^4 \times Q^2} = \frac{3.142\times 10^{-3}}{Q^2} \quad \text{(i)}$$

When $A = 1$, linear region increases, therefore, noise is:

$$\text{Quantization noise} = \frac{(1+\ln A)^2}{3A^2Q^2} = \frac{1}{3Q^2} = \frac{0.33}{Q^2} \quad \text{(ii)}$$

Comparing results 1 and 2, it is seen that quantization noise increases as linear portion increases. **Ans.**

SUMMARY

In this chapter we have learnt about the different losses that take place as the EM wave travels to and from satellite and how to arrive at the received power. We also studied the commonly used modeling techniques for rain absorption. For an engineer to design a link it is necessary to know the requirement of SNR at the signal recovery end, from which knowing the losses and gains provided in the complete link he can arrive at the required transmitter power. This is called **link budgeting** and this was also illustrated. The calculations for analog and digital links are similar accept the way it is interpreted at the receiving end. For analog links one looks for SNR while for digital BER. These were discussed in this chapter along with improving channel efficiency and signal to noise ratio.

REVIEW QUESTIONS

1. Explain in detail the losses that occur during propagation of EM wave from earth station to satellite and vice versa. In what way they help in satellite communication link design?
2. Discuss ionospheric and tropospheric effects in space communication.
3. Explain the working of a FDM/FM system having two super groups and one basic group in a telephone link via satellite.
4. Mention the sources of noise in satellite systems.
5. A satellite receiving system consists of an aerial, waveguide runs from the aerial to the input of the first amplifier, low noise first amplifier and succeeding stages. Derive an expression for the system noise temperature in terms of standard parameters.
6. Define the following terms:
   (i) G/T ratio of an earth station.
   (ii) Back off in a power amplifier.
   (iii) Multiplexing of signals.
7. Briefly explain the sources of noise in satellite communication. What is the importance of noise temperature in the link design?
8. What are the factors on which a digital communication satellite link depends on? Explain in brief.
9. With a block diagram explain a typical satellite repeater.
10. Enumerate the advantages of FM in space communication. Explain how bandwidth of FM signal is estimated.

11. What are the major subsystems of a satellite? Explain their role with particular reference to a communication satellite.
12. Differentiate the different types of orbits in which satellites are placed.
13. Sketch the ground trace of an almost geostationary satellite and briefly explain what parameters decide its shapes.
14. Explain the term multiplexing and distinguish between FDM and TDM.
15. Describe the concept of threshold in an FM demodulator and how this is useful in satellite communication system.
16. Compare the performances of the major digital modulation schemes.
17. With a block diagram explain a typical PCM/TDM system. Discuss its merits and demerits.

PROBLEMS

1. A test tone has a BW = 800 Hz and peak deviation of 2 kHz. Calculate the modulation index and B_{if}.

   (**Ans.:** 2.5, 5600 Hz)

2. In a satellite link the propagation loss is 200 dB. Other losses are 3 dB. The receiver G/T is 11 dB/K and the EIRP is 45 dBW. Calculate the received C/N for an FDM baseband consisting of 96 voice channels.

   (**Ans.:** 10.37 dB)

3. Calculate the rain attenuation in the case of a 6/4 GHz link if the probability of rain rate for 0.01% of time is 25 mm/hr. The earth station is situated at an altitude of 3450 ft. Use both SAM and CCIR model for $a = 42.1 \times 10^{-6} f^{2.42}$ and $b = 1.5 f^{-0.08}$.

   (**Ans.:** 1.48 dB)

4. Compute the effective input noise temperature of a receiver whose noise figure is 10 dB.

   (**Ans.:** 2610°K)

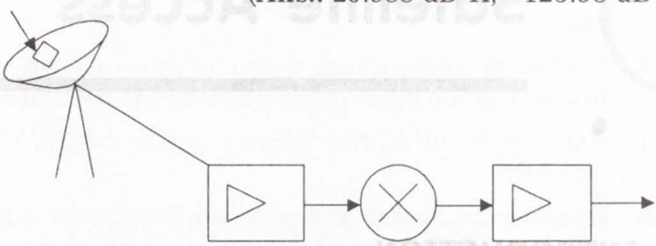
5. A video signal has a BW of 4.2 MHz and deviation ratio of 2.56. Calculate the system BW required. Also calculate the signal to noise ratio for C/N = 20 dB.

   (**Ans.:** 29.9 MHz, 38.44 dB)

6. In a satellite receiving system the equivalent noise picked up by antenna is 18°K. The antenna is connected to the receiver through a cable having a loss factor of 0.15 dB/m and of 15 m length. The physical temperature for the design is to be considered as 290°K. The stages of the receiver is shown in

Figure 4.32. Calculate the overall noise temperature and G/T ratio if the received power is –96 dB.

(Ans.: 29.988 dB°K, –125.98 dBW/°K)



$l = 15$ m	$G_{LNA} = 15$ dB	$G_m = -1$ dB	$G_{if} = 40$ dB
$T_o = 290$ K	$T_a = 29$ K	$T_m = 300$ K	$T_{if} = 800$ K

Figure 4.32

7. Explain the working of a FDM/FM system having two super groups and one basic group in a telephone link via satellite. Calculate the overall signal to noise ratio received if G/T of the front end of the receiver is 38.3 dB/K. Satellite EIRP being 24 dBW and overall losses being 196.8 dB.

(Ans.: 105.26 dB)

8. An FM system has a receiver threshold of 15 dB. How much received carrier power and RF bandwidth is needed to transmit a 4 kHz baseband signal with a demodulated SNR of 40 dB? Take N_o = 10 to the power of –10 W/Hz.

(Ans.: 27.94 dBW, 4 MHz)

9. In a satellite link transmitting video signal the required S/N ratio is 45.7 dB. Determine the required G/T of the receiver if the transmission is FM with the following details:

(i)	EIRP	54 dBW (uplink)	34 dBW (downlink)
(ii)	Slant range	38500 km	40000 km
(iii)	Rainfall attenuation	0.1 dB/km	0.1 dB/km
(iv)	Carriers	6.954 GHz	4.25 GHz
(v)	Other losses	5 dB	5 dB
(vi)	Pre-emphasis improvement		5 dB
(vii)	Multiplexing peaking factor		13.57 dB
(viii)	System bandwidth		36 MHz

Assume suitably the additional data required.

(Ans.: 48.727 dB)

10. In a coherent QPSK digitally coded speech onto RF carrier, PCM is used with 8 kHz sampling frequency and 8 bit word using linear quantization. Assuming that E_b/N_o is equal to 9 dB, calculate the signal to noise ratio. What will be the bandwidth of the system?

(Ans.: 36.89 dB, 64 kHz)

5 Satellite Access

5.1 INTRODUCTION

In this chapter we will deal with different Multiple Access techniques possible to access satellites for communication. The resource sharing in satellite communication is of utmost importance as in any multiple user system. There are certain limitations of access techniques used in satellites, which will also be discussed in brief. The applications of each technique and basic design equations are explained while derivations have been dealt in single link design in Chapter 4. The detailed quantitative analysis is out of scope of this book.

5.2 TYPES OF MULTIPLE ACCESS

Any service is not fully utilized to its capability unless it is accessible by different users. Satellite is such a versatile service that its usefulness can be brought out only when different users access it. Hence multiple access is defined as *the ability of a service to be accessible by different users*. In satellite there are four domains that can be considered by the users to access the satellite. These are:

1. Frequency
2. Time
3. Space
4. Code

Either of these domains (many a times term division is also used) or combinations of these domains can be used by a user to approach and utilize satellite facilities. The payload of the satellite has to be designed depending on the facilities that the user agencies want to provide. These variations are discussed in this chapter. As per the above mentioned domains or variables the following categories as shown in Figure 5.1 are defined.

FDMA. Frequency domain multiple access, where 'n' number of stations on 'n' different frequency bands can access the satellite.

TDMA. Time domain multiple access, where each station is allotted

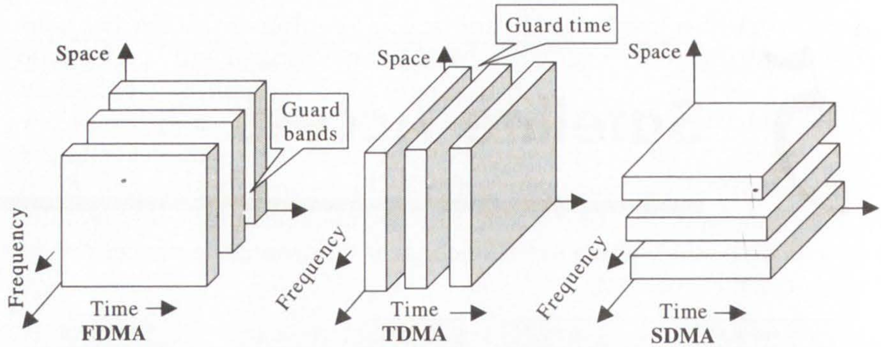


Figure 5.1 Representation of multiple access domains.

specific time slots to access the satellite, may be in the same frequency band.

SDMA. Space domain multiple access, where different antennae beams or polarization can be used to access the satellites, resulting in frequency re-use.

CDMA. Code domain multiple access, where each station transmits on specific random codes and access the satellite resource without interference.

The transponder assignment depends on many factors including percentage utilization, economy in terms of user, types of information to be relayed, etc. Three basic access assignment modes in vogue are:

1. Pre-assigned or fixed assigned multiple access (PAMA or FAMA)
2. Demand assigned multiple access (DAMA)
3. Random multiple access (RMA)

In case of pre-assigned multiple access, the transponder is leased out permanently either for lifetime of satellite or for long duration. No other earth station can use the transponder during this period. Pre-assignment can be in terms of frequency, time or code. The main disadvantage of PAMA is that it is not economical when transponder is not effectively utilized during the assignment time.

When transponders are required for short durations or occasionally, DAMA can be used. Demand assigned multiple access require short notice to use a transponder. The user earth station demands a transponder from the control station or agency. Just consider a situation when certain event has to be relayed or telecast. In such a situation the broadcasting agency can demand a transponder for one or two hours and use it. This is not only economical to the user but also the transponder efficiency is quite high.

In the case of random multiple access, any earth station at will can try to occupy a transponder and use it for short durations. RMA requires different level of control signals and special equipment. RMA becomes impossible during heavy traffic hour. RMA can be linked with a telephone exchange, where during heavy traffic hours it is difficult to get through a call. If you have a EPABX connected to many telephones with very few incoming trunk lines it is very difficult for an outside subscriber to get through the EPABX to reach you, isn't it? This is an ugly situation. RMA has the same pitfall, apart from this as packet bursts are usually associated with RMA, there are fare chances of loosing the packet due to collision (refer Figure 5.2).

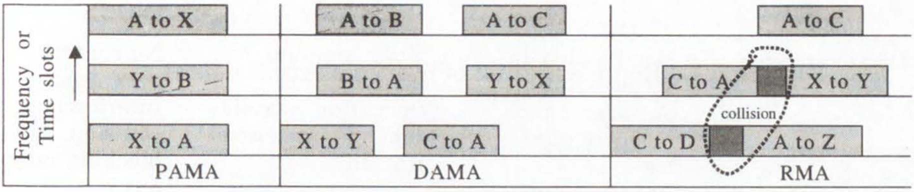


Figure 5.2 Typical assignment distribution.

A comparison of PAMA, DAMA and RMA is given in Table 5.1 and comparison of multiple access techniques is tabulated in Table 5.2.

Table 5.1 Comparison of Assignments

Comparison points	*Type of assignment* *Pre-assigned multiple access* (PAMA)	*Demand assigned multiple access* (DAMA)	*Random multiple access* (RMA)
Access permission for Earth Station	Through written document as API	Via request through network operations centre	Not required
Function of Network operations centre (NOC)	Addition and deletion of frequency or time slot assignments	Assignments to be done through administrator and/or computer and notify each earth station.	Monitor network performance to detect lockout conditions.
Period of assignment	Months or years	Duration of conversation, program relay, data burst etc.	Connectivity exists during burst or packet
Domains used	Long-term exclusive assignment in frequency, time or code	Temporary exclusive assignment in frequency, time or code	Shared (Contention) basis
Busy-hour effects	No effect as assignment is for exclusive earth station	Permission of access depends on availability of transponder during the required time and duration	Interference and collision

(Continued)

Table 5.1 Comparison of Assignments (*continued*)

Advantages	• Low earth station costs • Intermodulation and power • Back off control possible	• Dynamic reassignments of satellite resources • Good use of resources • Economical as rent to be paid for duration of usage/ assignment	• Earth station equipment is small • No requirement of; No objection certificate (NOC)
Disadvantages	• Not flexible to actual traffic patterns hence resource efficiency low Reassignment traffic not possible	• More complex earth station • Operation heavily depends on control station	• No control over users • Interference, collision and blocking may occur
Examples of assignments in use	INSAT FDMA television and radio network	INMARSAT SPACE system	ALOHA, data collection terminal systems
Comparison with terrestrial telephone	Leased lines	Dial up lines	Private communication exchange
Comparison with terrestrial radio	AM, FM, and TV	Mobile telephones	Private communication and amateur radio

Table 5.2 Comparison of Multiple Access Techniques

Domain	*Frequency FDMA*	*Time TDMA*	*Code CDMA*	*Space SDMA*
Channel separation through	Frequency spectrum	Guard time	Orthogonal codes or frequency hopping	Spatial (beams, antenna orbits or polarization)
Channels per transponder	One or more	One	Many	One or more
Channel spectrum	Non-overlapping	Sequentially used	Overlapped	Spectrum reuse
Base band building scheme	FDM	TDM	Direct PN sequence, frequency hopping	*

(*Continued*)

Table 5.2 Comparison of Multiple Access Techniques (*continued*)

Synchronization requirement	None	Timing of frame and slot	Pseudo random sequence, code or frequency	*
Channel capacity dependence	• Intermodulation (IM) products • Guard bands	• Bandwidth-to-band ratio • Guard times • TDMA frame efficiency	Self-interference	Self-interference
Number of carriers per transponder	• Depends on intermodulation (IM) products • Amplifier characteristics	Generally only one per transponder	Chip bits	*
Operating point of satellite amplifiers	Substantial backoff required in MCPT	Can operate in saturation	Similar to FDMA	*
Size of earth station	Depends on traffic, generally medium	Depends on EIRP and equipment bigger than FDMA	Small due to processing gain	*
Flexibility	Not flexible	Highly flexible	Dynamic	*
Blocking of transponder	No blocking	No blocking unless filled	Only when interference jams	Depends on traffic
Security	No security	Inbuilt in frame	Highly secure	Good for small duration of burst
Interference from other stations	High as analog	Low as digital and sequential	Least, depends on randomness	Beamwidth and cross polarization
Spectrum conservation	Moderate	Good	Poor	Best
Earth station requirements	Economical	TDMA equipment costly	Fairly economical	*
Complexity of access equipment	Simple hetrodyne type	Highly complex but automatic	Depends on application	*

(*Continued*)

Table 5.2 Comparison of Multiple Access Techniques *(Continued)*

Power amplifier	High dissipation	Burst (low duty cycle)	Depends on application (often FM-like)	*
RF bandwidth	Depends on base band	Occupies full transponder	Spread spectrum characteristics	*
Antenna size	Generally big	Medium	Depends on the application	VSAT
Uplink power	Requires control of power depending on channels	Control not required	As in FDMA	*
Typical application	Generally low-traffic analog	Selective or high-traffic analog or digital	Defence, mobile, data collection etc.	When additional capacity is required

* Denotes depends on the other associated domains, refer the text.

5.3 FREQUENCY DOMAIN MULTIPLE ACCESS (FDMA) CONCEPTS

This is sometimes also called **frequency division multiple access**. We know that the satellite bandwidth is given by

No. of transponders × Bandwidth of each transponder

Generally the satellites in C and Ku band have an overall bandwidth of 500 MHz. This bandwidth can be accessed by a number of earth stations at the same time using non-overlapping frequency spectrums. The number of simultaneous accesses depends upon the type of service. Though FDMA is an old technology it is still popular in many applications. Figure 5.3 shows the basic configuration of FDMA. Every earth station can either occupy the whole of the transponder or a part of it depending upon the usage and application. For example if the base band built is an FDM/FM occupying, say 2.5 MHz, the earth station does not require full transponder and the same transponders can be shared by other stations but on adjacent non-overlapping frequency spectrum. This is called **multiple carrier per transponder (MCPT) operation**. But some applications like television transmission require wider bandwidth and a single television earth station can occupy the whole of the transponder frequency spectrum, this is called **single carrier per transponder (SCPT).**

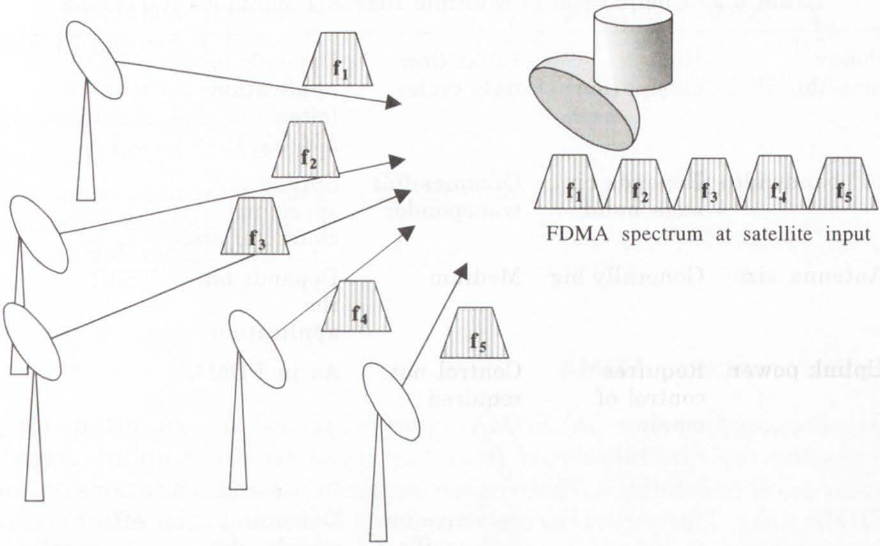


Figure 5.3 FDMA link configuration for SCPT transmission.

Types of FDMA

FDMA are defined depending upon the baseband and type of modulation. A few of these are categorized as follows:

1. FDM/FM/FDMA (mux-mod-mac) — Frequency division multiplexed, frequency modulated, frequency domain multiple access as shown in Figure 5.4.

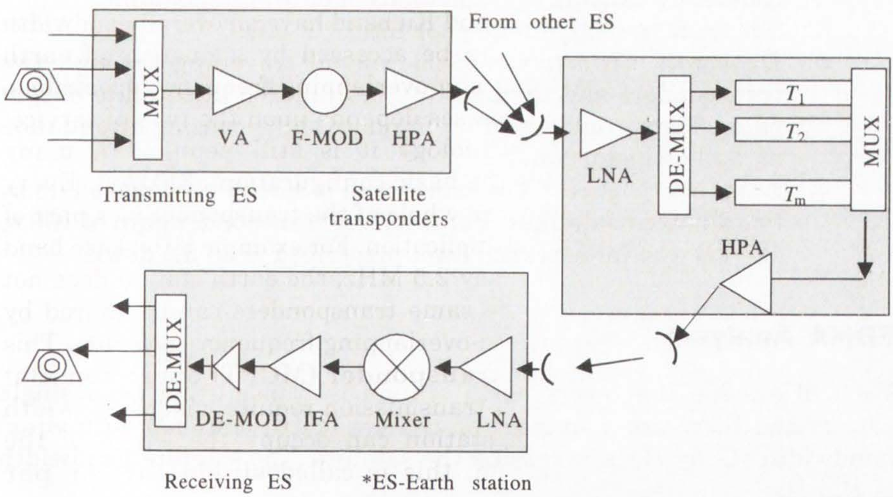


Figure 5.4 A telephone network in FDM/FM/FDMA configuration.

2.	PCM/PSK/FDMA	Pulse code modulated, phase shift keying, FDMA.
3.	PCM/TDM/PSK/FDMA	Pulse code modulated, time division multiplexed, phase shift keyed.
4.	PCM/SCPC/MAD/FDMA (SPADE)	Pulse code modulated, single channel per carrier, multiple access demand assignment.

Interference in FDMA

As discussed earlier in FDMA many carriers are simultaneously accessing the satellite. Apart from this there are other uplink signals going to other satellites. These cause impairments and limitations on the FDMA links. The important ones are listed below and their effect is also discussed.

1. Due to non-linearity in power amplifiers cross talk and intermodulation takes place particularly in the case of MCPT. The common practice is to keep a guard band of about 10% of BW of channels.
2. Co-channel and adjacent channel interference.
3. Cross-polarization interference and polarization rotation due to path irregularities during propagation as well as due to misalignment of antenna.
4. *Spurious emissions:* There is a possibility that the output filter BW may be more and emission outside the band may occur. These could be due to improper setting of modulator or converters causing over modulation or over deviation.
5. Spectrum overlap due to poor filter cut-offs.
6. *Dual path distortions:* Same signal travelling through two transponders and then getting multiplexed at satellite output stage. There could be different phase shifts causing attenuation as well as distortion.
7. *Beam interference:* The same beam is spread to be picked up by two adjacent satellites. For a typical transponder gain of 100 to 125 dB, the interference level prescribed is 33 dB down.

FDMA Analysis

We will assume that every earth station is transmitting on a single carrier and there are n number of carriers (earth stations) with equal bandwidth of, say B Hz, accessing the satellite. The satellite bandwidth is B_{sat} Hz.

Thus,

$$n = \frac{B_{sat}}{B} \tag{5.1}$$

If individual earth stations are sending uplink signals and received power due to ith station is P_{ir} where i varies from 1 to n, then total uplink power P_{ur} including noise under worst case will be

$$P_{ur} = \sum_{i=1}^{n} P_{ir} + nP_{un} \tag{5.2}$$

where P_{un} is the uplink noise.

If the gain of satellite is G_{sat}. Then

$$G_{sat} = \frac{(P_T)_{sat}}{P_{ur}} = \frac{(P_T)_{sat}}{\sum_{i=1}^{n} P_{ir} + nP_{un}} \tag{5.3}$$

where $(P_T)_{sat}$ is the transmitted satellite power.

The received power due to ith earth station by the downlink station will, therefore, be

$$P_{ir} = \alpha(P_T)_{sat} = \alpha G_{sat}\, P_{ur}$$

where α being the total link losses.

Now,

$$P_{ir} = \alpha(P_T)_{sat}\left[\frac{P_{ur}}{\sum_{i=1}^{n} P_{ir} + nP_{un}}\right] \tag{5.4}$$

Since there are n carriers travelling from earth station to satellite and vice versa, the total C/N changes as compared to single access. If we consider the ith carrier then downlink C/N will be the ratio of total downlink power of the ith carrier to the sum of noise power due to uplink and system noise itself.

$$(C/N)_{di} = \frac{P_{di}}{\alpha GP_{un} + N_{sys}\, B} \tag{5.5}$$

where $(C/N)\ di$ is the downlink ith signal.

The denominator consists of uplink noise plus the noise of satellite system with bandwidth B.

Therefore,

$$\frac{1}{(C/N)_{di}} = \frac{\alpha GP_{un}}{P_{di}} + \frac{N_{sys}\, B}{P_{di}}$$

$$= \frac{1}{(C/N)_{ui}} + \frac{1}{(C/N)_{sys}} \tag{5.6}$$

We can compute the required P_T for a satellite to produce a given CNR at the receiver. Since

$$(C/N)_{\text{sys}} = \frac{P_{di}}{N_{\text{sys}}B} = \frac{P_T\alpha}{N_{\text{sys}}B}\left(\frac{P_{ui}}{P_u}\right)$$

$$P_T = \frac{N_{\text{sys}}B}{\alpha}\left[\frac{(C/N)_{di}}{1-\left\{\dfrac{(C/N)_{di}}{(C/N)_{ui}}\right\}}\right] \qquad 5.7$$

Since P_T is proportional to bandwidth, the satellite output power should increase proportionately as the number of earth stations increase but it is not possible as the TWT has a maximum output power. With the result as the access bandwidth approaches $(B_{RF})_{\text{sat}}$, the power amplifier saturates. This necessitates either decreasing the power level P_T or limits the bandwidth within the specified level of TWT. **Hence an FDMA system has to be either power-limited or bandwidth limited in terms of number of carriers that can access the satellite.**

Back Off in Power Amplifiers

Travelling wave tube (TWT) is commonly used as power amplifiers in satellites. These TWTs in satellites use permanent magnet for focusing unlike in the case of earth stations where solenoids are used. This is obvious, as satellite cannot afford to have heavier solenoids which also requires additional electrical power. The power amplifiers invariably have non-linear transfer characteristics, it is seen that for smaller inputs the output power is proportional to input power but as input increases output does not follow input and for larger inputs, output saturates, (see Figure 5.5). In the case of single carrier the saturation operation

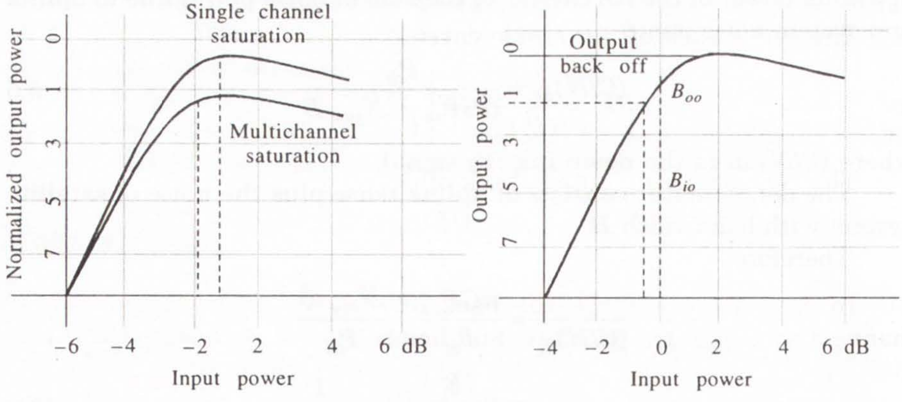


Figure 5.5 Typical TWT transfer characteristic showing back offs.

causes no distortion of carrier but limits the output power. In the case of multiple carriers the intermodulation products should be considered more seriously as number of frequency components are produced (refer Figure 5.6). The amplitude of each of these components depends upon the extent of non-linearity.

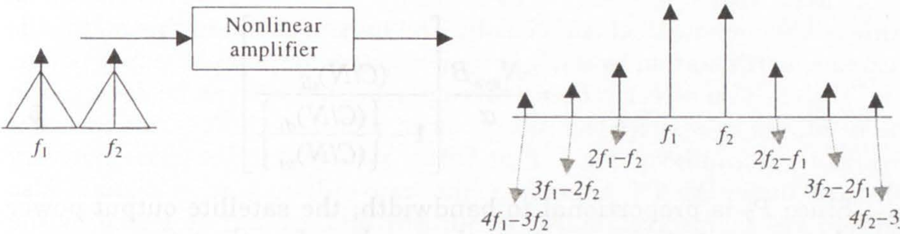


Figure 5.6 Generation of intermodulation frequencies.

The input power for which output saturates is called **input saturation power**. Generally 0 dB of input power is the power at which the output is 1 dB down the saturation (see Figure 5.5). The transfer characteristic shows that lesser the input power better is the linearity of power amplifiers. This facilitates faithful reproduction without any distortion. We also know that any active device has a gain bandwidth product. As the gain of the device increases the bandwidth decreases. This is particularly important in MCPT operations. Thus, it is customary to define back off in amplifiers. The input back off is defined as *the reduction or ratio of saturated power to the desired power to keep output well below saturation*, while the corresponding output back off is *the ratio of the peak single carrier output power to the total desired output power as a function of the total input power*. The input saturation power depends on the input voltage to take the power amplifier to saturation. For TWTA the input saturation power is given by

$$(P_i)_{\text{sat}} = \frac{\left[(v_i)_{\text{sat}}\right]^2}{2} \qquad 5.8$$

The input back off for single carrier is:

$$B_{io} = \frac{(P_i)_{\text{sat}}}{(P_c)_{\max}} = \left[\frac{(v_i)_{\text{sat}}}{(v_c)_{\max}}\right]^2$$

The corresponding output back off is given by:

$$B_{oo} = \frac{(P_o)_{\text{sat}}}{P_T} \qquad 5.9$$

In the case of FDMA the back off is dependent on number of channels accessing the satellite, and hence the output back off will be

$$B_{oo} = \frac{(P_1^2)_{\text{sat}}}{nP_n^2} \qquad 5.10$$

where n is the number of accesses.

To achieve linear operations in satellites the techniques adopted are:

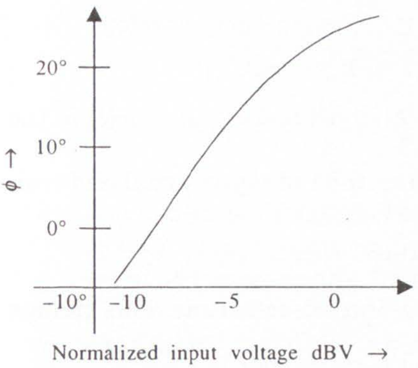
1. Linearizer
2. Limiter
3. Maximum output level selection

Linearization is achieved by reducing the input power. This can be achieved by any earth station easily. The only problem in this method is that each earth station by itself or under instruction should reduce power, if it fails to do so *power robbing* takes place. Limiters can be designed in the satellites to restrict the input power such that it does not exceed a certain level and keep the output below saturation. These are not very effective under MCPT operation and cause distortion of signal. Also limiters are themselves highly non-linear and are not preferred by the designers in commercial FDMA. When the amplifier is driven near saturation called **hard-limiting amplifier** under 2CPT the output power is reduced compared to single carrier. The power lost in individual cases is due to intermodulation component and the output power is stronger for the carrier with the larger input amplitude. That means the weaker carrier is robbed of its share of power. When the power amplifier is driven much below saturation called **soft limiting**, the input power is small (more back off) and evidently non-linearity is negligible and more number of carriers can be accommodated. The back off setting in satellite communication is very critical to get proper downlink performance. For single carriers one may go for hard limiting but for FDMA soft limiting is advisable. Table 5.3 shows the typical back off requirement in MCPT operations.

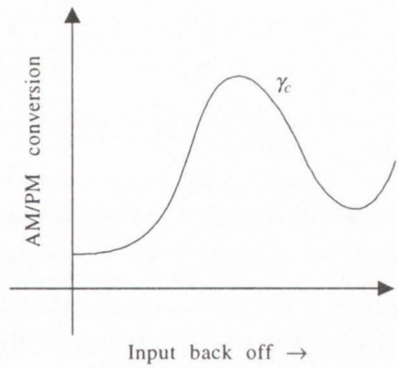
Table 5.3 Typical Back off Table

No. of carriers	*Mode*	*Ratio of peak to average power*	*Out-put back off in* dBs
1	SCPT	4	0
2	MCPT	4	3
6	MCPT	3	4.5
20	MCPT	1	5
200	MCPT	0	5

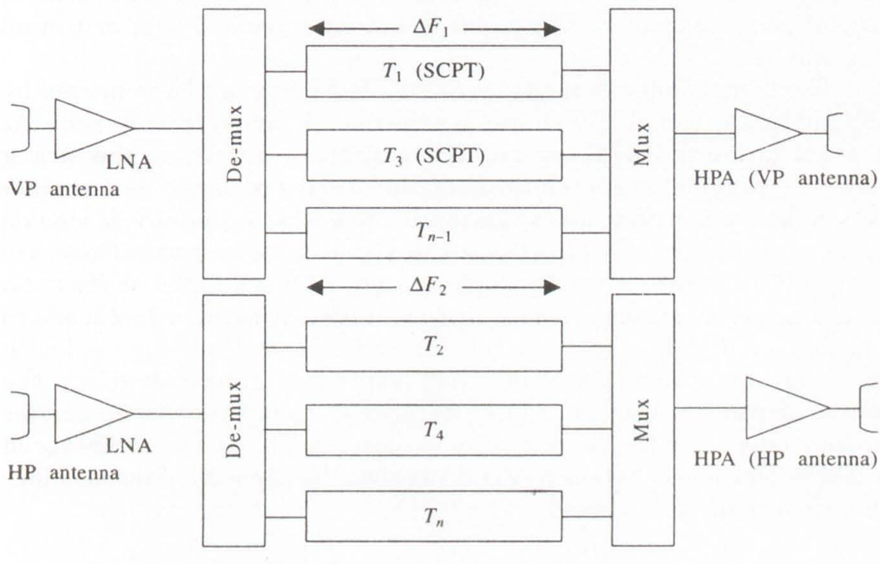
Most of the TWTA are designed for constant amplitude input carrier operations. The ideal characteristic of TWTA is that the cavity gain provides change in only amplitude called **AM/PM conversion**. But it so happens that the cavity field provides variable retardation in cavity which causes phase change. Any change in amplitude causing phase modulations and hence phase shift, leads to AM/PM conversion as shown in Figure 5.7. In angle modulation this can add up to generated noise. Also due to non-linearity this term couples to the carrier. The change in phase and AM/PM conversion is shown in Figures 5.7(a) and (b), respectively.



(a) Change in phase.



(b) AM/PM conversion



(c) Typical frequency reuse configuration.

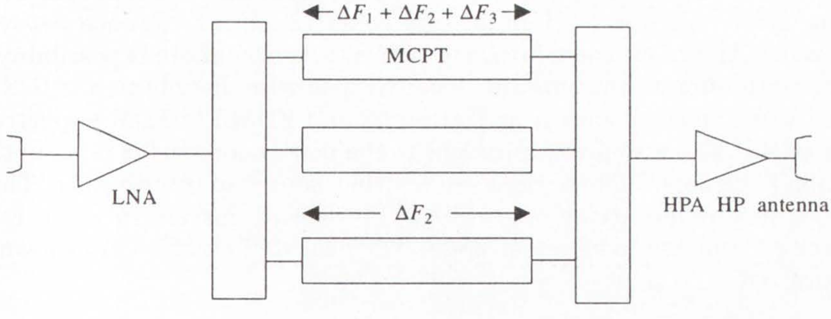


Figure 5.7 Causes of distortions in a TWT.

The waveform is represented by

$$x(t) = [V + \Delta v(t)] \cos \{\omega_c t + \theta(t) + \phi[\Delta(t)]\}$$

where $\phi[\Delta(t)]$ is called the AM/PM conversion function and $\Delta v(t)$ is the change in amplitude.

Since $\phi[\Delta(t)]$ is dependent on the amplitude of input signal and non-linearity, hence it can be related as:

$$\phi[\Delta(t)] = \eta \Delta v(t)$$

where η is called as the **AM/PM conversion co-efficient**. This change in phase is shown in Figure 5.7(a).

The value of η depends on the back off. AM/PM conversion causes additional cross talk in FDMA systems, since the envelope of this gets detected at the receiver along with the information causing cross talk. This disturbance is therefore called as **intelligible cross talk**. Due to this AM is avoided in FDMA satellite systems using TWTA or tunnel diode amplifiers.

The transponder capacity in FDM/FM/FDMA can be improved by companding the signal. This improves the overall signal to noise ratio. At the transmitter the weak signals are amplified more than the strong signal, for example, in speech transmission during pauses if gain is more than at the transmitter, as expansion is done, the level of these signals reduce to a great extent improving the signal to noise ratio. These are called **syllabic companders**. Compression ratio is defined as *the ratio of input power to output power of a compander*. A ratio of 1 : 2 leads to an expansion of half at the receiver. This scheme is effectively used with single side band (SSB) multiplexing leading to almost doubling the channel capacity. Another aspect of SSB is that there is no carrier transmitted so that the carrier noise is reduced. The major advantage of SSB/AM/FDMA over FDM/FM/FDMA is that the capacity of transponder is better in multiple access.

Overall Carrier to Noise Ratio in FDMA

As has been discussed earlier the uplink in FDMA has number of carriers being fed to the same antenna, this could cause interference between channels. Also due to non-linearity of active devices there is possibility of intermodulation in the satellite. Typical spectrum distribution of INSAT and INTELSAT are shown in Figure 3.3 and FDM/FM/FDMA spectrum flow in Figure 5.9 to give an insight to the discussions being done in this section. The downlink carriers are another source of interference. Thus, unlike in single carrier operations the overall carrier to noise ratio decreases and has to be re-estimated. Typical route traffics are shown in Figure 5.8.

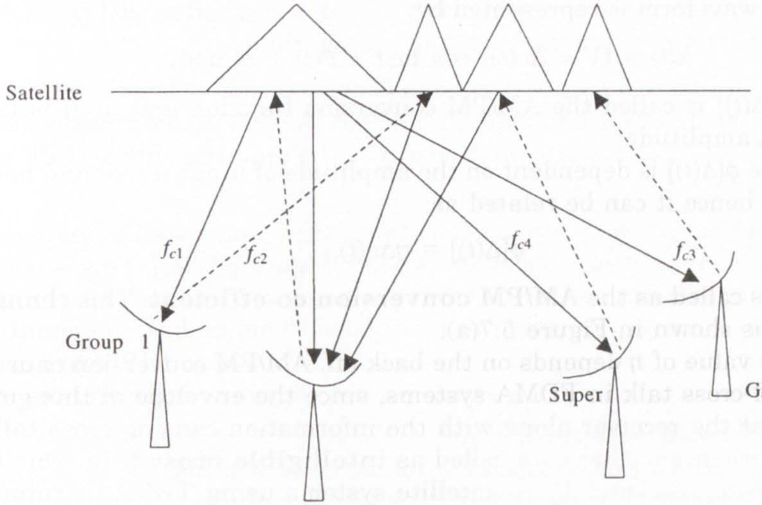


Figure 5.8 Typical route traffics in FDMA.

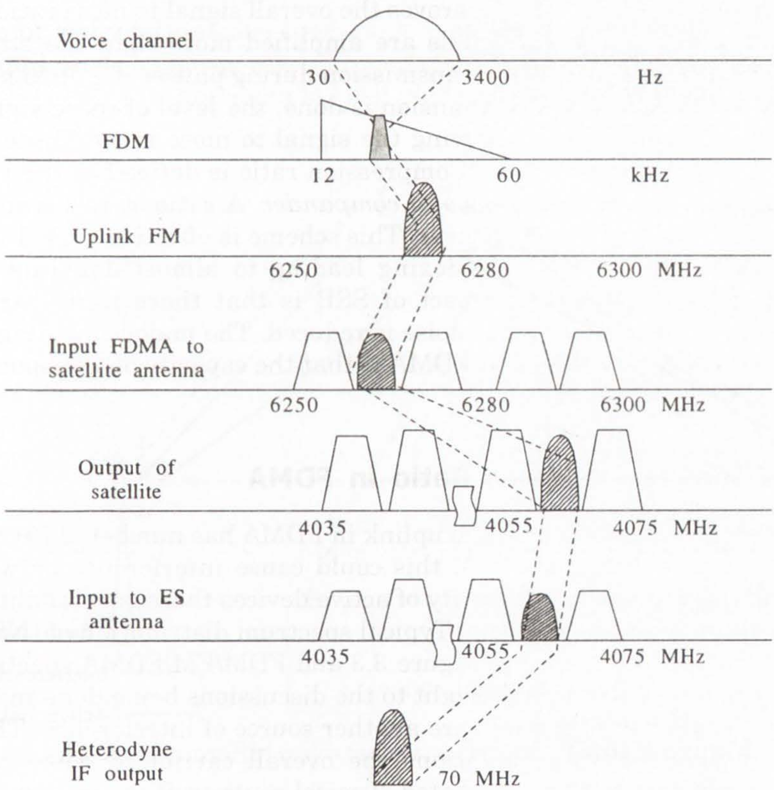


Figure 5.9 FDM/FM/FDMA spectrum flow.

In order to make these calculations for a link influenced by FDMA impairments, we will make following assumptions:

1. Only one link out of n links is considered.
2. The bandwidth is same throughout the link under consideration.
3. The input power is limited as per the requirements by BPF and active device.

