NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical and Electronic Engineering

DIGITAL SATELLITE COMMUNICATION SYSTEMS

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ABSTRACT

A major feature of the European Orbital Infrastructure is the communication network; this facilitates the exchange of information between space and ground through interconnection of the various elements of the infrastructure. The aim of this work is to provide an overview and an independent synthesis of a global scenario which is to be discussed within ESA, and which will contribute to the gradual implementation of the integrated communication network. This paper provides an overview of a procedure for data transfer over the space to ground link of the communication network.

This project examines the role of Advanced Satellite Systems as providers of backbone tracking services in the integrated digital Network. The forces shaping the architecture of the new networks are contrasted with the advanced functionality offered by new satellite concepts. This 'leads to a reappraisal of the way satellites and terrestrial networks should integrate. The advantages and problems of this integration are discussed.

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INTRODUCTION

The general conclusion of these studies is that satellites are expected to play a dual role in the networks resulting from the catharsis caused by the process of digitalization, the introduction of new technologies and the emergence of new services:

(i) Satellites may be used to implement backbone transmission facilities in the public Integrated Digital Network (IDN). This is (be major subject of this paper.

(ii) Satellites provide an excellent medium to implement other forms of integrated Services Digital Networks. These can be either Specialized Services Public Network e.g. SMS services on EDTELSAT system, or user-oriented networks e.g. that are those that are designed and satisfy specific users requirements e.g. VSAT networks or private networks.
The emergence of these alternative networks in Europe is conditioned to a great extent by the regulatory environment. In this respect, it is important to emphasize the tremendous impact that on-going CEC legislation efforts may have in the development of industry. Three applications will not be discussed further in this paper.

Satellite systems have been used to provide trucking services for a number of years. They have been fairly successful as is proven by the fact that a substantial part of the international traffic and two-thirds of the intercontinental traffic worldwide are routed by satellite. However, the emergence of optical fibers has caused some forecasters to predict the eventual substitution of all satellite trucking systems by fibers.

The main argument against the use of satellites in trucking applications is the continuous growth of the break-even distance. This is the distance at which the cost of providing a circuit between two specific points by satellite, which is distance independent, is the same as providing the same circuit by terries trial (e.g. optical fiber) means, which are distance-dependent. As the capacity of systems. Grows, the cost per circuit diminishes and the break-even distance increases more and more. This reduces the applicability of satellites to remote applications.

The break-even distance argument disregards however the fact that the satellite offers functionality that is not directly comparable with the point-to-point transmission that the optical fiber allows. The satellite allows communication between any points of the earth's surface illuminated by its beams. This result in satellites being Flexible in their application, reconfirm grumble, able to match the requirement of the network operator (or the end user), to provide service over extended areas and to support com: special services. How in the light of all this, can we discard satellite: basing our argument on the growth of the break-even distance? In this paper, we try to project the full functionality of state-of-the-art and future satellite systems to the evolving European network. Section 2 reviews the present and future of the network. Section 3 analyses the major features of the satellite systems being considered and the advantages brought about by the integration. Finally, Section 4 reviews the system problems associated with the integration of the advanced satellite system in the terrestrial network.

At the ESA council meeting at ministerial level 1985, a long term plan was approved for year 2000 (and beyond). This plan focuses on, and supports, a basic space infrastructure with a view to European autonomy, and centers on transportation using the Ariane-4 and 5 launchers, the Hermes space plane, participation in the Space Station programmed with COLUMBUS, and the preparation of future Earth observation and communication satellite systems. An essential part of this infrastructure is the communication network, which will enable the exchange of information between space and ground via the various elements of the infrastructure. The communication network is based on the use of Data Relay Satellite Systems (DRSS) which will satisfy communication requirements between Low Earth Orbit (LE0) user satellites and ground. The data generated within the LEO user satellite are received by the earth terminal of the control centre via the DRS and are routed through the control centre network to the end user (directly or via ISDN public networks), The data to be transferred can be subdivided into continuous data (i.e., video, voice) Which requires minimum end-to-end delay, and into computer data which requires minimum error rate ant less contraltos in terns of delay.

1. ELEMENTS OF SATELLITE COMMUNICATION

1.1 OVERVIEW

The unique feature of communications satellites is their ability to simultaneously link all users on the earth's surface, thereby providing distance insensitive point-to-multipoint communications. This capability applies to fixed terminals on earth and to mobile terminals on land, in the air, and at sea. Also, with satellites, capacity can be dynamically allocated to users who need it. These features make satellite communications systems unique in design. This chapter serves as an overview of satellite communication and prepares the reader for more elaborate study in the rest of the book. Arthur C. Clarke, author of many famous books on exploration, wrote in *Wireless World* in 1945 that a satellite with a circular equatorial orbit at a correct altitude of 35,786 km would make one revolution every 24 h; that is, it would rotate at the same angular velocity as the earth. An observer looking at such a geostationary satellite would see it hanging at a fixed spot in the sky. Clarke showed that three geostationary satellites powered by solar energy could provide worldwide communications for all possible types of services. Clarke's vision became a reality 20 years later when the *International Telecommunications Satellite Organization* (INTELSAT), established in 1964, launched the *Early Bird (INTELSAT 1)* in April 1965. Many INTELSAT satellites have a launched or are in the planning stages, ranging from instruments with a small capacity (240 voice circuits or one television channel) to those with a huge capacity

Table 1.1 Electromagnetic frequency spectrum

Frequency	Wavelength (m)	Designation
3 Hz–30 kHz	10^8–10^4	Very low frequency (VLF)
30–300 kHz	10^4–10^3	Low frequency (LF)
300 kHz–3 MHz	10^3–10^2	Medium frequency (MF)
3–30 MHz	10^2–10	High frequency (HF)
30–300 MHz	10–1	Very high frequency (VHF)
300 MHz–3 GHz	1–10^{-1}	Ultrahigh frequency (UHF)
3–30 GHz	10^{-1}–10^{-2}	Superhigh frequency (SHF)
30–300 GHz	10^{-2}–10^{-3}	Extremely high frequency (EHF)
10^3–10^7 GHz	3×10^{-5}–3×10^{-7}	Infrared, visible light, ultraviolet

(40,000 voice circuits for INTELSAT VI) and covering three regions the Atlantic, Pacific, and Indian oceans (Fig. 1.1). By 1989 hundreds of geostationary satellites were in service. Asumma of satellite locations can be found in.