In addition there are several terrestrial and satellite networks simultaneously transmitting and receiving [Figure 5.10(a)]. This is bound to create interference as long as there are radiations and pickups through side lobes and sometimes due to main lobes. This makes an communication engineer not only to arrive at CNR but also CIR (carrier to interference ratio). The ITU has categorised the major interferences into

1. Terrestrial to earth station
2. Earth station to satellite (uplink and downlink)
3. Terrestrial to satellite (uplink and downlink)
4. Earth station to earth station
5. Satellite to satellite

The interference levels have to be kept substantially low to avoid deterioration in SNR during reception. ITU has specified these limits to keep the signal above the threshold level of detection.

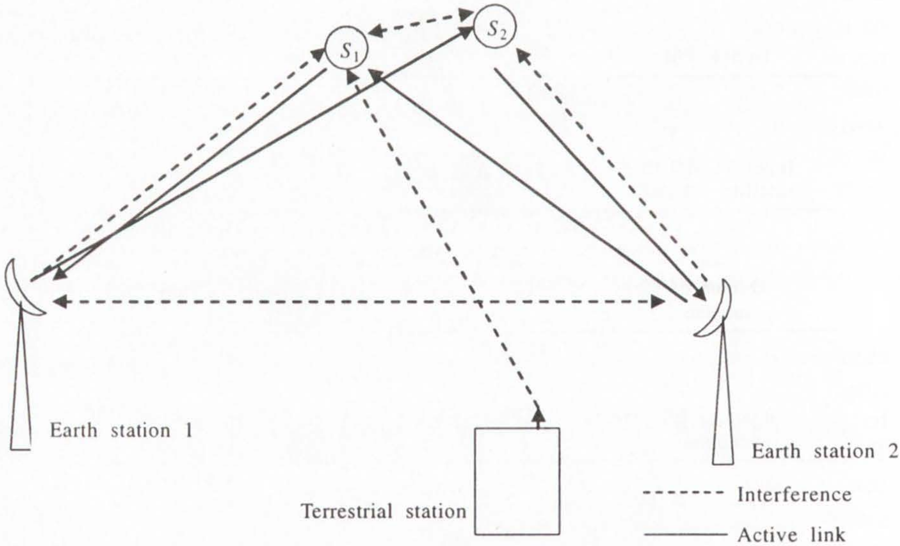


Figure 5.10(a) Interference between different networks.

Interference between earth stations and satellites. Though in actual scenario a number of signals may be received by an receiving antenna (at satellite or earth station), it is not possible to exactly arrive at any figures because of:

1. Variations in fading
2. Positional variations
3. Instability in number of interfering signals
4. Location of antennas on the footprints of the down link

In order to arrive at the total CNR therefore single entry point interference is calculated, that is a single interfering wave being received at the receiving antenna. Later these can be summed up in inverse ratio to get the total carrier to interference ratio. This leads to increasing the noise content in the total signal.

During the calculation of interference, the half power point or the 3 dB point of the main lobe is considered. If the interference components are $i_1(t)$, $i_2(t)$ . . ., $i_n(t)$ in the uplink within the satellite bandwidth then the total interference is the sum of all these interferences, i.e.

$$\sum_{K=1}^{n} i_K(t)$$

The total carrier to interference power ratio in one path is therefore given by

$$\left[\frac{C}{I}\right]=\left[\sum_{K=1}^{n}\left(\frac{C}{I}\right)_K^{-1}\right]^{-1} \tag{5.11}$$

The carrier power in the downlink at the EOC point of footprint is given by

$$[C] = [EIRP]_{S_1} - 3 + [G_{ANT}]_m - [\alpha_p] \tag{5.12}$$

where $[G_{ANT}]_m$ is the on-axis main lobe gain.

The interference power depends on the polarization and off-axis gain of the receiving antenna, hence

$$[I] = [EIRP]_{S_2} - 3 + [G_{ANT}(\theta)] - [\alpha_p] - [Y] \tag{5.13}$$

Therefore,

$$\left[\frac{C}{I}\right]=[C]-[I]=[EIRP]_{S_1}-[EIRP]_{S_2}+[G_{ANT}]_m-[G_{ANT}(\theta)]+[Y]$$

$$=\Delta[E]+\Delta[G_{ANT}]+[Y]$$

A similar equation will be for uplink and downlink, hence total

$$\frac{C}{I}=\left[\left(\frac{C}{I}\right)_u^{-1}+\left(\frac{C}{I}\right)_d^{-1}\right]^{-1} \tag{5.14}$$

When two satellites are separated by a distance d_x, the interference from the adjacent satellite onto the earth station will depend on slant ranges and the angular separation seen by the earth station between two satellites. From Figure 5.10(b), the separation distance

$$d_x \propto ds_1 - ds_2$$

$$d_x^2 = ds_1^2 + ds_2^2 - 2ds_1 ds_2 \cos\theta \qquad 5.15$$

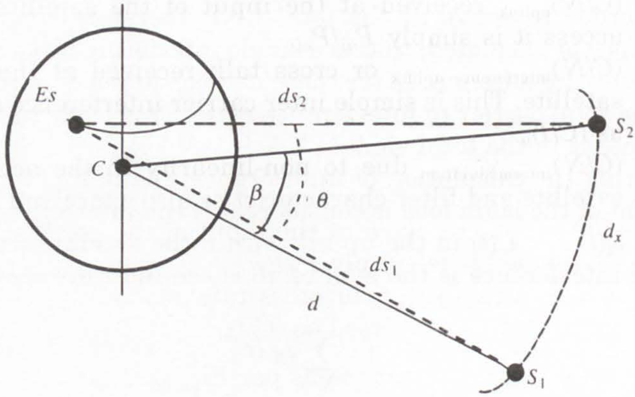


Figure 5.10(b) Interference due to sateliites.

In terms of the separation angle β at the centre of earth and the radius of orbit d

$$d_x = 2d^2 - 2d^2 \cos\beta$$

$$= 2d^2(1 - \cos\beta) \qquad 5.16$$

Hence

$$ds_1^2 + ds_2^2 - 2ds_1 ds_2 \cos\theta = 2d^2(1 - \cos\beta)$$

or

$$-\cos\theta = \frac{2d^2(1-\cos\beta) - ds_1^2 - ds_2^2}{2ds_1 ds_2}$$

Therefore the satellite separation

$$\theta = \cos^{-1}\left[\frac{ds_1^2 + ds_2^2 - 2d^2(1-\cos\beta)}{2ds_1 ds_2}\right] \qquad 5.17$$

The off-axis gain depends on the satellite separation angle and

$$G(\theta) = 29 - 25 \log \theta \text{ for } 1° \geq \theta \geq 7°$$

The interference between the terrestrial and satellite earth stations is mainly in 6/4 GHz links as over the years these carrier were allocated to terrestrial links. The interference depends on the side lobes, the elevation angle and the EIRP dissipated by the terrestrial station antenna. Fortunately, most of the terrestrial networks have narrower bandwidth compared to satellite links and hence the interferences can be limited as these are specified in terms of dBW/Hz. Typically, the interference should be 25 dB down compared to the actual link power. That means if a satellite has transmitted 40 dBW, the overall losses are about 200 dB. The net received power will be −160dB, therefore the interference power from terrestrial station should be below −185 dBW.

The different CNRs coming into picture are:

1. $(C/N)_{\text{uplink}}$ received at the input of the satellite. For the *i*th access it is simply P_{ui}/P_{ni}.
2. $(C/N)_{\text{interference uplink}}$ or cross talk received at the input of the satellite. This is simple inter carrier interference and expressed as $(C/I)_u$.
3. $(C/N)_{\text{intermodulation}}$ due to non-linearity in the active devices of satellite and filter characteristics also expressed as $(C/IM)_{\text{sat}}$.
4. $(C/N)_{\text{downlink}}$ received at the input of the earth station. For the *i*th carrier it is simply $P_{di}/(P_n + N_{\text{osys}})$.
5. $(C/N)_{\text{interference downlink}}$ or cross talk received at the input of the earth station expressed as $(C/I)_d$.

The total link performance as per Eq. (5.6) is:

$$\frac{1}{\left(\frac{C}{N+I}\right)_{\text{total}}} = \frac{1}{\left(\frac{C}{N}\right)_u} + \frac{1}{\left(\frac{C}{I}\right)_u} + \frac{1}{\left(\frac{C}{IM}\right)_{\text{sat}}} + \frac{1}{\left(\frac{C}{N}\right)_d} + \frac{1}{\left(\frac{C}{I}\right)_d} \qquad 5.18$$

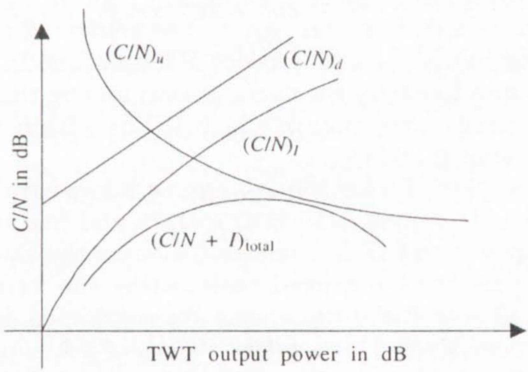


Figure 5.10(c) Optimum power requirement of TWT.

The interference in satellite communication could be system interference or external interference. In the link design we consider interference caused due to coupling of orthogonally polarized carriers, interference due to signals to and from other satellites, terrestrial link interference and satellite off-axis. Consider two adjacent geostationary satellites whose beams overlap. This yields the interference power as sum of the two reducing the over all *C/I* value if the signal of a third satellite also interferes the interference power adds up reducing the *C*/*I* further. In order to remove the uncertainties it is necessary to have proper frequency coordination and antenna beam selection. Intermodulation noise occurs due to both amplitude and/or phase non-linearity. The TWTA output amplitude equations can be represented by the following equation:

$$V_o = a_1 v_i + a_3 v_i^2 \qquad 5.19$$

where v_i is the input voltage consisting of m frequency components, such that

$$v_i = \sum_{i=1}^{m} A \cos [\omega_i t + \theta_i (t)]$$

Substituting v_i in Eq. (5.9) yields harmonic components out of which $2\omega_i - \omega_{i+1}$, $\omega_i + \omega_{i+1} - \omega_{i+2}$ are very dominant frequency components. It is observed that these are third order intermodulation interferences. The amplitude of $\omega_i + \omega_{i+1} - \omega_{i+2}$ is 3 dB higher than $2\omega_i - \omega_{i+1}$. It is seen that the total multi-carrier power $mP_m^2/2$ is always smaller than the total single carrier output power $P_1^2/2$, because power is lost in intermodulation product terms. Another interesting phenomena that happens due to nonlinearity is that the output power is not proportional to input power but stronger inputs give larger output levels while weaker inputs lower output level causing power robbing. Since in this phenomena stronger carriers suppress the weaker hence this is also sometimes called as **carrier suppression**. Another important point to be noted is that the intermodulation effect is maximum at the centre of the multi-carrier R.F. spectra and hence the interference is maximum. In case of multiple carriers due to non-linearity the carriers beat among themselves causing additional frequency components which if lies within the transponder spectrum will cause interference.

The suppression of weak signals can be taken care of by **channelization**. This avoids suppression in downlink and has sufficiently equal distribution of power in FDMA systems. Dividing the satellite bandwidth into smaller frequency bands and reallocating the frequencies achieve channelization. These R.F. frequencies are regrouped depending on the comparative power level. There are two ways of achieving this as shown in Figures 5.11(a) and 5.11(b). By doing so the gains of the amplifiers can be controlled easily depending on the sum power of each group. The scheme uses number of BPF, separating the channels, down converting, summing and finally power amplifying.

Channelization is very helpful in satellite switched systems.

FDMA Link Design Equations

The design equations follow the same logic used in Chapter 4, except that depending on the accesses the backoffs have to be provided. The uplink

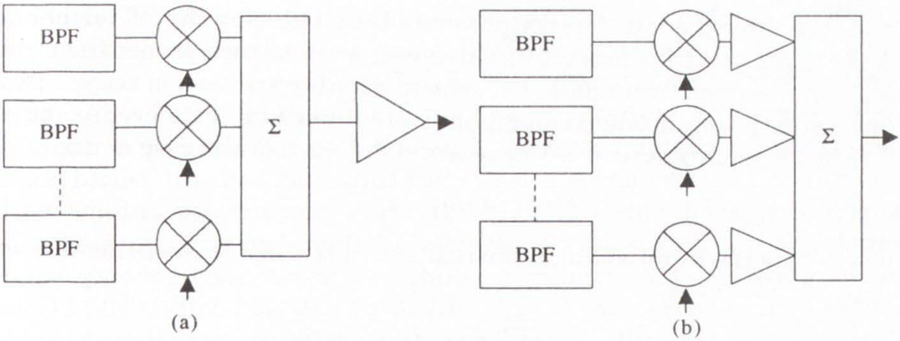


Figure 5.11 Methods of channelization.

carrier to noise ratio for any satellite is therefore represented by the illumination (field strength received) of the receiving antenna of the satellite.

$$\left[\frac{C}{N}\right]_u = [W]_{\text{sat}} + \left[\frac{C}{N}\right]_{\text{sat}} - [B_{OI}] - [k] - 10 \log B_{\text{sat}} + [G]_{\text{satant}} \qquad 5.20$$

where W_{sat} is the power received by the satellite antenna in dBW/m^2, B_{OI} is the single carrier transponder input backoff, k is the Boltzmann's constant (228.6 dB/°K/Hz) and G_{satant} is the gain of satellite antenna.

Similarly downlink C/N will be

$$\left[\frac{C}{N}\right]_D = [W]_{ES} + \left[\frac{G}{T}\right]_{ES} - [B]_{OO} - [k] - 10 \log B_{if} + [G]_{\text{ESANT}} \qquad 5.21$$

The bandwidth B_{if} can be calculated using Carson's rule:

$$B_{if} = 2(\Delta f_u.l.g + f_{\max})$$

where $f_{\max}$ is the top FDMA baseband frequency, G_{ESANT} is the gain of earth station antenna.

The designer should be able to decide the optimum signal to noise ratio requirement for given number of channels and tradeoff between carrier to noise ratio and transponder access capacity.

$$\left[\frac{S}{N}\right]_T = \left[\frac{C}{N+I}\right]_T + \left[\frac{B}{\Delta f_{\text{channel}}}\right] + 20 \log \left(\frac{\Delta f_{\text{tone}}}{f_{\max}}\right) + [P] + [W] \qquad 5.22$$

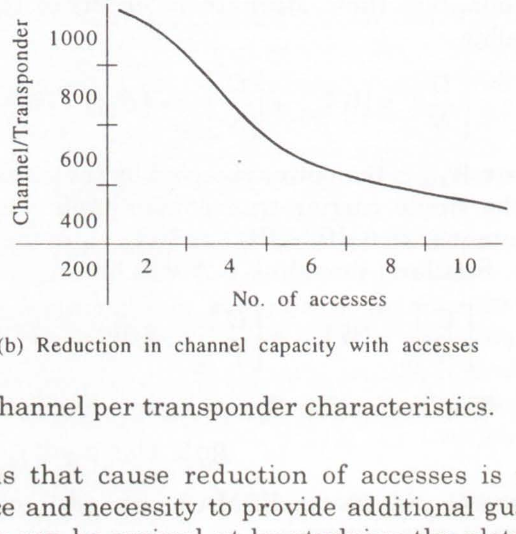
The definitions of each of the terms in the above equations are already discussed in Chapter 4. The FDMA simplex channel capacity of analog signals can be estimated from required carrier to noise density C/N_o and the output back off required.

$$m = [EIRP]_{\text{sat}} + \left[\frac{G}{T}\right]_{ES} - [B_{oo}] - [\alpha] - [k] + [VA] - \left[\frac{C}{N_o}\right] - [M] \qquad 5.23$$

This equation takes into account the voice activity of telephone network. In a telephone network, there is a silence in between the conversation and hence only 40% of the time the channel is active. This reduces power requirement and intermodulation interference, thus increasing the channel capacity. This is not true in the case of digitally interpolated voice as modems are active throughout the call period and a tone always exist thus *VA* is zero. In order that the access links work satisfactorily it is necessary to consider additional margin indicated as *M* in the equation. This margin depends on the carrier frequency band. Recommended values for *M* are 1.5 dB at 6/4 GHz and 3 dB at 12/14 GHz. As discussed earlier the output back off depends on number of channels per transponders. Typical values are shown in Figure 5.12(a) and number of accesses vs channels per transponder is plotted in Figure 5.12(b) for a typical case.

Channels/ Transponder	B_{oo} (dB)
SCPT	0
2CPT	3
6CPT	'.5
200CPT	5

(a) Back off requirement



(b) Reduction in channel capacity with accesses

Figure 5.12 FDMA channel per transponder characteristics.

The two main reasons that cause reduction of accesses is the intermodulation interference and necessity to provide additional guard bands. The cross talk factor can be arrived at by studying the plots of TWT as shown in Figure 5.7, which gives the AM/PM conversion and non-linearity such that

$$XT_R = 20 \log \left[\frac{\frac{180}{\pi}}{(\gamma_c S f_{\max})} \left(\frac{\Delta f}{f_{\text{int}}} \right) \left(\frac{P_t}{P_{\text{int}}} \right) \right] \qquad 5.24$$

where γ_c is AM/PM conversion coefficient, S is the linearity gain slope (P_o/P_i), Δf is the peak deviation of wanted channel carrier, and P_t is the power of wanted RF signal.

P_{int} is the power of interfering signal that creates cross talk and f_{int} is the interfering carrier frequency.

5.4 TIME DOMAIN MULTIPLE ACCESS (TDMA) CONCEPTS

Time domain multiple access shares the transponder resources at different time slots. Thus, each earth station transmits bursts of data orthogonally during assigned time slots (see Figure 5.13). Generally

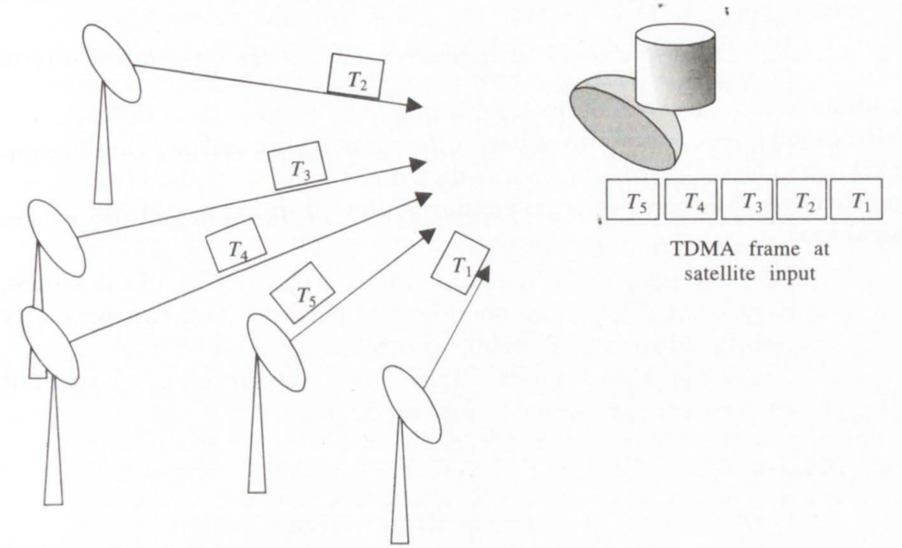


Figure 5.13 TDMA link configuration for SCPT transmission.

TDMA is more often a packet burst transmission technique rather than analog. It is a digital compatible system for telecommunication, fiber optics, digital video, packet communication and computer load sharing. It is essentially a single carrier per transponder technique but in some cases MCPT could also be adopted. TDMA is a sequential access system. In TDMA each station is assigned an exclusive non-overlapping time slot during which it transmits its accumulated traffic digital bits (store and forward). The control office depending upon the traffic priority and demand assigns the duration. Many of the concepts of TDM can be directly applied to TDMA though they serve different purposes.

After the station sends its burst, a guard time is allotted. Guard time avoids burst collision and hence loss of information. The guard time depends on:

1. Delays in the equipment
2. Synchronization time required
3. Variation in slant range from earth stations to satellite and vice versa.

Comparison of TDMA and FDMA

Advantages

1. Bit capacity independent of the number of accesses.
2. Transponder power amplifier can always be operated in saturation mode, thus increasing the capacity of multiple accesses.
3. The preamplifier of transponder can be used as limiter due to saturation operation.
4. Duty cycle of earth station is low.
5. Digital techniques like digital speech interpolation, satellite on-board switching, etc. can be used.
6. More flexible as use of high-speed logic circuits and processors handle high data rates.
7. Economical as it can handle more data irrespective of the source, easy to multiplex, independent of distance and can be easily interfaced with terrestrial services.
8. Can tolerate higher carrier to interference. Excellent performance at *C/I* of as low as 30 dB.

Disadvantages

1. Peak power of amplifier is always large.
2. TDMA is a more complex system and the earth station requires ADC, clock recovery, synchronization, burst control and data processing before transmission.
3. In case of MCPT "Back off" is required to reduce intersymbol interference.
4. TDMA uses high-speed PSK/FSK circuits.

Types of TDMA

1. Preassigned, in which every station is given specific time slots. Due to this no control and addressing are necessary, resulting in high frame efficiency.
2. Demand assigned, in which time slots are allotted under request from the control station. This method is economical but the frame efficiency is poor and earth station complexity is more as addressing, control and perfect synchronization is required.
3. Limited preassigned with demand overflow, is another technique in which busy hours are handled by demand.
4. Space domain satellite switched TDMA (SDMA/SS/TDMA) is another technique by which the space segment can be used more effectively.

SPADE is a combination of FDMA and TDMA.

Sequence of Operation in TDMA

Typically any TDMA traffic undergoes the following steps before the burst is actually transferred:

1. On request from the earth station the central control station allots an idle time. In many cases a 'Tag' code is also assigned. The tag is used before each burst is sent for identification during forward and return path. The network control station should be in touch with all the traffic stations at all times.
2. The sending station sends a request to the destination earth station and waits for the return acknowledgement. The destination picks up the time slot channel and sends return signal.
3. The transmit station must establish a transmit frame timing. During this process local supervisory information like local area code, central office code, line number, routing, voice recognition, password, special billing information, etc. are simultaneously processed.
4. The processed information is stored and waits for the communication to be set up. From the frame timing the transmit burst timing is calculated, so that the traffic burst is received at the satellite at the correct slot without any overlap.
5. Once the burst has been successfully completed the control centre gets the information about idling of time slot.

For this process to take place successfully the TDMA frame has two almost identical headers, one the frame reference and the other the burst preamble. A typical frame structure is shown in Figure 5.14 and the

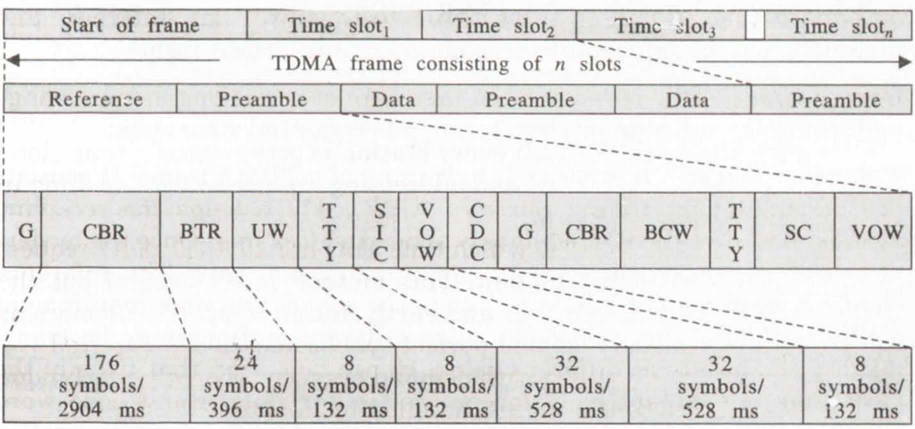


Figure 5.14 Typical TDMA frame structure.

signal flow in Figure 5.15. If we consider the TDMA frame, it is seen that each TDMA frame may consist of n time slots allotted to n number of stations. Each time slot starts with a preamble and may end with a post-

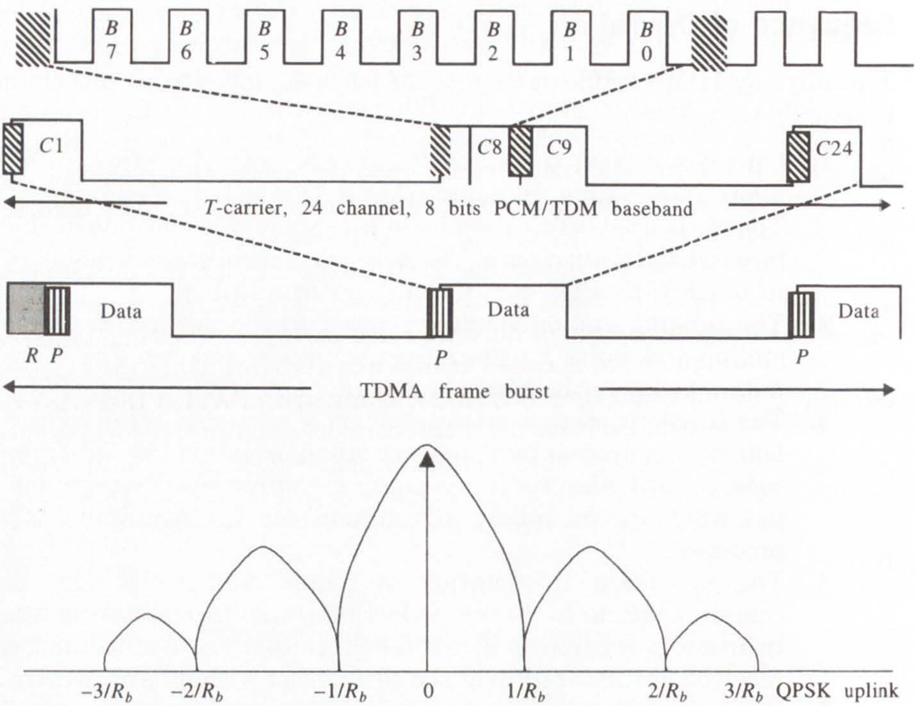


Figure 5.15 PCM/TDM/TDMA signal transmission flow.

amble. The data packet being sandwitched between the two. It just means that every station transmits a burst consisting of preamble, data and post-amble. In addition the TDMA frame starts with a reference header and guard time. All these three namely the guard time, reference and preamble are the important components of any TDMA frame.

Guard time. This is required to take care of variations in slant range and avoid any collision or overlapping of sequential time slots.

Reference burst. It marks the beginning of a TDMA frame. It consists of Carrier and bit timing recovery (CBR), which helps the receiving modem to receive the unmodulated carrier and lock to it. Once the modem is locked it can synchronize to the transmission rate. The reference should have sufficient pulses to satisfy the acquisition time requirement of the modems. This is needed since different stations may be transmitting the bursts at different rates. Hence it is seen that usually the CBR time is comparatively larger than other slots. Burst code word (BCW) is unique of a reference input carrier and hence sometimes called **unique word (UW)**. It also represents station identification code in many cases. The loss of or non-recognition of UW causes loss of burst. Also it is possible that due to bit error a particular UW not meant for a station may be detected, this is called **false alarm**. To avoid this, unique word are divided into sub-words UW_0, UW_1, UW_2, etc. depending on the type of modulation and detection. Additionally Forward error correction (FEC) encoding may be used, particularly in case of noisy links. These codes are detected using shift registers which compare the incoming stream of UW with the stored one. Whenever these matche, the output goes high and charges a capacitor. The threshold detector decides whether to accept the burst or not depending upon the accumulated charge.

In some cases redundant reference burst (one + one) is used for reliable operation.

In order to have a successful TDMA transmission the detection of unique word is important. This is achieved using search mode in the receiver by a combination of hardware and software. The time taken to lock to the unique word is called **frame acquisition**. Once the stations are in communication they remain synchronized provided there are no changes in timings. Unfortunately this cannot be maintained in satellite communication due to satellite motion or drift resulting in a necessity of continuous frame synchronization. In many cases the acquisition becomes difficult in which case algorithms for assisted frame acquisition have to be employed.

Preamble. Preamble is the initial portion of a traffic burst which carries information similar to that carried in the reference burst. The duration of reference and preambles are also same. Same UW can be used both for reference and preamble, as the detectors for both are the same. To distinguish between the start of frame and start of burst the UW pattern is inverted. Additionally it also has information about Service channel (SC) indicating the network protocol and alarm messages, order wire TTY and VOW for the stations to communicate. The last information is the Coordination control and delay channel (CDC) that takes care of the burst positions of individual stations in the network. Codes indicating delays in earth station burst with respect to satellite clock.

Post-amble. Some phase detectors require recovery time called **decoder guarding** and hence post-amble slot has to be provided.

Burst Synchronization

In satellite communication it is necessary to keep track of the range of the satellite and transmit the bursts accordingly so that the bursts reach the satellite at correct allotted time slot. The reference control station administers control and calculates exact burst position. There are three methods used depending upon the satellite orbit:

1. Open loop
2. Loop back
3. Cooperative synchronization

When the satellite position is relatively stable and constant with respect to earth stations, open loop synchronization can be used in the case of geostationary satellites. But when the satellites are in the inclined plane it is necessary to track and synchronize. In mobile applications it is more complicated to synchronize as both satellite and transreceivers are moving and cooperative synchronization is necessary. We know that there is a time delay $t_d = 3.83 \times d_s$ μs for a signal to reach the satellite. As the slant range changes, this time delay varies by hundreds of microseconds. If this happens the throughput of TDMA bursts will be very poor. It is, therefore, necessary to do range measurement for which markers are required from the satellite. Satellite beacon generates markers for this purpose and ranging of satellite can be done.

Open loop. The transmission in a TDMA network has to be synchronized so that traffic bursts appear in their allotted time slots. Let us assume that two stations A and B are transmitting TDMA packets such that station A is supposed to transmit starting of reference marker after T_A and station B after T_B as shown in Figure 5.16. But that is not

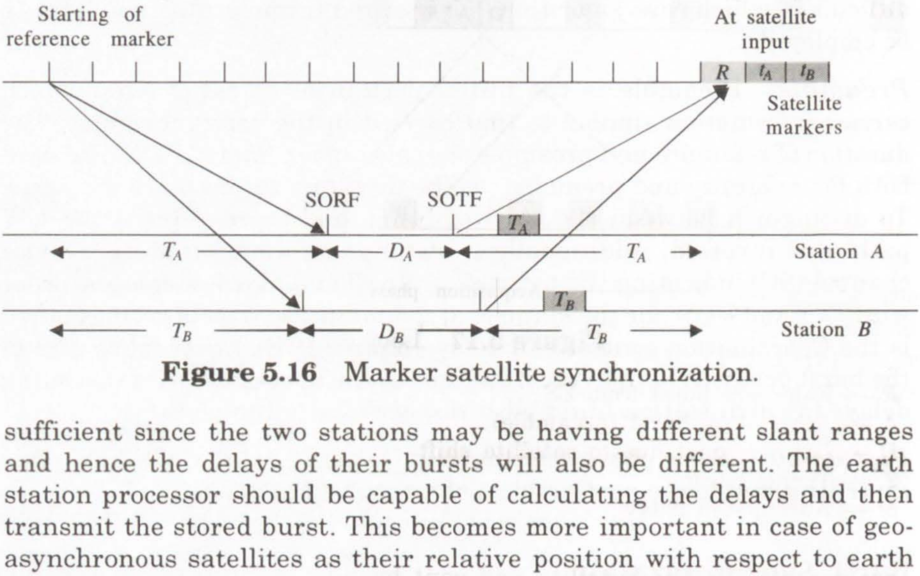


Figure 5.16 Marker satellite synchronization.

sufficient since the two stations may be having different slant ranges and hence the delays of their bursts will also be different. The earth station processor should be capable of calculating the delays and then transmit the stored burst. This becomes more important in case of geo-asynchronous satellites as their relative position with respect to earth stations changes.

In the case of closed feedback loop system the satellite emits clock pulses/codes at equal interval as reference, which are received by every earth station. The delay in receiving of the satellite bursts SORF (start of receive frame) and the earth stations own burst SOTF (start of transmit frame) is calculated for each station. In the figure these delays are shown as D_A and D_B for stations A and B having different slant ranges. D_A and D_B should be chosen such that at satellite both should coincide so that burst of A and B do not overlap. The total time between transmit and receive from satellite is equal to C ms and it should be integer number of TDMA frame period. Such that

$$2T_A + D_A = C$$
$$2T_B + D_B = C$$

In general

$$2T_i + D_i = C$$

It would vary if the position of satellite varies but due to station keeping this is not allowed above ±0.55 ms. Hence D_i has to be modified after sometime period, about 1 to 1.0426 s, i.e after every 510 to 515 frames. In Figure 5.13 the traffic supposed to be received by satellite after reference is shown.

Loop back. Loop back basically is a technique by which a station can see its own timing burst that is retransmitted from the satellite. This way it can calculate the delays involved and place its TDMA burst at the allotted time slot. The satellite loop back control is a closed loop synchronizing technique. This technique has two phases of operation, the first phase is the acquisition phase and the second phase is synchronization phase as shown in Figure 5.17. It works like a PLL. The reference bursts

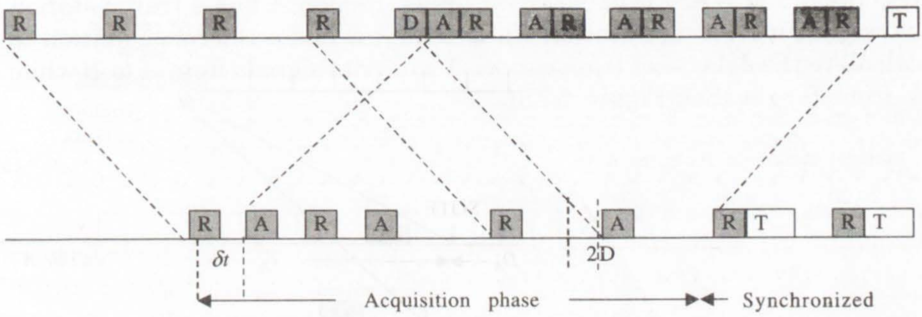


Figure 5.17 Loop back.

R — Reference burst from ES
A — Acquisition burst (preamble)
D — Displacement due to satellite shift
T — Traffic burst
δt — Anticipated delay

are received by the satellite and sent back establishing a local timing reference. The station then sends acquisition burst after a small time. The initial delay between reference and acquisition burst δt is calculated on the basis of slant range or PN sequence using correlated modulator. This acquisition burst reaches the satellite and is compared with the reference timing: the difference between the two yields the error e, which is corrected by the earth station and acquisition burst is retransmitted. This continues till the reference and acquisition burst's error is nullified. The acquisition cycle is completed at this juncture and synchronization is achieved. The traffic burst is then replaced with the acquisition burst and is transmitted. The acquisition burst is just the preamble of traffic burst. After the acquisition is completed both preamble and data are transmitted to keep the frame in synchronization. The power requirement during acquisition is almost 20 dB below that required during traffic burst transmission.

The position of the burst in TDMA frame is most important to avoid overlap of time slot and full transmission of burst from satellite back to earth. This becomes more difficult to achieve, when receive and transmit stations use different beams or transponders. This is because the footprints are different and loop back cannot be applied. In such cases co-operative control is very useful.

Cooperative control. This requires exact ranging of the satellite from both the stations, calculating the error in burst time and providing the correction with the help of reference stations. This type of synchronization is applicable when two stations are not in line of sight or when they lie in different footprints. Hence these can be used in multibeam systems. The range determination is done either by delay calculation by reference station or by double hops technique. Let us assume that the two footprint regions A and B are isolated cover areas. Region A has a traffic station as well as a reference station while region B has a reference station to calculate the delay. Let transponder X caters to signals from A to B while Y from B to A (See Figure 5.18).

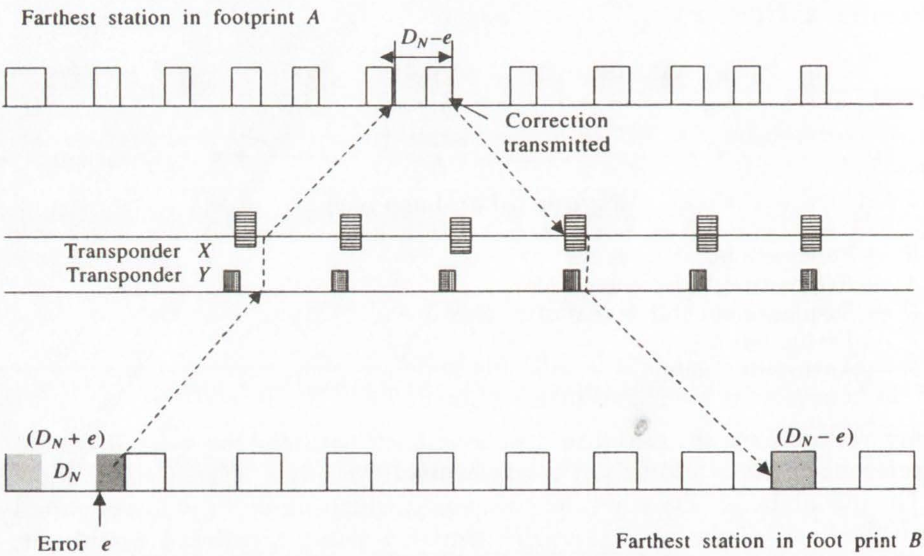


Figure 5.18 Cooperative control.

The delay D_N is transmitted by the reference station from the range calculated. SOTF is calculated from this delay and is transmitted by B. The traffic station delays its burst by D_N and transmits. The station B if misses the burst estimates the error e and transmits to reference station A via transponder Y. The station A corrects this error by adding or subtracting the estimated error e and transmits the burst at $(D_N - e)$.

This technique has lot of drawbacks as the accuracy depends on the co-operating station, reference station, motion of satellite and estimation. Many a times to get proper reference burst alignment another station which can see the burst of both A and B can be used. This calculates the difference of occurrence of bursts from both A and B and sends correction to both A and B.

Transponder hopping. It is a multiple access technique under TDMA in which an earth station can transmit to more than one transponder or receive from more than one transponder or both. This is achieved by sending bursts of the same frame on different frequencies or polarization (also discussed in the next section on SDMA). This is helpful in case of traffic management flexibility. This requires a common reference time burst for all transponders. In this case secondary reference burst sent by secondary reference station is separated from primary reference burst sent by main or primary reference station at the transponder and a fixed off set is generated. This helps in patting all the transponders in synchronization. Many a times separate transponder with processor is used for this purpose.

Frame Efficiency

Out of the total frame time the actual traffic time is much less or in terms of bits. Guard time, reference, preamble and post-amble is called the **overheads** of a TDMA frame while the data packet burst is the payload. This necessitates in defining frame efficiency which is the ratio of payload bits to the total bits. Sometimes it is also defined in terms of period as payload time to the total TDMA frame period.

$$\text{Frame efficiency } \eta_f = \frac{\text{Traffic bits}}{\text{Total bits}}$$

Since many times it is difficult to define number of bits flowing as data because the overhead bits are fixed. Thus the frame efficiency can be rewritten as:

$$\eta_f = 1 - \frac{\text{Overhead bits}}{\text{Total bits}} \qquad 5.25$$

Another term commonly defined by certain designers is the preamble efficiency.

$$\text{Preamble efficiency } \eta_p = \frac{\text{Number of preamble}}{\text{Total preamble slots}} \qquad 5.26$$

From η it is possible to calculate the number of voice channels in a frame.