1.2 Satellite Frequency Bands

Communications systems employ the electromagnetic frequency spectrum shown in Table 1.1. The frequencies used for satellite communications are allocated in super high-frequency (SHF) and extremely high-frequency (EHF) bands which are broken down into sub bands as summarized in Table 1.2. Spectrum management is an important activity that facilitates the orderly use of the electromagnetic frequency spectrum not only for satellite communications but for other telecommunications applications as well. This is done under the auspices of the.

Table 1.2 Satellite frequency spectrum

Frequency band	Range (GHz)
L	1–2
S	2–4
C	4–8
X	8–12
Ku	12–18
K	18–27
Ka	27–40
Millimeter	40–300

International Telecommunication Union (ITU) which is a specialized agency of the United Nations (UN). It predates the UN, having come into existence in 1932 as a result of the merging of the International Tele-graph Union (1865- 1932). There are four headquartered technical permanent organs of the ITU: (1) the general secretariat, and headquartered in Geneva and responsible for executive management and technical cooperation; (2) the *International Frequency Registration Board(IFRB), responsible* for recording frequencies and orbital positions and for advising member countries on operation of the maximum practical number of radio channels in portions of the spectrum where harmful interference may occur; (3) the *International Radio Consultative Committee* (CCIR, from the initial letters in French), responsible for studying technical and operational questions relating to radio communications which results in reports, recommendations, resolutions, and decisions published as a group in the *Green Books* every 4 yr following CCIR plenary assemblies; and (4) the *International Telegraph* and *Telephone Consultative Committee* (CCITT), responsible for studying technical, operational, and tariff questions relating to telegraphy and telephony and for adopting reports and recommendations. The ITU has developed rules and guidelines called radio regulations at a series of international radio conferences held since 1903. The 1979 *World Administrative Radio Conference* (WARC-79) was the most recent in this long series. The frequency bands allocated by WARC-79 for satellite communications involve 17 service categories (although some of them represent special subcategories), as listed in Table 1 .3, and three geographic regions: region 1 which includes Europe, Africa, the USSR, and Mongolia; region 2 which includes North and South America and Greenland; and region 3 which includes Asia (except the USSR and Mongolia), Australia, and the Southwest Pacific. Tables 1 .4 and 1 .5 show the WARC-79 frequency allocations fixed *satellite service* (FSS) and *broadcasting satellite service* (BSS).

Table 1.3 Satellite services

Fixed	Meteorological
Intersatellite	Space operation
Mobile	Amateur
Land mobile	Radiodetermination

Maritime mobile	Radionavigation
Aeronautical mobile	Aeronautical rationalization
Broadcasting	Maritime rationalization
Earth exploration	Standard frequency and time signal
Space research	

Table 1.4 Frequency allocations for fixed satellite service

Frequency range (GHz)	Restrictions[a]	Frequency range (GHz)	Restrictions[a]
2.5–2.535	1n, 2d, 3d	18.1–21.2	d
2.535–2.655	1n, 2b, 3n	27–27.5	1n, 2u[c], 3u[c]
2.655–2.690	1n, 2b, 3u	27.5–31	u
3.4–4.2	d	37.5–40.5	d
4.5–4.8	d	42.5–43.5	u
5.725–5.85	1u, 2n, 3n	47.2–49.2	u[c]
5.85–7.075	u	49.2–50.2	u
7.25–7.75	d	50.4–51.4	u
7.9–8.4	u	71–74	u
10.7–11.7	1b[b], 2d, 3d	74–75.5	u
11.7–12.3	1n, 2d, 3n	81–84	d
12.5–12.7	1b, 2n, 3d	92–95	u
12.7–12.75	1b, 2u, 3d	102–105	d
12.75–13.25	u	149–164	d
14–14.5	u	202–217	u
14.5–14.8	u[b]	231–241	d
17.3–17.7	u[b]	265–275	u
17.7–18.1	b[b]		

[a] 1, Region 1; 2, region 2; 3, region 3; up uplink (earth to space); d, downlink (space to earth): n, not allocated; b, bidirectional.

[b] uplink limited to BSS feeder links.

[e] Intended for but not limited to BSS feeder links.

Table 1.5 Frequency allocations for broadcasting satellite service

0.62–0.79	t
2.5–2.69	c
11.7–12.1	1, 3 only
12.1–12.2	
12.2–12.5	1, 2 only
12.5–12.7	2, 3c only
12.7–12.75	3c only
22.5–23	2, 3 only
40.5–42.5	
84–86	

[a]t, Television only ; c, community reception only; 1, region 1 ; 2, region 2: 3, region 3.

1.3 Satellite Systems

A satellite system consists basically of a satellite in space which links many earth stations on the ground, as shown schematically in Fig. 1.2. The user generates the base band signal which is routed to the earth station through the terrestrial network. The terrestrial network can be a telephone switch or dedicated link to the earth station. At the earth station the base band signal is processed and transmitted by a modulated radio frequency (RF) carrier to the satellite. The satellite can be thought of as a large repeater in space. It receives the modulated RF carriers in its uplink (earth-to-space) frequency spectrum from all the earth stations in the network, amplifies these carriers, and retransmits them back to earth in the downlink (space-to-earth) frequency spectrum which is different from the uplink frequency spectrum in order to avoid interference. The receiving earth station processes the modulated RF carrier down to the base band signal which is sent through the terrestrial network to the user. Most commercial communications satellites today utilize a 500-MHz bandwidth on the uplink and a 500-MHz bandwidth on the downlink. The most widely used frequency spectrum is the 6/4-GHz band, with an uplink of 5.725 to 7.075 GHZ and a downlink of 3.4 to 4.8 GHz. The 6/4- GHz band for geostationary satellites is becoming overcrowded because it is also used by common carriers for terrestrial microwave links. Satellites are now being operated in the 14/12-GHz band using an uplink of 12.75 to 14.8 GHZ and a downlink of either 10.7 to 12.3 GHz or 12.5 to 12.7 GHz. The 14/12-GHz band will be used extensively in the future and is not yet congested, but one problem exists-rain, which attenuates 14/ 12-GHz signals much more than it does those at 6/4 GHz. The frequency spectrum in the 30/20-GHz band has also been set aside for commercial satellite communications, with a downlink of 18. 1 to 2 1.2 GHz and an uplink of 27.5 to 31 GHz. Equipment for the 30/20-GHz band is still in the experimental stage and is expensive. The typical SX-MH: satellite bandwidth at the 6/4 and 14/12-GHz bands can be segmented into many satellite transponder bandwidths. For example, eight transponders can be provided, each with a nominal bandwidth of 54 MHz and a center-to-center frequency spacing of 61 MHz. Modem communications satellites also employ frequency reuse to

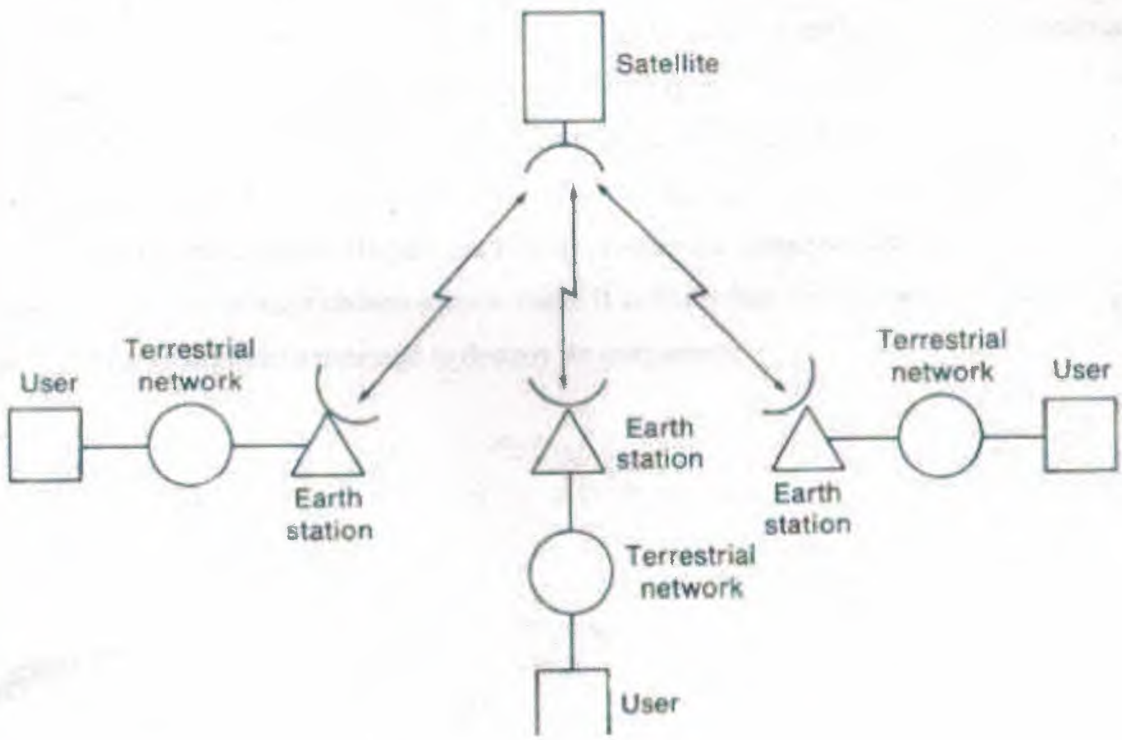


Figure 1.2 A basic satellite system

increase the number of transponders in the 500 MHZ allocated to them. Frequency reuse can be accomplished through orthogonal polarizations where one transponder operates in one polarization (e.g., vertical polarization) and a cross-polarized transponder orates in the orthogonal polarization (e.g. , horizontal polarization). Isolation of the two polarizations can be maintained at 30 do or more by staggering the center frequencies of the cross-polarized transponders so that only sideband energy of the RF carriers overlaps, as shown in Fig. 1.3. With orthogonal polarizations a satellite can double the number of transponders in the available 500-MHz bandwidth, hence double its capacity. A review of orthogonal polarizations will be presented in Sec. 1.6. With this brief discussion of a general satellite system we will now take a look at an earth station that transmits information to and receives information from a satellite. Figure 1.4 shows the functional elements of a digital earth station. Digital information in the form of binary digits from the terrestrial network enters the transmit side of the earth station and is then processed (buffered, multiplexed, formatted, etc.) by the base band equipment so that these forms of information can be sent to the appropriate destinations. The presence of noise and the no ideal nature of any communication channel introduce errors in the information being sent and thus 'limit the rate at which it can be transmitted between the source and the destination. Users generally establish an error rate above which the received information is not usable. If the received information does not meet the error rate requirement, error-correction coding performed by the encoder can often be used to reduce the error rate to the acceptable level by inserting extra digits into the digital stream from the output of the base band equipment. These extra digits carry no information. But are used to accentuate the uniqueness of each information message. They are always chosen so as to make it unlikely that the channel disturbance will corrupt enough digits in a message to destroy its uniqueness.