Since TDMA is a store and forward technique. The received data gets into the memory at a certain rate R_b while the stored data is transmitted at a rate depending on many factors like number of bits stored, number of overheads, frame efficiency and allotted time slot for transmission. If the total incoming traffic bit rate is nR_b where n is number of channels and the traffic bit rate of frame is $\eta_f R_T$ such that

$$nR_b = \eta_f R_T$$

$$n = \frac{\eta_f R_T}{R_b} \tag{5.27}$$

where R_T is transmission rate.

It should be noted that as the number of accesses increase, the frame efficiency comes down and so also the number of channels for a given transmission rate.

The system efficiency increases as the frame efficiency increases which requires reduction in overheads. The overheads cannot be decreased beyond a certain limit as discussed in succeeding sections. This requires a imaginative design of the system overheads. The clock recovery and acquisition of the frame are the most important aspects of any TDMA system. In a TDMA system as we are aware a central control or reference station is necessary which will always be addressing to the n traffic stations by sending n messages. To improve the reliability, redundancy in such messaging is necessary, like tele-command. Out of the m times the addressing is done, at least 60% of the repeated transmissions will coincide. This in turn increases the overheads and decreases the frame efficiency. For example if a 4-bit address with a redundancy of 8:1 is used then 32-bits address form the overhead. One way of reducing this is to use one sub-frame for one traffic station addressing using a unique word. That is every station is addressed during a particular sub-frame avoiding require-ment of redundancy. This helps in reducing the number of overheads.

The super frame has N number of service stations that have fixed

Example 5.1

Calculate the frame efficiency and number of voice channels in QPSK and BPSK in case of INTELSAT Frame shown in Figure 5.11.

Given

Total frame length = 120,832 symbols
Traffic burst per frame = 14
Reference burst per frame = 2
Guard interval = 103 symbols
Preamble = 280 symbols
Voice channel bit rate = 64 kbps
Post-amble = 8 symbols
Frame period = 2 ms

Solution

Number of symbols lost due to reference is given as:

$$= \frac{2(288 + 103)}{\text{Reference burst}} + \frac{14(280 + 8 + 103)}{\text{Preamble}}$$

$$= 2 \times 391 + 14 \times 391 = 782 + 5474 = 6256 \text{ symbols}$$

Therefore, frame efficiency,

$$\eta_f = 1 - \frac{6240}{120832}$$

$$= 0.95$$

120832 symbols are transmitted in 2 ms

Hence

1 symbol is transmitted in $\frac{2}{120832}$ ms bit rate would thus be $\frac{120832}{2}$ ksymbols/s

If there are 2 bits per symbol then transmission rate is:

$$\frac{120832}{2} \times 2 = 120832 \text{ kb}$$

Therefore, number of voice channels

$$n = \frac{\eta_f R_T}{R_b} = 0.95 \times \frac{120832}{64}$$

$$= 1793$$

In BPSK it will be $\frac{1793}{2} = 896$ **Ans.**

time slots and markers. The marker of the first station also identifies the starting of the main frame or super frame.

Traffic Burst

In a TDMA frame the traffic burst starts with a preamble, which has same constituents as the reference and the width of this can be represented by S_p symbols.

The number of bits/symbol in traffic burst field is given by:

$$b_{TR} = R_b T_F$$

where T_F is the frame period.

The frame period can be determined by the maximum allowable frame frequency f_o, a clock generator, generates this frequency.

Such that,

$$T_F = \frac{b_{TR}}{f_o} \tag{5.28}$$

The duration of traffic data field is dependent on the transmission rate R_T and the number of traffic bits such that:

$$T_{TR} = \frac{R_b T_F}{R_T} \tag{5.29}$$

In case of QPSK since two bits form a symbol therefore the total length of traffic burst will be:

$$S_T = \frac{R_b T_F}{2} + S_p \text{ where } S_p \text{ are preamble symbols.}$$

The burst duration is:

$$T_T = \frac{2.S_T}{R_T} \tag{5.30}$$

If there are n bits in a sample and N channels in TDMA frame then

$$S_T = \frac{nN}{2} + S_p \tag{5.31}$$

In case there are W multiplexed frames then

$$S_T = \frac{nNW}{2} + S_p \tag{5.32}$$

The coordination and revised planning burst time is important from management point of view. This is because the network traffic increases as the users increase. Hence new control and management (reference and preamble) bursts have to be transmitted to traffic stations from time to time, which are then stored in the memory to be implemented as and when required. This requires that all stations should adjust their burst timings according to the new timing requirements.

Another interacting problem in TDMA as discussed earlier, in satellite communication is that the satellite slant range is variable. Think of a geostationary satellite that is not stable (generally the case and requires station keeping). Its motion induces different frame periods at traffic station as well as at satellite which is shown in Figure 5.19.

As we have seen the reference frame period is given by

$$(T_F)_{\text{ref}} = \frac{N}{f_o}$$

Consider the situation shown in Figure 5.19, where a burst is transmitted at T_1 by the reference station and picked up by the earth station at a slant range of d_{s2}.The time at which the satellite receives the burst transmitted at T_1 is:

$$T_1 + (d_{s1}/c) \tag{5.33}$$

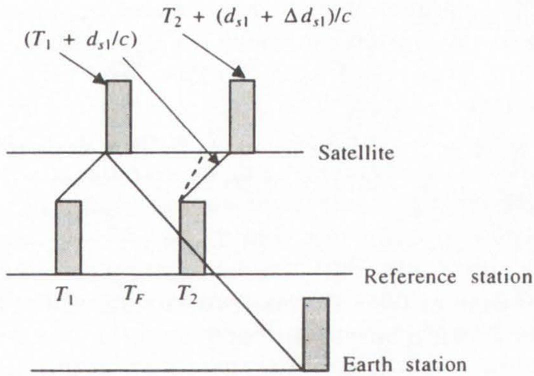


Figure 5.19 TDMA timing variation due to satellite drift.

where d_{s1} is the slant range of reference station from satellite at instant the burst transmitted at T_1 is received at the satellite and c is the velocity of EM wave. After the frame period let another burst be transmitted at T_2, where $T_2 = T_1 + T_F$. Ideally this burst should have reached the satellite at $T_2 + (d_{s1}/c)$, but this will not happen as the satellite might have drifted by $\pm\Delta d_{s1}$ and burst will be received at the instant

$$T_2 + \left(\frac{d_{s1} \pm \Delta d_{s1}}{c}\right) = T_1 + T_F + \left(\frac{d_{s1} \pm \Delta d_{s1}}{c}\right) \tag{5.34}$$

Similarly the time at which the burst will be received at the earth station can be estimated as:

$$T_1 + \left(\frac{d_{s1} + d_{s2}}{c}\right) \tag{5.35}$$

and

$$T_1 + T_F + \left(\frac{d_{s1} \pm \Delta d_{s1} + d_{s2}}{c}\right) \tag{5.36}$$

It is seen that the difference in timing is because of the change in slant range, which turns out to be

$$\frac{(d_{s1} \pm \Delta d_{s1}) + d_{s2}}{c}$$

The problem becomes more grave in a situation like VSAT and many other applications where there has to be a interface and synchronization between satellite and station switches. To overcome such problems one method is to provide additional memory in switches which act as buffers and store the incoming burst. The stored burst is then sent into the terminal equipment at a rate controlled by the switch. The selection of the capacity of this switch is a tricky problem because if the memory capacity is less it may be insufficient for the burst and bits of data will be lost. Also the rate at which the data is read plays a big role, for example if the rate at which the burst is read is slower than incoming rate, there is a possibility of the memory being overwritten or if it is faster than stored data may be repeatedly read during scanning process of the memory. Hence the average clock frequencies of all the systems should match avoiding slip of bits. Two methods commonly adopted are bit stuffing and use of PLL to achieve nearly synchronous operation.

The size of the buffer depends on the receive bit rate, variations in clock frequencies between transmitter terminal and receiver terminal with respect to the expected clock and allowable slip period, i.e.

$$B = R_F\left(\frac{f_t - f_r}{f_{\text{oref}}}\right)\Delta_s \qquad 5.37$$

where R_F is frame transmission rate, f_t the transmitted frequency and f_r receiver frequency. f_{oref} is expected correct frequency.

EXAMPLE 5.2

Estimate the buffer requirement of a TDMA switch if the transmitter and receiver are operating at 52.35 MHz and 55.5 MHz respectively. While 672,128 symbols are transmitted during a frame period of 15 ms. The stability requirement is 25.92×10^5 seconds and frame transmission rate 54 Mbps.

Solution

The reference clock frequency requirement is

$$f_{\text{oref}} = \frac{672{,}128}{15 \times 10^{-3}} = 44.808 \text{ MHz}$$

$$\text{The relative clock variation} = \frac{52.35 - 55.5}{44.808} = 0.0703$$

Buffer size = $54 \times 10^6 \times 0.0703 \times 25.92 \times 10^5 \approx 10 \times 10^{12}$ bits

Guard Time Estimation

Guard time is the duration or interval during which the unique word correlation spikes will be detected. The total guard time depends on the time taken by the burst to reach the destination station and the return of acknowledgement. As the burst is released, it first faces a delay T_{TDMA} in TDMA equipment, the next delay is caused in transmitting earth stations 'T_{TR}'. As the signal is transmitted from the antenna towards

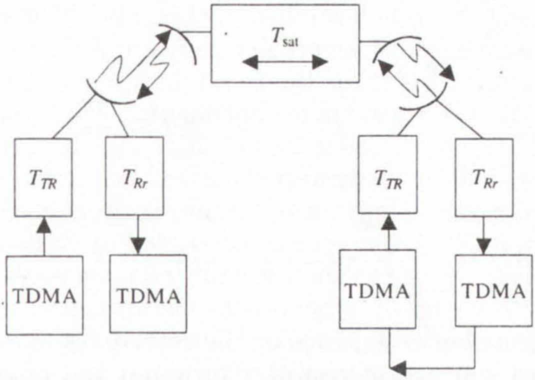


Figure 5.20 Showing loop back delays.

satellite it faces delay in atmosphere due to moisture content in the atmosphere 'T_{AT}'. The satellite itself causes a delay 'T_{SAT}'. There is also corresponding delays in receiving T_{Rr} and loop back destination station 'T_{RTDMA}'. The estimation will have certain uncertainty since it involves delays caused by the circuits and the propagation conditions.

The total uncertainty delay is, therefore,

$$T_{\text{total}} = 2T_{\text{TDMA}} + 2T_{TR} + 4T_{AT} + 2T_{\text{sat}} + T_R + 2T_{Rr} + 2T_{\text{RTDMA}}$$

TDMA Link Design

Since TDMA is basically a digital access technique the link design is similar to that discussed for TDM in Chapter 5. The total carrier to noise ratio is given by

$$\left(\frac{C_t}{N_t}\right) = \left(\frac{E_s}{N_o}\right) + 10 \log_{10} \frac{R_b}{B} + M_t \qquad 5.38$$

where, M_t is system margin for a given BER.

In order to improve the performance of link the designer needs to add the margin.

$$\text{Burst bit rate } R_b = (NP + CT_F)/T_F - NG$$

where

N is number of earth stations,
G is guard time,
P is preamble bits,
C is information bit rate and
T_F is frame period.

It is customary to specify the received signal by carrier to noise power density such that

$$\left(\frac{C_t}{N_{ot}}\right) = \left(\frac{C_t}{N_t}\right) + 10 \log_{10} B \qquad 5.39$$

where B is the bandwidth of the receiving system.

Therefore uplink illumination 'W_n'—for saturated operation at satellite is given by

$$W_n = \left(\frac{E_s}{N_o}\right)n + 10\log_{10}\left(\frac{R_b}{B}\right) + 10\log_{10} B + 20\log_{10} f_n - \left(\frac{G}{T_s}\right)_{\text{sat}}$$

$$- M_I - 207.1 \text{ dBW/m}^2 \qquad 5.40$$

and

$$207.1 = 20\log\frac{4\pi K}{c}$$

where K is Boltzmann constant and c is EM velocity, and M_I is margin to overcome distortion due to PA and TWT uplink power required is given by the relation

$$P_u = W_u - G_{tu} + \alpha_{\text{total}} - B_{Oi}$$

Typical Scheme for TDMA Station

A typical TDMA station equipment is shown in Figure 5.21. The equipment consists of a MODEM which performs IF modulation, provides

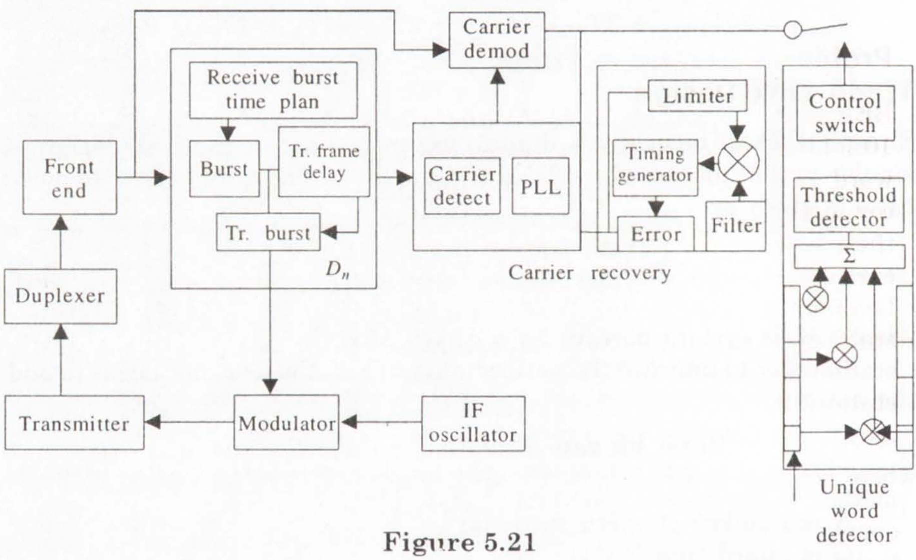


Figure 5.21

incoming carrier synchronization, performs unique word detection. It also has a processor and an terrestrial interface equipment. The IF carrier in TDMA is generally 70 MHz or 140 MHz.The front end has a duplexer, which takes care of signals coming downlink and going uplink. When a satellite TDMA link is connected the TDMA equipment receives the carrier burst from the satellite in the front end. Proper carrier recovery is most important in TDMA systems. The receiver has a local carrier of known frequency but the phase is unknown. The management control processor has receive burst time plan. The phase locking of TDMA burst and earth station is taken care of by this section using PLL. This also performs unique word detection and preamble generation. If the carrier burst is of short duration and the phase is more than 90 degrees loop hang-up may occur, hence it is necessary to predict lock-in period intelligently and allow sufficient period for carrier recovery/synchronization. This section also sends details of earth station status and assignment (in case of demand assignment) to the central control station and transmits.

The other problem faced by the TDMA equipment is when a satellite link is connected to terrestrial network. The terrestrial clock rate may not match with satellite clock rate due to the motion of satellite, this necessitates a buffer called Doppler buffer to store the incoming data before processing (store and forward). The synchronization is achieved with local station clock by using a separate PLL. The stability of local clock should be very high so that error is low of the order of 1 in 10^7. Another method of keeping synchronization is by bit stuffing in which additional pulses are added to the frame during transmission at the transmit side to account for the difference in satellite and terrestrial network clocks. The additional bits are removed by destuffing at the receiver.

Problems Involving TDMA

BER is very sensitive to E_b/N_o and a 1 dB change may change BER by 10 folds. Loss of clock synchronization may cause loss to detect unique word, tag and hence loss of burst information. Since the RF spectrum is common to all stations it is necessary that the respective stations keep their timing. If the transmission is randomly transmitted from any one earth station it will block or jam other station transmissions or access. Leakage in transmitted power may increase N_o and BER. Positional stability of satellite is very important in TDMA. In order to make earth station economical it is necessary to use, Microprocessor controlled earth station which are unmanned. Non-linearity in amplifier characteristics may cause Intersymbol interference.

In spite of many problems the modern technology and good design methodologies have made TDMA extremely popular because of economical operating cost, low maintenance, better performance compared to analog techniques and easier demand assignment techniques.

SPADE

SPADE is a special mixed mode FDMA which requires a special equipment called **Single carrier PCM multiple Access Demand Assignment Equipment**. SPADE was initially designed for telephone networks, where 800 channels (400 above and 400 below the pilot carrier) were accommodated. A typical SPADE spectrum is shown in Figure 5.22.

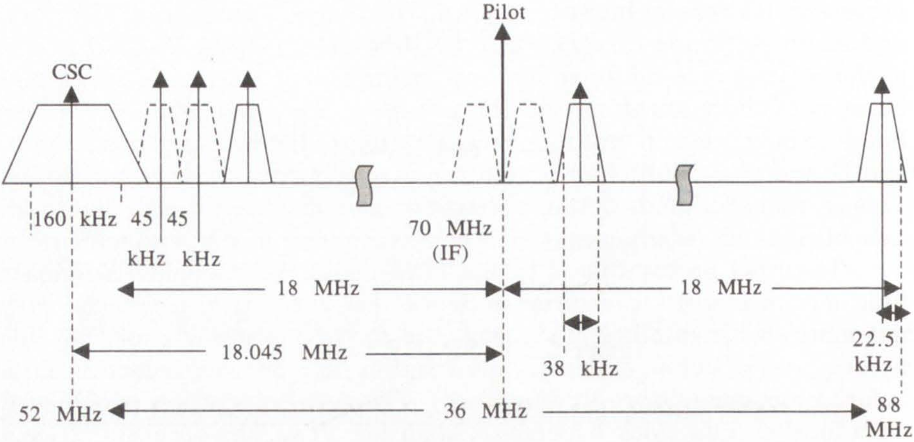


Figure 5.22 SPADE spectrum distribution.

Common signalling channel (CSC) provides dynamic channel assignment as discussed in TDMA. The common signalling channel occupies a 160 kHz BW with centre frequency 18.045 MHz below the main pilot carrier. It is in the TDMA mode using BPSK at 12.8 kbps with a frame of 50 ms. This accommodates one reference or network control station and 49 other stations each transmitting a burst of 1 ms. The reference contains a burst of 128 bits equivalent to 1 ms.

128 bits/1 ms reference

7 bits	49 bits	40 bits	32 bits
Guard time	Carrier recovery	Bit time recovery	Unique word

The voice is conventional 64 kbps, QPSK having an IF bandwidth of 38 kHz, non-overlapping. The BER is typically 10^{-6}. The main pilot carrier is at 18.00 MHz above the cut-off of traffic channel and the upper cut-off of the traffic channel is further 18.00 MHz above the pilot. There are 800 channels, 400 above and 400 below the pilot. Individually the channels are simplex, but work in pairs during a conversation. The outgoing channels are below the pilot carrier, i.e. from 1 to 400 and incoming channels are above the pilot carrier, i.e. from 401 to 800. The centre frequencies of these simplex pairs are kept at 18.045 MHz apart so that to make heterodyning easy. Hence for one conversation the Demand Assignment Signalling Switch (DASS) at the control earth station allocates pairs 3-3′ (3 and 403), 4-4′ (4 and 404) and so on. This set-up is shown in Figure 5.23. A computer in the DASS station keeps track of vacant and occupied channel pairs. The two channels adjacent to pilot are kept vacant to avoid noise interference from the high power pilot. Further to avoid interference with common signalling channel the first two channels are also kept vacant or are not used. Therefore, 1′ and 2′ are also vacant. Hence out of 800 channels, three pairs (6 channels) are unused resulting in 794 effective carrier frequencies.

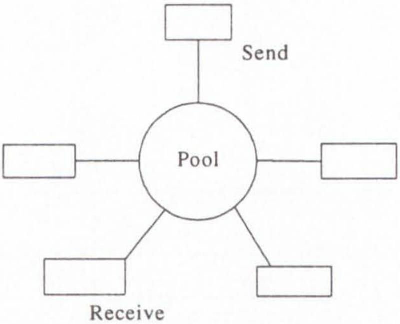


Figure 5.23 SPADE switching.

The DASS station updates the availability list from time to time and all the earth stations in the pool know about it. Any station randomly picks a pair and sends the information through the CSC to the receiving earth station, on acknowledgement the control station removes this pair from the list of available pairs and duplex circuit is established. The set-up time varies from 500 to 700 ms depending upon the slant ranges.

In the SPADE system due to voice activity, only 40% of the channels work at a time in pairs, this results in an average saving of 60% of power, as no carrier exists during the silence period. This gives a 4 dB advantage. Not only this results in IM noise is also reduced.

5.5 CODE DOMAIN MULTIPLE ACCESS (CDMA) CONCEPTS

Code domain multiple access has become very popular in both low earth orbit and geostationary satellite system. The main advantages are high satellite utilization efficiency, no controller uplink, no bit control and secure. The disadvantages being ability to neguise address, complexity and used for digital signals only.

The information is coded in orthogonal codes and could be transmitted in overlapped frequency or time domain without any interference. This is an ideal way of using satellite sources effectively and efficiently. Spectrum reuse and security are its major characteristics. It is insensitive to interference on jamming. CDMA can be used with other multiple access methods, particularly SDMA, effectively.

Spread spectrum is the basic technique adopted to achieve CDMA, where orthogonal codes are generated and mixed with data at the transmitter while at the receiver the same codes are generated to receive the data. This can be achieved by any of the following methods:

1. Direct sequence PN generation
2. Frequency hopping

3. Time hopping
4. FH/PN
5. PN/TH
6. Hybrid

Direct Sequence PN Generation

In this method pseudorandom codes or chips are generated. These codes are designed to get non-zero combination and to avoid introduction of noise. If the chip has m bits then the data is also converted to m bits from n bits. If the corresponding rates of arriving at the SS transmitter are R_m and R_n then the ratio of R_m to R_n is called **processing gain**, for m is always greater than n.

$$\text{Processing gain } G_p = \frac{R_m}{R_n} \qquad 5.41$$

In the CDMA operation a PN sequence is generated as subcarrier codes. The spread signal S_i (t) and carrier C (t) are given to an exclusive NOR to get the DS-CDMA output. This results in a scrambled output as shown in Figure 5.24. Walsh code is a typical code that could be used to generate S_i (t) as shown in Table 5.3. The output is '1' when S_i (t) and C (t) are at same level while it is '0' when the two have complementary levels. To transmit this coded message over the spread spectrum an RF carrier is required hence any of the digital modulation techniques can be adopted depending on the requirements of S/N ratio. In Figure 5.25 direct sequence decoder is shown.

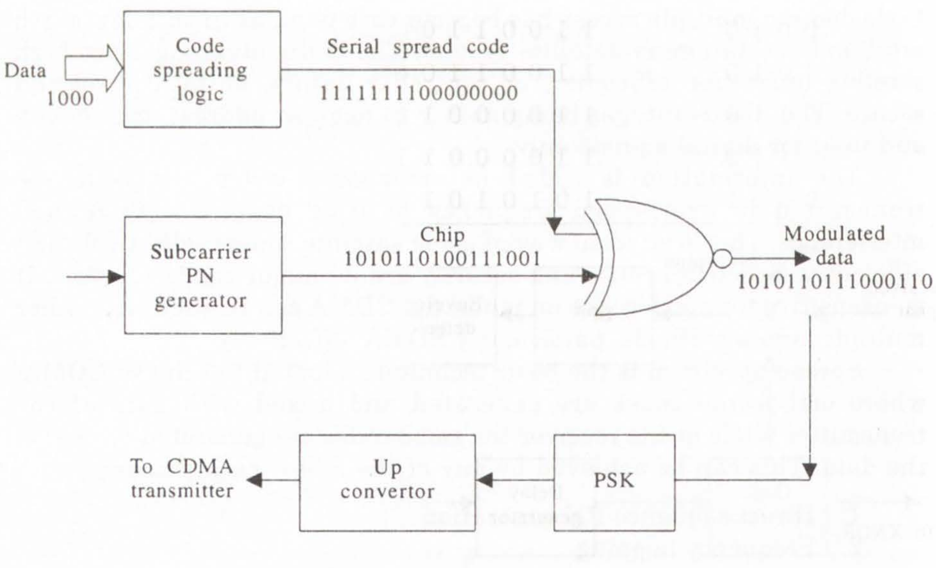


Figure 5.24(a) Direct sequence coder.

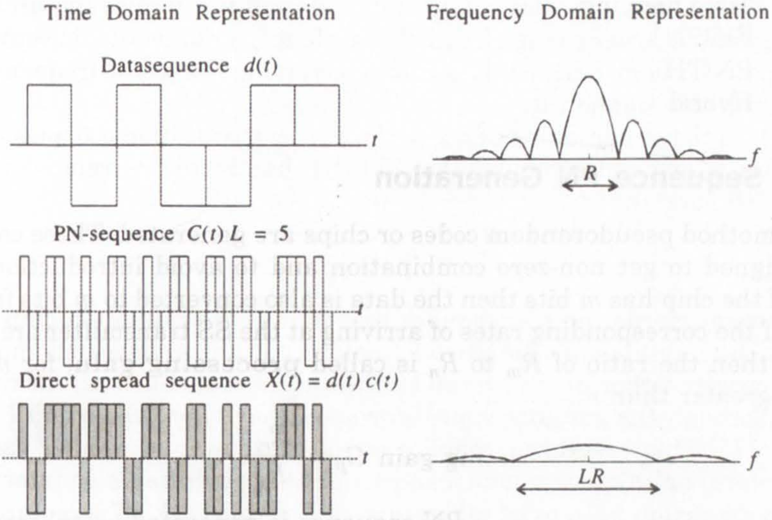


Figure 5.24(b) Direct sequence waveforms.

Table 5.3 Example of Walsh Code

Binary	*Walsh*
0 0 0 0	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 0 0 0	1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0
0 1 0 0	1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0
1 1 0 0	1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1
0 0 1 0	1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0
1 0 1 0	1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1
0 1 1 0	1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1
1 1 1 0	1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0
0 0 0 1	1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0

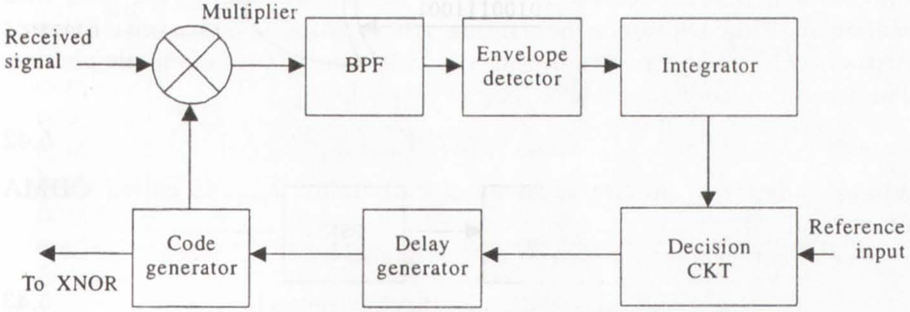


Figure 5.25 Direct sequence decoder.

Modulation, especially digital modulation techniques requires to be carried out at lower carrier frequencies. Hence, a number of up converters are required before transmission for converting these low frequencies to transmittable frequencies.

Due to the spreading of spectrum each earth station occupies almost the full transponder bandwidth. The RF bandwidth is related to chip bitwidth such that

$$B_{rf} = \frac{1}{2}\ t_{\text{chip bitwidth}}$$

or in other words the transponder determines the minimum chip width *W*. At the satellite only the carrier frequency is down converted and there is no change either in the overall bandwidth or code. Since all the carriers pass through the satellite simultaneously they share the overall power available. This results in robbing off of the power of weaker carriers. Therefore, uplink power control equipment is essential, also intermodulation distortion have to be taken care of. For this back off is required like in FDMA.

1	0	0	1
1 0 1 0 1 1 0 1	1 0 1 1 0 1 1 1	1 0 1 1 0 1 1 1	1 0 1 0 1 1 0 1

In the decoder the subcarrier PN sequence should be stored/ generated to retrieve the data as shown in Figure 5.25. Initially it is necessary that the receiver is locked with the incoming PN sequence before the decoding starts. This is called **CDMA acquisition time** or **lock time**. When the receiver is turned on, the receiver has no information of phase and this necessitates an acquisition loop. A typical hardware loop is shown in Figure 5.25. It is assumed that using the usual demodulation techniques the stream of spread spectrum code has been retrieved. Further the received signal is passed through a multiplier. The BPF filter averages the received spread data filtering the locally generated data. This when fed to the envelope detector gives an output, which could be phase shifted. It results in an output which will be L_o for phase-shifted input while above a threshold for no phase shift. When output L_o is zero, the decision circuit forces a delay in the locally generated code and rechecks. This sequence continues till locking is achieved. Present systems achieve this partly through software, as in case of mobile phones. The time required to achieve lock is given by

$$t_{\text{cdma}} = t_r / BW_{\text{receiver}} \tag{5.42}$$

where t_r depends on the receiver circuit delay, t_{cdma} is called **CDMA risetime**.

The corresponding search rate is given by

$$R_{\text{search}} = 2/t_{\text{cdma}} \text{ searches/second} \tag{5.43}$$

Even though noise in the spectrum may be more or C/N less, the receiver looks at only a small portion of the spectrum for the data. Thus, E_b/N_o is a function of $(C/N)_{\text{total}}$ and processing gain such that

$$\left[\frac{E_b}{N_o}\right] = \left[\frac{C}{N}\right]_{\text{total}} + [G_p] \qquad 5.44$$

The total noise N_{oT} at the CDMA receiver is expressed as:

$$N_{oT} = N_{or} + (P_t)_{\text{sat}}\ \alpha_t \left(\frac{N_o}{C}\right)_{\text{uplink}} \gamma^2 + N_{oI} \qquad 5.45$$

where $P_{t\text{sat}}$ is the transmitted satellite power, α_t is the total downlink losses, N_{oI} is the intermodulation noise density and γ is the noise factor.

In the case of orthogonal code CDMA the E_b/N_o for the ith station will be ratio of energy received at the ith station to the corresponding noise power density, that is,

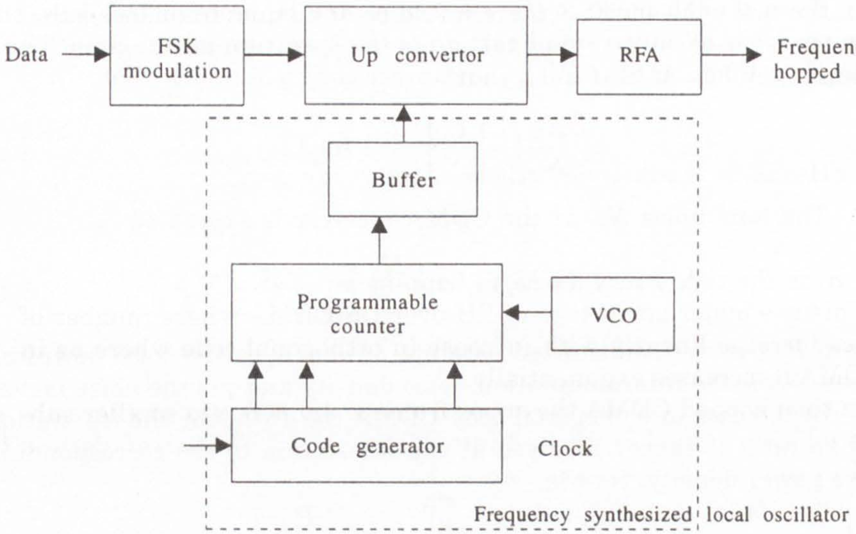
$$\frac{E_b}{N_o} = \frac{P_i T_b}{N_{oT}} = \frac{(P_t)_{\text{sat}}\ \alpha T_b \left(\dfrac{P_{\text{adj}}}{P_u}\right)}{N_{od} + (P_t)_{\text{sat}}\ \alpha_t \left(\dfrac{N_o}{C}\right)_{\text{uplink}} \gamma^2 + N_{OI}} \qquad 5.46$$

The satellite transponder receives the RF carrier and simply sends after down conversion on the downlink. The three major factors that may affect the CNR are intermodulation interference, noise and cross talk. The intermodulation interference can be taken care of by proper backoff so that non-linear operation is avoided. The crosstalk is an important factor and depends on:

1. The data bits transmitted on uplink carrier.
2. The addressing sequence during the bit correlation.
3. On the strength of the signals received from different earth stations, evidently the amplitude of signal nearer stations is more than that of the farther ones.

Frequency Hopping

This type of CDMA could be non-orthogonal or orthogonal type of CDMA. In the case of frequency hopping the digital sequence produces different carrier frequencies with the satellite transponder spectrum. For different codes different carriers are generated using programmable frequency synthesizer. The frequencies generated could be due to PN codes and hence randomness can be achieved. The spread data or direct data is frequency shift keyed at a lower carrier frequency. This bi-frequency signal is up converted by using local oscillator that produces different frequencies during consecutive time slots as shown in Figure 5.26.



Code pattern frequency	1 0 1 1 f_{11}	1 0 0 1 f_9	1 1 0 0 f_{12}	1 1 1 1 f_{15}

Figure 5.26 Frequency hopped CDMA.

Every transmitter has a different frequency-hopping scheme. This is required to avoid interference. The receiving station hops in synchronization with the transmitter. Once the receiver locks with the hopping sequence of the transmitter synchronization is achieved, this as if that particular station has been addressed through a encrypted key. The number of hops depends on the code levels that are generated by the programmable counter, each code generating a new local oscillator frequency. In order to have better utility of frequency band and no overlapping, only K codes are used out of 2^n codes. These selected randomly generated codes are then repeated after a time t. It also indicates that there is a possibility of 2^n carriers generated. Thus $K < 2^n$.

If during time t an FSK signal is transmitted assuming with one frequency then bandwidth requirement is $2/t$ or in order to detect a change of frequency shift the carrier frequencies should be shifted by a minimum of $2/t$ Hz. Resulting in a hopping of,

$$\left(\frac{\Delta f}{2/t}\right) \times \frac{1}{2} = \frac{\Delta ft}{4}$$

where Δf is the satellite bandwidth.

Hence

$$K < \frac{\Delta ft}{4 \times 2^n} \tag{5.47}$$

This shows FH-CDMA increases as satellite bandwidth increases.

In the case of M-ary FSK there would be M distinct frequencies that can be transmitted as hopping takes place. Each frequency would be represented by $\log_2 M$ bits, such that

$$R_b = (\log_2 M)\, R_H \qquad 5.48$$

as far FH-CDMA is concerned where K codes are used.

$$K = 2^{R_c/R_H}$$

where R_c is the code rate and R_H is hopping rate.

This is a major advantage of FH over DS-CDMA where number of accesses increase linearly with increase in orthogonal code where as in FH-CDMA it increases exponentially.

In time hopped CDMA the super frame is divided into smaller sub-frames which are further divided into M time slots. The stored data is spread in the time domain and hence the data rate is slowed down and takes longer time for transmission. The transmission of TH burst is carried out at pre-assigned slots in each frame. The time slot is PN variable hence difficult to synchronize and detect. This technique is still not popular in satellite multiple access as it requires high peak power burst. These can be used in packet transmission.

FH/PN is a combination of PN frequency hop and uses Multi frequency shift keying (MFSK). This is less power efficient but requires simple receiver. It also has low CDMA rise time. PN/TH uses variable PN code for time hopping. These are sometimes categorized under hybrid CDMA though strictly hybrid CDMA uses a combination of more than one of the above techniques. The above mentioned techniques provide very good antijamming characteristics.

Anti jamming. For a good and reliable communication it is necessary that uplinks and downlinks to be jamming free. The aim of a jammer is to see that reliable communication particularly point to point is denied by increasing the power spectral density in a small portion of the band so that the user fails to reproduce the required information or data.

Antijamming can be achieved by following methods:

1. Appropriate PN sequence design for DS, FH or TH spreading.
2. Diversity techniques like frequency or time.
3. Narrow beam selection to provide spatial discrimination.

In CDMA, an additional term defined is the jamming noise spectral density J_o, such that the signal to noise ratio is now $E_b/(N_o + J_o)$ dependent instead of E_b/N_o dependent.

$$\frac{E_b}{J_o} = \frac{C/R_b}{J/W_{ss}} = \frac{W_{ss}/R_b}{J/C} \qquad 5.49$$

where W_{ss} is the spread spectrum bandwidth and R_b is the rate of transmission. But we also know that in CDMA W_{ss}/R_b is the processing gain G_p and hence

$$\frac{J}{C} = \frac{G_p}{E_b/J_o} \qquad 5.50$$

This ratio is the figure of merit of antijamming process. Another term defined is the antijamming margin M_{aj}, which tells how many dBs above E_b/J_o is required for safe operation.

In satellite communication uplink, jamming is dangerous as it effects all the downlink terminals. While in case of downlink every individual terminal or earth station has to be jammed.

5.6 SPACE DOMAIN MULTIPLE ACCESS (SDMA) CONCEPTS

Space domain multiple access is another useful method by which the use of satellites in accessing its resources can be enhanced. From the structure of the satellite it is evident that the satellite bandwidth is dependent on the number of transponders and their distribution in the satellite so that the noise is minimized. Apart from this the satellite has another variable component called **antenna** which can be effectively used. Any antenna pick up the signal depending upon the polarization. For example, a vertically polarized antenna can pick up only vertically polarized EM wavefront and converts it into electrical signal that is fed to LNA. Suppose a satellite has two antennae one vertically polarized and other horizontally then it can receive two EM wavefronts of the same carrier frequency but polarized differently, that is, the vertically polarized picked up by vertically polarized antenna and horizontally polarized by horizontal. This is called **frequency reuse**. Similarly if a number of smaller antennae with sharp beams can be used then each of these can pick up individually signals from stations in their line of sight. This is called **spot beam access**. Apart from these if there are a number of satellites in the line of sight then each station can access any one of the satellites by either changing the beam direction or the carrier frequency. Satellite switching is another method by which frequency, time or channel grouping is possible on-board.

All these techniques provide special separation and hence come under SDMA. But remember that SDMA by itself has no meaning unless it is associated by either frequency or time or code.

Typical space domain multiple access are:

1. SDMA/FDMA
2. SDMA/TDMA
3. SDMA/SS/FDMA
4. SDMA/SS/TDMA/FDMA
5. SDMA/BH(TH)/TDMA
6. SDMA/SS(FH)/CDMA

SDMA/FDMA Technique

In this technique a number of antennae could be used to receive frequencies in the allotted band but reused. These received signals are filtered, regrouped, multiplexed and retransmitted to specific earth stations.

This technique can either use multiple spot beam antenna or multi beam antennae with single reflector. It is possible to incorporate different polarization to achieve better and efficient usage of spectrum. From Figure 5.27 it is seen that the input has a set of band pass filters which demux the incoming frequency bands and send them to selected output beams. The drawback of this method is that the allocations have to be pre-assigned and goes to specific output stage.

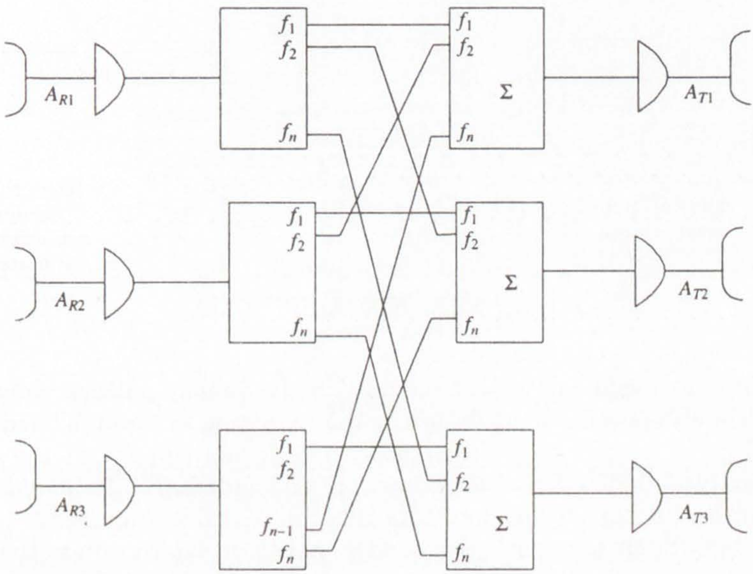


Figure 5.27 SDMA/FDMA with spot beams.

SDMA/SS/FDMA Technique

To provide flexibility in channel frequency transfer, satellite switching is adopted. Any uplink frequency band meant for a particular downlink station can be switched on-board. Microwave diode gates connected in the form of a matrix are used for this purpose. Such a system is called **SDMA/SS/FDMA system** which is shown in Figure 5.28. A simple system consists of channel filters for every uplink beam whose outputs of same bands are connected together to one converter and local oscillator. The uplink has different frequency bands on the same spot beam, which

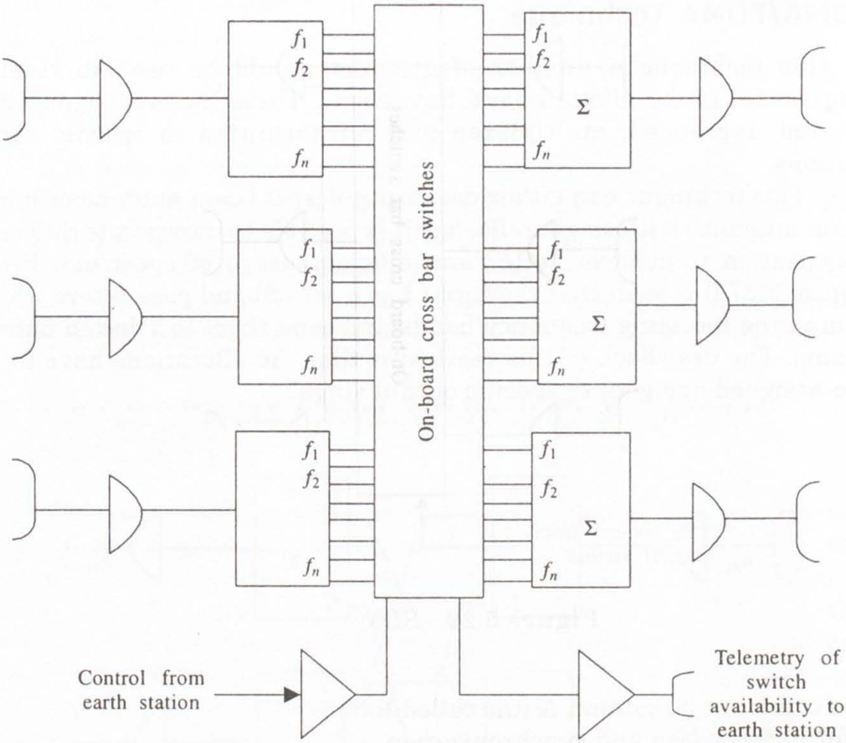


Figure 5.28 SDMA/SS/FDMA.

are routed to specific downlink beams. The frequency pattern should be appropriately chosen during design as the switching is through hardware. It is also to be seen that the same bands do not appear at the same time, or else this will cause distortion and crosstalk. To avoid such interferences a high isolation of the order of 60 dB is required.

It is difficult to reconfigure such switches on-board unless they are software driven for which recurring costs are high for the user. The transponders are always operated under MCPT with 'M' uplink and downlink beams with narrow bandwidths. A similar technique is adopted in SDMA/SS/TDMA, as shown in Figure 5.29, where sequential inputs are switched. Thus, these are SCPT and occupy the full transponder band. Another advantage of this system is higher C/N_o as a few downlink channels share the power amplifier at a time.

Modern satellites employs satellite matrix switch which is controlled by central Earth Station to select time slots. These systems use regional antenna beams which get interconnected through matrix operated beams.

The on-board cross bar switches have rows and columns. The rows could represent uplink beams while columns downlink beams. Thus when row A is connected to column C, the data flows from Earth Station 'A' to earth station 'C' for the duration the cross bar switch is closed. If row A

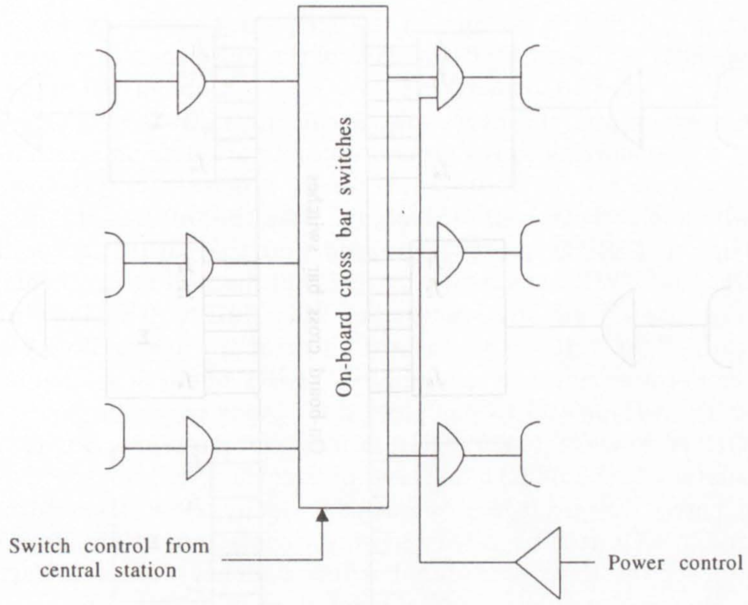


Figure 5.29 SDMA/SS/TDMA.

is connected to column A it is called **loop back**. Such a situation is used for initialization and synchronization.

The traffic duration and pattern are to be programmed for optimum efficiency of TDMA operation.

5.7 IN-ORBIT TESTS

Once the satellite is launched and placed in the pre-assigned longitudinal slot and all its deployments are deployed, it is mandatory to make initial quick-detailed checks on all the payloads. For this the ground station should have well calibrated measuring and recording equipment. The ground station needs to be validated well in advance. The parameters like *G*/*T*, transponder gain, polarization, uplink and downlink frequency response, group delays, third order intermodulation, amplitude and phase linearity, dynamic range, saturation point, maximum EIRP capabilities, waveguide losses, spurious responses, intermodulation product, DC power consumption, antenna pattern (for pitch biasing on deployment), cross polarization and discrimination have to be measured and characterized at all the usable frequencies.

To conduct these tests, calibrated instruments, such as sweep oscillators, spectrum analyzers, power meters, recorders, directional couplers, attenuators, frequency counters, noise figure meter, etc. are used. There are certain procedures to be followed to do these tests. Before switching on the transponder and verifying it's working, no RF signal is fed from the ground station in the frequency spectrum for which the transponder is designed. Observation of the noise spectrum is carried out. A small signal of 20 to 25 dB input back off is transmitted to the satellite in the uplink and the downlink carrier strength is verified. With the above data, confirmation of ground antenna orientation is carried out for maximum output so that the antenna precisely points towards the satellite and its polarization is aligned with that of the satellite antenna. The uplink EIRP is slowly increased and the saturation point of the transponder TWTA is verified by AM null method or 1 dB compression point in case of solid-state power amplifier (SSPA). The downlink C/N is determined for 1 dB above saturation point in case of TWTA and 1 dB above operating point in case of SSPA. EIRP of earth station is reduced by 20 dB in steps and C/N is plotted for every transponder.

At microwave frequencies it is a common practice to use PIN attenuators. It should be made certain that the satellite as well as ground station are in linear mode of operation as set by network operating control centre (NOCC). It is necessary to note variation of attenuation value by monitoring the downlink signal when a measurement is carried out. Steps should be taken to correct the values of attenuation.

EIRP Stability

The EIRP stability is extremely important as the received power is small and keeping AGC active is difficult. For good recovery or reception it is necessary to calibrate the spacecraft for uplink and downlink power through a power meter and attenuator. The uplink EIRP is set to give spacecraft EIRP corresponding to 10 dB back off. Confirmations of linear operation of all the ground station system are necessary. The uplink EIRP and downlink power on the spacecraft has to be observed continuously for at least 24 hours. The power variation over 24 hours is noted.

Frequency Stability

Due to long propagation and movement of satellite, frequency stability tests conducted cannot be guaranteed. Frequency stability is an important factor as the received power depends upon the frequency. Every half an hour both uplink and downlink frequency are noted using a suitable frequency counter. The difference in frequency that the local oscillator has to undergo is determined each time. A stability of 1 in 10^{-6} is essential.

On-board Transponder *G/T*

Earth station antenna is pointed towards spacecraft and then to the cold sky with same elevation. *Y*-factor and noise temperature as received at earth station are computed, i.e.

$$T_{IN} = T_{ES}(Y - 1) \qquad 5.51$$

where T_{IN} is the noise temperature received by computation.

Similarly noise temperature at output of spacecraft transmitting antenna is computed in dB°K.

$$T_{\text{sat}} = T_{IN} - G_{ES} + \alpha_{\text{downlink}} \qquad 5.52$$

Also, noise temperature at the output of spacecraft is given as:

$$T_{\text{sat}} = T_{U/L} + G_{\text{transponder}} + G_{\text{Tr. ant}} \qquad 5.53$$

where $T_{U/L}$ is the received noise temperature at the spacecraft from uplink transmission.

By injecting a small carrier power, the total spacecraft gain is computed which is expressed as:

$$G_{\text{sat}} = \text{Spacecraft output power} - \text{Spacecraft input power}$$

$$= [P_{\text{inj}} + \alpha_{\text{waveguide}} - \text{G}_{\text{ES}} + \alpha_{D/L}] - [\text{EIRP}_{U/L} - \alpha_{U/L}] \qquad 5.54$$

where P_{inj} is injected carrier power, while α stands for attenuation in respective links.

The total transponder gain is

$$G_{\text{Rr ant}} + G_{\text{transponder}} + G_{\text{Tr ant}} \qquad 5.55$$

From Eqs. (5.52) and (5.55) one can calculate $G_{\text{Rr ant}} - T$ or G/T of space craft transponder at the look angle of Earth Station for which measurement is being done.

Resulting in

$$G_{\text{Rr ant}} = T_{\text{sat}} \text{ or } G/T \text{ of satellite in dB/K} \qquad 5.56$$

Note that this G/T is the spacecraft figure of merit in the direction of measuring earth station.

Check Frequency Response

Frequency response is another important test to be carried out in space. This can be done using a microwave link analyzer. The response is got over the frequency band of interest at the rated output power of a transponder. The measurement is repeated at 10 dB input back off. The transponder full band response is to be measured by switching off adjacent transponders. If adjacent channels are ON then only about 60% of the bandwidth shows a meaningful response due to multipath effect, through adjacent transponders. It may be noted that earth station contributions have to be cancelled.

Group Delay in Transponders

Method is same as that used in frequency response except link analyzer is to be set for group delay measurement. It is to be noted that results are to be normalized with respect to the earth station group delay responses. Group delays are computed in terms of linear, parabolic and ripple components.

Spurious Response

Once the transponder is driven to its rated output, spurious signal peaks are to be monitored by scanning on a spectrum analyzer. These measurements will be meaningful under weak signals.

Third Order Intermodulation Products

Two carriers 1 MHz apart are determined at the centre of transponder frequency band. These are transmitted from the earth station. The EIRP of the earth station is adjusted such that the spacecraft illumination flux density W of the two carriers is 3 dB below that required for saturation or for given rated output. The third order intermodulation products with respect to the carrier are recorded. This procedure is repeated at different back offs depending on the application requirements for which the satellite is designed. Typical values being 6 dB, 10 dB and 17 dB back off. These are usual operating points for different services like telephony, TV transmission, etc.

Antenna Pattern

For antenna pattern measurement of the spacecraft in space, the operating point of the transponder has to be fixed once for all. In the case of TWTA the operating point is the saturation point, which is determined using AM null method. In the case of solid-state power amplifiers (SSPA), operating point has to be fixed using intermodulation method. It has to be made certain that earth station antennae are precisely pointing to the spacecraft all the time. This can be achieved by using auto mode. It is also essential that the earth station systems are operating in linear region. The transponder is driven to a known operating point and the earth station EIRP and downlink C/N_0 is recorded. The spacecraft is moved by biasing it in small tolerable steps along the appropriate axis. After transients have settled down, the transponder is driven to same operating point and new values of earth station EIRP and downlink C/N_0 are noted down. This has to be repeated for all spacecraft bias values. Variation in earth station EIRP gives spacecraft receive antenna pattern.

Variation in downlink C/N_0 gives the spacecraft transmit antenna pattern. The antenna patterns thus got are corresponding to the direction of earth station, which need not be at the beam centre.

Cross Polarization Discrimination

Two earth stations operable in the same frequency band are identified. Out of the two earth stations at least one earth station should have a good cross polarization discrimination (XPD) value preferably better than XPD value of the spacecraft. In the case of frequency reuse satellites, the adjacent transponders have to be switched off whose frequency of operation is same as that of transponder under test. A stable EIRP from the earth station that has good XPD transmits to the satellite in same polarization mode as the satellite antenna is. The carrier level is recorded in the other earth station. The polarizer of uplink station is changed to cross polarization and new level in the co-polarized station is recorded.

The difference will give combined XPD of uplink earth station and spacecraft, i.e.

$$(\text{XPD})_{\text{Spacecraft}} = \{(\text{XPD})_{\text{Measured}}^{-1} - (\text{XPD})_{\text{Earth station}}^{-1}\}^{-1} \qquad 5.57$$

The measurement can be carried out at all the frequencies of interest.

SUMMARY

In this chapter we looked into how a satellite can be accessed by different users for their specific applications. The different multiple access techniques and methods like FDMA, TDMA, SDMA and CDMA were discussed and their performance characteristics compared. Design equations of single link were modified to multiple links and effect of interference discussed. Hybrid techniques like SPADE were also discussed. Finally some light was thrown on antijamming.

REVIEW QUESTIONS

1. What is meant by multiple access of a satellite?
2. Compare the major differences, advantages, disadvantages and applications of different multiple access techniques used in satellite communication.
3. Explain what is meant by back off and why is it necessary in multiple access systems.

4. What is meant by band limited and power limited operation?
5. Explain why "Back off" is generally necessary in FDMA and not in TDMA.
6. What do you mean by multiple access in satellite communication? Explain in detail the different techniques adopted.
7. Draw the scheme of a PCM/TDM/PSK/TDMA link and explain its essential operating procedure if a super group of VC has to be transmitted.
8. What is a burst? Explain the difference between the reference burst and the traffic burst. Explain their positions in a TDMA frame. Explain their structures.
9. What are different types of SDMA?
10. Explain the principle of CDMA satellite system. How does it compare with TDMA and FDMA?
11. Explain the working of direct sequence CDMA.
12. Explain multiple accesses and compare the performance characteristics of FDMA, TDMA, CDMA and SDMA. Also give their typical applications.
13. What are the in-orbit tests that have to be conducted for proper operation of a satellite?

PROBLEMS

1. A satellite has an EIRP of 24 dBW and eight earth stations each with G/T of 38.3 dB/K share equally the total transponder in FM/FDMA. These links are characterized as:

   Uplink C/N = 27 dB
   Intermodulation C/N = 20 dB
   Output back off = 6 dB
   Downlink path loss = 197 dB
   RMS frequency deviation of carrier = 260 kHz

   Calculate the number of 4 kHz voice channels that each earth station can transmit in order to meet an overall C/N of 16 dB at receiver input. Assuming voice activity advantage of 10 dB.

   (**Ans.**: 147 voice channels/station)

2. In an FDMA link the following data is available:

$$\left[\frac{C}{N}\right]_{\text{uplink}} = 22 \text{ dB}, \left[\frac{C}{N}\right]_{\text{downlink}} = 25 \text{ dB}, \left[\frac{C}{N}\right]_{\text{intermodulation}} = 22 \text{ dB}$$

$$\left[\frac{C}{I}\right]_{\text{uplink}} = 200 \text{ dB}, \left[\frac{C}{I}\right]_{\text{downlink}} = 175 \text{ dB}$$

Calculate the over all CNR of the link.

(**Ans.:** 18.01 dB)

3. In a FDM/FM/FDMA link, consisting of audio signals, the uplink carrier frequency is 6.125 GHz in the band 5.94 GHz to 6.4 GHz and the downlink is 4.25 GHz in the band 3.7 GHz. Draw the uplink and downlink spectrum starting from the transmitter to the received signal.

4. A satellite link uses FDM/FM/FDMA technique to transmit 960 telephone channels through a satellite orbiting at 42120 km. The slant ranges of earth stations are 38500 km and 37800 km respectively. The link is a 6/4 GHz. Calculate the carrier to noise ratio at the output of the front end of the receiver if:

   Transmitted power = 10 kW
   Overall satellite gain = 86 dB
   Transmitting and receiving antenna are 10 m parabolic dishes.
   G/T of the receiver being 10 dB/K
   $g = 3.16$, $\Delta f = 200$ kHz and FDM top frequency = 3852 kHz
   Also calculate the overall C/N if $(C/N)_{IM} = 12$ dB, and $(C/N)_{\text{IDL}} = 5$ dB.

   (**Ans.:** 3 dB)

5. Calculate the frame efficiency of a TDMA frame of period 2.2 ms.

   Total Frame length = 128000 symbols
   Guard interval = 110 symbols
   No. of traffic bursts = 14/frame
   No. of reference bursts = 1/frame
   CDC during reference burst = 10 symbols
   No. of preamble symbols = 208

   Also calculate the channel capacity of the link if the data is transmitted at 64 kbps with QPSK modulation.

   (**Ans.:** 0.973, 884)

6. Calculate the preamble period and frame efficiency with the help of following:

   No. of Traffic burst = 12
   Frame period = 10 milliseconds
   Total number of equivalent frame bits = 64000
   CBR = 56 bits, UW = 28 bits, SIC = 16 bits, Miscellaneous information = 24 bits

   (**Ans.:** 0.994)

7. A BPSK TDMA system is to transmit 1000 digital voice channels, each with 4 bits per sample at a 64 kbps rate. The system must accommodate 1000 data bits/slot at a frame efficiency of 90%.
   (a) What is the number of slots in a frame?
   (b) What is the length of TDMA frame?
   (c) How many preamble bits can be used?
   (d) What is the required satellite bandwidth?

   (**Ans.:** 115, 12800 symbols, 114, 8192 MHz)

6 Satellite Sub-systems

6.1 INTRODUCTION

In this chapter we will discuss some of the sub-systems of the satellite and their importance in satellites. Power system, power amplifiers and antenna are being considered here. The discussions are of general nature and depending on the requirements these can be modified and used. Some basic design concepts have also been discussed as used in satellite system design.

6.2 POWER SUPPLY

The electrical power requirement in satellites depend on a number of factors, particularly:

1. Communication payload
2. House keeping circuitry
3. Power amplifiers
4. Losses
5. Miscellaneous

The communication transponders consume about 5% of the total power generated while house keeping circuits and systems about 12% of the power. The high power amplifiers at the output of the satellite that produce the required downlink EIRP take away the major power, almost 80%. The remaining power generated goes into charging the backup batteries, regulator losses, bus losses, etc. The total power requirement varies on the type of application for which satellite is launched. INSAT-2 power system is designed for 1455 W in normal orbit and 323 W during transfer orbit.

The design aspects of a satellite depends on:

1. Number of buses
2. Redundancy required
3. Availability of space qualified components
4. EMI/RF noise coupling due to various loads

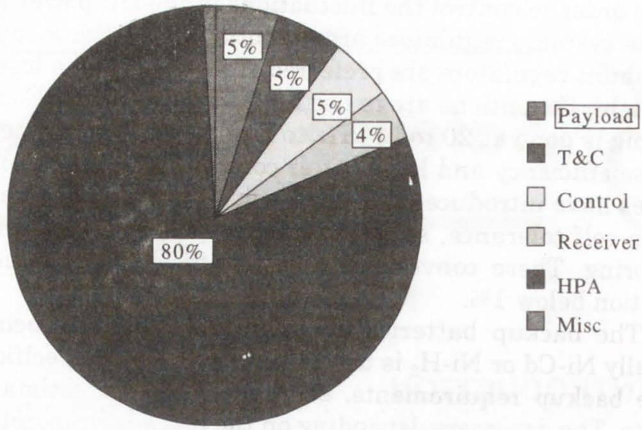


Figure 6.1 Electrical power distribution.

5. Minimize losses and increase over all efficiency
6. Optimization of power/kg mass
7. Power distribution
8. Backup batteries

During earlier space programmes most of the satellites used single bus concept, as the power requirements were limited. Due to the increase in the power demand and reliability, multiple bus concept took the front seat. The primary source of electrical power is solar arrays. There could be one or more arrays depending upon the type of satellite (geostationary or otherwise). Solar arrays consist of number of solar cells connected in series and parallel to get the required voltage and power requirement. In most of the present day satellites, the numbers of satellite's solar arrays are grouped depending on the individual bus requirements. INSAT-2 has six panels, three each side on the northern and southern sides. One problem with multi bus configuration is that it increases the bus routing complexity and weight due to additional conductors.

Power failure in satellite can occur due to:

1. Bus failure (open circuit or short circuit, which can happen due to defective workmanship, material failure, overheating or over loading, etc.)
2. Component failure
3. EMI/RF noise pickups

In order to control such power failure during launch or when satellite is in orbit, it is essential to provide redundancy of critical buses and components. One approach is to use multiple bus concept as described earlier. The second is to use components which have undergone space technology tests including passive components like tantalum capacitors, mica film capacitors, rotatory transformers, epoxy packaged transformers and inductances which are properly shielded to avoid EMI.

In order to control the fluctuations in the DC power supplies to the satellite systems regulators are essential. Since the loads on board are fixed, shunt regulators are preferred. To minimize the losses and reduce the weight, the options are to use high frequency DC/DC converters. The chopping is done at 20 to 25 kHz to reduce the size of filter components, increase efficiency and have better control. Microprocessor-based power supplies have introduced new dimension with the designers introducing built in self tolerance, self-test, frequency control and on board health monitoring. These converters have an efficiency in excess of 95% and regulation below 1%.

The backup batteries are maintenance free, rechargeable type generally Ni-Cd or Ni-H_2 is used. The capacity and specifications depend on the backup requirements, eclipse period and estimated life of the satellite. The designers depending on the link requirement during eclipse provide backup. Most of the satellites work at 20% backup. INSAT-2 has two 24AH batteries (as per literature provided by ISRO). The backup batteries are charged through a charge array, which keeps the charge voltage greater than bus voltage for proper charging. During eclipse the batteries discharge as there is no solar power available. As soon as the spacecraft comes out of eclipse there is a transient condition and care must be taken to protect batteries as well as other devices from such sudden changes.

The batteries have controlled charging circuit and the discharge is also regulated to extend the life of the batteries and also to avoid short circuit conditions that may exist due to failure of circuit components or bus.

A typical block of INSAT-2 power supply system and power supply are shown in Figures 6.2 and 6.3.

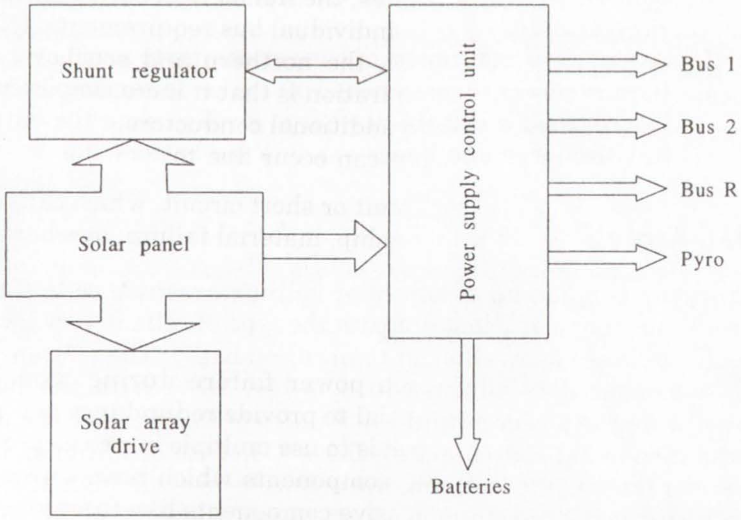


Figure 6.2 Block of INSAT-2 power sub-system.

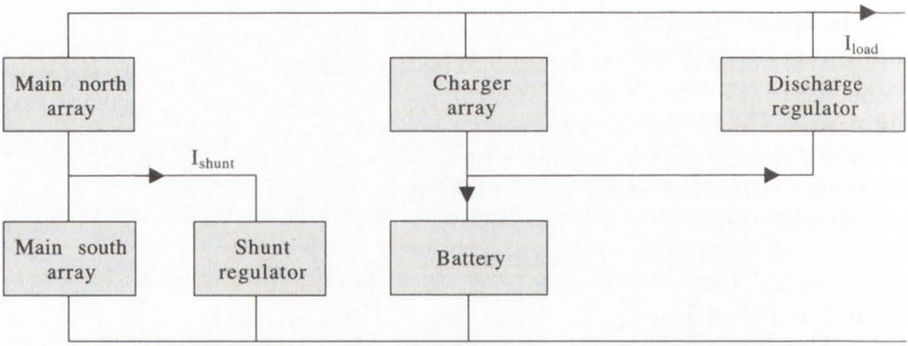


Figure 6.3 Block diagram of typical power supply.

In case of satellites, which are not geostationary, the solar array power requirement depends on the eclipse (satellite not receiving sun rays) duration t_e and illumination period t_i such that the solar power is given as:

$$P_{sp} = \frac{P_L}{\eta_r}\left[1 + \frac{t_e}{\eta_s t_i}\right]$$

where P_L is the load power required, η_r is power supply circuit efficiency and η_s is the total battery and charger efficiency.

Minimum wattage required for charging

P_{charge} = minimum current to charge battery charging voltage (The design criterian is discussed later in this chapter).

Power control unit requirements

1. Smooth switch over of power sources from solar to battery and vice-versa.
2. Switch over and control of battery charge to avoid over charging.
3. Battery power to be switched off to the power amplifiers when it has reached a certain discharge level to save the battery from full discharge and hence extends the battery life.

Solar Array

Solar array is made up of silicon or gallium arsenide cells. Though the over all conversion efficiency of both the type of cells is very low, gallium arsenide cells are more efficient than silicon based. The efficiency of GaAs is 17% compared to silicon which is just 15%. With the increase in temperature the power output capabilities of these cells come down. The degradation being approximately 0.5%/°C in case of silicon and 0.25%/°C in case of GaAs cells. Gallium arsenide cells provide high efficiency and high resistance, tempting designers to use these in many spacecrafts. Indium phosphate (InP) is another good candidate for future solar cells and arrays. The power output of a single cell being very small, an array of series and parallel cells have to be used as shown in Figure 6.4. Since these arrays comprise additional piggy back or mounted loads, it is essential for the designer to consider watts/kg as an important parameter while designing. Hence efforts have gone in to fabricate thin but tough panels. Different structures have been shown in Figure 6.5. These structures are:

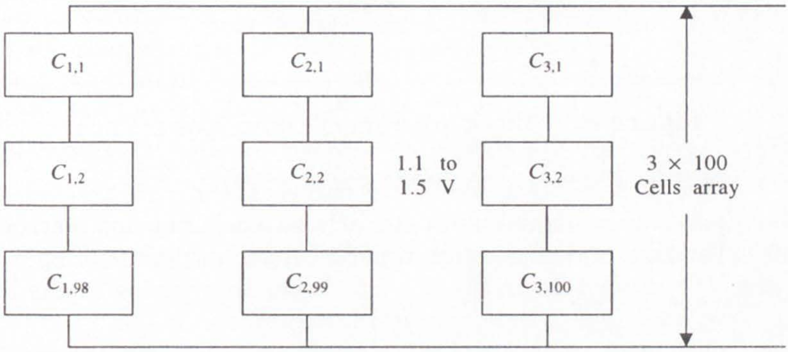
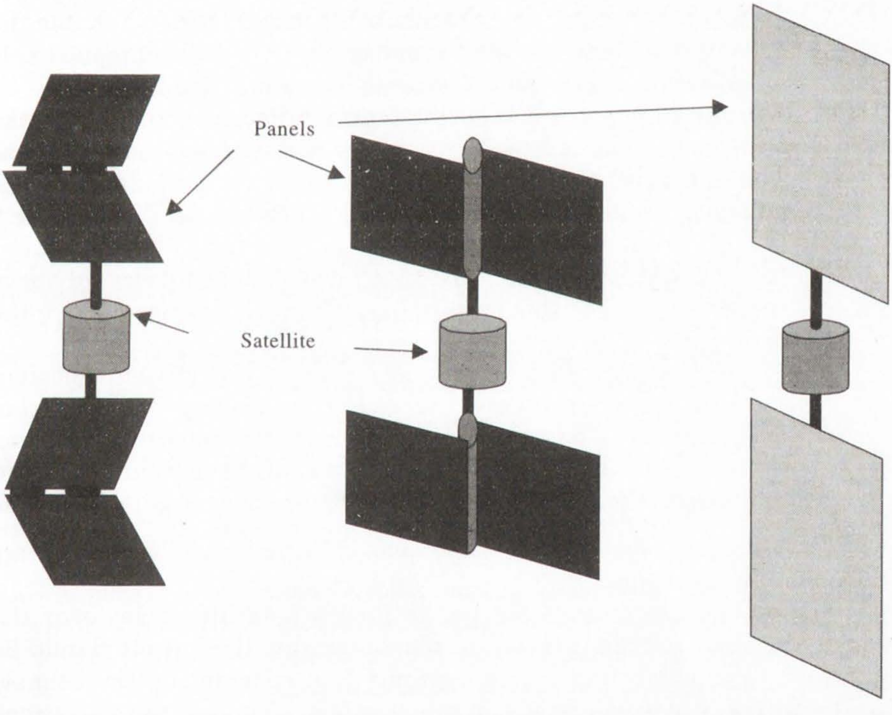


Figure 6.4 Typical cell array.



(a) Flexible fold-up (b) Flexible roll-up (c) Rigid honey comb

Figure 6.5 Types of arrays.

1. Flexible fold-up
2. Flexible roll-up
3. Rigid honey comb
4. Honey comb with stiffeners

The requirement of solar array is the total power requirement plus that dissipated in the charger circuit as well as any additional losses. Each cell consists of number of series solar cells producing a total of 1.1 to 1.5 V. The solar cells and hence the arrays have to undergo stringent thermal, space and optic conditions when in space or during launch. The cells, therefore, are to be protected from these and they should undergo tests from –190°C to 60°C and about 1000 eclipse cycles. The cell packages are required to have following optical layers to provide good conversion efficiency, durability and stability:

1. The base material is aluminium based honey comb structure.
2. The base material is sandwiched between graphite or epoxy film.
3. A thick film insulator is pasted over the base with the help of an adhesive to take care of interconnects.
4. The solar cells are then grown on this with interconnects connecting every p-material to adjacent cell n-material.
5. The cells are protected by optical interface. The first layer of optical interface consists of anti-reflective coating to enable the cells to absorb as many photons as possible. Silicon mono oxide or tantalum oxide can be used as anti-reflective film.
6. A cover adhesive is put over the anti-reflective coating to make sure that the amount of light energy reaching approaches 100%.
7. The ultraviolet spectrum in the sun rays can damage the adhesives and also the cells do not convert this wavelength into electrical energy, therefore, these have to be filtered out. For this purpose ultraviolet reflective layer is to be fabricated above the adhesive. For this cerium based thin film is used above the cover.
8. The top most exposed layer consists of anti-reflective magnesium fluoride which protects the array consisting of cells from environmental hazards, charged particles, space debris, etc. Cover materials like CMS, CMX and CMZ have been developed to improve the performance.

The efficiency of solar cells are increased by providing back reflectors and surface passivation.

The solar array output for geostationary satellite varies over the year as the sun's declination varies. Theoretically, the output should be maximum at autumn and spring equinox (not considering the eclipse) while minimum at summer and winter solstice. Though the variations may be limited but this necessitates the need of regulators. Also the output reduces from beginning of life (BOL) of the satellite to the end of life (EOL) of satellite. This variation is of the order of 20%.

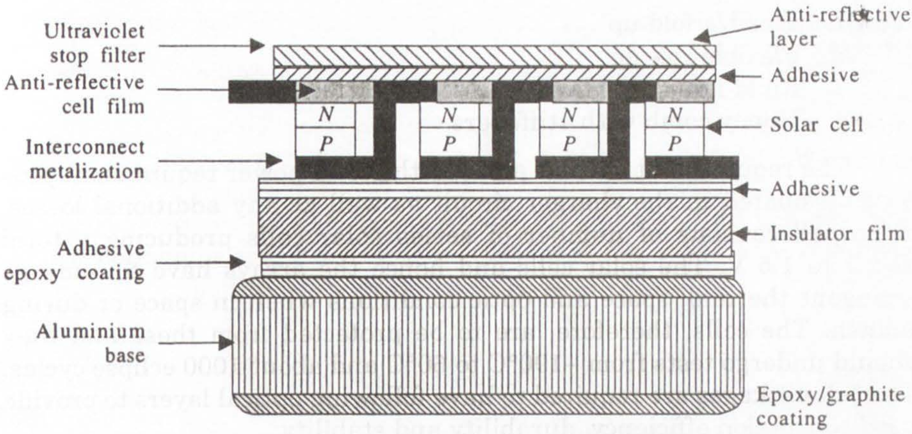


Figure 6.6 Solar array construction.

Batteries

Space crafts require maintenance free rechargeable batteries packs. The number of batteries and type of batteries depend on:

1. Expected life of satellite
2. Backup power required
3. Charging cycles
4. Extent of discharge or load
5. Temperatures of operation

During solar eclipse the battery packs have to supply power for about 45 days from a few minutes to 75 minutes. For the remaining period the batteries have to be under trickle charge. Also if the life of satellite is 5 years the battery has to discharge and charge for about 400 cycles. During the eclipse the temperature drops down to as low as 5°C while on normal days it may reach 40°C. Commonly used batteries are nickel-cadmium, nickel-hydrogen and silver-zinc. Some of the characteristics are compared in Table 6.1.

Table 6.1 Characteristics of Maintenance Free Batteries

Characteristics	*Ni-Cd*	*Ni-H_2*	*Ag-Zn*	*Units*
Energy density	25	70	120	Wh/kg
Life cycle	High	Highest	Low	
Optimum temperature of operation	–10 to 25 (at higher temperatures performance degrades)	10 to 15 (beyond 15 degrees performance degrades)	Better	

Table 6.1 Characteristics of Maintenance Free Batteries (*continued*)

Characteristics	*Ni-Cd*	*Ni-H_2*	*Ag-Zn*	*Units*
Chemical characteristics	Oxygen produced during discharge recombines, but hydrolysis takes place	No hydrolysis or oxygen effect during discharge	Oxygen produced during discharge recombination difficult	
Voltage	Fairly constant till discharged to 50%	Not as good as Ni-Cd	Poor	
Charge-discharge cycles	1000	900	200	Cycles
Suitability	Up to 7 years	Up to 10 years	Short life satellites	

In most of the present day communication satellites, $Ni(OH)_2$ batteries are being used because of its better charge-discharge life cycle and more stable operation. Both Ni-Cd and Ni-H_2 batteries have to be stored in an enclosure to keep the temperature inside the enclosure with in optimum temperature for good performance.

Regulators

To keep the bus voltage constant both from the point of view of the seasonal variations at the output of solar panel as well as backup batteries, it is essential to use voltage regulators. Any one type of voltage regulator can be used for this purpose:

1. Series regulator
2. Shunt regulator
3. Switch mode regulator

For constant loads shunt regulators can be used while in systems where there is large fluctuation of input supply, switching mode regulators are preferred and in case of varying loads series regulators are preferred. The detailed design of these regulators is beyond the scope of this book but is available in most of the basic electronics circuit's books or can be seen in reference. Table 6.2 shows some comparison of electrical power used in some satellites.

Table 6.2 Comparison of Electrical Power used in Satellites

Satellite	*Approximate power in watts*	*Bus configuration*	*Solar panel*	*Battery*
INSAT-I	900	Two	Rigid 11 sq.m	Ni-Cd
IRS	700	Two	Rigid 8.5 sq.m	Ni-Cd
Apple	240	Single	Rigid 2.8 sq.m	Ni-Cd
INTEL-Sat-IV-A	900	Two	20 sq.m	Ni-Cd
INSAT-II	1105	Two	Rigid 15.5 sq.m	$Ni\text{-}H_2$
INSAT-IIE	2050	Two	20.52 sq.m	$Ni\text{-}H_2$

Design Criterion

To design the power sub-system the most important data that the designer will have to keep in mind is the total power requirement, Back up requirement, launch requirement, housekeeping requirement, allowable weight, number of buses and their voltage/power ratings. Here under we will discuss simple design criterion which can me modified depending upon the requirement.

Solar array design

Solar power requirement is the sum of total load requirement plus the losses.

$$P_{SP} = (P_{load} + P_{charge} + P_{margin}) \qquad 6.1$$

P_{margin} consists of losses that may occur. It can be considered 10% of total power.

$$P_{load} = V_{load} \times I_{load} \qquad 6.2$$

$$P_{charge} = I_{charge\ specified\ for\ battery} \times \text{No. of batteries} \times \text{voltage of battery}$$

$$= I_c \times N \times V_B \qquad 6.3$$

The requirement of solar power for charging, being different, during equinox and solstice. These can be individually calculated. In order to calculate the number of parallel cells required, we require the current capability of each cell and total current requirement.

$$\text{Cell current } I_C = [I_{mp} + \alpha_1(T - 25)]L_A L_D K_S \qquad 6.4$$

where I_{mp} is solar cell current

α_1 is temperature coefficient for current,

L_A is assembly losses in current (0.9 to 0.95),
L_D is environmental degradation in current (0.8 to 0.85), and
K_S is solar ray intensity factor depends on angle of incidence (0.85 to 0.9).

$$\text{Bus current } I_B = \frac{\text{Load power in the bus}}{\text{Bus voltage}} \tag{6.5}$$

Thus,

$$\text{Number of parallel cells} = \frac{\text{Total current}}{\text{Individual cell current}}$$

Therefore,

$$\text{Number of parallel cells } N_P = \frac{I_B}{I_C} \tag{6.6}$$

To calculate the number of cells in series, individual cell voltage and bus drop is required.

$$\text{Cell voltage } V_{cell} = [V_{mp} - V + \alpha_2(T - 25)]K_E \tag{6.7}$$

where V_{mp} is maximum cell voltage,
V is Panel wiring loss,
α_2 is temperature coefficient of voltage, and
K_E is Radiation degradation factor of voltage (0.9 to 0.95).

Thus,

$$\text{Number of series cells } N_S = \frac{\text{Bus voltage + Bus drop}}{V_{cell}} \tag{6.8}$$

Battery Design

Bus voltage = Number of cells in series × Cell voltage

Usually a diode is connected in series to avoid current flowing back. Hence the drop in bus voltage is:

$$V_{DB} = N_s \times V_{cell} - V_D \tag{6.9}$$

In case during launch or deployment some of the cell gets damaged there is a possibility of bus voltage getting affected. Hence this margin should be considered while calculating V_{DB}. For which the worst-case bus voltage is:

$$V_{DB} = (N_s - n) \times V_{cell} - V_D \tag{6.10}$$

where n is the probability of number of cells getting damaged.

Power requirement for each bus will be

$$P_B = \frac{\text{Total power}}{\text{Number of buses}}$$

Hence battery capacity required will be

$$C = \frac{P_B \times \text{Number of hours}}{V_{PB} \times \text{DOD}} \tag{6.11}$$

where DOD is the depth of discharge.

Charging voltage required at the output of charger as per arrangement shown in Figures 6.2 and 6.3.

$$V_{BC} = \text{Battery voltage} \times N_S + \text{Diode drops} \tag{6.12}$$

Charging power requirement = charging current × Charging voltage

Time required to recharge the battery depends upon the extent of discharge such that

$$T_{\text{charge}} = \frac{P_{\text{discharge}} \times t_{\text{discharge}}}{P_{\text{charge}} \times \eta} \tag{6.13}$$

where η is the efficiency of changing circuit and battery.

EXAMPLE 6.1

Design a power supply system for a satellite for the following data:

$V_{\text{bus}} = 42 \pm 0.5$ V, Backup requirement = 50%, Load power of a 1000 watts is distributed over a two bus system.