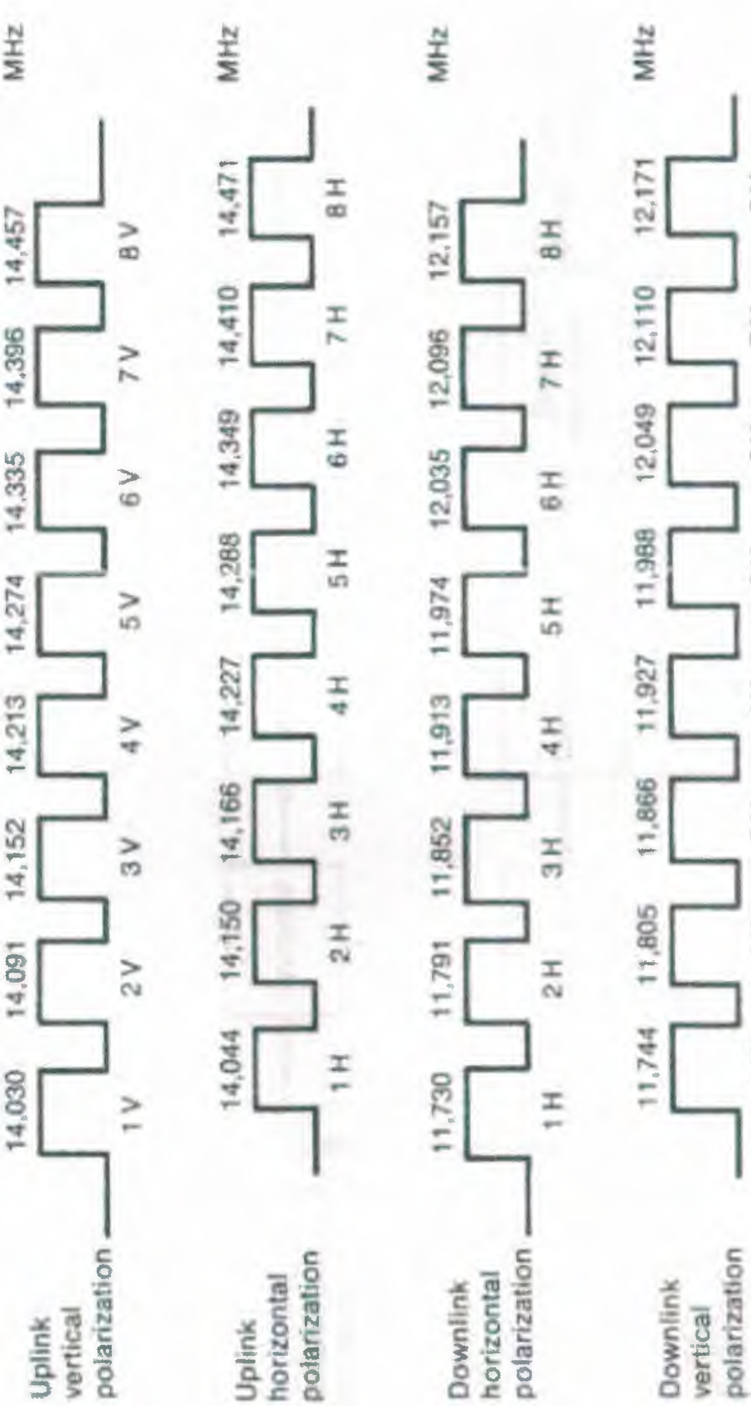


Figure 1.3 Staggering frequency reuse Ku-band transponders

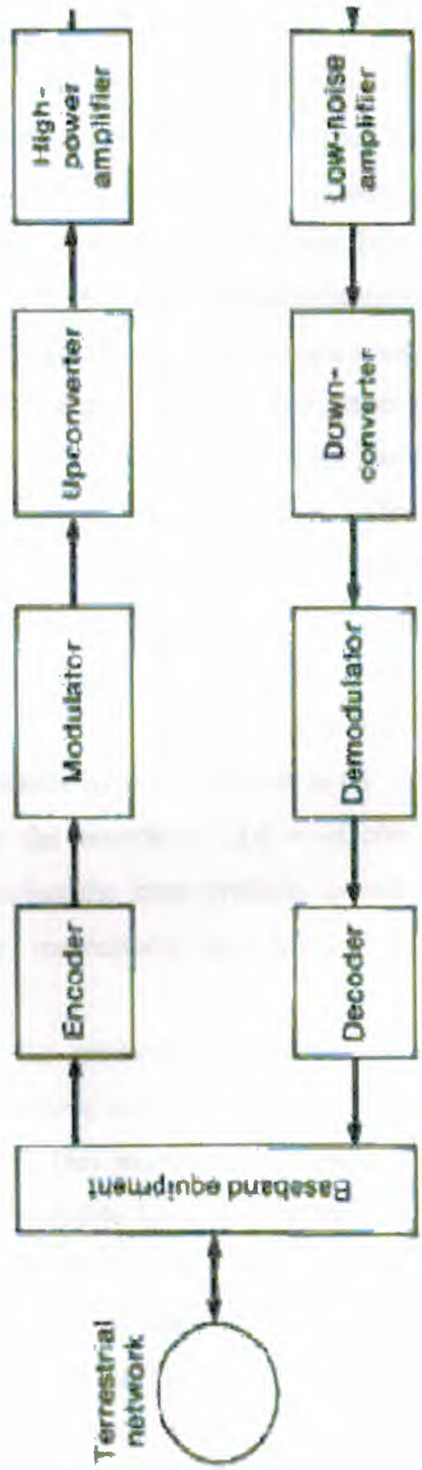


Figure 1.4 Functional block diagram of a digital earth station

In order to transmit the base band digital information over a satellite channel that is a band pass channel, it is necessary to transfer the digital information to a carrier wave at the appropriate band pass channel frequency. This technique is called *digital carrier modulation.* The function of the modulator is to accept the symbol stream from the encoder and use it to modulate an intermediate frequency (IF) carrier. In satellite communications, the IF carrier frequency is chosen at 70 MHZ for a communication channel using a 36-MHz transponder bandwidth and at 140 MHZ for a channel using a transponder bandwidth of 54 or 72 MHz. A carrier wave at an intermediate frequency rather than at the satellite RF uplink frequency is chosen because it is difficult to design a modulator that works at the uplink frequency spectrum (6 or 14 GHz, as discussed previously). For binary modulation schemes, each output digit from the encoder is used to select one of two possible waveforms. For Mary modulation schemes, the output of the encoder is segmented into sets of k digits, where M = $2k$ and each Fe-digit set or symbol is used to select one of the M waveforms. For example, in one particular binary modulation scheme called *phase-shat keying* (PSK), the digit 1 is represented by the waveform s_0 (t) = - A cos ω_0 t, where ω_0 and the digit 0 is represented by the waveform $S_0(t)$ = $-A$ cos ω_0 t, where ω_0 is the intermediate frequency. (In this project the letter symbols ω and f will be used to denote angular frequency and frequency, respectively, and we will refer to both of them as "frequency").

The modulated IF carrier from the modulator is fed to the unconverted, where its intermediate frequency ω_0 is translated to the uplink RF frequency ω_u in the uplink frequency spectrum of the satellite. This modulated RF carrier is then amplified by the high-power amplifier (HPA) to a suitable level for transmission to the satellite by the antenna.

On the receive side the earth station antenna receives the low-level modulated RF carrier in the downlink frequency spectrum of the satellite. A low-noise amplifier (LNA) is used to amplify this low-level RF carrier to keep the carrier-to-noise ratio at a level necessary to meet the error rate requirement. The down converter accepts the amplified RF carrier from the output of the low-noise amplifier and translates the downlink frequency ω_d to the intermediate frequency ω_0. The reason for down converting the RF frequency of the received carrier wave to the intermediate frequency is that it is much easier to design the demodulator to work at 70 or 140 MHz than at a downlink frequency of 4 or 12 GHz. The modulated IF carrier is fed to the demodulator, where the information is extracted. The demodulator estimates which of the possible symbols was transmitted based on observation of the received IF carrier. The probability that a symbol will be correctly detected depends on the carrier-to- noise ratio of the modulated carrier, the characteristics of the satellite channel, and the detection scheme employed. The decoder performs a function opposite that of the encoder. Because the sequence of symbols recovered by the demodulator may contain errors, the decoder must use the uniqueness of the redundant digits introduced by the encoder to correct the errors and recover information-bearing digits. The information stream is fed to the base band equipment for processing for delivery to the terrestrial network. In the United States the *Federal Communications Commission* (FCC) assigns orbital positions for all communications satellites to avoid interference between adjacent satellite systems operating at the same frequency. Before 1983 the spacing was established at 4^0 of the equatorial arc, and the smallest earth station antenna for a simultaneous transmit receive operation allowed by the FCC is 5 m in diameter. In 1983, the FCC ruled that axed service communications satellites in the geostationary orbit should be spaced every 20 along the equatorial arc instead of 40. This closer spacing allows twice as many satellites to occupy the same orbital arc. The FCC ruling poses a major challenge to antenna engineers to design a directional feed for controlling the amount of energy received of axis by the antenna feed, thus reducing interference from an adjacent satellite. This challenge is especially great because the trend in earth stations is toward smaller antennas, but smaller antennas have a wider beam width and thus look at a wider angle in the sky. The FCC ruling specified that, as of July1, 1984, all new satellite earth station antennas had to be manufactured to accommodate the spacing of 2^0 and that, as of January 1 , 1 987, all existing antennas must be modified to conform to the new standards.

1.4 Transmission And Multiplexing

In the above section we took a look at a simplified satellite communications system where digital information (a sequence of symbols instead of continuous signals) is carried between terrestrial networks. Historically, analog transmission has dominated satellite communications since its inception. Even today many satellite systems still transmit telephone and television signals using frequency modulation (FM) and this trend will continue for some time to come because of the large investment in existing earth stations. With the advent of digital electronics and computers, many earth stations have begun to use digital transmission to improve satellite capacity over analog transmission. These digital earth stations can interconnect digital terrestrial networks or analog terrestrial networks with appropriate analog-to-digital (A/D) conversion equipment. A clear advantage of digital transmission is that it permits integration of information in various forms. Such analog information as speech and visual signals can be converted to digital from and thereby combined with data for transmission, switching, processing, and retrieval.

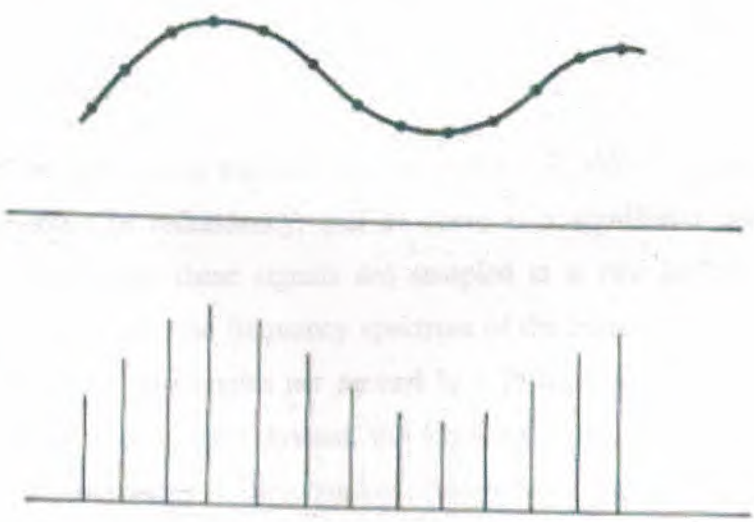


Figure 1.5 Sampling of an analog signal.

1.4.1 Pulse Code Modulation

One commonly used technique form is *pulse code modulation* for converting an analog signal to digital (PCM) which requires three operations: sampling, quantizing, and coding. *Sampling* converts the continuous analog signal into a set of periodic pulses, the amplitudes of which represent the instantaneous amplitudes of the analog signal at the sampling instant, as shown in Fig. 1.5. A question naturally arises: What sampling rate is required in order to reconstruct the signal completely from these samples? Nyquist [3, 4] proved that, if the analog signal is band-limited to a bandwidth of B hertz, the signal can be completely reconstructed if the sampling rate is at least the Nyquist rate which is $2B$. For example, telephone speech is band-limited to 4 kHz and thus requires 8000 samples per second. Since analog signals have a continuous amplitude range. The samples are continuous in amplitude. When the continuous amplitude samples are transmitted over a noisy channel, the receiver cannot discern the exact sequences of transmitted values. This effect of noise in the system can be minimized by breaking the sample amplitude into discrete levels and transmitting these levels using a binary scheme. The process of representing the continuous amplitude of the samples by a finite set of levels is called *quantizing.* If F quantized levels are employed to represent the amplitude range, it will take log: F bits to code each sample. In telephone transmission 256 quantized, levels are employed, and hence each sample is coded using log: 256 = 8 bits, and thus the digital bit rate is 8000 x 8 = 64,000 bits per second (bps).