Eclipse duration during equinox 1.2 hrs and maximum allowable discharge is 55%.

The battery available has following characteristics:

$V_{\text{Bat max}} = 1.75$ V $V_{\text{Bat min}} = 1.1$ V

Average voltage = 1.5 V Charger drop = 1.75 V

Operating temp = 40°C

Solar cell ratings:

$I_{mp} = 0.3$ A	$V_{mp} = 0.45$ V	$I_{sc} = 0.315$ A
$V_{os} = 0.548$ V	$\alpha_1 = 0.24$ mA/°C	$\alpha_2 = 2.2$ mV/°C
$L_A = 0.96$	$L_D = 0.815$	$K_S = 0.88$, $K_E = 0.935$

Solution

1. Let the discharge bus voltage be 0.64 times the actual bus voltage. Hence

   $V_{DB} = 0.64 \times 42 = 28$ V

   If the number of cells in each battery is assumed to get damaged is one, then $n = 1$

   $\therefore \quad 28 = (N_S - 1) \times 1.1 - 0.8$

   Hence number of batteries in series is

   $N_S = 27.18 \approx 28$ batteries.

2. Required capacity of battery during eclipse if full load of 500 watts (.1000/2) in each bus is to be served

   $$C = \frac{500 \times 1.2}{28 \times 0.55} = 38.961 \text{ Ah}$$

If only 50% of power is required

$$C = \frac{38.961}{2} = 19.48 \text{ Ah}$$

3. Maximum battery charge voltage will be
$V_{BC} = 1.5 \times 28 + 0.8 = 42.8$ V
4. Minimum bus voltage available would be
$V_{OB\,\min} = 42 - 0.5 = 41.5$ V
5. To obtain this voltage the voltage required at the input of charger
$= 41.5 + 1.75 = 43.25$ V
6. The charging current required immediately after eclipse if full charge is required within 15 hrs.

$$I_{\text{charge}} = \frac{C}{15} = \frac{38.961}{15} = 2.59 \text{ A (for full load)}$$

7. Charging power required after eclipse under worst case
$P_{\text{charge}} = 2.59 \times 41.5 = 107.485$ W
Actually it will be much less since charge requirement is 19.48 Ah, but designers usually design for worst case.
8. But since as per requirement maximum allowable discharge is 5.5%. Hence,
$P_{\text{discharge}} = 500 \times 0.55 = 275$ W
Hence recharging time for charging efficiency of 0.9

$$T_{\text{recharge}} = \frac{275 \times 1.2}{107.485 \times 0.9} = 3.41 \text{ hrs.}$$

9. Charging requirement during the normal days is given as:

$$P_{\text{charge}} = \frac{C}{45} \times V_{BC} = \frac{38.961}{45} \times 42.8 = 37.05 \text{ W}$$

10. Solar array requirement immediately after eclipse is expressed as

$$\begin{aligned} P_c &= V_{\text{load}}\,(I_L + P_{\text{charge}} + P_{\text{margin}}) \\ &= 42 \times 11.9 + 107.485 + 5 \\ &= 612.485 \text{ W} \end{aligned}$$

11. Solar panel requirement during normal days
$P_c = 500 + 37.05 + 5 = 542.05$ W
12. Solar cell current requirement

$$\begin{aligned} I_c &= [I_{\text{imp}} + \alpha_1(T - 25)]\, L_A L_D K_S \\ &= [0.3 + 0.24 \times 10^{-3}(40 - 25)]\, 0.96 \times 0.815 \times 0.88 \\ &= 0.209 \text{ A} \end{aligned}$$

13. Total load current to be supplied by solar cell is:

$$= \frac{500}{42} = 11.9 \text{ A}$$

14. Therefore parallel cells required

$$N_P = \frac{11.9}{0.209} = 56.92 \approx 57 \text{ cells}$$

15. Solar cell voltage at the end of eclipse is:

$$V_c = [0.45 - 0.005 - 0.0022\,(40 - 25)] \times 0.935$$
$$= 0.385 \text{ V}$$

16. Therefore number of series cells required

$$N_s = \frac{42 + 0.5}{0.385} = 110.39 \approx 111 \text{ cells}$$

17. If a regulator is used after the cells then 120 cells can be used such that input of regulator would be

$120 \times 0.385 = 46.2$ V

and each series battery will have $= \dfrac{120}{28} = 4.28 \approx 5$ cells

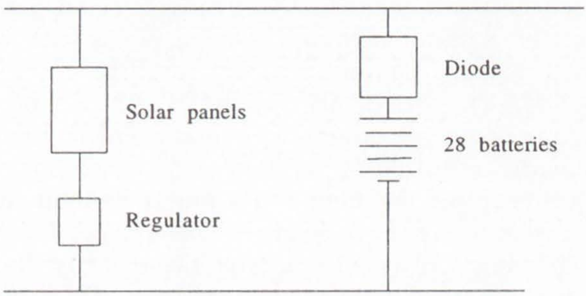


Figure 6.7

6.3 SATELLITE ANTENNA

Transmit and receive antenna are the primary component of any satellite system without which the satellites can neither be put in orbit nor controlled. The payload will also be crippled without antenna. There are instances in the past when a mission had to be abandoned because of failure of the antenna to open. Hence, lot of research and importance have been given to develop newer space antennae.

There can be three types of antenna used in space missions:

1. Earth station antenna
2. Space borne antenna
3. Launch vehicle antenna

The antennae required for satellite and earth stations depend on several factors. Some of them are:

1. Structure (Space erectable type, rigid type—fixed at the time of launching)

2. Type of beam required (Spot beam, global or elliptical shaped, streerable, etc.)
3. Type of feed (Dipole feed, horn feed, flared horn, helical, etc.)
4. Type of Polarization (Linear, circular)
5. Directive gain
6. Bandwidth
7. Power to be fed
8. Efficiency
9. Environmental requirements

The simplest antenna that can be used is a fixed parabolic reflector with a single feed at the focal point. This has many limitations including size, limited bandwidth, small directive gain and efficiency. For telemetry, tracking and control omni directional antenna are required, global horn are required during transfer orbit while in geo-synchronous orbit global beam antenna is commonly used. This is done to rescue and control the spacecraft even if control station fails to lock to the satellite. Since an ideal omni directional pattern is possible only with a non-existent isotropic antenna, other methods have to be adopted to get omni directional pattern without any null. Global beam with reflectors are commonly used in any communication satellite, such as, INSAT, INTELSAT, COMSAT, ARABSAT, SATCOM, ANIK and so on. Most common antennae being pyramidal or conical horns having plain tapers for wide beamwidth required for broadcast or larger footprints. When higher gains are required the horn taper has to be long enough.

Multiple feed antennas have been developed to get different contours. These designs have not only made control of beams easy but also inbuilt redundancy and smaller power requirements. Such antennas are extremely useful for satellites that scan the earth. Both shaped reflectors and multiple feed systems have achieved shaped footprint requirements. Mutual coupling between the feeds and cross polarization are the major constraints of such systems. Mechanical steering has never been considered as a good method in the case of satellites as it affects the stability and control is difficult. The mechanical movement has an inertial effect, which makes attitude control of inclined plane orbiting satellite pretty difficult. Antenna with linear as well as circular polarizations have been used. Linear polarization is one in which the EM waves are mutually perpendicular and the electric field depends upon the antenna co-ordination. But this is sensitive to changes in plane. It is sensitive to echoes and changes in atmospheric conditions. Circular polarization is one in which the transmission is in two orthogonal co-ordinates both horizontal and vertical such that the resultant field appears to rotate circularly as the wave propagates. These are free of changes in plane during propagation.

Antennas with zero thermal expansion have been made using composite materials. Carbon fiber reinforced plastic (CFRP) is being used atop many 6/4 GHz crafts as they are light weight, have good dielectric characteristics, stable in extreme environmental conditions varying from – 165°C to 120°C. These antenna use aluminium honey comb core over which M55J or M18 CFRD is moulded. This mould is cured at 175°C. In higher frequency band their reflection efficiency drastically reduces.

6.4 EARTH STATION ANTENNA

The earth station antenna are simple and are all rigid type but their elevation and azimuth angles can be varied either manually or through a motorized system. These could be transmitting, receiving or transmit/receive type. The antenna system consists of:

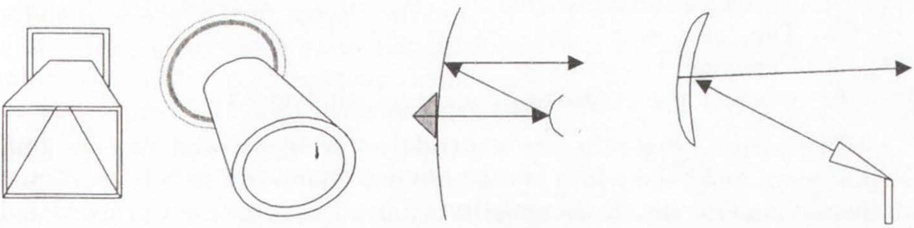
- Feed system
- Antenna reflector
- Mount
- Antenna tracking system

Feed System

The feed along with the reflector is the radiating/receiving element of electromagnetic waves. The reciprocity property of the feed element makes the earth station antenna system suitable for transmission and reception of electromagnetic waves. Earth station feed systems most commonly used in satellite communication are:

1. Primary feeds (dipoles, horn or helical)
2. Cassegrain
3. Offset feed

In primary feed is located at the focal point of the parabolic reflector. Cable or Master TV receive only antennas are mostly prime focus feed. Figure 6.8 shows a parabolic reflector with prime focus feed. Common Cassegrain type of antenna is a dual assembly of paraboloid main reflector and sub reflector. The feed is located at one of the sub reflector, which is closer to the main reflector. This type of feed is in transmit-receive type of large antenna. Figure 6.8(b) shows the configuration of a Cassegrain antenna feed system.



(a) Primary feed (b) Cassegrain feed (c) Off set feed

Figure 6.8 Feed system.

The position of the feeder is at the focal point f of a reflector and is governed by the diameter of the reflector such that:

$$\frac{f}{D} = 0.25 \cot \frac{\varphi}{2}$$

where ϕ is the flux density and D the diameter of parabolic reflector.

Antenna Reflector

Mostly parabolic reflectors are used as the main antenna for earth stations because of the high gain available from the reflector and the ability of focusing a parallel beam into a point at the focus where the feed, i.e., the receiving/radiating element is located. For large antenna system more than one reflector surfaces may be used as in the Cassegrain antenna system. The diameter of antenna reflectors used presently for satellite communications vary from 1 m to 15 m. An earth station in VSAT terminal uses about 1 m antenna. However, for some specialized services like radio determination services, parabolic reflectors are not found to be suitable and omni directional antennas are preferred.

Earth stations are also classified on the basis of services for example:

1. Two way TV, Telephony and data
2. Two way TV
3. TV receive only
4. TV receive only and two way telephony and data
5. Two way data.

From the classifications it is obvious that the technology of earth station will vary considerably on the performance and service requirements of the earth station.

For mechanical design of parabolic reflector the following parameters are required to be considered:

1. Size of the reflector
2. Focal length/diameter ratio
3. RMS error of main and sub reflector
4. Pointing and tracking accuracies
5. Speed and acceleration
6. Type of mount
7. Coverage requirement
8. Operational gusting and survival wind speed

The size of the reflector depends on transmit and receive gain requirement and beamwidth of the antenna. Gain is directly proportional to the antenna diameter whereas the beamwidth is inversely proportional to the antenna diameter. For high inclination angle of the satellite, the tracking of the earth station becomes necessary when the beamwidth is too narrow.

While selecting the size of the antenna, it is preferable to select a standard size, which will be cost effective. Diameters of some of the antenna reflectors available commercially for domestic satellite systems are 11 m, 7.5 m, 3 m, 2.5 m, 1.37 m. Antenna reflectors used in VSATs may not be always circular in shape. Offset fed antenna reflectors of VSAT may be square, rectangular and elliptical in shape depending upon the design of the feed and illuminated surface area requirement.

The gain of an antenna is given by

$$\text{Gain} = \eta \frac{A_{\text{eff}}}{A_{\text{iso}}} = \eta \frac{4\pi A_{\text{eff}}}{\lambda^2} \tag{6.14}$$

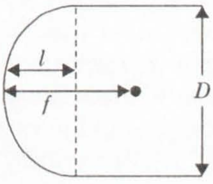
where A_{eff} is aperture of the antenna,
λ is wavelength, and
η is efficiency of antenna system.

For a parabolic antenna with circular aperture diameter D, the gain of the antenna is:

$$\text{Gain} = \eta \frac{4\pi}{\lambda^2} \cdot \frac{\pi D^2}{4}$$

$$= \eta \left(\frac{\pi D}{\lambda} \right)^2 \tag{6.15}$$

The focal length depends on the depth from normal drawn aperture plane to vertex, i.e.



$$f = \frac{D^2}{16l}$$

The overall efficiency of the antenna is the net product of various factors such as:

1. Cross polarization
2. Spill over
3. Diffraction
4. Blockage
5. Surface accuracy
6. Phase error
7. Illumination
8. Ohmic and mismatch loss

The ohmic losses of the feed and the antenna contribute to the internal sources of noise. In the design of the feed, the ratio of focal length F to the diameter of the reflector D of the antenna system control the maximum semi angle subtended by the reflector surface on the focal point. Larger the f'/D ratio larger is the aperture illumination efficiency and lower the cross polarization. The radiation pattern of the feed is mostly confined to the cone defined by the solid angle subtended at the focal point of the optical aperture. The illuminating fields from the feed form cophase wavefront after reflection from the reflector. The reflected cophase wavefront and the spill over radiation pattern combine at the far distance and form the secondary radiation pattern, consisting of the main lobe and the side lobes.

For an earth station antenna, the side lobes of the secondary radiation pattern have to meet the CCIR recommendation 580. As per which

1. For antenna size $D/\lambda \geq 100$, the gain for given beamwidth is

   $G(\theta) = 29 - 25 \log_{10} \theta$ dB $1° \leq \theta \leq 20°$ (6.16)

   $= 32 - 25 \log_{10} \theta$ dB $20° \leq \theta \leq 48°$ (6.17)

   $= -10$ dB $\theta > 48°$ (6.18)

2. For antenna size $D/\lambda \leq 100$,

   $G(\theta) = 49 - 10 \log (D/\lambda) - 25 \log_{10} \theta$ dB

   For $100\ D/\lambda \leq \theta \leq D/5\lambda$ (in degrees) (6.19)

   $= 52 - 10 \log (D/\lambda) - 25 \log_{10} \theta$ dB

   For $D/5\lambda \leq \theta \leq 48°$ (6.20)

   $= 10 - 10 \log (D/\lambda)$ dB for $\theta = 48°$ (6.21)

where θ is 3 dB beam width.

For Cassegrain antenna, single aperture corrugated horn has been found to meet the side lobe specifications of CCIR Rec. 580.

Apart from the main radiating element of the feed, the feed system consists of diplexer, polarizer, rotary joint, etc. The diplexer enables the feed system to operate at two separate frequencies for transmission and reception. The rotary joint and the rotating polarizer aligns the polarization of the feed with that of the transmit and receive waves. Different elements of a feed system are shown in Figure 6.9.

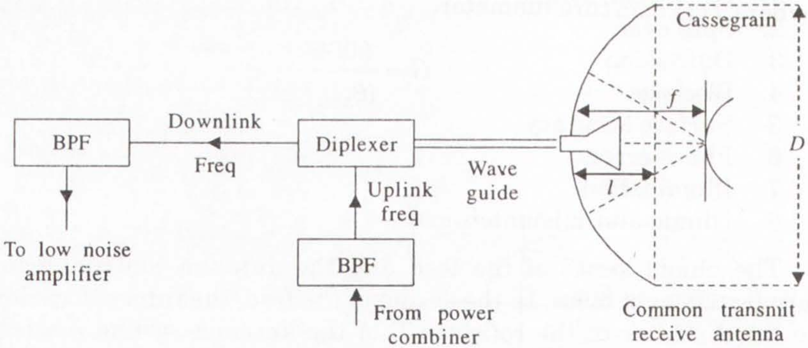


Figure 6.9 Feed system of typical antenna setup.

Parabolic Dish Antenna

The parabolic dish antennas are most commonly used with the types of feed systems, as shown in Figure 6.10.

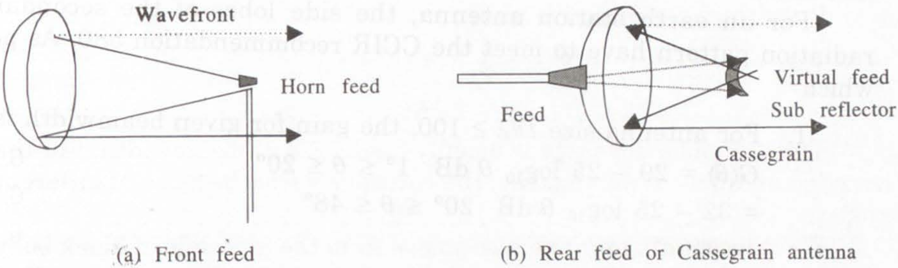


Figure 6.10 Feeding a parabolic dish.

In microwave frequencies it is common they are horn antenna also called flared aperture antenna. The flaring is provided to match the impedance of free space to that of the antenna. Such antenna provide maximum gain between 20 dB to 23 dB and their beamwidth cannot be reduced below 10°.

For higher gains reflector antennae with horn feed are used. The reflector is chosen such that the aperture created by it concentrates all the energy reflected to and creates a plane front with no phase change. One reflector shape that satisfies this is the paraboloid with feed placed at its focal point.

The beamwidth at 3 dB gain is shown in Figure 6.11(a) and given by

$$\theta_{3\text{ dB}} = \frac{75\lambda}{D}$$

where D is aperture diameter.

$$G = \frac{30000}{(\theta_{3\text{dB}})^2} \qquad 6.22$$

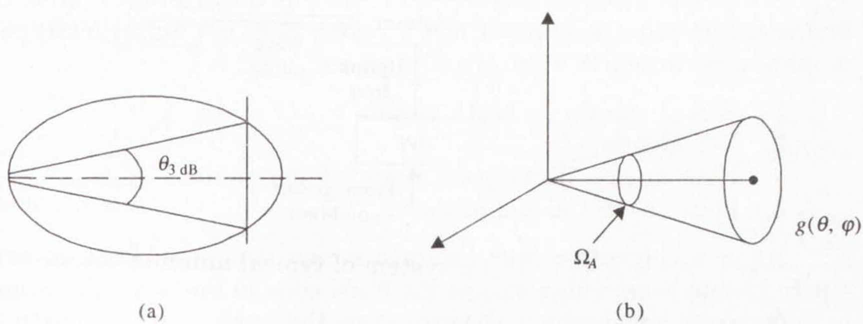


Figure 6.11 Main lobe beam width and radiation pattern.

The radiation pattern in unidirection is shown in Figure 6.11(b) and the cone represents the beam spread. Outside this beam the radiation is assumed to be zero. For a narrow beam this results in a solid angle;

$$\Omega_A = \text{(Half power beamwidth in E-plane)} < \text{(Half power beamwidth in H-plane)}$$

Resulting in a directive gain

$$G = \frac{4\pi}{\Omega_A}$$

The design for coverage is usually done for 3 dB beamwidth. For the horn fed of different dimensions, the coverage varies because of different angles.

The concept of antenna noise comes from the principle of black body enclosure as shown in Figure 6.12 where isothermal radiation exists. Two major sources, which contribute to antenna temperature, are external sources and internal sources. The contributions from external sources are due to emissions from earth, from atmosphere and galactic sources. The antenna surroundings are equivalent to the isothermal enclosure. In order to maintain its own temperature constant, the antenna should dissipate as much noise power as it has absorbed. As shown in Figure 6.12, $P_1 = P_2$ under matched condition. Thus, T_a is equal to temperature of black body enclosure or atmosphere around.

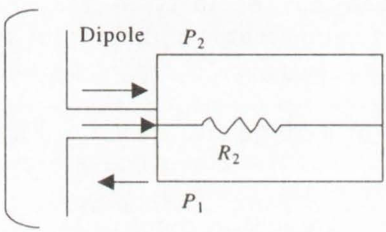


Figure 6.12 Antenna noise model.

Antenna Mount

Type of antenna mount is determined mainly by the coverage requirement and tracking requirements of the antenna systems. Different types of mounts used for earth station antenna are:

1. Elevation over azimuth mount
2. X-Y mount
3. Hour angle—declination mount (Polar mount)
4. Four axis stabilized platform

By using elevation over azimuth mount it is possible to cover the entire visible hemisphere except the blind cone in line with the primary axis (azimuth axis) which is vertical to the surface of the earth and carries the secondary axis (elevation axis).

In X-Y mount blind cone occurs in line with the primary axis (X-axis) which is parallel to the surface of the earth. Y-axis is perpendicular to the X-axis, for maximum coverage of the visible hemisphere. It is necessary to have near 180° movement of both X and Y-axis.

In polar mount, the primary axis is parallel to the earth's axis and is fixed for a particular location. Secondary axis is at right angle to the primary axis. Polar mount is becoming very popular for receiving satellite TV signals from a number of satellites in the geosynchronous orbit. It is to be noted that the polar mount becomes X-Y mount at equator and elevation over azimuth at the poise.

Four axis stabilized platform type of mount is used on board ships for mobile communication with satellite. In this type of mount in addition to azimuth and elevation movement, the roll and pitch movement of the ship are also required to be considered in the design of the mount. This type of mounts are used in standard A type of ship earth stations operating with INMARSAT satellites.

Antenna Tracking System

The antenna control may be affected by any of the following modes:

1. Slew
2. Manual
3. Auto
4. Programme
5. Step track

In the slew mode the antenna control is provided by independent velocity control of each of the axes. This mode is useful in orienting the antenna towards a particular satellite position.

In manual mode the antenna is brought to the desired position by rotating the two axes of the antenna by hand wheels or by geared motors. This type of tracking system is suited for operation with satellites with low inclination of the satellite orbit where the antenna position is not required to be adjusted frequently.

In auto tracking mode the antenna follows the position of the satellite. Monopulse type tracking feed is usually used for auto tracking. In this mode an error signal for each axis is generated by the monopulse tracking feed and the tracking receiver by comparing the strength of signals through two RF Beams geometrically offset on opposite sides of the main beam centreline. These error signals are the true tracking error signals so that when the error signals are nulled out by the control system, the peaks of the transmit and receive beam are pointed towards the satellite.

In programmed tracking system the antenna control system accepts an analog or digital tracking programme and compares the axis encoder readouts with the ephemeris data. This type of tracking is used while operating with a satellite with known orbital parameters.

Step track steering technique operates in the same way as an operator does when manually tracking satellites. It uses a hill climbing technique to locate and follow the point in space of maximum signal strength. AGC voltage from the communication receiver is used as an input to the servo electronics. The tracking accuracies are comparable to monopulse tracking system and because of its simplicity, substantial improvements in the reliability of the system can be expected. Step tracking system is well suited for an earth station operating with geosynchronous satellite.

Types of Beams

Depending on the application and types of communication, global beam or multiple beam antennas can be used. In broadcast it is essential to go in for global beams while for point-to-point communication spot beams are preferable. In case of search and rescue or burst transmission, scanning beams can be used. As mechanical steering disturbs the stability of crafts antenna, beams are steered electrically by using antenna arrays as shown in Figure 6.13.

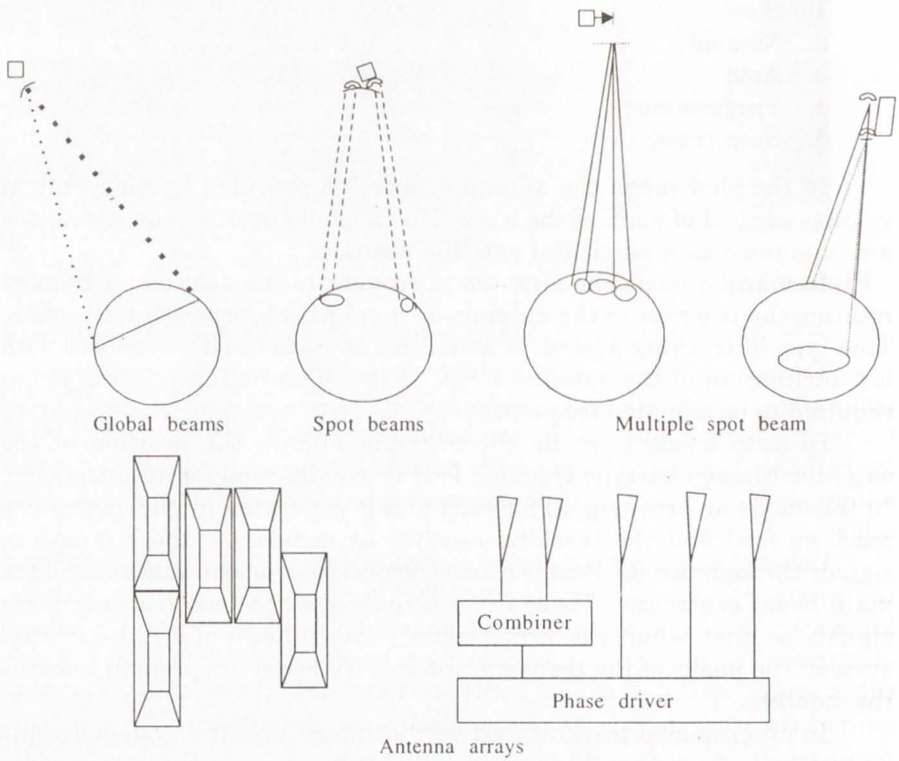


Figure 6.13 Different antenna and footprints.

Power Amplifiers

The choice of power amplifier depends upon several factors such as:

1. Types of access
2. Allowable mass
3. Acceptable non-linearity
4. Back off requirements
5. Efficiency
6. Saturated power

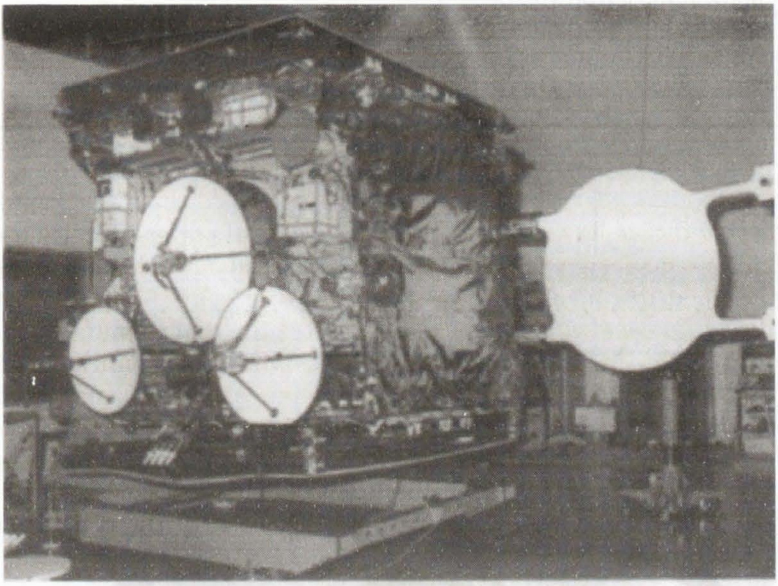


Figure 6.14 INSAT—3B on board antenna (Courtesy ISRO, India).

Travelling wave tube amplifier or solid-state power amplifier is generally used. TWTA are wideband amplifiers but have non-linear transfer characteristics. They can handle large powers but needs back off for FDMA where large bandwidths have to be handled. Figure 6.15 shows a high power 'O' type of travelling wave tube amplifier, which can handle a few watts of power.

Using multicavity structure, as shown in the figure, can increase the power output. State of the art TWTs give output power of tens of kilowatts. The magnetic field is parallel to the direction of flow of electrons. The gains of such tubes vary between 30 dB to 60 dB. These tubes can be operated from 2.0 GHz to 18.0 GHz. There is a reduction in gain as the frequency increases so also the length of the tube. The TWTs require either forced air cooling or liquid cooling. Detailed discussion of

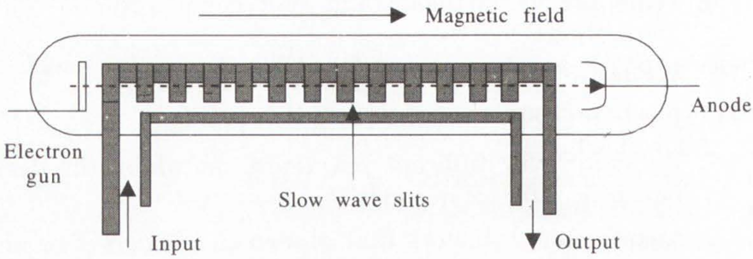


Figure 6.15 High power 'O' type TWTA.

TWT amplifiers are beyond the scope of this book and is available in numerous texts on microwave circuits.

SUMMARY

In this chapter we have studied brief discussion of power supplies used in satellites. Some design aspects had also been studied with an example. In this the need to consider requirements during eclipse period was also considered. In case of inclined orbit satellites the requirement of backup increases as the duration of solar panel receiving direct sunrays is much less and accordingly changes in the design are necessary. Another importatn subsystem in satellite communication is antenna. This is not only required during satellite in orbit but also during launching for launch vehicle and control of satellite orbit path. These aspects have been dealt in brief. Power amplifiers are also discussed without going much into the details.

REVIEW QUESTIONS

1. What is the overall distribution of electrical power requirement in a satellite?
2. Why backup batteries are necessary in spite of solar arrays?
3. What are the different types of solar array used?
4. Suggest a schematic of satellite power system giving its important features.
5. What is the need of regulators in satellite power block?
6. What are the different types of batteries used in satellites?
7. Explain the need of reflective layer and ultraviolet filter in solar batteries.
8. What are the characteristics that are most important in satellite antenna?

9. What are global beam and spot beam antenna? Give their applications.
10. What are the different types of antenna mounts?
11. Explain briefly antenna tracking systems.
12. What are the different prameters on which the design of a parabolic reflector depends?
13. List the major factors that govern the design of earth station antennas for satellite communication.

PROBLEMS

1. It is required to design a power supply for a satellite that has two buses each of 12 V. The peak power consumption during non-eclipse period is 500 W while the requirement increases by 20% as soon as the satellite comes out of eclipse. What are the solar panel requirements?

   (**Ans.**: 32 cells)

2. If in Problem 1, the eclipse period is 46 minutes what will be the battery requirement in ampere hours, assuming that only 50% of the load is in use during eclipse.

   (**Ans.**: 35.29 Ah)

3. An antenna has a gain of 46 dB at 12 GHz. Calculate its effective area. Calculate the gain of a 3 m reflector antenna at (a) 6 GHz and (b) 14 GHz.

   (**Ans.**: 46.67 m^2, (a) 43.55 dB, (b) 51.192 dB)

4. Find the gain and beamwidth of an antenna of diameter 2 m operating at 14 GHz. Assume an aperture efficiency of 60%.

   (**Ans.**: 47.12 dB, 0.88°)

5. Suppose the receiving antenna is a parabolic dish antenna with diameter of 1.75 m and is operating with a horn at 5.956 GHz. Calculate the antenna aperture and the gain in dB. The efficiency of receiving antenna is 80%.

   (**Ans.**: 2.40 m^2, 435.46 dB)

6. Calculate the 3 dB beamwidth of antenna in Problems 4 and 5.

   (**Ans.**: 2.35°)

7. If in Problem 4 a beamwidth of 1.5° is required, calculate the dish diameter.

   (**Ans.**: 1.185 m)

8. If a parabolic dish of diameter 2 m is used at 4 GHz, calculate the gainwidth with respect to beamwidth as per the CCIR equations.

   (**Ans.**: 25.89 dB)

7 Satellites in Mobile Communication

7.1 INTRODUCTION

In this chapter we will see some applications of Geo-stationary and Low earth orbit satellites in mobile environment. As a preamble an introduction to land mobile will also be discussed without going into a detailed study, as Land mobile itself is a vast field. Mainly we will discuss some examples of satellites for mobile communication and its applications.

7.2 LAND MOBILE CONCEPTS

Mobile personal communication is at the verge of overtaking landlines for the simple reason that it is more convenient, easy to carry and provides unlimited services. Mobile services started with analog short distance wireless paging systems especially for military and police applications. Later hand held LCD display digital services became popular in the private sector. Paging systems use various dynamic call batching, multiplexing and interleaving algorithms. Service providers have patented many codes. The earlier systems were one-way (simplex) systems. Subsequently two-way (duplex) systems were introduced. It has always been felt that the best way of communicating is direct online communication to avoid misinterpretation. Hence the necessity of talk-back system became essential. This required number of repeaters for a well-knit mobile network. This was the starting point of today's cellular mobile network.

ITU allotted 470–512 MHz, 806–890 MHz as RF carriers for land mobile services. The standard land mobile channel widths are: 30 kHz for HVHF, 25 kHz for UHF and 25 kHz for 800 MHz Bands. The increase in number of users had also necessitated the use of trunking system. Earlier trunking systems used five group stations or base stations. Four of them worked as relay/repeater while the fifth one controlled the channel allocation and management. To initiate a call, all mobile stations have to constantly maintain contact with control station. When a call is to be setup the subscriber handset sends a burst of 0.35 sec on pressing talk button. This burst is sensed by control station, which then searches for an unoccupied channel. This is allocated to the subscriber to set up a call between him and called subscriber through the allocated channel and channel station acts as a relay station.

In the event of failure of control station one of the remaining four becomes the control station, which is intimated to other stations through a burst. This is necessary since control station is the key to the operation of the whole systems. The number of channel stations can be increased to some extent as prescribed by the CCIR/FCC.

Such a mobile system undergoes attenuation due to:

1. Free space loss (Transmission loss)
2. Plane earth attenuation
3. Fresnel zone effect
4. Refraction
5. Diffraction
6. Multipath/obstruction losses

Some typical values are illustrated in Table 7.1.

Table 7.1 Typical Losses in Land Mobile

Carrier frequency	450	900	MHz
Transmission loss	–1	–2	dB
Building losses	–25	–20	dB
Foliage	–6	–15	dB
Antenna gain of receiver			
Outside	–3	–2	dB
Inside	–15	–15	dB
Other losses	–15	–2	dB

A cellular mobile system is interconnection of the three major subsystems as shown in Figure 7.1. The mobile telephone communicates with a nearby cell site over a radio channel implemented at that cell. The cell site, in turn, is connected by land-line station to a central or distributed switch. This interfaces the cellular radio system to the

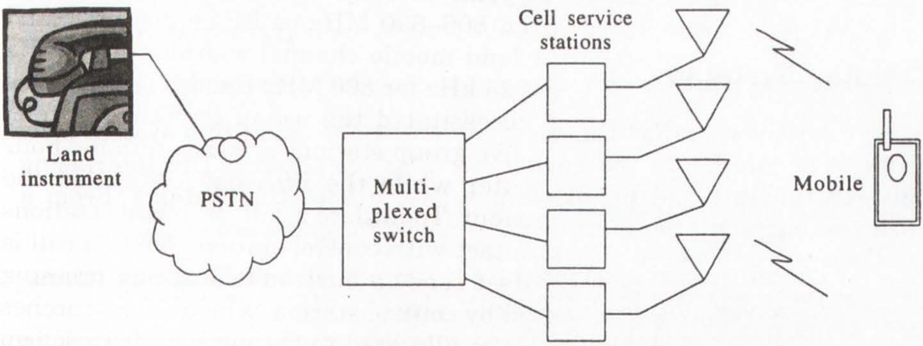


Figure 7.1 Land-mobile network (Terrestrial network).

wire-line network. Data are exchanged between the mobile terminal and the cell site over a special control channel reserved for that purpose. In addition, the voice channel also carries data that controls the handoff function. A further essential control function is called **cell supervision**. In Public switched telephone network (PSTN) the change of status is defined by the change/reversal in voltage. The mobile uses a continuous out-of-band tone modulation of the radio carrier for supervisory purposes called **supervisory audio tone** (SAT) and a short burst called **signalling tone** (ST).

SAT is generated by the Base station control (BSC) in the cell site and combines it with the voice-channel modulation. It also monitors the signal received from the mobile unit to determine whether the same tone is present. The presence of SAT implies that the call should be maintained, and its absence indicates that the call should be released. Normally the decision to end a call because of the absence of SAT is taken care by an algorithm residing either in the cell service station or the switching office and the time taken to release a call after the disappearance of the SAT depends on this algorithm. In most systems, before the call is dropped, SAT has to remain absent for a certain time period. It varies from a few seconds to tens of seconds. 5970, 6000, and 6030 Hz are typically used supervisory audio tones which are allotted to a cluster of cells, while for adjacent cluster it may be different. An off hook mobile terminal receives SAT from a cell site continuously and sends it back. (i.e., closes the loop). The cell site looks for a specific SAT and if some other SAT is returned, the cell service station interprets the incoming RF carrier as interference. The use of three SAT tones, properly assigned to cells, effectively multiplies the cochannel reuse (D/R) ratio for this loop supervision by 3.

The signalling tone is sent over 10 kHz carrier and is required for mobile station to be:

1. Alerted
2. During hand off
3. During disconnecting
4. Flashing for custom services

Cellular Systems

A user cannot visualize the main advantage of using this system as it looks to be similar to the earlier wireless telephones. The interfacing between landline and mobile is possible in both the systems. From a designer/engineer's perspective the major differences are:

1. A cellular system contains number of base stations (trans-receiver station), called **cell sites**.
2. Cellular system use large number of channels and work in frequency reuse mode.

3. Complex multiple access techniques are employed.
4. Calls have to be transferred from one channel/cell to another many a times.

These aspects will be discussed as we proceed further.

Why Cellular System?

By combining both advanced wireless and switching technologies, service operators get a cost-effective alternative to service delivery without much charge in infrastructure.

Wireless network is more flexible and economical than to build the fiber/copper network from scratch, also wireless broadband is more attractive.

1. It caters to large subscribers at low blocking rate.
2. Improves spectrum efficiency by having more number of cells/hr/ MHz.
3. Use of same frequency spectrum in and out of the cluster.
4. Universal subscriber number
5. Quality of services
6. Flexibility of services
7. Wireless access rate up to 155 MB/s per user.
8. Link availability can be engineered from 10^{-10} to 10^{-12} W

In land mobile the base station antenna could be at the centre of the cell and is omni directional. This station keeps track of the movement of every mobile terminal and reallocates the frequency (automatic link transfer) as the mobile terminal moves from one cell to another. Thus, it is disconnected from previous base station and connected to new base station. This is called **handover** or **hand off**. Cellular mobile consists of N number of cluster of m cells. These cells basically are coverage areas of an omni directional antenna system. The coverage area is hexagonal to see that there is no area uncovered and the boundaries of every cell exactly fit in. Each of the m cells uses one of the RF frequencies to carry the message. These m RF frequencies are reused in another cluster with a pattern chosen such that the interference is minimum, as shown in Figure 7.1.

Dividing the coverage area into small cells has the following advantages:

1. *Frequency reuse.* The available bandwidth is limited. The utility of available bandwidth is enhanced by reusing the frequency of one cell in another cell separated by a distance, without interfering with each other.

2. *Smaller power requirement.* As the size of the cell is small, the power requirement is less and hence the mobile unit can be small in size.

The maximum cell size for the service area is related to the desired reliability level. Most of the cells range from 2 km to 100 km depending on the service provider and local regulations. The reliability level is derived from the link budget and is used to estimate the maximum distance a subscriber can be located from a cell site and still achieve adequate service reliability. The cell size can vary within a coverage area due to the type of antenna and its height, foliage loss and other effects. These effects are generally related to the coverage area, service type, (such as urban, suburban or low density coverage). As the number of subscribers increase it is difficult to accommodate them in the service area. One method is to split the cells, this is called **splitting**. By doing so the channel capacity is enhanced, reliability is increased and blocking is removed. These are shown in Figure 7.2(c).