1.4.2 Delta Modulation

It has been found that analog signals such as speech and video signals generally have a considerable amount of redundancy; that is, there is a significant correlation between successive samples when these signals are sampled at a rate slightly higher than the Nyquist rate. For example, the frequency spectrum of the human voice is 300 to 3400 Hz but it is sampled at 8000 samples per second in a PCM system. When these correlated samples are coded as in a PCM system, the resulting digital stream contains redundant information. The redundancy in these analog signals makes it possible to predict a sample value from the preceding sample values and to transmit the difference between the actual sample value and the predicted sample value estimated from past samples. This result in a technique called *deference encoding.* One of the simplest forms of difference encoding is *delta modulation* which provides a stair- case approximation of the sampled version of the analog input signal as shown in Fig. 1.6. The difference between the input and the approximate mat ion is quantized into two levels, $+\Delta$ and $-\Delta$ corresponding to a positive and a negative difference, respectively. Thus at any sampling instant the approximation is increased by Δ or decreased by Δ depending on whether it is below or above the analog input signal. A digital output of 1 or 0 can be generated according to whether the difference is $+\Delta$ or $-\Delta$. In delta modulation, overloading can occur if the amplitude of the analog input signal changes too fast for the encoding to keep up. Increasing the step size Δ will result in poor resolution and increasing the sampling rate will lead to a higher digital bit rate. A better scheme for avoiding overloading is to detect the overloading condition and to adjust the step size Δ to a larger value. This is called *adaptive delta modulation.* Delta modulation has been used to encode speech with good quality at 32,000 bps. Another important approach in digital encoding of analog signals is *deferential pulse code modulation.* This is basically a modification of *deferential pulse code*

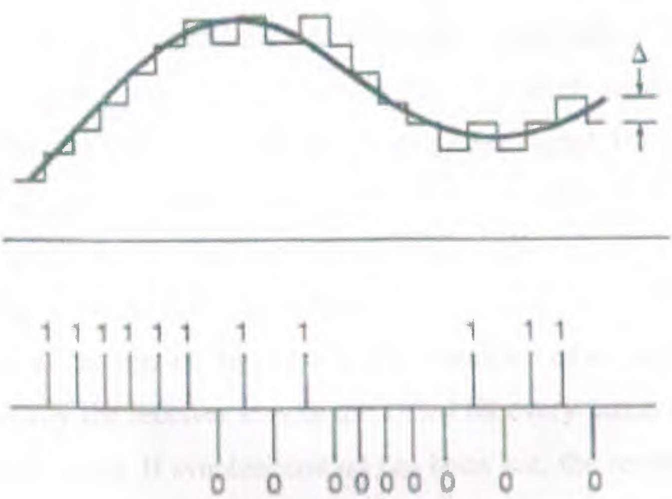


Figure 1.6 Delta modulation

deferential pulse code modulation. This is basically a modification of delta modulation where the difference between the analog input signal and its approximation at the sampling instant is quantized into levels and the output of the encoder is coded into log: F bits. Differential PCM combines the simplicity of delta modulation and the multilevel quantizing feature of PCM, and in many applications it can provide good reproduction of analog signals comparable to PCM with a considerable reduction in the digital bit rate. There are other new strategies to encode speech at lower bit rates than the above methods. One method is *linear predictive coding* (LIND which achieves speech compression by estimating a speech signal as a linear function of past outputs of the speech quantizing system. Near-toll-quality speech voiceovers (speech digitizing systems) at 4.8 kbps are now being developed for mobile satellite communications.

1.4.3 Time Division Multiplexing-Pulse Code Modulation

Information tragic between a terrestrial network and an earth station involves much more than a PCM channel at 64,000 bps. In order to carry many more channels simultaneously over a single transmission facility such as a wire pair or coaxial cable, multiplexing must be employed. One of the most widely used multiplexing techniques for telephone speech signals is *time division multiplexing-pulse code modulation* (TDM-PCM) as shown in Fig. 1.7. Here 24 speech signals are fed to 24 contacts pf a pair of synchronized electronic switches at the transmit and receive ends. The continuous amplitude of the speech signals is repeatedly sampled as the switch rotates. Each of the 24 speech signals is sampled every 125 Ms and interleaved to form a time division-multiplexed signal. Each sample of the time division-multiplexed signal is quantized and converted to an 8-bit PCM codeword. The 8-bit PCM codeword forms a time slot corresponding to a sample from one of the 24 speech signals. Twenty-four time slots form a 125-.s frame which consists of 192 bits and an additional 193rd bit at the end of the frame that is used for establishing and maintaining frame timing. Normally the receiver checks the 193rd bit every frame to make sure that it has not lost synchronization. If synchronization has been lost, the receiver can scan for the framing pattern and be resynchronized. Since there are 193 bitsy 125 Ms, the total bit rate is 1.544 Mbps. In addition to the voice signal, the frame also carries signaling information needed to transmit telephone dial tones as well as on-hook and of- hook signals. Every sixth frame, the least significant bit (the eighth bit) of each voice channel is deleted and a signaling bit is inserted in its place. This type of TDM-PCM bit stream is employed in the Bell System's T 1 carrier which is used in North America [5]. An international standard also exists for PCM transmission. The CCITT has a recommendation for a PCM carrier at 2.048 Mbps. In this carrier, there are 32 8-bit time slots in each 125-.s frame. Thirty of these time slots are used for speech at a bit rate of 64 kbps, one for synchronization and one for signaling. The 2.048- Mbps PCM carriers are used outside North America and Japan.

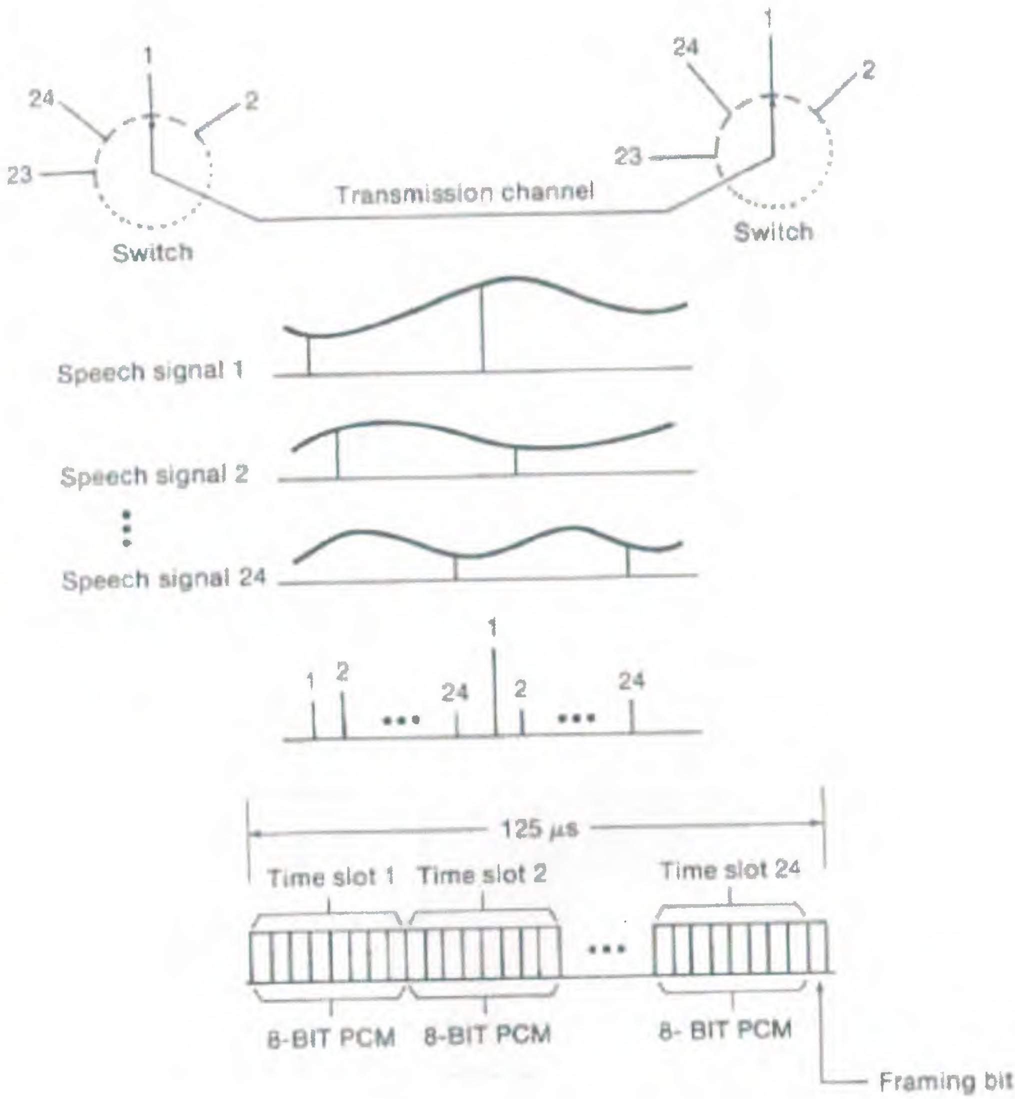


Figure 1.7 Time division multiplexing-pulse code modulation.

1.4.4 Digital Hierarchy

To transmit digitized analog signals such as telephone speech and visual signals having different bit rates, and data with a diversified bit rate over the same transmission channel, higher-order digital multiplexing or a digital hierarchy must be used. Figure 1.8 illustrates the Bell System digital hierarchy which consists of four levels. The respective data signals with bit rates of 1.544 Mbps (T1), 6.312 Mbps (T2), 44.736 Mpbs (T3), and 274. 176 Mbps (T4) correspond to levels 1, 2, 3, and 4. Level 1 is the out- put of a D 1 channel bank which

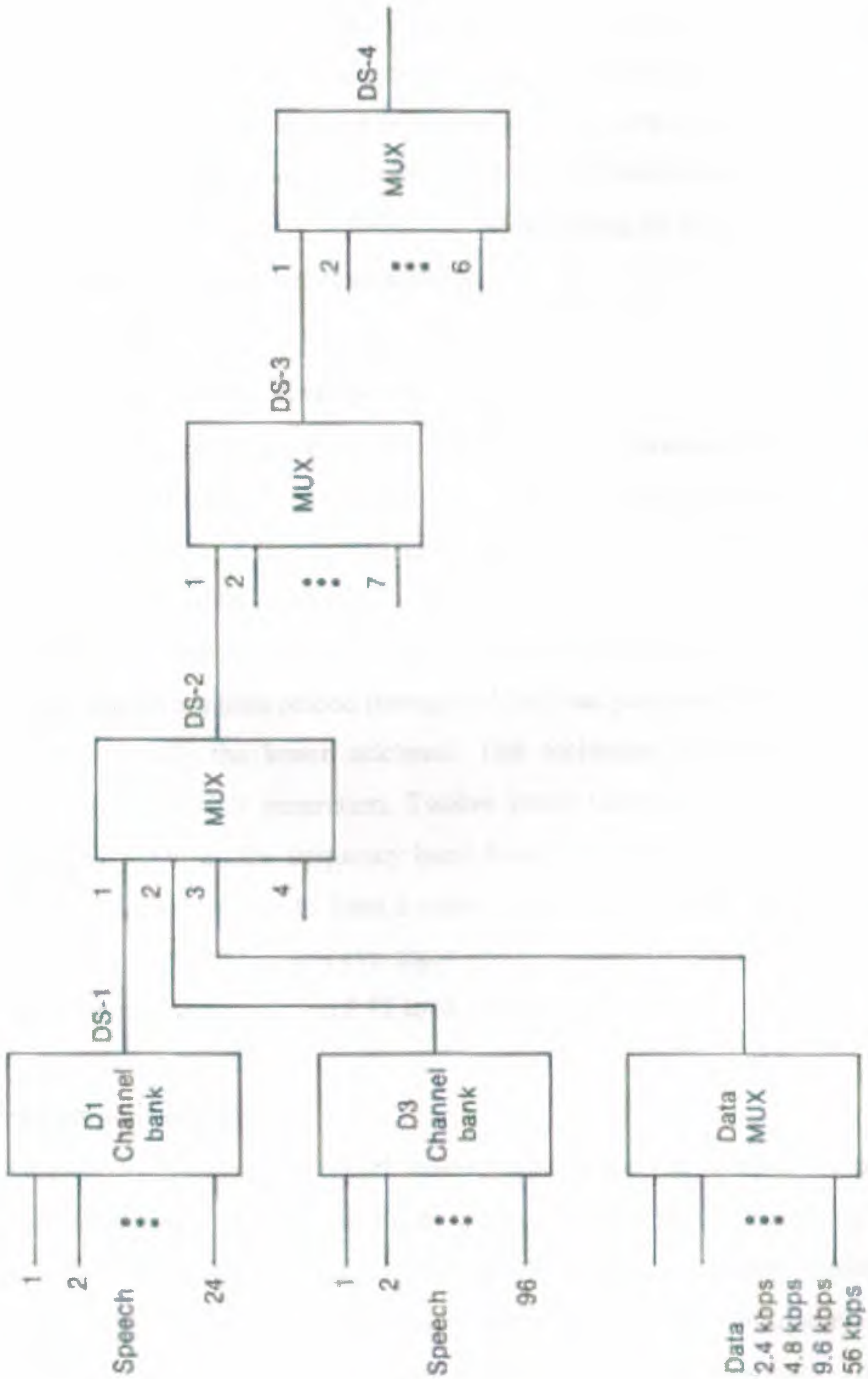


Figure 1.8 Digital hierarchy

time division-multiplexes and PCM-en- codes 24 speech signals, or one of the four outputs of a D3 channel bank which multiplexes and encodes 96 speech channels, or the output of a data multiplexer which multiplexes data with bit rates of 2.4, 4.8, 9.6, and 56 kbps. The DS-I data signal is carried by the T1 carrier system over a wire pair. Level 2 is formed by multiplexing four DS-I data signals and is carried by aT2 carrier system over a wire pair. Level 3 is formed by multiplexing seven DS-2 data signals and is carried by a 7-3 carrier system over coaxial cable. Level 4 is formed by multiplexing six DS-3 data signals and is carried by a 7-4 carrier system over coaxial cable.