Cell sectors are obtained by using special separation/filtering and an orthogonal polarization scheme on adjacent sectors. This allows a high degree of frequency reuse, sector-to-sector. The sector requirement for the service area is based on the estimated traffic demand from the required traffic capacity. The higher the traffic, the more sectors are required to maintain the spectral efficiency. Cell sectorization provides additional traffic capacity per cell as the number of sectors increases, by permitting frequencies to be reused even within a single cell. The number of cell sectors affects the cost per cell and is the third determinant considered. The channel capacity can be arrived at, knowing the number of clusters, number of channels in each cluster and number of cells in each cluster. This is shown in Figure 7.2(d).

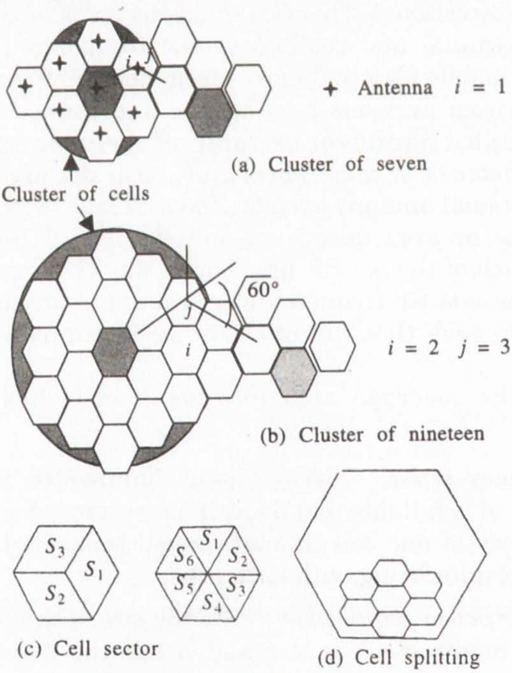


Figure 7.2 Cell structures.

Because of hexagonal structure, the number of cells in each cluster can be given by

$$m = i^2 + ij + j^2$$

where i is the number of cells from central base station cell and j is the number of cells covered under the line drawn at 60° from centre of the boundary cell of the one cluster to the adjacent cluster.

In Figure 7.2(a),

$$i = 1 \text{ and } j = 2 \text{ so that } m = 7$$

In Figure 7.2(b)

$$i = 2 \text{ and } j = 3 \text{ so that } m = 19$$

Observe that the number of cells in a cluster are always odd.

The channel capacity is, therefore,

$$C = N \times n \times m$$

where N is no. of sectors, n no. of clusters.

The received power at the edge (boundary) of the cell will be

$$P_r = \frac{P_t G_t}{4\pi R^2}$$

where R is the radius of each cell.

The channel capacity is restricted by co-channel interference and frequency reuse characteristics. Co-channels are those cells using the same carrier frequency. The nearest of such cells will evidently be generating interference and hence cause co-channel interference during detection at the mobile station. This interference can be reduced if the co-channels are far apart. Hence minimum distance will have to be maintained between co-channels. Co-channel reuse ratio is defined as *the ratio of distance between co-channels to the radius of the cell using that frequency* (D/R). Higher the D/R lower is the interference.

Cell Size Selection

The maximum cell size for the service area is related to the desired reliability level. The reliability level is derived from the link budget and is used to estimate the maximum distance a subscriber can be located from a cell site and still achieve adequate service reliability.

The cell size can vary within a coverage area due to the type of antenna and its height, foliage loss and other effects specified in this section. These effects are generally related to the coverage area service type such an urban, suburban or low-density coverage. Cell size selection affects the total capital cost for the required coverage area.

Traffic Capacity

Traffic capacity is determined by the spectrum available the technology adopted and modulation technique, for example, capacity in QPSK is less than in QAM. Multiple accesses is another factor, TDMA is more efficient than FDMA. Assuming a service provider has 500 MHz bandwidth, the modulation efficiency is 90% in case of QAM64 using 5 bits/sample/Hz, for 2.25 Gigabits/s traffic capacity.

Weather Effects

Rain can have a significant effect on microwave links as discussed in Chapter 4. In land mobile using microwave carriers rain fades naturally depends on:

1. Rain rate
2. Operating frequency
3. Polarization
4. Actual path length on a rainy day

Each of these factors can be used to calculate the effective signal attenuation caused by rain and is discussed under the section of link design. This attenuation is accommodated during link budget analysis and cell planning such that the link does not fail during these weather conditions.

The link budget is used to estimate the maximum distance for proper reception and signal strength that a subscriber can be located from a cell site. The budget considers, all outages due to multipath and rain fading that are accumulated over intermediate trunking links and a final distribution link must be taken into consideration. The link budget depends on:

1. Carrier-to-noise ratios (CNR)
2. Carrier-to-composite triple beat ratios (C/CTB)
3. Self-repeat site interface (C/I)
4. Link fade margins, including automatic gain control (AGC) circuitry located in low noise amplifiers.
5. Path length

7.3 ANTENNA FOR MOBILE

It has become a practice to use a common pole serving three cells instead of having the base station antenna at the centre of the cell. This common pole has three sectorial arms at 120 degrees on which three bi-directional or unidirectional antennas are mounted. The centre antenna transmits signals from the base station while the antennae at the extreme are used as receiving antennae. This enables reduction in the requirement of number of antenna structures. The three main classifications of broadband wireless antenna systems are:

1. Cell site antenna systems
2. Trunking antenna systems
3. Subscriber premises antenna systems

Cell Site Antenna Systems

These antennas are available in both horizontal and vertical polarizations and are capable of handling up to 50 W (47 dBm) of power. Each cell site within a digital broadband wireless network requires both a transmitting and a receiving antenna system. There are various types of antenna systems which can be used based mainly on the following four factors:

1. Azimuth pattern, sectorization scheme
2. Elevation pattern, cell site antenna height and location
3. Antenna gain depending on link budget
4. Polarization

Trunking Antenna Systems

In small broadband wireless networks, high performances parabolic trunking antennas can be used to deliver broadband signals between cell sites. These trunking antenna systems are provided with radomes (flexible or moulded) which protect the antennas against the accumulation of ice, snow and dirt, and reduce wind loading.

Subscriber Premises Antenna Systems

Subscriber premises antenna are available in various designs depending on application. Typical technology choices include micro strip, patch antenna, parabolic and grid-parabolic reflectors and horn designs. All of these antenna technologies are applicable in different locations. The flat-panel design is the most popular for subscribers who are close to cell sites due to their low profile and minimally obtrusive mounting. Subscribers that are farther from the distribution site require high-gain antennas. These antennas interface to an outdoor trans-receiver, which enables two-way operation.

7.4 HANDOFF OR HANDOVER

A simple mobile scheme is shown in Figure 7.3. When a subscriber moves out of one cluster (PCS) to another he is registered as a visitor to continue service, this is called **roaming**.

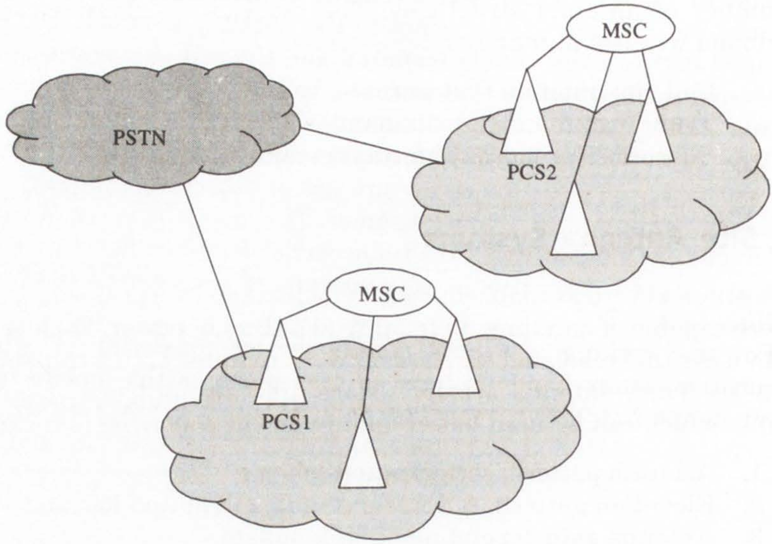


Figure 7.3 Mobile services scheme.

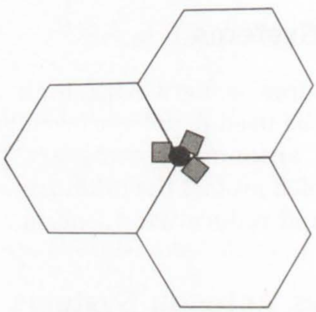


Figure 7.4 Antenna placement.

This involves four steps:

1. The subscriber's transreceiver momentarily suspends traffic (conversation, data, etc.) transfer and base station (BS) seeks a vacant channel in the new BS.
2. The network mobile switching centre (MSC) transfers the encryption details to the new vacant channel to create a new path.
3. The new BS sends signal to MSC of acquisition and registration. The subscriber continues transfer of traffic as well as MSC knows about it.
4. The new BS serves the subscriber.

There are three major elements of a cellular mobile system as shown in Figure 7.3. The mobile telephone communicates with a nearby cell site over a radio channel implemented at that cell. The cell site, in turn, is connected by landline facilities to a central (or distributed) switch, which interfaces the cellular radio system to the wireline network. Data are exchanged between the mobile terminal and the cell site over a special control channel reserved for that purpose. In addition, the voice channels also must carry data to control the handoff function.

A further essential control function is called **cell supervision**. The PSTN performs supervision as the process of detecting changes in the switch hook state caused by the customer. The mobile uses a continuous out-of-band tone modulation of the radio carrier for supervisory purposes. These are known respectively, as supervisory audio tone (SAT) and signalling tone (ST).

For the working of a land mobile service consisting of cellular configuration, many handoffs have to take place as the mobile trans-receiver moves from cell to cell. The handoff basically involves transfer from one base station to another and simultaneously the network switching control should bridge the two base stations for smooth transfer. This involves

1. Inter cell handoff
2. Inter base station controller handoff in the same cluster
3. Inter MSC handoff
4. Interpersonal communication services network handoff

Two types of Handoffs adopted are hard handoff and soft handoff. Hard handoff are used for Mobile controlled handoff (MCHO) as well as Network controlled handoff (NCHO)/Mobile assisted handoff (MAHO). This involves a temporary suspension of messaging to make a handoff request by the mobile station to base station. The new base station acknowledges the receipt of message. At the end of acknowledgement the message resumes (for example in cell phone conversation) on old link. The mobile station synchronizes with new base station. After synchronization is complete a handoff execution message is received from the new base station to mobile station and handoff is completed.

In the case of MAHO/NCHO signal strength measurement report is sent to the BS, which decides whether handoff is required. A mobile unit at a high level within the confines of a cell should have controlled output so that the other active mobiles do not suffer from co-channel or adjacent-channel interference. The location function in a cell site or system function can use measured interference, signal level or range. In either case, analysis of the information received by a central computer determines whether a channel change and/or cell site handoff is required. If required, base station sends handoff message to Mobile services control station (MSC) which in turn sends request to new BS. New base station acquires cipher key and sends acknowledgement to MSC, which sends a command permitting handoff to mobile station. Thus, handoff is completed. The handoff completed message is sent from the new BS to MSC for registration and voice communication resumes.

Soft handoff is basically used with CDMA cellular systems with MAHO. In this system the CDMA base station transmits a pilot that helps mobile station to carry out ranging and synchronizing. The field strength is reported to the base station which requests handoff to MSC. MSC in turn sends request to new BS, which sends a null traffic message to the mobile station to establish contact. The MSC and new BS communicate to join the link with required PN sequence. Once the link is established, handoff acknowledgement is sent to MSC, which is forwarded to old BS and MS. Thus, handoff is completed and new BS serves the MS. Typical hierarchial architecture of cellular mobile system is shown in Figure 7.5.

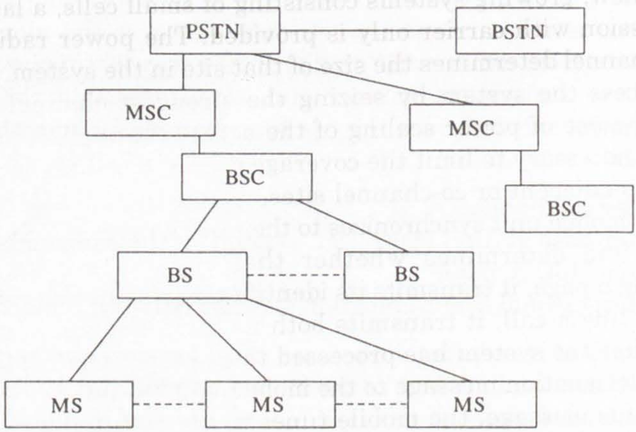


Figure 7.5 Typical hierarchial architecture of cellular mobile system.

The main difference between hard handoff and soft handoff is that the transfer takes place in a fading link in the former case while in the latter case handoff occurs even when the link field strength is sufficiently good.

Paging and Access

The term paging is used to describe the process of determining a mobile's availability to receive an incoming call. The complementary functions use special channels called **setup channels**. When power is applied to a mobile unit, it scans a designated set off control channels and picks the strongest one on which to read an overhead message. From the overhead message the mobile determines if it is in its "home" and retrieves descriptive information about the local system. A parameter CMAX which specifies the number of setup channels to scan when a call is made, and a parameter called CPA which tells the mobile units whether paging and access functions are shared on the same duplex setup channel. There are 21 available setup channels in each of the wireline and radio common carrier bands, which are scanned, in sequential order by mobiles. Setting a higher-than-needed value for CMAX will have little system impact but will increase the scan time for mobiles.

In start up systems the functions of paging and access is combined on a single (duplex pair) setup channel. However, unlike voice channels, these channels are always on and always radiate omni directionally. Larger repeat patterns are necessary, are less costly and, therefore, should be used. However, as a system grows, the separation of paging and access functions into different channels (no longer duplex pairs) becomes beneficial to control interference for the paging function.

In new, growing systems consisting of small cells, a land to mobile transmission with carrier only is provided. The power radiated on this access channel determines the size of that site in the system, since mobile units access the system by seizing the strongest channel available to them. The use of power scaling of the access channel is useful when it becomes necessary to limit the coverage area of a cell this controls interference to adjacent or co-channel sites.

The mobile unit synchronizes to the word pattern of the chosen setup channel and determines whether that channel is idle or busy. If answering a page, it transmits its identification on an idle setup channel. If originating a call, it transmits both its identification and the dialled digits. After the system has processed this setup information, it sends a channel designation message to the mobile unit on the paging stream. On reading this message, the mobile tunes to the designated voice channel and the call can proceed.

Paging and access functions are combined on the same duplex set of control channels when large cells with omni directional antennas are used. As the system grows, with cell splitting and change to cells using directional antennas, more setup channels are needed to handle access functions. Omni directional antennas continue to handle paging functions.

Seizure Collision Avoidance

The initiation of a call by a mobile unit is a random event in space and time. Since all mobiles use the same setup channels, collisions can occur. A bit in the cell-to-mobile (forward) setup stream, called the **busy/idle bit** is set to busy by a cell site that detects a legitimate seizure attempt in the reverse (mobile-to-cell-site) setup message. The mobile decodes the forward stream, attempting a seizure only if the reverse path has been marked idle. It also opens a "window" in time in which it expects to see the channel become busy because of its own access attempt. If the idle-to-busy transition does not occur within the time window, the seizure attempt is aborted. In the event of an unsuccessful attempt, the mobile is programmed to try again after random delay.

7.5 LAND MOBILE SYSTEMS

Land mobile has undergone a lot of standardization since its inception the following systems have been in use for quite sometime:

1. Advanced mobile phone services (AMPS)
2. Global system for mobile (GSM)
3. Digital EIA/TIA (DAMPS)
4. Third generation services

AMPS

AMPS were one of the first systems evolved for analog signals. This used FDMA at 824–849 MHz band. It consisted of 12-frequency groups clustered together and employed frequency reuse. Each cell used 50 radio frequency channels. This used 832 channels from BSC to mobile stations and 832 channels from mobile stations to BSC individually in simplex mode but combinedly in full duplex mode. Thus, each duplex occupies a bandwidth of about 15 kHz. Since the transmission is FM, applying Carson's rule for voice transmission, the total bandwidth required for a deviation of 12 kHz is [2(12000 + 3000)], i.e., 30 kHz. In some European standards 25 kHz is being used and is called **ETACS (European total access communication system)**. Hence the centre (carrier) frequency of N^{th} channel is determined by logical calculation from the allowed voice channel frequency of 3000 Hz, that is, $0.03N + 825.0$. This will be the frequency from MS to BSC. If 45 MHz is added to this frequency, the receive frequency can be arrived at. Figure 7.6 shows the spectrum allocation in case of AMPS. It is necessary to have information exchange between the MS and the BSC for which control channels are dedicated and centred at frequencies of 835 MHz and 880 MHz. Control channels

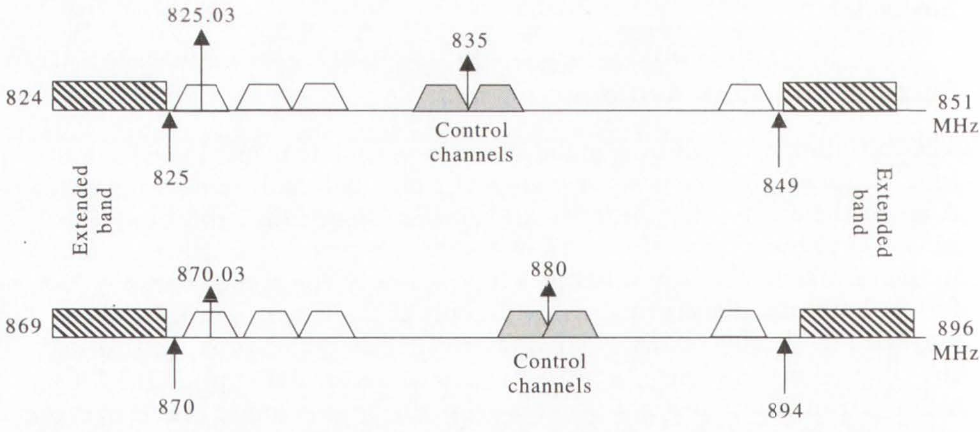


Figure 7.6 Spectrum allocation in AMPS mobile to BSC (top), BSC to mobile (bottom).

take care of call management, call through, call termination, MS lock/ synchronization during idle condition and paging services as explained earlier under interfacing. AMPs use FSK to transmit forward and reverse control. In view of the demand additional 166 channels are allocated in the extended bands. To cater to increasing demands, Motorola adopted N-AMPS (Narrow band-AMPS) in which 30 kHz channel is shared by three mobiles using FDMA.

SNR varies with distance from base station and the frequencies used. Since within a cell the carriers may interfere hence adjacent cells as well as within the cell the same carrier frequencies are avoided. The signal to interference is kept within 18 dB. Frequency reuse in other clusters is allowed. Amps follow EIA/TIA IS41 for mobility management. IS41 follows inter system handoff. In this both the BS are connected to two different MSCs, served by respective MSC. The MSC communicate among themselves to estimate the quality of link. As the signal quality deteriorates MSC 'X' asks MSC 'Y' to serve Mobile Station (MS) by providing a channel. MSC 'Y' checks a vacant channel in new BS and on finding one, instructs MSC 'X' to transfer the link. MSC 'X' instructs MS to synchronize with new BS.

Global System for Mobile (GSM)

GSM is one of the systems very popular with mobile phone providers since 1982. This is a second-generation (2G) system compatible with landline network like PSTN and ISDN. GSM is a digital cellular system. This system is a combination of FDMA/TDMA. In a GSM base station every trans-receiver supports eight VC as compared to AMPS, which handles only one duplex. Frequency carrier is divided into eight time slots. GSM was initially used in Europe but now is also used in other continents. The main three GSM are **GSM 900** in the spectrum 890–915 MHz/935–960 MHz, **GSM 1800** [1710–1785 MHz/1805–1880 MHz], **GSM 1900** [1850–1910 MHz/1930–1990 MHz]. The main thrust of GSM was to provide roaming facility to the user with interfacing to PSTN and ISDN. GSM services were made available to public in 1993 with 36 GSM networks operational in 22 countries. GSM has become popular in as many as 86 countries all around the world.

GSM defines three services:

1. Bearer
2. Tele
3. Supplementary

Bearer services. These are used for synchronous and asynchronous data transfer. These are circuit switched to connect mobile service station to PSTN. The bearer services consist of interrupt and non-interrupt type. In the former case the data could be lost during shadow period or handoff. As the non-interrupt services use FCC and radio link protocol the data can be retrieved. The transmission is at 9600 bps with a BER of as low as 10^{-7}. Because of circuit switching there are long delays, which can not be tolerated by applications like internet and world wide web.

Tele services. The tele services handle encrypted voice, message and basic data communication like SMS—short message service. A mobile subscriber is connected to public land mobile network (PLMN) via U_m interface. This interfaces the mobile terminal to PSTN/ISDN. It is essential also to connect other technical network to GSM for proper roaming facility.

Supplementary services. These are divided into unstructured and structured services. The former being compatible with older MS sets. The services provided are user identification; call forwarding or redirect, group or conferencing etc. In order to make it compatible with older versions command codes are specified.

GSM Architecture. The GSM architecture consists of three sub-systems, each connected with specific protocols consisting of different level standard interfaces as shown in Figure 7.7(a). This required for security and network management. The three subsystems are:

1. Radio subsystem (RSS)
2. N/W switching subsystem (NSS)
3. Operating subsystem (OSS)

Radio subsystem. It represents all wireless communication to access the mobile stations and the base stations. The access interface (A-interface) is a circuit switched PCM system. This carries thirty 64 kbps connections in TDM mode amounting to 1920 kbps with overheads of 128 kbps. A-interface of 64 kbps or 2.048 Mbps is used from BSC to MSC.

The radio communication is over a 25 MHz spectrum with carrier frequencies from 890 MHz to 915 MHz in forward link (MS to BS) and 935 MHz to 960 MHz band in the reverse (BS to MS) transmission in GSM 900. Each voice channel is divided into 200 kHz wide spectrum. These are shared using TDMA among eight mobile units. In the radio subsystems there is one base Trans-receiver per cell and many Base station controllers controlling a cluster of cell stations. Base station controller (BSC) manages BTS and is connected to several BTS. BSC assists in Handover from one BTS to another and Multiplexes radio channels for connecting BTS and MSC. The BSCs are connected to Mobile switching centre (MSC) through access interface. In a GSM network a number of base station have to be used, which encodes/decodes the voice and interfaces with landline. The BTS and BSC communicate through A-bis interface. The A-bis interface is of 16 or 64 kbps connectivity.

A U_m interface is the wireless interface between MS and BTS which use TDMA/FDMA. The U_m connectivity is a ISDN mobile protocol connecting mobile station and base station. It takes care of media access and multiplexing.

While BSC looks after management of radio channels (including frequency hopping, terrestrial channel management), handover management, encryption and decryption, paging, traffic measurement, etc., BTS takes care of channel coding and decoding, rate adaptation, signal strength measurement and also some times frequency hopping and encryption and decryption.

Network subsystem (NSS). It is the most important subsystem in GSM and connects the wireless network to PSTN and performs handover functions between BSSs and caters to many BSSs through an MSC. In the network subsystem the MSCs interface the telephone networks to BSS. These connections are signalling system No. 7 (SS7) based, where personal communication services network (consisting of MSC, BSS etc.) is connected to PSTN. Every MSC has a coverage area. In order that a PSTN subscriber can get his call through to mobile station (MS), MSC communicates with SSP of the PSTN using SS7 through the Gateway Global mobile service center. The Service switching point (SSP) processes the call. SSP in a PSTN serves the same purpose as MSC in PCS network. Signal transfer point (STP) relays SS7 messages between NSS and Global mobile service centre (GMSC), which in turn communicates with the operating sub-system or database. Interfacing of GSM subsystems is shown in Figure 7.7(b).

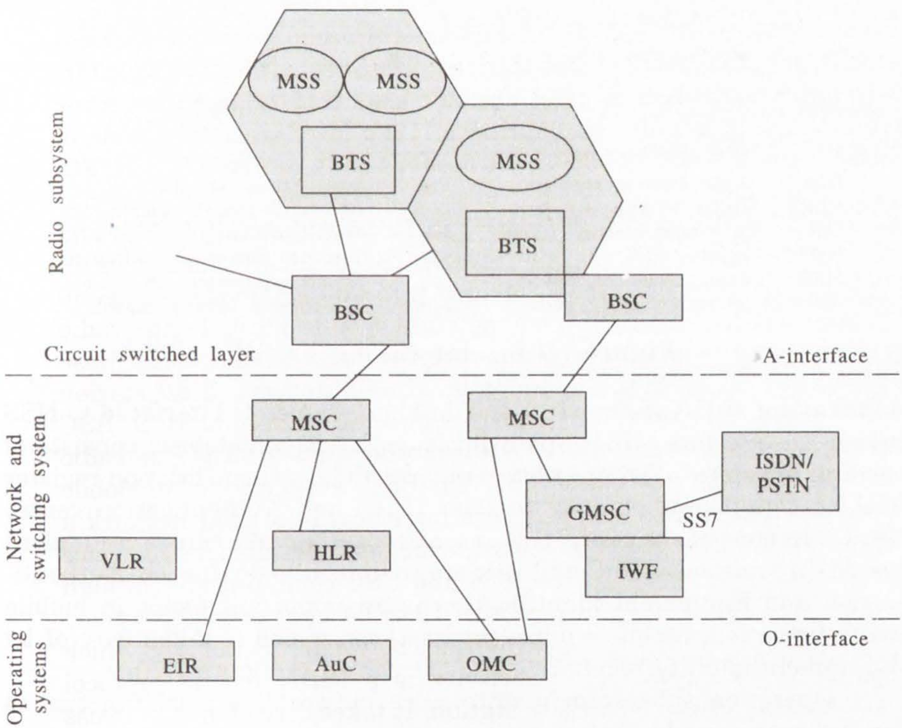
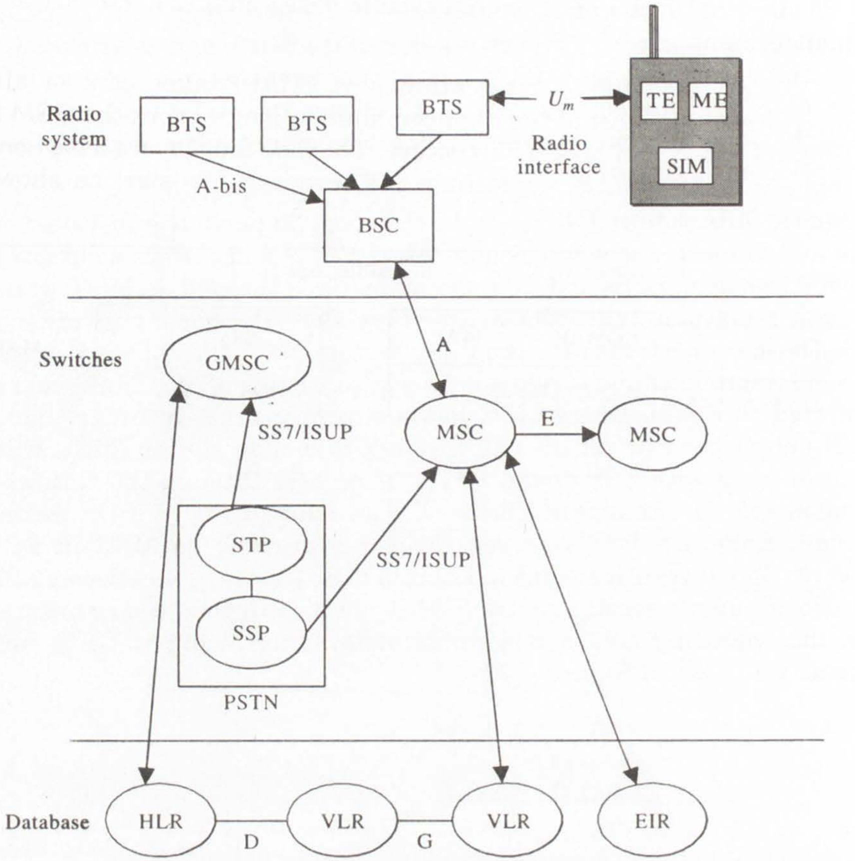


Figure 7.7(a) GSM architecture.



HLR	Home location register	BSC	Base station controller
VLR	Visitor location register	BTS	Base trans-receiver station
EIR	Equipment identity register	MS	Mobile station
GMSC	Gateway MSC	TE	Terminal equipment subsystem
MSC	Mobile switching centre	ME	Mobile equipment subsystem
SSP	Service switching point	SIM	Subscriber's identity module

Figure 7.7(b) Interfacing in GSM.

Operating subsystem. It is the database, which is interfaced to NSS using 'O' interface. GSM operating subsystem or database consists of several registers—Visitor location register (VLR), Home location register (HLR), Equipment identity register (EIR) and Authentication centre (AuC). In most of the cases HLR and EIR together take care of fraudulent users. In some cases AuC and EIR are combined to do this job. Authentication and Equipment identification is an important factor in mobile communication. Mobile equipment has lock, which is taken care of by Equipment identity register. These are shown in Figure 7.7(b).

Operation subsystem maintenance network's typical function is traffic monitoring, status report, subscriber service management, security management, accounting, tarrif management and billing.

O – interface is SS 7 signal system based on X .25 and carries data management.

The GSM Mobile application part (MAP) takes care of all the interfaces. Like most of the data communication network the GSM MAP protocol consists of layered structure. This has four layers based on SS7 namely, MAP, TCAP, signalling and message transfer, as shown in Figure 7.8.

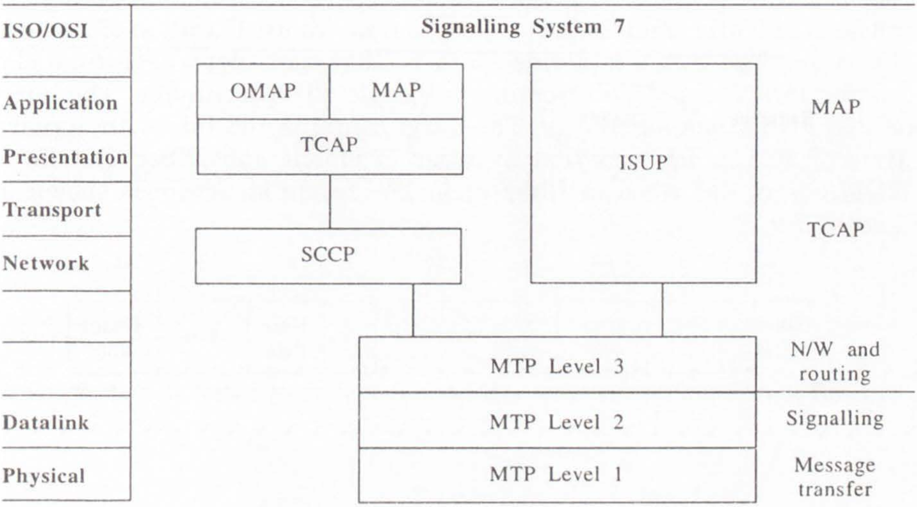


Figure 7.8 GSM protocol layer equivalence with ISO/OSI.

Message transfer part is equivalent to the physical and datalink layers of the open system interface. MTP level 1 handle the physical, electrical and functional characteristics while MTP level 2 takes care of signalling message transfer between PSTN and PCN. Level 3 is a part of the network layer that takes care of routing and network management. Part of the OSI network layer consists of signalling connection control part (SCCP). This separates the non-circuit related signalling and circuit related signalling.

Transaction capability application (TCAP) as the name indicates corresponds to the application layer of the OSI and takes care of information exchange between applications using SCCP. These applications are non-circuit related. The circuit related and circuit switched connections are taken care of by Integrated services digital network user part (ISUP).

OMAP is the operations, maintenance and administration part. GSM requires a standard OMAP similar to wireline network. This should be compatible with the ITU-T, Telecommunication management network (TMN).

The bearer services are connected to the lower three layers of ISO/OSI model that is the application, presentation and transport layers.

These are U, S and R interfaces of ISDN. Teleservices are application specific and may require all the seven layers of OSI model.

GSM frame. As we have defined earlier the GSM uses spectrum 890.2 to 915 MHz for uplink or forward path and 935.2 to 960 MHz for downlink or return path. Each channel occupies 200 kHz and hence the channel frequency in uplink is 890 + n0.2 MHz, that is, the channels are frequency division multiplexed. Also the GSM 900 has 248 TDM channels. These channels are further subdivided into TDMA frames enabling the reuse of 200 kHz channel in continuous time frame. Duration of frame is 4.615 ms. The frame is divided into 8 GSM time slots, each time slot lasting for 577 μs. This is similar to simple TDM technique. The burst of 200 kHz exists for 577 μs. The burst contains 148 bits with a guard time of 30.5 μs for variation in range of mobile subscriber. Details of TDMA were described in Chapter 5. The frame structure is shown in Figure 7.9.

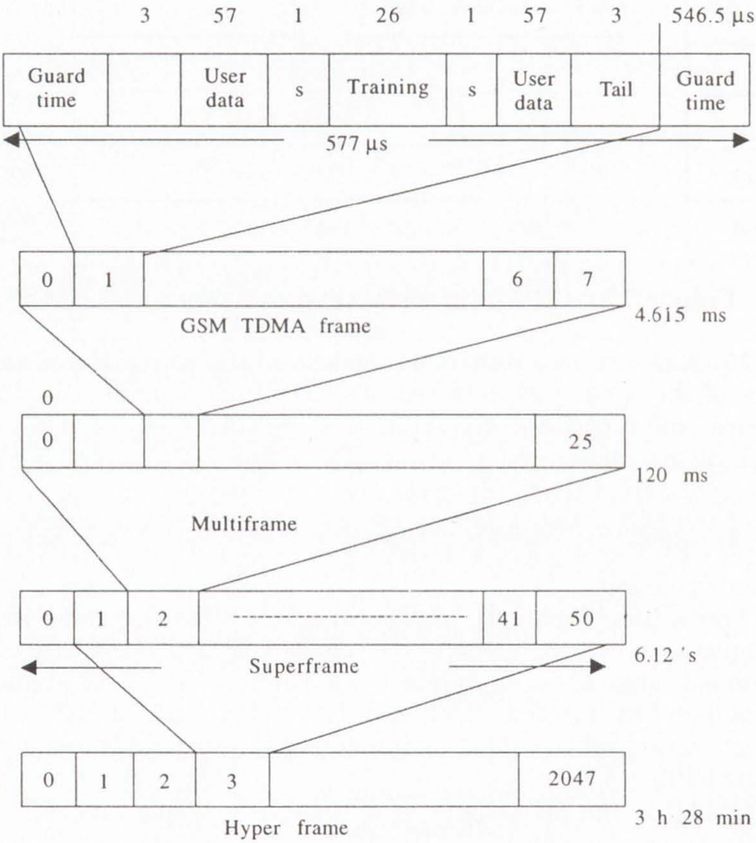


Figure 7.9 GSM frame structure.

The GSM mobile station transmits a burst of 546.5 μs, which consists of 3 bits of tail and helps in stabilizing the receiver performance.

The user data is 57 bits long followed by one bit of service information indicating whether the data of 57 bits is user data or network control information. The training burst helps in setup, synchronization and frequency correction. It selects strongest signal in case of multipath reception. This is one slot of the GSM TDMA frame. In order to overcome fading due to frequency after each GSM time frame, frequency hopping may be used. This hopping will not improve security aspects as these have preassigned sequences.

There are two types of multiframe—one data and the other control. Data or traffic channel (TCH) has 26 TDMA frame lasting for 4.615 ms. Traffic channel consists of voice or data at 13 kbps or 9600 bps, respectively. The control multiframe consisting of 51 TDMA channels lasting for 235.4 ms. The combination of these form a super frame lasting for 6.12 s. Many such super frames make a hyper frame. This is similar to the TDM adopted in voice channel multiplexing of T-1 system. The hyper frame can last for three and a half hours. In between, guard time takes care of variation in path length and recovery. In order to accommodate more channels newer coding techniques using TCH/F48 and TCH/F96 are being adopted. A slower rate called **half rate** TCH is also used which is 6.5 kbps/4.8 kbps.

The control channel takes care of signalling. Three types of control channels used are broadcast control channel, common control channel and dedicated control channel. BCCH takes care of frequency correction and synchronization. CCCH takes care of paging and access; slotted 'Aloha' is often used for the purpose for random access but as usual this has to face collision. DCCH takes care of handovers, channel exchange, signal quality, power measurement and decision. In GSM multiplexing scheme is hierarchically defined and has to be strictly followed.

Security. Authentication and encryption is used to avoid unauthorized usage. A 128 bit Random number (RAND) is used in mobile, which is stored, received and compared; if they do not tally, access is denied. If access is accepted, encryption key is produced and sent to MS. The SIM (Subscriber identity module) is protected by a PIN (personal identity number) to avoid misuse. Network operator loads the PIN. When an MS is to be used the PIN number is asked or automatically scanned. The appropriate system servers deliver services, such as, registration, authentication, encryption and service categories. If it does not tally, the SIM is blocked and MS cannot be used. The SIM contains subscriber related information.

Capacity planning in BSC is extremely important since during any particular time the work distribution is:

Handoff management-20 to 25%
Hardware checking and authentication-15 to 25%
Call activity-20 to 25%
SMS-10 to 15%

Digital AMPS (EIA/TIA*—IS-136 and IS-95)

Digital mobile also referred to as United States Digital Cellular system or D-AMPS supports TDMA with different frequency slots. A subscriber can use a particular channel only during conversation and other subscribers can share the same channel during vacant period. The main advantages of D-AMPS over AMPS is that it is easy to manage as all services including voice are encoded. Encryption is possible to keep privacy, less noisy and compatible with other digital services. The control channel allocation is same as AMPS (42 primary channels) in addition 42 additional secondary channels are used. The modulation technique used is differential QPSK instead of FSK.

Linear predictive coding with CRC is used that helps in reducing the data rate half that of conventional codes. This helps to transmit voice at 4.8 kbps and overall rate is 7.95 kbps. Since many syllable patterns are predictable the coding is divided into class-1 and class-2 bits. Class-1 bits are essential to build back the speech while any error in class-2 does not affect the speech significantly. Special algorithms have been built to carryout such coding and error correction bits are added to class-1 bits. Frequency spacing is 30 kHz and spectrum 1850 to 1990 MHz. Sleep mode handset is used to conserve battery power.

D-Amps uses IS95 CDMA with constant SNR throughout the cell. The channel bandwidth is 1.25 MHz. Channel reuse possible as CDMA is used.

Third Generation Systems

Third generation started in 1992 under the aegis of IMT-2000. It is now called **3G mobile services**. In 1997 WorldSat started CDMA based 3G services. 3G supports 144 kbps BW. It is a data centric traffic instead of voice centric traffic. Since 3G uses CDMA it requires very broad frequency spectrum. 3G is supposed to incorporate MPEG-4 employing space time coding and loss less compression. These are made compatible with existing internet applications by using micro browsers and WAP. These are expected to provide an integrated approach to audio, video, data and multimedia services. These are high speed employing wideband CDMA (W-CDMA).

3G is focused on physical and MAC layers. The three types of 3G modes recommended are:

1. Direct sequence frequency division duplexing (DSFDD)
2. Multicarrier frequency division duplexing (MCFDD)
3. Time division duplexing (TDD)

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* EIA: Electronic Industries Association; TIA: Telecommunication Industries Association.

3G use both TDM and CDM technologies facilitating asynchronous and synchronous Base station synchronization. In view of numerous users using 2G, it is necessary 3G should be compatible with 2G where 2G is a circuit switched network and 3G is a packet switched supporting IP and multimedia. While the 2G used a spectrum in the range of 800 MHz and 1800 MHz with a bandwidth of 50 MHz, 3G uses the spectrum frequency of 2100 MHz with a bandwidth of 155 MHz.

With the improvement in DSP technology and embedded multimedia systems 3G handsets have become a reality. With wireless OS like WinCE, EPOC and PalmOS the handsets can be switched on and off by messaging.

There are many 3G configurations from different service providers using W-CDMA in which has mobile station consisting of terminal interface compatible with ISDN and Internet. It has a trans-receiver with signal processing which can handle visual phone, MPEG-4, mobile multimedia alongwith voice and data. These run on special operating system for control. User identification is taken care of by a UI module similar to SIM. The base station has a modem with the number of amplifiers and antennae. These are connected for diversity operation. These take care of combining signals for good SNR. ATM is used as backbone and BTS is connected to this through A-bis interface at 1.544 Mbps. The mobile service station takes care of switching between ATM-LAN, ISDN and PSTN. W-CDMA helps in better reception and use of multiple applications.

Another 3G system is the CDMA based on IS95A, it is also called 3G-3X. The main advantage of this scheme is improved packet data transmission, better error correction, higher voice channel capacity and higher battery life. This also uses ATM, PSTN, ISDN and Internet access. 3G systems and schemes are still getting improved and standardized to be acceptable by all service providers, as shown in Figure 7.10.

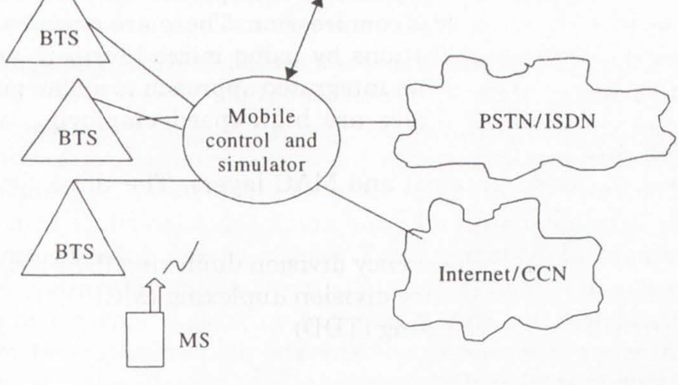
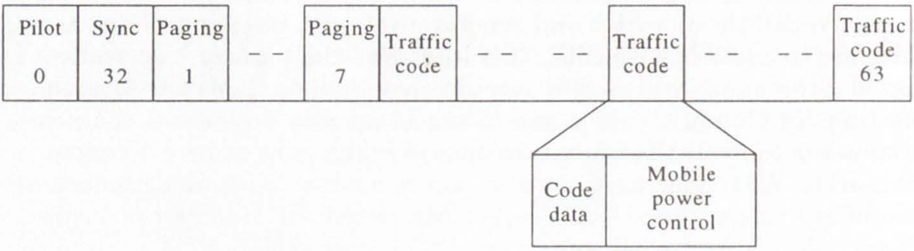


Figure 7.10 A typical 3G scheme.

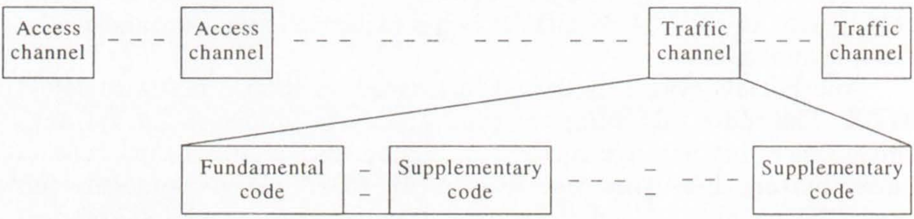
Channel Structure in IS95 CDMA

CDMA uses time interleaving of 20 ms span with error control coding to avoid multipath fading and shadowing. Speech is encoded using variable rate vocoder depending on the voice activity. The 20 ms channel consists of one pilot, one synchronization, seven paging and number of traffic channels. The pilot provides reference to all base stations and is required for demodulation. Quadrature phase shift keying is generally used. The information in each channel is modulated by appropriate Walsh sequence.

There are seven paging channel that provide system information, acknowledgement and instruction as shown in Figure 7.11(a). The sync



(a) Forward link channel structure of CDMA



(b) Reverse link structure

Figure 7.11 CDMA channel structure.

channel which is the 32nd Walsh slot has a data rate of 1200 bps. The sync follows the pilot to give time for synchronization. The sync can be divided into message, data, CRC and padding. Message is of 8 bits, data varies up to a maximum of 1146 bits and CRC of 30 bits. Depending on the length of data padding is added. One sync channel starts with a one bit start of message (SOM) followed by 31 bits of data. TA group of three sync frames is called a **super frame** and many such super frames exist which take care of system identification, network identification, pilot short PN sequence, system time, paging channel data rates, etc. The paging channel provides system information, instructions, called **parties number**, number of messages waiting and acknowledgement to access channel of mobile station. The number of bits in traffic channel depends upon the rate of transmission, for example, at 9600 bps 172 scrambled data, 12 CRC and 8 encoder tail bits are used while in case of 4800 bps 80 data 8 CRC and 8 tail bits are used in 20 ms. In between two bits of power control are also associated.

During return path the link channels are either reverse traffic channels or access channels. Mobile stations to get information about call origination and paging use the access channels. There could be 32 access channels with access rate of 4800 bps. All data on the reverse traffic is convolutionally encoded, block interleaved and modulated. The modulation is on one of the 64 orthogonal Walsh code. The reverse traffic channel has data rates of 1400 to 9600 bps. Six code symbols are used per modulation. OQPSK is preferred, as shown in Figure 7.11(b).

Idling time is extremely important in CDMA services as during this period the MS monitors and synchronizes with paging services and also is in the power save mode. This increases the battery backup time.

The number of mobile users is given by the ratio of processing gain to E_b/N_o. However due to interference, power control to avoid near-far effect, antenna radiation and voice activity the number of users per cell reduces drastically to:

$$M = \frac{G_p}{E_b/N_o} \times \frac{1}{1+\beta} \times \rho \times \frac{1}{\gamma}$$

where β is the interference factor, varies from 0.4 to 0.55, ρ is power control factor between 0.6 to 0.9 and γ is voice activity from 0.5 to 0.9.

7.6 INTERFACING

Interfacing of satellite to terrestrial networks is carried out through gateways (routes). The gateways have to function to match the data rates, change protocols, take care of protection by firewalls. The data rates may be very high if the terrestrial network is a broadband one (ATM) and it may be bursty if it is packet switched (IP). The access of channel in the satellite link may be discrete time—Dynamic virtual topology routing (DT-DVTR) for ATM traffic and Virtual node (VN) for carrying IP traffic. In DT-DVTR the system time period is divided into a set of time interval during which the satellite topology does not change. In VN, a virtual topology is set up with a virtual node; to make sure that the change in physical topology of datalinks is shielded from routing the packets.

The base trans-receiver station (BTS) is the hub that delivers and collects all the traffic to and from subscribers within the coverage area. The BTS is also the linking point between subscribers and the backbone network. Network management system (NMS) provides end-to-end management to all system components. Network configuration, quality of service, administration and control, monitoring, simulation, trouble shooting, and statistics reporting will all be managed under a central umbrella management system. It encompasses a highly integrated solution for cell site equipment by combining and managing the ATM and

RF (radio frequency). The number of physical components that combine at the cell site is small and the interconnections among different components are minimal.

This offers service providers the following features:

1. Ease of network planning
2. Ease of network deployment
3. High equipment reliability
4. Lower costs on site and building (small footprint at the cell site)
5. Simple, expandable base station hardware with minimum interconnection
6. Spectral efficiency

7.7 LOCAL BROAD BAND NETWORKS

GSM and CDMA networks are predominately voice based networks. These networks can also provide for some data transmissions with variations like in GPRS. However, for data transmission over wideband in local networks (WLAN), technologies like IEEE 802.11 and Hyper LAN are available. IEEE 802.11 is a packet based network and Hyper LAN is a (Virtual circuit switched) ATM network. These can offer data rates up to several tens of Mbps.

IP Networks

The infrastructure of 802.11 consists of Access points (AP) which connects the wireless terminals (TE) to a backbone wired network called **Distribution system** (DS). Each wireless terminal (TE) and the AP carry interface cards. These cards support MAC and Physical layers of 802.11, thus establishing data transfer between TE and AP. The rest of AP device acts as a bridge to convert the 802.11 protocol to MAC and Physical layers of backbone DS. All TEs communicate through AP, with each other or with devices in other networks connected through the backbone.

ATM Networks

The ATM radio interface card (ARIC) provides an interface between the ATM and RF world. Its main functions are ATM cell grooming and distribution, radio modulation/demodulation, forward error correction (FEC) and digital coding. An ARIC can be plugged into a standard universal slot. The ARIC also collects various performance matrices and passes them to the network management system. Each ARIC supports up to a 25.6 Megabits ATM cell rate. Multiple ARIC cards can be plugged into the same BTS to provide the required service capacity. In order to increase the overall system service capacity, Time division multiple access (TDMA) is implemented for the uplink so that a bandwidth shared environment is created at the ATM air interface level of subscriber access. The ARIC works together with the application service cards to support all TDMA related operations down to DSO granularity. A typical single-shelf configuration could consist of following:

1. One or two hub cards (for redundancy)
2. One or two control cards (for redundancy)
3. One ARIC
4. One network access line card

The above configuration will provide up to 25.6 Megabits/cell rate capacity and is expected to support up to 10 Gigabits capacity with a multiple-shelf system. When more than one ARIC is installed in a BTS, an RF combiner-splitter is required to combine multiple intermediate frequency (IF) channels from each of the ARICs.

Broadband Outdoor Transmitters and Receivers. Once the individual IF signals are combined, the signals are subsequently applied to a broadband transmitter. The outdoor transmitters are designed to be located on the antenna tower or rooftops and interconnected to the combiner using a single coaxial cable. Within the transmitter, the IF signals are up converted to the desired carrier frequency. These are amplified using multistage power amplifiers and sent to the antenna for transmission. A separate broadband outdoor receiver is located on the antenna tower or on a rooftop. It is connected to the ARIC card or a combiner using a single coaxial cable. This unit receives the entire band at carrier frequency and down converts the signals to the IF band.

The IF signals are then applied to the coaxial cable for distribution to the ARIC card(s). Separate transmitters, receivers and antennae can be used in each direction to minimize the near-end cross talk effects between transmit and receive signals. The distance between the radio modem and the outdoor transmitter and receiver can be over 150 m. This allows the RF equipment to be located on a tower or on a building, while ARIC cards, with modems onboard, are installed in an indoor environment. Power for the outdoor transmitter and receiver is duplexed over the IF coaxial cable.

Broadband Mobile Trans-receivers. The combined transmitter and receiver functions are provided in the broadband mobile trans-receiver. This can handle voice, video, internet and message services. Sensitivity, Noise figure, Power control range, Flexibility of use decide the broadband wireless ATM access network in mobile communication.

Features of ATM access in Mobile communication. ATM is a high-speed packet transport and switching technology that meets the networking requirements of all types of traffic, such as video, audio and data. The network access to subscribers is handled in a cell format through digital microwave transmission media. ATM has the following benefits to broadband access:

1. Convergence of voice, data and video traffic
2. Allow multiple services over one transport medium
3. Scalability
4. Maintenance and control of quality of service (QoS)
5. Statistical gain
6. End-to-end network management
7. Service provisioning flexibility
8. Future development compatible

Wireless access brings several key benefits to ATM networks, namely,

1. Rapid deployment with no need for heavy and costly construction work
2. Lower infrastructure cost for gradual deployment and build-out with demand
3. Extends statistical gain over the air with access media sharing
4. Easy implementation for broadcast service
5. Flexibility and scalability to match growth with 'take' rate
6. Capability to capture high value customer with flexible or non-uniform distributed network services
7. No access plant for easy maintenance
8. Resistant to natural and man-made disasters

Many satellite constellations (Cyberstar, Astrolink, Spaceway and Skyway) use ATM as network protocol, with a satellite specific signalling protocol. A discrete time Dynamic virtual topology routing (DT DVTR) where all virtual channel connections are grouped into virtual path connection (VPC) and onboard switching is done according to VPC labelling.

7.8 SATELLITES FOR MOBILE COMMUNICATION

AMPS and GSM do not provide a global solution to a subscriber in mobile communication. A backbone of satellite is the answer for such roaming. A typical global solution using satellite may consist of satellites with small footprints as the backbone. These satellites may be linked in space through inter-satellite RF connectivity. These satellites may be linked to gateways. In case of LEO satellites direct connectivity from mobile stations is possible. A typical scheme is shown in Figure 7.12.

A satellite system together with the gateways and terrestrial networks route the data from one mobile unit to another. The satellites can either handle individual links from mobile to satellite which sends it to another satellite which in turn sends signal downlink to the called mobile. The other possibility is that the routing takes via gateways earth station. The terrestrial network handles the call/data and sends to another gateway through the satellite. The frame can handle one channel

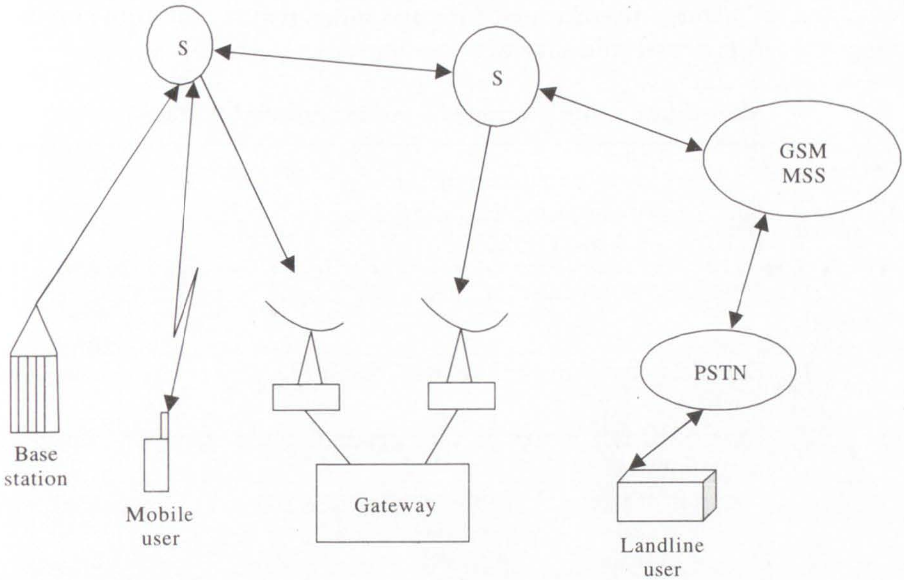


Figure 7.12 Typical scheme of mobile through satellite.

while numbers of gateways reduce. In the second case signals can be multiplexed but more gateways are required. Satellite complexity in Intersatellite Link (ISL) is more.

In satellite mobile alongwith home location and visitor location registers, satellite mapping register (SAMR) is essential. This register helps in storing the position of satellite and usage by the user. Satellite handover is another important aspect particularly in case of LEOS.

The satellites themselves could be having switching and processing circuits to be able to connect two mobile stations or gateway and PSTN. The satellites can have VUR and mapping register to keep track as both satellite and MS are moving.

As in case of cellular communication even satellites require handover as the MS moves from one place to another. Hence similar to land mobile, satellite mobile will require:

1. Inter-satellite handoff
2. Gateway handoff
3. Terrestrial N/W handoff
4. Base station handoff

Recent technology advancements and regulatory changes have enabled the spectrum in the 12 to 60 GHz range to be utilized for various applications. Use of the spectrum at these frequencies leads to a significant increase of the available bandwidth over the air and created a substantial opportunity for service providers.

In various markets worldwide, frequency allocations and/or licensing have been issued in the 12 to 60 GHz range for operation of multipoint radio access systems. The characteristics of three popular satellite mobile projects is shown in Table 7.2.

Table 7.2 Three Popular Satellite Mobile Projects

Parameters		*Iridium*	*Global star*	*ICO*
No. of satellites		72	52	12
Altitude [km]		780	1.414	10,390
Coverage		Global	± 70° Latitude	Global
Minimum elevation		8°	20°	20°
Frequencies [GHz]	Uplink	29.2	6.9	7
	Downlink	19.5	5.1	5.2
	Inter-satellite	23.3	–	–
	Mobile station	1.6 MS	2.5	2
Access method		FDMA/TDMA	CDMA	FDMA/TDMA
Bit rate		2.4 kbit/s	9.6 kbit/s	4.8 kbit/s
No. of channels		4,000	2,700	4,500
Lifetime [years]		5.8	7.5	12

Satellite Mobile Services

Mobile services in satellite are defined as *those services that connect the mobile stations and fixed station/stations.* The mobile services can be classified as:

1. Land mobile satellite services (LMSS)
2. Aeronautical mobile satellite services (AMSS)
3. Maritime mobile satellite services (MMSS)

Apart from these, ITU classifies mobile satellite services also as a distinct service particularly for distress and safety communications.

Land services are between two stations on land via satellites. Satellites perform the function of a repeater. The services may be made available to remote and isolated areas on land, where very little or no communication capability exists such as under the earth exploration, like mining, oil, gas recovery, etc. While aeronautical applications include air traffic control and navigation. Maritime applications could be distress calling for alerting the rescue centre during emergencies and safety broadcast for providing information to the mobile station regarding meteorology, navigation, environmental data, etc. This may also include fleet/truck/wagon monitoring and management.

For quite sometime, the mobile services were in HF and later VHF/ UHF frequency bands because of the technology available at that time and cost. These services had inherent limitations of reliability, availability, coverage, etc. The advantages of satellite systems for mobile communication have been recognized ever since the introduction of satellite communication systems in mid 60's. In fact, satellites are ideally suited for such purposes, even more than their suitability for providing fixed satellite services. The reasons are obvious. By the very nature, mobile communication needs large coverage, extensive reach and ability to communicate from any point to any other point in the coverage area. Base stations and type of accesses can control the traffic densities.

Several experiments using Advanced technology satellites (ATS) launched by United States during mid 70's demonstrated the feasibility of satellites for Mobile satellite services (MSS). However, the development of MSS has been comparatively slower than the Fixed satellite services (FSS). To date only the INMARSAT (International maritime satellite organization) organization provides operational services. But over recent years several systems like NOAA, GEOSTAR, SPACENET, etc. for digital messaging, NAVSTAR for global positioning and low altitude IRRIDIUM and GLOBAL STAR for MSS roaming services and so on, have been used. Some of the main reasons for this slow development are techno-economical. Mobile satellite systems have small antennas on mobile stations, thereby requiring high power satellites with larger antenna sizes, need of advanced spectrum conserving techniques, stability requirements of satellites, affordability, etc. have slowed down the development of MSS. Also the large number of relatively low traffic density users was an hurdle but the advent of cheaper DSP processors and with governments as well as private operators realizing the advantages of satellite based mobile systems have made the future of these services bright.

While the maritime mobile satellite services have been accepted since a long time, it is only recently that the International civil aviation organization (ICAO) has defined the requirements for Future air navigation systems (FANS). By 2010 AD satellite based systems for providing communication and navigation an Automatic dependent surveillance (ADS) has been recommended.

On the other hand, the military satellite systems have incorporated mobile satellite services since a long time. In fact, the primary aim of these systems has been to provide communication to the mobile units in the far-flung areas across the globe. However, there are certain important differences between civilian and military systems. These pertain to the frequency bands generally employed the cost of the ground terminals, the extent of the ruggedness required, the need for secrecy and anti-jamming capability.

Features of Mobile Satellite Services

Mobile satellite communication system comprises:

1. Space segment which consists of satellites and the associated ground control
2. Mobile earth station or stations

Space segment. Space segment is an area where particular attention to the technology is given. This is due to the high powers required to provide the satellite-to-mobile link for simple mobile terminals equipped with very low gain antennae. The mobile terminals with low gain antenna are susceptible to multipath fading, blockage by trees, buildings and other obstructions, which can severely attenuate the signal. To compensate for these factors, the space segment has to make up the deficiencies in the link budget by providing higher EIRPs. One solution is to use large number of channels with high power satellites and high gain multiple spot beams with associated beam pointing accuracies. Alternatively, medium sized satellites provide only limited number of channels, which for initial system operation may be sufficient. For better utilization of the space segment and available spectrum, power efficient technologies have to be used. The discussions elsewhere in this book give methods of achieving this.

Mobile earth station. The mobile station is required to communicate while in motion. This puts a constraint on the size and complexity of the terminal, in particular, on the antenna size and the power requirements. Since mobile terminals are individually owned terminals, the costs of these terminals are to be kept as low as possible. The mobile station antenna must be in the line of sight of satellite while the vehicle is in motion. The look angles and tracking aspects put a constraint on the mobile station especially in case of aircraft. Under these conditions the antenna should either be equipped with pointing and tracking facilities or should be near omni directional. Low gain (0 to 5 dB) antennas with hemispherical coverage are generally considered for providing low bit rate data communications. Large ships can be equipped with larger antennas having gain as high as 25 dB with simple tracking facilities for providing voice service. Recent trends in array antenna with gains of 15 dB and electronic steer ability are candidates for efficient mobile services.

In order to keep the equipment and complexity of the mobile stations low, the mobile stations have to communicate with a large fixed earth station. The fixed earth station acts as a gateway station to connect the mobile station to the public switched networks. The interconnection between mobile stations is also through the fixed station in a double hop mode. The gateway earth station can also provide the network control, switching, channel assignment, protocol check, etc. The gateway stations are also sometimes called as **hub stations** or **distribution land stations**. The links between the satellite and the mobile station operate in frequency bands allocated for MSS by the ITU while the links between the fixed earth station and the satellite (feeder links) fall under Fixed satellite service (FSS) category and hence operate in the bands allocated for FSS.

Space Segment for Mobile Communication

The three main orbits that have been considered for mobile communication are:

1. Geosynchronous
2. LEO altitude orbits
3. Medium altitude orbit

A geostationary satellite follows a circular orbit in the plane of the equator at a height of 36,000 km so that it appears to be fixed at a chosen point on the earth's surface (this was discussed in Chapter 2). Three such satellites are enough to cover most of the globe and mobile users rarely have to switch from one satellite to another. Other mobile satellite systems use larger numbers of satellites in lower, non-geostationary orbits. From the user's point of view, they move across the sky at a comparatively high speed, often requiring a switch from one satellite to another in mid-communication and risking the possibility of an interrupted call. To choose these orbits/altitudes for MSS, following criterion have to be considered:

1. Complexity of satellite
2. Complexity of trans-receiver
3. Orbital environment
4. Cost economics (both capital and recurring)
5. Power considerations
6. Link performance

As the satellite orbiting radius increases, the power requirement of both satellite and receiver increases. With the result, it is not favourable for mobile communication to have large orbiting radius. It may be necessary to keep the satellite in elliptical orbit so that the satellite is close to the footprint during its perigee for a long period of time.

The orbital environment requires that these satellites should be either well below Van-Allen radiation belt or well above this belt. The satellite cannot frequently cross this belt as they will be exposed to energetic charged particles causing logic upsets and even damaging the components permanently. The main source for this radiation is a stream of Plasma from the sun, which consists of energies to the tune of kilo electron volts. These have huge energy to penetrate thick metallic surfaces. The effect of this belt ranges from about 7700 km to 18,000 km.

Solar eclipse is another important criterion to be considered. Most of the satellites for mobile communication spend about 35% of their orbit period under darkness due to shadow of earth falling on them, which occur several times in a day. As has been discussed in Chapter 6, the power supply goes under stress as the satellite goes into eclipse and comes out of eclipse. Due to these stress cycles, additional care for design of power supply units is required; moreover it shortens the life of the satellite. The farther the satellite the more time the solar panels are illuminated by sun rays. For example, a LEO satellite is illuminated for about 55 to 60% of the time while MEO 85 to 90% of the time and GEO 99% of the time.

In mobile communication, delays caused due to propagation of EM waves in space affect the reliable performance of voice/video/data systems. Larger the delay more unnatural is the performance, for example, in case of GEO it takes about 400 ms for voice to travel uplink and downlink, thus the conversation over mobile networks due to the path delays is irritating to the subscribers. To reduce these delays it is necessary that slant-ranges should be as small as possible. Additionally because of larger path and system or equipment, mismatch echo and cross-talk can be experienced in MSS.

Since the satellites are mobile and a LEO sweeps the horizon from one end to another in 20 to 25 minutes, a satellite can only be used for this period. But even during this period the EM waves from the satellite get blocked by trees and buildings cutting off or deteriorating the reception. This is a serious drawback of MSS. Moreover the elevation angle and slant range are varying during the period the link is setup—causing variation in signal delays. ODYSSEY'S orbit constellation is designed such that at least two satellites are quite close to the receiver to overcome the above difficulties. Another problem faced by fast moving mobile trans-receivers is effect of Doppler shift, which affects the performance of MSS. Hence designers are looking for hybrid mobile systems with earth relay hubs connected to MSS.

For quite sometime the economics of MSS were not favourable, as the cost to build, launch and maintain the satellite was quite high compared to the revenue. For example, AT & T faced the problem because the subscribers were not happy with the reception and large delays caused in the link so that the expected growth never occurred.

With the modern mobile technology using CDMA/SDMA techniques, MSS is again picking up. Many of the designs are yet to be implemented and are in the laboratories or design centres. Table 7.3 shows the design criterion of MSS.

Table 7.3 Design Criterion of MSS

Selection criteria	*Low altitude constellations*	*Medium altitude constellations*	*Geosynchronous*
Complexity of satellite	· EIRP requirement less. Shortest lifetime, typically 5 year. · Limited footprint.	· EIRP requirement more. · More lifetimes, typically 10 years. · Footprint better than LEO.	· EIRP requirement highest. · Long lifetime, typically 10 to 15 years. · Large footprint.
Complexity of trans-receiver	· Most complex and costly ground control links. · Moderately complex trans-receiver. · Lowest cost transmission.	· Relatively low-cost ground control segment. · Moderately costly communicators of moderate weight.	· Relatively low cost for ground control segment. · Inexpensive but heavy communicators.
Van-Allen radiation	· Low levels of radiation. · Requires shielding as altitude increases.	· Moderate levels of radiation. · Requires shielding.	· Lowest radiation. · Requires shielding as passes through the belt during launch.
Effect of eclipse	· Frequent, 20 to 25 times a day. · Larger Backup requirement. · Stress designs of power supply a must.	· Infrequent, satellite in darkness hardly 3% of the time. · Less backup requirement. · Stress design not very stringent.	· Infrequent, hardly 1 to 2% of time in eclipse. · Very less backup requirement. · Stress design of power supply not very stringent.
Signal delays	· Negligible (μs).	· Moderate (ms).	· Longest (ms).
Variation in elevation angles	· Rapidly varying elevation angles.	· Slowly varying elevation angles.	· Negligible.
Doppler effect	· Yes.	· Yes.	· Limited.
Number of satellites required (Depends on altitude)	· Very large number for continuous communication, greater than 50.	· Moderate numbers required, less than 20.	· Few numbers required, typically 4 to 6.
Cost economics	· Satellite cost lowest, simple and light. · Launch cost low.	· Launch cost higher.	· Satellite cost highest. · Launch cost high.
Handoff requirement if any	· Yes.	· Sometimes.	· No.
Earth station hub	· Not necessary.	· Required.	· Required.
Type of modulation/access	· CDMA.	· TDMA/CDMA.	· CDMA/SS.

Baseband Processing, Modulation and Multiple Access Techniques

Due to the power limited situation in mobile satellite systems suitable baseband, modulation and multiple access techniques to conserve power are to be used. Single channel per carrier (SCPC) systems are highly suitable for mobile satellite systems and have been in use right from the beginning of introduction of MSS. The low-density traffic encountered in the mobile services also allows Demand assigned multiple access (DAMA) techniques to be used effectively for better utilization of the space segment resources. Presently many services have preferred CDMA/RMA as it provides lot of flexibility and security.

Initial systems like INMARSAT had adopted analogue voice with commanded FM for voice with limited number of voice channels and low bit rate communications in TDM/TDMA/SCPC mode. The emerging mobile satellite systems use either Amplitude commanded single sideband (ACSB) system with low bit rate encoding of 4.8 kbps or less for voice. Use of Forward error correction (FEC) techniques to conserve power has been accepted as a must in mobile satellite services. Suitable techniques such as interleaving, etc. are also used to provide multipath fading resistance.

7.9 MSS FREQUENCY BAND ALLOCATION

MSS involves a mix of operation of MSS and FSS frequency bands. The choice of the FSS bands for the feeder links are governed mainly by the FSS bands available on the 'host' satellites carrying the MSS packages and by the FSS co-ordination constraints. These links usually operate in the C-band or in the Ku-band allocations for FSS and generally, are not critical factors in the design of a mobile satellite system.

The MSS frequency bands, on the other hand, are critical for the operation of the mobile station and have an important bearing in the design of the system. The factors affecting the choice of frequency bands are:

1. Propagation effects like free space loss, atmospheric effects, ionospheric effects, etc.
2. Background noise like cosmic noise, man-made noise, etc.
3. Satellite and mobile station antenna size
4. ITU frequency allocations, bandwidth availability and future growth
5. Current usage and equipment availability
6. Sharing with other satellite and terrestrial systems/services
7. Technology
8. Cost

The free space attenuation and the atmospheric losses are more at the higher frequencies. However, ionospheric effects, multipath effects, satellite antenna size, background noise, man-made noise are more dominate at the lower frequencies. These considerations have lead to a choice of frequencies between 100 to 3000 MHz for mobile satellite services. For many years the bands from 235 MHz to 322 MHz and 335.4 MHz to 399.9 MHz have been used in defence satellite systems like FLTSATCOM, LEASAT, VOLNA, etc. The 1.5/1.6 GHz bands are being used for MMSS and AMSS. The allocations in the 800/900 MHz bands have been allocated for MSS. Due to the limited spectrum available for MSS, the frequency resource must be efficiently utilized especially as the systems grow. Frequency reuse by multiple antenna spot beams is being projected for future mobile systems. Polarization diversity technique, however, requires large and complex antenna systems. Polarization diversity technique for frequency reuse is not effective in MSS as the simple mobile station antennas have poor axial ratios and are susceptible to multipath effects.

Co-ordination Aspects

The simple nearly omni-directional antenna of the mobile station would make co-ordination between mobile satellite systems very difficult. The orbital spacing required between the satellites for co-channel, co-coverage operation would be extremely large. Closer orbital spacing of satellites requires narrow beams from the vehicle antennas. This, in turn, implies a satellite-tracking vehicle antenna constrained by size, shape and cost. Thus, in MSS there is likely to be a shortage of orbital slots. Co-ordination with terrestrial systems sharing the same band with MSS would also be required.

7.10 INMARSAT SYSTEM

INMARSAT was the world's first global mobile satellite communication operator and is still the only one to offer a mature range of modern communication services to maritime, landmobile, aeronautical and other users. Starting with a user base of 900 ships in the early 1980s, it now supports links for phone, fax and data communication at upto 64 kbps to more than 240,000 ships, vehicles, aircrafts and portable terminals. That number is growing at several thousands a month. It operates a constellation of geostationary satellites designed to extend phone, fax and data communication all over the world. The constellation comprises five third-generation satellites backed up by four earlier spacecraft. Today's INMARSAT's system is used by independent service providers to offer a range of voice and multimedia communication.

INMARSAT system is an international organization whose purpose is to provide the satellite system required to support mobile communication and radio determination services on a worldwide basis. Established in 1979, it now comprises 67 member countries and since 1982 has operated a global network of L-band satellites. These provide services for ships, aircraft and now, also, for land mobile users throughout the world. INMARSAT provides services conforming to agreed international standards which enables the mobile to roam and operate throughout the world subject to national licensing requirements.

Composition

The three essential components of the INMARSAT system are:

1. The space segment which consists of the satellites and ground support facilities.
2. The Land earth station (LES) which provide an interface between the space segment and the national and international telecommunication networks.
3. The Mobile earth stations (MES)—the satellite communication terminals which are purchased or leased to individual owners/operators.

Land-to-mobile communication and satellite to LES are in the 6 GHz band (C-band) while satellite to mobile is in the 1.5 GHz band (L-band). While mobile-to-land communication are in the 1.6 GHz band and mobile to satellite in the 4 GHz.

The Space Segment

The first generation INMARSAT space segment essentially consisted of leased space segment from different organizations. INMARSAT leased three MARISAT satellites from COSMAT to start the service in three regions namely Atlantic ocean, Pacific ocean and Indian ocean. This capacity was augmented by further leasing of two MARECS satellites from the European space agency (ESA) for the Atlantic and Pacific Ocean regions. INMARSAT also leased from INTELSAT, Maritime communication system packages, on three of its INTELSAT-V satellites in the three ocean regions. The capacity from each MARISAT satellite was about 8 channels, that of MARECS satellite 40 channels. The INTELSAT-V MCS package provides about 30 channels.

INMARSAT's second-generation project consisted of its own spacecraft (INMARSAT-2) launched during 1990 and is operational since then. They provide services for 250 channels capacity per satellite and a total satellite EIRP of 39 dBW. INMARSAT's primary satellite constellation consists of four INMARSAT-2 satellites in geostationary orbit. Between them, the main global beams of the satellites provide overlapping coverage on the whole surface of the Earth apart from the poles. Launched in the early 1990s, the four second-generation satellites were built to INMARSAT's specification by an international group headed by British Aerospace.

The third generation INMARSAT satellite, viz. INMARSAT-3 consists of seven multiple spot beams to increase frequency reuse and to derive maximum EIRP from these. The spot beams provide frequency reuse and thus help in increasing service capability to areas where demand from users is high. INMARSAT-3 F1 was launched in 1996 to cover the Indian Ocean Region. Over the next two years, F2 entered service over Atlantic Ocean Region-East, followed by F3 for Pacific Ocean Region, F4 for Atlantic Ocean Region-West and F5 as back-up and leased capacity. These satellites are nearly ten times more powerful than the second-generation spacecraft with a total EIRP of about 48 dBW in L-band. The high EIRP will permit smaller terminals to operate with satisfactory reception. The space segment provides almost global coverage with the exception of the polar regions above about 80° latitude which cannot be seen by geostationary satellite.

Since the INMARSAT system began, INMARSAT-A has been the main mobile communication satellite. Today, it is still the main mobile user equipment and although originally developed for maritime purposes, it has over the years evolved technically to serve many land mobile, transportable and fixed thin route requirements so that today they account for more than 10% of the terminals in use. INMARSAT-A terminals provide a high quality telephone and telex channels having analogue voice with companded FM modulation. The TP services are provided through multiplexing of 22 TP channels on a 1.2 kbps channel. Use of Demand assigned multiple access (DAMA) enables several users to share a pool of telephony and TP channels on a need to need basis. The system provides direct dialing to any telephone or telex machine throughout the world. Terrestrial subscribers can also use the mobile as easily as calling any other international number. Mobiles can also communicate direct with each other through a LES. The recent growth of FAX machines, electronic mailbox services and computer-to-computer data exchanges via telephone voice-band modems is now a common feature of many mobile or transportable INMARSAT-A. Data at 2400 bps in the voice channel is also a standard service on INMARSAT-A. As an option 56 kbps ship-to-shore services is also available for high data users such as oil rigs, ocean data collectors, etc. INMARSAT-A requires about 0.9 m to 1.2 m mobile antennas. For ship borne terminals, stabilization and tracking platforms are required.

INMARSAT-C is an advanced, packet data communication system using a small low cost mobile earth station suitable for any type and size of mobile platform. The system provides two-way messaging and data communications on a store and forward basis. One-way position, data reporting, polling and an Enhanced group call (EGC) broadcast service capable of addressing both groups and specific geographic areas. The system (Figure 7.13) provides public and private Closed user groups

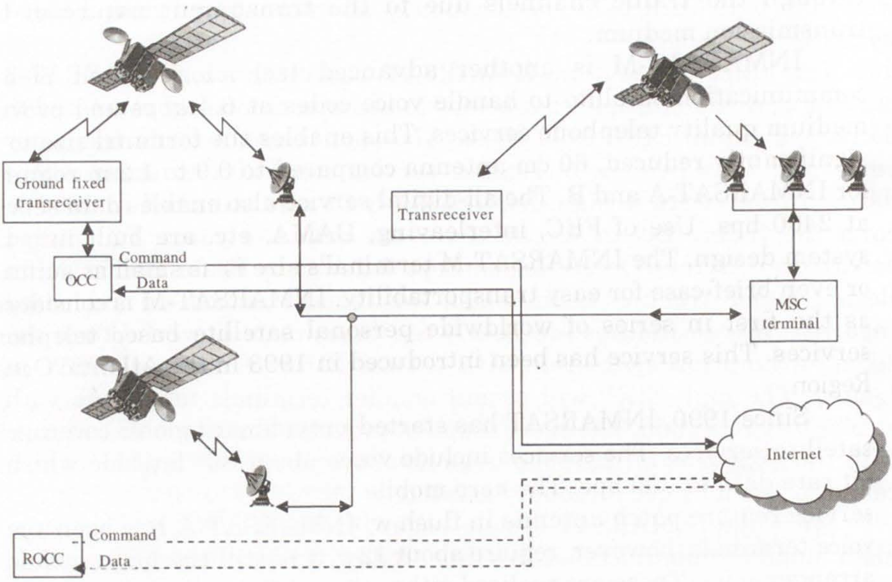


Figure 7.13 Inmarsat system.

(CUG) access for International, Regional or National services. The store and forward feature enables the system to interconnect with any terrestrial message or data network (Telex, X.400, X.25, voice band data via the PSTN, etc.) as the store and forward acts as a buffer between the mobile and Land earth station (LES). Data is transferred between the mobile and land earth station at an information rate of 600 bits/s. A call from an INMARSAT mobile terminal goes directly to the satellite overhead, which routes it back down to a gateway on the ground called a **land earth station (LES)**. From there the call is passed into the PSTN.

To keep the mobile equipment small and costs to a minimum a very low G/T of –23 dB/k at 5° elevation angle was selected to permit the use of a non-stabilized, omni-directional antenna. BPSK modulation is used and this coupled with the relatively low EIRP requirement of 12 dBW can be achieved with a class-C HPA using existing semiconductors. To alleviate the effects of multipath it employs a highly robust modulation and coding scheme. Transmissions from the mobile take place between 1626.5–1646.5 MHz and reception between 1530.0–1545.0 MHz with tuning increments of 5 kHz. INMARSAT-C is, therefore, capable to operate on all frequencies available on INMARSAT's existing and next generation satellites for land mobile use. The narrow channel spacing also helps ensure maximum efficiency of the limited spectrum.

The system has been designed with considerable flexibility of access control and signalling protocols so that it can handle future services and applications. The all digital design enables any type of data to be passed through the traffic channels due to the transparent nature of the transmission medium.

INMARSAT-M is another advanced technology based mobile communication satellite to handle voice codes at 6.4 kbps and provide medium quality telephone services. This enables the terminal size to be significantly reduced, 60 cm antenna compared to 0.9 to 1.2 m required for INMARSAT-A and B. The all-digital service also enables data service at 2400 bps. Use of FEC, interleaving, DAMA, etc. are built into the system design. The INMARSAT-M terminal's size is as small as suitcase or even brief-case for easy transportability. INMARSAT-M is considered as the first in series of worldwide personal satellite based telephony services. This service has been introduced in 1993 in the Atlantic Ocean Region.

Since 1990, INMARSAT has started providing aeronautical mobile satellite services. The services include vocoded voice at 9.6 kbps and low bit rate data at 300 bps. The aero mobile terminals for low bit rate data service require patch antenna in flush with the body of the aircraft. The voice terminals, however, require about 12 dB gain antenna with tracking arrangements. These are realized either through phased array antennas or through blade antennas mounted on the aircraft body. The design of the system apart from FEC and interleaving specially takes into account the large Doppler component arising due to the high speed of the aircraft. Over 100 aircrafts are already using aeronautical mobile terminals.

Under project 21, INMARSAT has introduced mobile telephone service using INMARSAT-P through hand-held low cost mobile terminals for providing personal communication. Several candidate systems inclusive of orbits, number of multiple beams, communication techniques, etc. are being studied to evolve the optimum system. The orbits include geostationary (36,000 km), intermediate circular (10,000 km) and low earth orbit (1800 km). Different multiple access techniques are TDMA and CDMA. Compatibility with terrestrial cellular system is also an important feature.

The INMARSAT's business strategy is to pursue a range of new opportunities at the convergence of information technology, telecom and mobility while continuing to serve traditional maritime, aeronautical, land-mobile and remote-area markets.

VSAT

After the larger earth station of the 1960s in the 1980s Telecom launched a new series of smaller earth stations called VSAT. The very small aperture terminal (VSAT) has now become an important service facility for many applications including personal communication. VSATs are small earth stations with antennae having a diameter less than 2.4 m. These can carry traffic as high as 64 Kbps. VSATs are easy to install at roof tops. (Also see MSS already discussed)

Since VSAT cannot transmit signals at large powers and the propagation loss in satcom being around 200 dB, a powerful earth station called **Hub** assists in transmission. The Hub receives carriers from all VSATs and transmits to the satellite after power amplifying. The VSAT network (Figure 7.14) is managed by hub stations using virtual circuits. The network is operated in star or mesh configuration with or without polling.

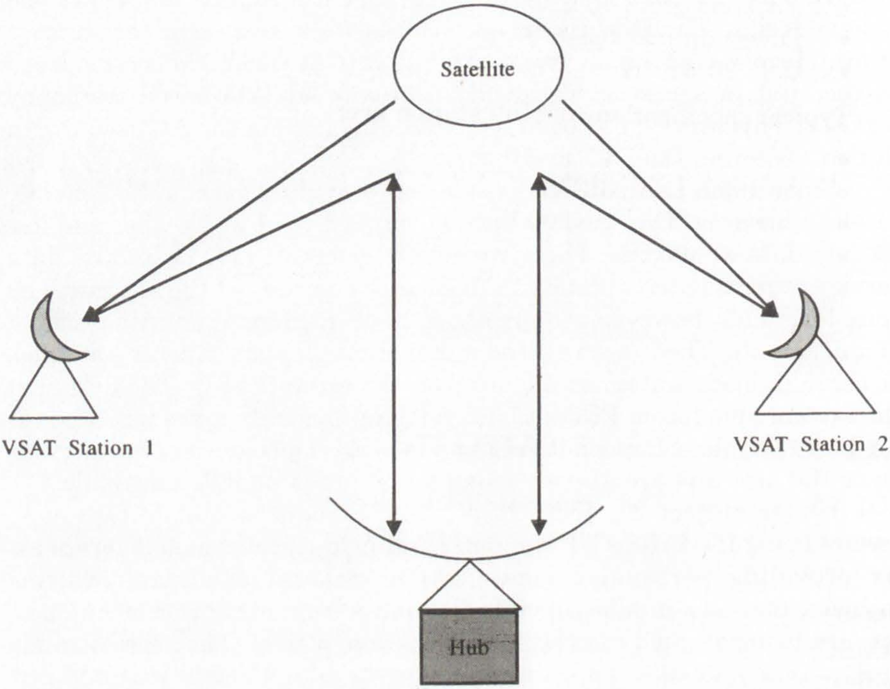


Figure 7.14 VSAT network.

VSATs can be divided into two categories:

1. One-way; where VSAT can only receive
2. Two-way; where VSAT can receive and transmit

Educational broadcast, news, stock details, TV broadcast are examples of the one-way VAST netwok. Computer network, reservation systems, personal communication, Internet, tele-medicine, etc. are examples of the two-way VSAT network. Frequency allocations for hub to satellite and VSAT to satellite have been allocated by the ITU in the Ku and C-band. The allocations are 14.0–14.5 GHz/5.925–6.425 GHz in the uplink and 10.7–12.75 GHz/3.625–4.2 GHz in the downlink. VSATs can be operated in SCPC or MCPC mode depending on the application. The modulation schemes adopted are BPSK and QPSK for higher data rates, typically 12 Kbps and MFSK for lower rates typically 600 bps. Most of the VSATs operate in the DAMA mode either as FDMA or TDMA. With the

present technology and increasing usage of such networks DS-CDMA is being used. Most of the VSATs are assisted by personal computers hence we can divide the VSAT system into outdoor unit and indoor unit. The RF receiver is the outdoor unit like all earth stations while a modem accompanied with PC is the indoor unit.
Some typical specifications of VSAT are:

- Antenna size: 1.2 m–3.5 m
- Antenna gain: 40 dB
- Power uplink: 0.5–5 W
- G/T: 20 dB/°K

Typical specifications of Hub station are:

- Antenna size: 3.5 m–10 m
- Antenna gain: 58 dB
- Power uplink: 50–200 W
- G/T: 30 dB/°K

In India EDUSAT program for distance education is one example of the VSAT network. Satellites like Intelsat and Inmarsat are also used for the VSAT network.

7.11 OTHER MOBILE SATELLITE SYSTEMS

VOLNA System. The Volna satellites of Russia (erstwhile USSR) carry L-band packages to provide MMSS and AMSS. Not many details of the system are available.

AMSC and MSAT System. American mobile satellite corporation (AMSC) of USA is introducing mobile satellite service in USA through dedicated GSO satellites launched in 1994. Telesat mobile, Canada is also introducing MSS in Canada through MSAT system. AMSC and Telesat mobile are collaborating with each other by sharing the space segment. The space segment consists of two active satellites one for AMSC and another for MSAT with a common in-orbit spare. These systems operate in L-band and offer a variety of fax and data services. Multiple spot beams generated through large (6 m dia) on-board antennas allow frequency reuse and higher capacity realization.

Mobilesat System. The second generation Aussat system (now named Optus-B) carries L-band payload to provide MSS in Australia. The first satellite, OPTUS-B1 was launched in August 1992 and is operational. The second satellite, OPTUS-B2, had failed at launch in December, 1992.

Engineering Test Series. Japan is carrying out extensive experiments through its engineer-ing test series of satellite communication for maritime, aeronautical and land applications.

Several other countries such as Mexico, Spain, Brazil, Singapore, etc. are introducing L-band mobile satellite services by carrying MSS payloads on their domestic satellites.

Omnitracs and Euteltracks System. Omnitracs of USA has introduced, since 1989, two-way short message service in USA through leased Ku-band transponders of an FSS satellite. Special techniques such as frequency hopping and SSMA are used. The mobile terminal has near-omni antenna. This service is being widely used by trucking companies. Euteltracs is the omnitracs equivalent in Europe.

Indian System. Mobile satellite services are introduced in India through INSAT-2C and 2D satellites launched in 1995–96 time frame. These satellites, in addition to FSS payloads, carry MSS payload operating in S-band. The frequency bands in S-band are 2670–2690 MHz uplink and 2500 to 2520 MHz downlink. The feeder links operate in C-band. Encoded voice and low bit rate data services are being planned to be provided.

7.12 LOW EARTH ORBIT (LEO) SATELLITE SYSTEMS

A number of LEO systems are being proposed world over to provide global hand held mobile communication. Each system proposed consists of a number of satellites in a low earth orbit constellation. The differences in the systems lie in the proposed orbital height, inclination, number of planes, number of satellites per plane, number of spot beams in mobile bands, communication techniques, etc. The Iridium system of USA was one of the first proponents with a constellation of 66 satellites (originally 77 satellites which corresponds to the atomic number of Iridium) to provide hand held telephony service using multiple beams, TDMA and Inter-satellite links techniques. Soon a number of other systems have also been proposed. Some of the 'Big LEO' systems (referring to those systems providing voice services) are Iridium, Global star, Ellipsat, Calling communications, Constellation communications, Odyssey, etc.

ORBCOM of USA is a 'small LEO' system designed to provide message communication only. It has a constellation of 26 satellites at a height of approximately 700 km. The system operates in VHF band (137/149 MHz band). STARSYS is another 'small LEO' system offering services similar to ORBCOM. The advantage of data or message only services is that, unlike voice service, the system can tolerate short breaks in the visibility as repeat requests can be made. The number of satellites, therefore, is much smaller than those required for voice service.

With the improvements on the technological front, the mobile satellite services have emerged after initial hiccups and a number of systems are becoming operational in this decade. The future is moving towards personal communication in which satellite based systems are expected to play a prominent role. Value addition to the basic services provided by the mobile satellite systems will greatly enhance the scope of the services for different applications.

7.13 INTRODUCTION TO GLOBAL POSITIONING SYSTEM (GPS)

For ages sun, moon and stars have been used as benchmark references to determine the position of heavenly bodies including man-made satellites and navigation. On earth, man has been using compasses and sextants for surveying. A GPS scheme in shown in Figure 7.15.

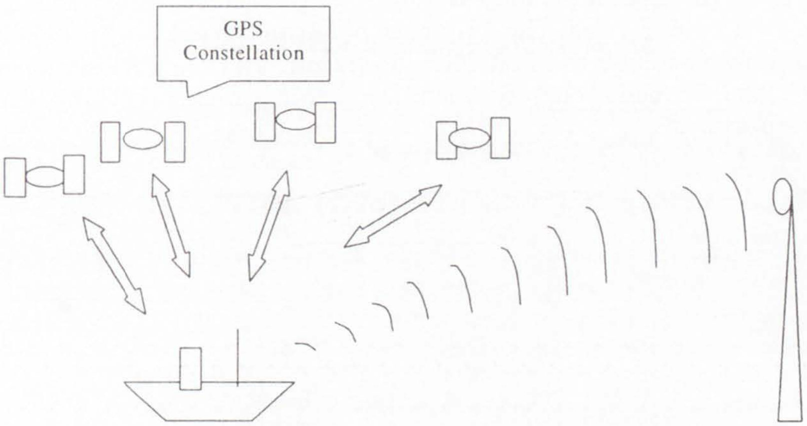


Figure 7.15 GPS scheme.

In recent years for many applications like search and rescue, navigation, adventure sports, military applications, etc. where better, reliable and constant ranging is required, man-made satellites are being used. To satisfy these applications 21 satellites called **GPS** are orbiting round the earth in six inclined planes at an orbiting radius of about 26,578 km with a period of 12 hours. NAVSTAR orbits in an inclined plane at 55° w.r.t. the earth's equatorial plane and each weighs about 2000 pounds. The orbital planes are spaced at 60°. It has wing like solar arrays on the sides and generates 710 W of electrical power. Though these satellites are supported by US defense department they can be used in public domain to determine latitude, longitude, altitude and time of any object at any place on and around the globe. INMARSAT-3 also supplements the services provided by NAVSTAR.

NAVSTAR and GPS are radio navigation systems that use triangulation to determine the user's position. Each NAVSTAR satellite broadcasts a pre-arranged sequence of timing pulses. When a receiver picks up a timing pulse, it multiplies the measured signal travel time by the speed of light (3×10^8 m/s) to obtain the range. Updates are provided every 12 hours with the help of geosynchronous INMARSAT. Theoretically such information from three satellites correlates the position but to compensate for losses in clock synchronization a fourth signal is taken from another satellite. The clock pulses are generated by an atomic clock which is accurate to just loosing one second in 300,000 years and thus every satellite has an accuracy of one billionth of a second. Even with this accuracy there is a possibility of one-foot error during navigation.

The modulation used is direct sequence spread spectrum modulation. This makes the GPS system jam resistant, secure and addressable. The in-phase component being C/A (coarse acquisition) code while quadrature component is P-code (precision code). See Figure 7.16 the equation governing the modulated output is:

$$M(t)= D\{(C/A)\cos(2\pi ft)\} + DPW\sin(2\pi ft)$$

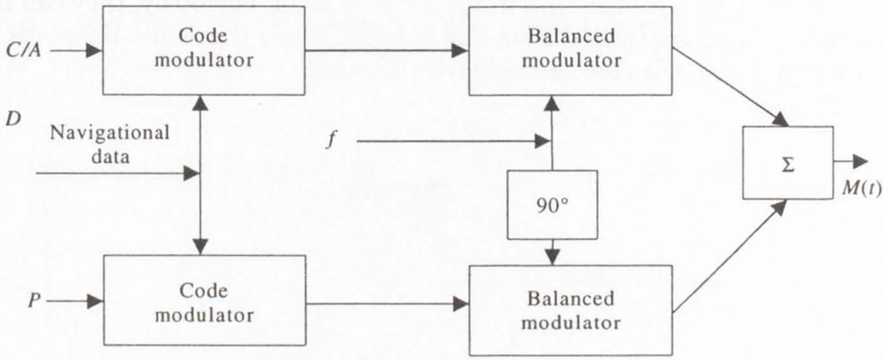


Figure 7.16 GPS signal generator.

GPS systems have applications, which have no bounds, newer and newer applications are coming up. Apart from search and rescue these are being used for truck routing and load matching, monitoring cargo ships and state of its contents, early financial arrangements to avoid demurrages and loss of goods, vehicle information system, etc. Many universities are carrying out tests and research to find new applications, for example, Stanford University has done appreciable work on GPS landing system which requires sufficient accuracy. Surveying, mapping, tracing water resources, study of propagation characteristics, etc. could be applications where academic work can be carried out.

GPS System Block

The GPS system consists of a control segment, a space segment and a user segment as shown in Figure 7.16. The control segment is the backbone of the whole system and consists of a master control station and five monitor stations. The functions of master control station are:

1. Collection of tracking data available in monitor stations
2. Calculation of satellite orbits
3. Calculation of clock parameters
4. Controls the satellites' house keeping of satellite systems

The monitor stations are spread all around the world with in 30° north to 30° south latitudes. The monitor stations carry out the following tasks:

1. Measures pseudoranges to all satellites in view
2. Computes and generates data for master control station
3. Receive orbit and clock parameters from the master control station
4. Uploads the data received from master control station to the satellites
5. For this system the monitoring stations are at Hawaii, Colarodo, Ascension Island, Diego Garcia and Kwajalein.

Since GPS satellites are in the inclined orbit, obviously, they can not be tracked and controlled from one station, hence there are 107 stations spread all over the globe to achieve this task.

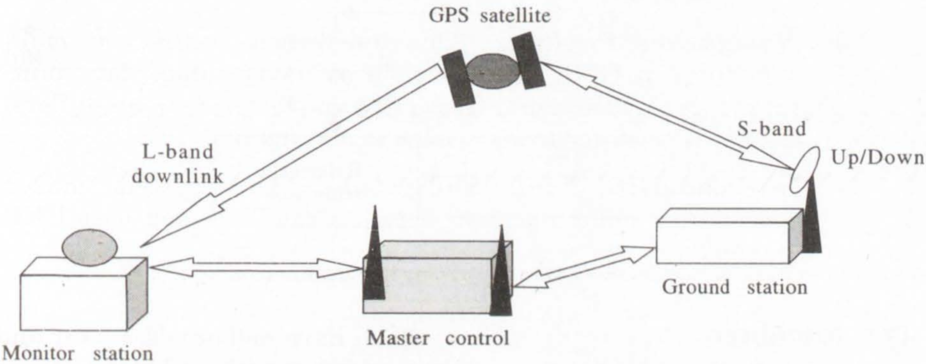


Figure 7.17 GPS telemetry, tracking and control.

GPS Satellites

There are currently three types of GPS satellites. The first two are manufactured by Rockwell international space division and the third by Lockheed-Martin. As in case of any satellites the health, orbit stability and attitude are of utmost importance, more so in GPS as the accuracy of position of user depends on this subsystem. The telemetry, telecommand and control (TT&C) of GPS satellite subsystems consist of:

1. ***Orbit Selection Subsystem.*** This subsystem places the satellite into proper orbit after the launch. The ground control stations track, range and command the satellite through the subsystem and keeps them in proper inclined orbits. Apart from the sensors these contain apogee kick motor and ignition assembly.

2. ***Altitude and Velocity Control Subsystem.*** This keeps the satellite in proper altitude and attitude with the help of sensors, linear accelerators, reaction wheels, nutation dampers, magnets and control circuitry.
3. ***Reaction Control Subsystem.*** The minor adjustment of satellite attitude and position from time to time is taken care of by this subsystem with the help of thruster motor control valves and associated electromechanisms.
4. ***Thermal Control.*** It is absolutely necessary to keep and maintain the different parts and housings in the GPS satellite subsystems within the designed temperature limits. Most of the subsystems have to be sealed for plasma discharges.
5. ***Electrical Power Subsystems.*** Solar panels, batteries, power control unit, sun-sensors and drives are the main components of this system.
6. ***Navigation Payload.*** This subsystem fulfils the main objectives of GPS. This consists of navigational data unit, frequency synthesizer, frequency converter and amplifiers. L-band is used for transmission of RF signals.
7. ***Inter-satellite Link Subsystems.*** This system makes possible for communication between satellites and uses UHF antenna.

The Receiver

As in any satellite receiver since the input power is of the order of pico-watts and the *C/N* to be maintained to get demodulated *S/N* above the threshold fixed for error free processing, the following configuration is (see Figure 7.18) necessary:

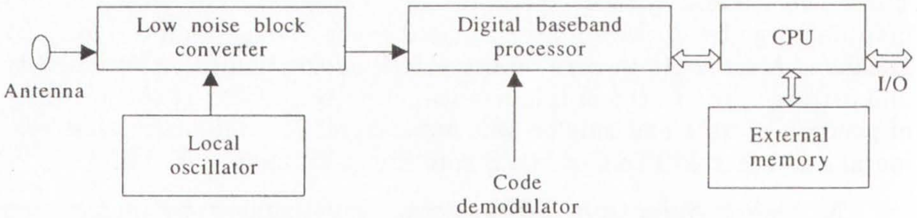


Figure 7.18 GPS receiver block schematic.

To recover the baseband, Costa's loop is used with phase synchronization of local oscillator or else the signal cannot be detected.

The required PN code is locally generated to detect the 'chip' of the spread spectrum received signal. This requires as many correlators as the visible satellites. Most of the receivers have 12 correlators. Diversity reception is used and the strongest signals are used for processing.

The CPU uses software to calculate XY and Z co-ordinates and hence find latitude, longitude and altitude. The equations used are discussed in Appendix 3:

SUMMARY

In this chapter the importance of satellites in mobile environment was discussed in brief. Enormous material is available on this topic. We first studied the land mobile communication with emphasis on cellular concepts. Different terms were brought into to make the reader know about these. The trends, road map and schemes were discussed in brief. Number of books apart from that given in references is available on these topics. The need of satellite in mobile communication was also discussed. A discussion on INMARSAT was taken up which is an established MSS satellite. A GPS scheme was discussed at the end.

REVIEW QUESTIONS

1. What is the need of mobile services.
2. What are the factors on which the fading of mobile signals depend?
3. What are the steps involved in making a mobile link through?
4. Why cells are preferred in land mobile services?
5. How and why cell sectorization is achieved?
6. What are the different types of antennae required in mobile communication?
7. What is the need of handoff and how is it achieved?
8. What is meant by paging and access?
9. Historically what are the land mobile systems that have been in use?
10. Explain the importance of control channel.
11. Explain GSM architecture.
12. How interfacing is achieved in GSM ?
13. Explain GSM frame structure.

14. What is the basic system on which 3G has been developed?
15. How satellite is useful in enhancing the capability of Mobile communication?
16. Explain different types of satellite based mobile systems.
17. What is the role of INMARSAT?
18. Explain how global positioning is achieved.

Appendix 1

Important Design Equations

1. *Eccentricity:*

$$e = \frac{\sqrt{a^2 - b^2}}{a}$$

2. *Velocity of orbit:*

$$v = \sqrt{\frac{GM}{(r_e + h)}} = \sqrt{\frac{g_o}{(r_e + h)}}$$

where

$G = 6.6672 \times 10^{-11}$ N/kg^2

$M = 5.97 \times 10^{24}$ kg

$g_o = 3.986 \times 10^{15}$ km^3/s^2

3. *Time of orbit:*

$$T_0 = \frac{2\pi (r_e + h)^{\frac{3}{2}}}{\sqrt{g_0}} \text{ s}$$

4. *Angular velocity:*

$$\omega_s = \frac{\sqrt{g_0}}{(r_e + h)^{3/2}} \text{ rad / s}$$

5. *Slant range:*

$$d_s = d \left[1 + \left(\frac{r_e}{d}\right)^2 - \frac{2r_e}{d} \cos \gamma \right]^{\frac{1}{2}} \text{ (neglecting parallax error)}$$

$$\xi_\infty \approx \xi \text{ and}$$

$$d_s = d \left[1 + \left(\frac{r_e}{d}\right)^2 - \frac{2r_e}{d} \cos(90 - \xi_\infty)\right]^{\frac{1}{2}}$$

6. *Minimum Height for visibility:*

$$d \geq \frac{r_e}{\cos \gamma}$$

7. *Area of coverage:*

$$A = 2\pi r_e^2 (1 - \cos\gamma)$$

8. *Elevation angle:*

$$\xi = \tan^{-1}\left[\frac{\cos L_{AE}\cos L - 0.151}{\sqrt{1-\cos^2 L_{AE}\cos^2 L}}\right]$$

where

L_{AE} = Lattitude of earth station

$L = L_E - L_g$ = longitude of ES – longitude of satellite

9. *Azimuth angle:*

$$(A_Z)_{\text{cal}} = \tan^{-1}\left[\frac{\tan L}{\sin L_{AE}}\right]$$

10. *Actual Azimuth for geostationary satellite:*

(i) $(A_Z) = (A_Z)_{\text{cal}}$ for L_{AE} and L_E –ve
$L < 0$(–ve)

(ii) $A_Z = 360 - (A_Z)_{\text{cal}}$ for L_{AE} –ve
$L > 0$(+ve)

(iii) $A_Z = 180 + (A_Z)_{\text{cal}}$ for L_{AE} +ve
$L < 0$(–ve)

(iv) $A_Z = 180 - (A_Z)_{\text{cal}}$ for L_{AE} +ve
$L > 0$(+ve)

Eclipse equations

1. Eclipse occurs if $\dfrac{r_e}{\sin\delta_e} > d$

2. *Eclipse angle:*

$$\alpha = 2\cos^{-1}\sqrt{\frac{1-\dfrac{r_e^{\,2}}{d^2}}{\cos^2\delta_e}}$$

3. When $\delta_e = 0$ there is no declination of sunrays.

$$\alpha = 2\sin\frac{r_e}{d}$$

4. *Period of eclipse:*

$$t_e = \frac{\text{Orbit period}}{360}\times\alpha$$

Orbit period for the geostationary satellite = 23 hr 56 min 4 sec

5. Time of starting of eclipse = 24.00 – 0.43 – 0.04 L_s
   where L_s = Longitude of satellite

Link Design Equations

1. Path loss:

$$|\alpha_p|_{dB} = 92.44 + 20 \log f_{GHs} + 20 \log d_s$$
$$= 32.44 + 20 \log F_{MHz} + 20 \log d_s$$

2. Rain attenuation:

$$\alpha_r = aR^b L$$

where R = Rain rate in mm/hr

L = Rain path length in km

$$a = 4.21 \times 10^{-5} f^{2.42} \; (2.9 < f < 52 \text{ GHz})$$
$$b = 1.41 f^{-0.0776} \; (8.5 < f < 25 \text{ GHz})$$

SAM MODEL

(i) Cloud height:

$$H_c = H_i \; (R = 10 \text{ mm/hr})$$
$$= H_i + \log_{10}\left(\frac{R}{10}\right) (R > 10 \text{ mm/hr})$$

where isothermal height H_i = 4.8 km for L_{AE} = 30°

= 7.8 – 0.1 (L_{AE}) for L_{AE} > 30° (L_{AE} = Longitude of ES)

(ii) Rain path length:

$$L_r = \frac{H_c - H_e}{\sin \xi}$$

(iii) Probability of attenuation:

$$A(p) = aR(p)^b L\gamma \text{ for } R = 10 \text{ mm/hr}$$
$$= aR(p)^b \left[\frac{1 - e^{-rb \log_e (R/10) L_r \cos \xi}}{rb \log_e (R/10) \cos \xi}\right] \; R > 10 \text{ mm/hr}$$

where $\gamma = 1/22$

CCIR MODEL

(i) $h_r = 5.1 - 2.15 \log_{10} [1 + 10^{(\lambda e - 27)/25)}]$ where h_r = rain height

(ii)
$$L_r = \frac{2(h_r - h_o)}{\left[\sin^2 \xi + 2(h_r - h_o)/8500\right]^{\frac{1}{2}} + \sin \xi} \text{ for } \xi < 10°$$
$$= \frac{h_r - h_o}{\sin \xi} \text{ for } \xi \geq 10°$$

(iii) $A(0.01) = aR(p)^b L_r \gamma_p$ where $\gamma_p = \dfrac{90}{90 + L_r \cos \xi}$

3. *Total losses in propagation:*

   $[\alpha_{total}] = [\alpha_p] + [\alpha_{rain}] + [\alpha_{other}] + [\alpha_{ion}] + [\alpha_{coupling}]$

4. *Received power:*

   (i) $[P_r] = [P_t] + [G_t] - [\alpha_{total}] + [G_r]$

   G_t = Transmitting antenna gain

   G_r = Receiving antenna gain

   (ii) $[G_t] = 20.4 + 20 \log D + 20 \log f + 10 \log \eta$

   D = Diameter of dish antenna in metres

   f = Carrier frequency in GHz

   η = Antenna efficiency

In general $G_{ant} = \dfrac{A_{eff}}{A_{iso}} = \dfrac{A_{eff}}{\lambda} \times 4\pi$

where A_{eff} = Area of aperture. For parabolic antenna it is a circle, i.e. $2\pi r^2$

5. *Noise calculations:*

   (i) Without cable loss:

$$T_s = T_{ext} + T_{ref} + \frac{T_m}{G_{ref}} + \frac{T_{if1}}{G_{ref}G_m} + \frac{T_{if2}}{G_{ref}G_mG_{if1}} + \cdots$$

   (ii) With cable between out and RF amplifier:

$$T_s = T_{ext} + T_0(L - 1) + T_{ref}\, L + \frac{T_mL}{G_{ref}} + \frac{T_{if}L}{G_{ref}G_m} + \cdots$$

   (iii) In case noise figure/noise factor F is given instead of equivalent noise temperature then

$$T_{AmpL} = T_0(F - 1)$$

   where T_0 can be assumed between 270 K and 290 K.

   (iv) When cable is connected between LNA and mixer (LNA is near the antenna):

$$T_s = T_{ext} + T_{ref} + \frac{T_0(L-1)_0}{G_{ref}} + \frac{T_mL}{G_{ref}} + \frac{T_{if}L}{G_{ref}G_m} + \cdots$$

   (v) $T_{ant} = T_{Sun}\, \dfrac{\Omega_s}{\Omega_\alpha}$

   where $T_{Sun} = 5 \times 10^5$ K

   Ω_s = Solid angle of sunrays

   Ω_a = Solid angle of main lobe of antenna

   (vi) $T_{rain} = T_0\left[1 - \dfrac{1}{A(p)}\right]$ $A(p)$ = Rain attenuation in ratio

6. *Carrier to noise calculations:*
   (i) $[C] = [EIRP] - [\alpha_{total}] + [G_r]$
   (ii) $[N] = [K] + [T_2] + [B_{if}]$
   (iii) $\left[\frac{C}{N}\right] = [EIRP] - [\alpha_{total}] + \left[\frac{G_s}{T_s}\right] - [K] - [B_{if}]$
   (iv) Total gain:
   $G_s = [G_{out}] + [G_{rf}] + [G_m] + [G_{if}]$
   (v) Quality factor of receiver:
   $\left[\frac{G_s}{T_s}\right] < \left[\frac{C}{N}\right]$
   (vi) Calculation of IF bandwidth:
   (a) FM with single modulating source
   $B_{if} = 2(\Delta f + f_{max})$: $M = \dfrac{\Delta f}{f_{max}}$
   M could vary between 2 and 10.
   (b) FDM/FM with N multiplexed channels
   Loading factor:
   $20 \log_{10}L = -15 + 10 \log_{10}N$ for $N \geq 240$
   $20 \log_{10}L = -1 + 4 \log_{10}N$ for $12 \leq N < 240$
   where N = Number of channels
   $\Delta f_{peak} = gl\ \Delta f_{rms}$
   where $g = 3.16$ or 10 dB for $N > 24$
   $= 6.5$ or 16.25 dB for $N < 24$
   $B_{if} = 2(gl\Delta f_{rms} + f_{max})$ where f_{max} = Top frequency of FDM
   $f_{max} = Nf_s + f_{initial}$ f_s = Maximum signal frequency
   (c) FDM/FM Deviation

Channels	Δf_{rms} kHz
12	35
60	50
120	100
300	200
960	200

7. *Signal to noise calculations (Analog signal with FM):*
   (i) $\dfrac{S}{N} = 1.5 \times \dfrac{C}{N} \times \dfrac{B_{if}}{W} \times \left[\dfrac{\Delta f}{W}\right]^2$
   (ii) $K_{det} = 1.5 \left[\dfrac{B_{if}}{f_{signal}}\right]\left[\dfrac{\Delta f}{f_{top}}\right]^2$ $f_{top} = f_{signal}$ for single channel FM

(iii) $K_{\text{det}} = \left[\dfrac{B_{if}}{f_{\text{signal}}}\right]\left[\dfrac{\Delta f_{\text{rms}}}{f_{\text{top}}}\right]^2$ for FDM/FM

(iv) $\left[\dfrac{S}{N}\right] = \left[\dfrac{C}{N}\right] + [K_{\text{det}}] + [P] + [W]$

where P = Pre-emphasis

W = Weighting factor

8. *Digital signal:*

(i) $\dfrac{E_S}{N_o} = \left[\dfrac{C}{R_s} \times \dfrac{B}{N}\right]$

where E_s = Symbol energy R_s = Symbol rate

(ii) $BW = \dfrac{[1+\rho]R_s}{2} \quad 0 \le \rho \le 1$

(iii) For BPSK:

$$R_b = \frac{1}{T_b} \text{ for QPSK}$$

$$R_s = \frac{1}{2T_b}$$

(iv) For BPSK:

$$BER = \frac{1}{2}\ erfc\ \sqrt{\frac{E_b}{N_o}} \text{ for } \frac{E_b}{N_o} > 6.5 \text{ dB}$$

$$BER = \frac{e^{\frac{-E_b}{N_o}}}{\sqrt{4\pi \frac{E_b}{N_o}}}$$

BER in terms of $\dfrac{C}{N}$

$$BER = \frac{1}{2}\ erfc\ \sqrt{\frac{B}{R_b} \cdot \frac{C}{N}}$$

For QPSK:

$$\frac{E_s}{N_o} = \frac{C}{N} \cdot \frac{2B}{R}$$

$$BER = \frac{1}{2}\ erfc\ \sqrt{\frac{2B}{R} \cdot \frac{C}{N}}$$

(v) (a) Signal to quantization Noise:

$$\frac{S}{Nq} = Q^2$$

(b) Signal to total noise $\dfrac{S}{N} = \dfrac{Q^2}{1 + 4Q^2(BER)}$

(vi) PCM channel:

$R_b = nf_s$

where n is No. of bits per level

f_s = Sample frequency

$BW = (1 + \rho)nf_s = (1 + \rho)nW$

where

W = Signal Bandwidth

(vii) TDM/PCM:

$R_{Tr} = (\eta N + 1)\, f_s$

where

N = No. of TDM channels

Total link performance

1. $$\frac{1}{\left[\dfrac{C}{N+I}\right]} = \frac{1}{\left[\dfrac{C}{N}\right]_{\text{up}}} + \frac{1}{\left[\dfrac{C}{I}\right]_{\text{up}}} + \frac{1}{\left[\dfrac{C}{IM}\right]_{\text{sat}}} + \frac{1}{\left[\dfrac{C}{N}\right]_{\text{down}}} + \frac{1}{\left[\dfrac{C}{I}\right]_{\text{down}}}$$

2. $$\left[\frac{C}{N}\right]_{\text{up}} = W_s + \left[\frac{G}{T}\right]_{\text{sat}} - [BO_r] - [K] + 10\log B_{\text{sat}} - [G_t]_{\text{of}}$$

3. $$\left[\frac{C}{N}\right]_{\text{down}} = W_s + \left[\frac{G}{T}\right]_{ES} - [BO_o] - [K] + 10\log B_{if} - [G_{\text{sat}}]$$

where W_s = Illumination level in dB W/m^2

4. $$\left[\frac{S}{N}\right]_t = \left[\frac{C}{N}\right]_t + \left[\frac{B_{if}}{W}\right] + 2\left[\frac{\Delta f}{fma}\right] + [P] + [W]$$

$$20\log\left(\frac{\Delta f}{f_{\max}}\right)$$

5. $B_{if} = 2(\Delta f_n \times l \times g + f_{\max})$

6. *Channel capacity:*

$$m = [EIRP + \frac{G}{T} - BO_o] - [\alpha] - [K] + [VA] - \left[\frac{C}{N_o}\right] - M$$

where VA = Voice activity advantage

C/N_o = Required carrier to noise density

M = Additional margin required

$[G/T]$ = Receiving earth station figure of

$EIRP$ = Transponder EIRP

TDMA

1. *Burst bit rate:*

$$\left[\frac{NP+CF}{F-NG}\right]$$

where N = No. of earth station allotted time slot

P = No. of pre-amble bits

C = Information bit rate BPS

F = Frame period

G = Guard time

2. *Frame efficiency:*

$$\eta_F = 1 - \left[\frac{\text{Overhead bits}}{\text{Total bits in frame}}\right]$$

$$= 1 - \left[\frac{\text{Overhead period}}{\text{Frame period}}\right]$$

3. $$\left[\frac{C_t}{N_t}\right] = \left[\frac{E_b}{N_o}\right] + 10\log_{10}\left(\frac{R_o}{B}\right) + M$$

where

B = Noise BW/channel

M = Margin for given BER

4. *Carrier to noise density:*

$$\left[\frac{C_t}{N_{ot}}\right] = \left[\frac{C_t}{N_t}\right] + 10\log_{10} B$$

5. *Channel capacity n:*

$$n = \eta_F \frac{R_T}{R_b}$$

where

R_T = Transmission rate

R_b = Channel bit rate

Bit rate $R_b = 10^{(10/\log B_{\text{transponder}} + 10 \log B_{\text{transponder}}/R_{\text{symbol}})/10}$

Appendix 2

Details of Some Satellites

INSAT-2B (Geostationary Multipurpose)

Parking place: 93.5° East

Transponders: 12, Fixed satellite service (FSS), each 36 MHz bandwidth

Edge of coverage (EOC) EIRP 32 dBW

Uplink: 5930–6425 MHz

Downlink: 3705–4200 MHz

Two (extended C-band, T.V. Channels)

Edge of coverage EIRP 42 dBW

Uplink: 5850–5930 MHz

Downlink: 2550–2930 MHz

One transponder for: Radio programs, disaster warning and very high-resolution radiometer (VHRR) for meteorological imaging.

Stabilization: Three axes

INSAT-2C (Geostationary Multipurpose)

Parking place: 93.5° East (co-located with INSAT-2B)

Transponders: 12, Fixed satellite service (FSS), each 36 MHz bandwidth.

7, have Edge of coverage (EOC) EIRP 36 dBW and use SSPA

3, have Edge of coverage (EOC) EIRP 32 dBW and use SSPA

2, have Edge of coverage (EOC) EIRP 36 dBW and use TWTA

Uplink: 5930–6425 MHz

Downlink: 3705–4200 MHz

6 are extended C-band

Edge of coverage EIRP 35 dBW and use SSPA

Uplink: 6750–7000 MHz

1, Broadcast satellite service (BSS) for T.V. and radio with 42 dBW TWTA.

Uplink: 5910 MHz

Downlink: 2610 MHz

3, Ku Band (14.25–14.5 GHz) having Edge of coverage (EOC) EIRP

41 dBW and use TWTA

2, Mobile satellite services (MSS) between hub and mobile station via satellite:

Uplink: 3690 MHz

Downlink: 2680 MHz

Mobile station to hub:

Uplink: 5910 MHz

Downlink: 2610 MHz

MSS coverage being from 5° south latitude to 45° north latitude

Stabilization: Three axes

INTELSAT-IVA (Geostationary communication)

Parking place: 63° East

Transponders: 20, Fixed satellite service (FSS) each 36 MHz bandwidth

Edge of coverage (EOC) EIRP 22 dBW (global)

Edge of coverage (EOC) EIRP 29 dBW (spot)

4, beams, one each NW, NE, and SW and SE only for transmit

Uplink: 5925–6425 MHz

Downlink: 3700–4200 MHz

Stabilization: Dual body spun with solar cells covered on the body.

IRRIDIUM: (Inclined orbit mobile communication)

Orbit: Six planes, starting from near polar at inclination of 85°

Transponders: Communication, Edge of coverage (EOC) EIRP 27.7 dBW

Uplink and down link: 1616–1626.5 MHz

Gateway communication: Edge of coverage (EOC) EIRP 23.2 dBW

Uplink: 2750–3000 MHz

Downlink: 1880–2020 MHz

Channel BW = 4.375 MHz

Intersatellite link: 38.4 dBW

Link: 2255–2355 MHz

Stabilization: Three axes.

Appendix 3

Position Calculations in GPS

Let there be four satellites visible from a moving transreceiver and there ranges at a unique time be R_1, R_2, R_3 and R_4. These will depend upon the time taken by the transmitted code being received by the receiver. Such that

$$\begin{aligned} R_1 &= c\ \Delta T_1 \\ R_2 &= c\ \Delta T_2 \\ R_3 &= c\ \Delta T_3 \\ R_4 &= c\ \Delta T_4 \end{aligned}$$

where c is the velocity of EM wave and ΔT_i the time taken for the wave to travel from satellite to receiver.

These ranges are sometimes called **pseudoranges** as these are dependent on Earth Centered Earth Fixed (ECEF) coordinates. These depend on the height of the transreceiver point h, the latitude λ_A and longitude λ_p. As the earth is a ellipsoid there is also an effect of eccentricity e, where

$$e = \frac{\sqrt{a^2 - b^2}}{b}$$

where a and b are the major and minor axis of the ellipsoid bulging at the equator. In general $R_i = c\ \Delta T_i$.

The ECEF coordinates of the receiver are given by

$$\begin{aligned} X &= (N + h) \cos \lambda_A \cos \lambda_p \\ Y &= (N + h) \cos \lambda_A \sin \lambda_p \\ Z &= \{N(1 - e^2) + h\} \sin \lambda_A \end{aligned}$$

$$\text{while } N = \frac{a}{\sqrt{1 - e^2 \sin^2 \lambda_A}}$$

The four satellites in space will have the coordinates:

$\{Sx_0, Sy_0, Sz_0\}$, $\{Sx_1, Sy_1, Sz_1\}$, $\{Sx_2, Sy_2, Sz_2\}$, $\{Sx_3, Sy_3, Sz_3\}$

Similarly, the receiver will have coordinates:

R_x, R_y, R_z resulting in ranges from Pythagoras equations:

$$R_i = \sqrt{(Sx_i - R_x)^2 + (Sy_i - R_y)^2 + (Sz_i - R_z)^2}$$

where i varies for corresponding satellites and receiver's coordinates (0, 1, 2, 3).

But due to the motion of satellite and receiver a clock biasing component has to be included as range correction $R_B = c\ \Delta T_B$.

This will result in following modified equation:

$$(R_i - R_B) = \sqrt{(Sx_i - R_x)^2 + (Sy_i - R_y)^2 + (Sz_i - R_z)^2}$$

When we substitute the coordinates, we will have four equations and four unknowns to be determined, from which latitude, longitude and height can be determined to good accuracy.

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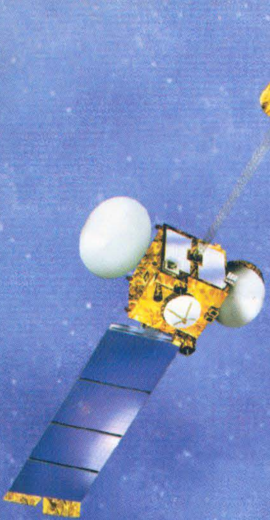

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