1.4.5 Frequency Division Multiplexing

Another form of multiplexing that characterizes analog communications is *frequency division multiplexing* (FDM), as shown in Fig. 1.9. Twelve speech signals, each of which occupies a bandwidth from 300 to 3400 Hz, are used to modulate 12 separate carriers each 4 kHz apart. The output of the modulator, which is the product of the speech signal and the carrier, consists of a lower sideband and an upper sideband centered on the carrier frequency. The signals are then passed through 4-kHz band pass alters that reject the upper sideband and pass only the lower sideband. This technique is called *single-sideband suppressed carrier* (SSBSC) generation. Twelve lower sidebands are then combined to form a group that occupies the frequency band from 60 to 108 kHz. Five groups can be multiplexed in a similar fashion to form a super group of 60 speech signals that occupies the band from 312 to 552 kHz, and eve super groups form a master group of 300 speech channels that occupies the band from 8 12 to 2044 kHz.

1.4.6 Transmultiplexing

Despite the explosive progress in digital telecommunications technology. a major portion of terrestrial transmission facilities still uses a frequency division multiplexing hierarchy and will do so in the future because of the large investment in existing systems. For a digital earth station to interface with such an analog terrestrial network, some means for conversion between a FDM hierarchy and a digital hierarchy is needed. This can be achieved by a FDM-TDM converter, for example between two super groups (120 speech channels) and eve T l carriers (1 20 PCM channels) as shown in Fig. 1.10. It consists of a FDM multiplexer or demultiplexer

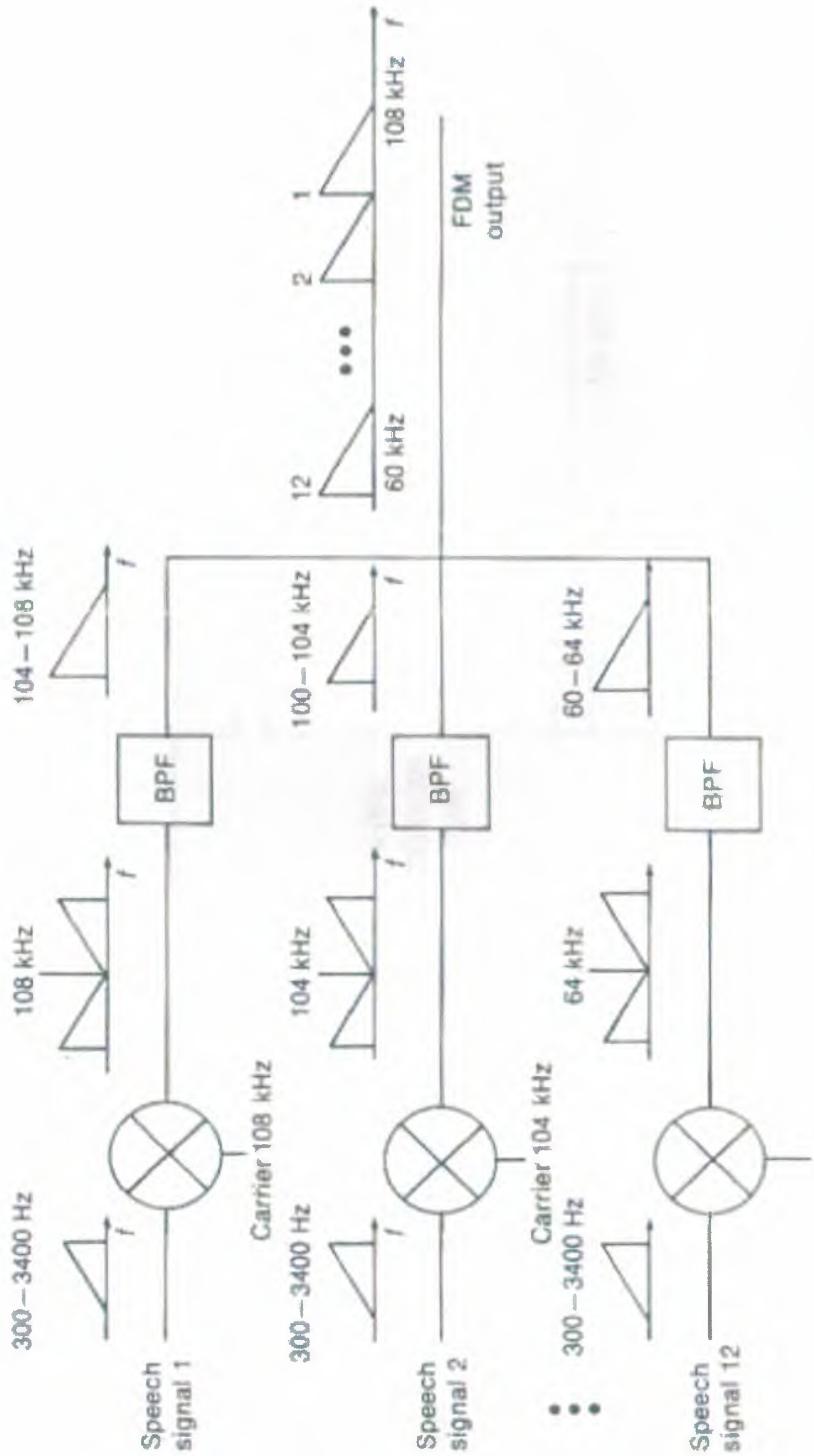


Figure 1.9 Frequency division multiplexing.

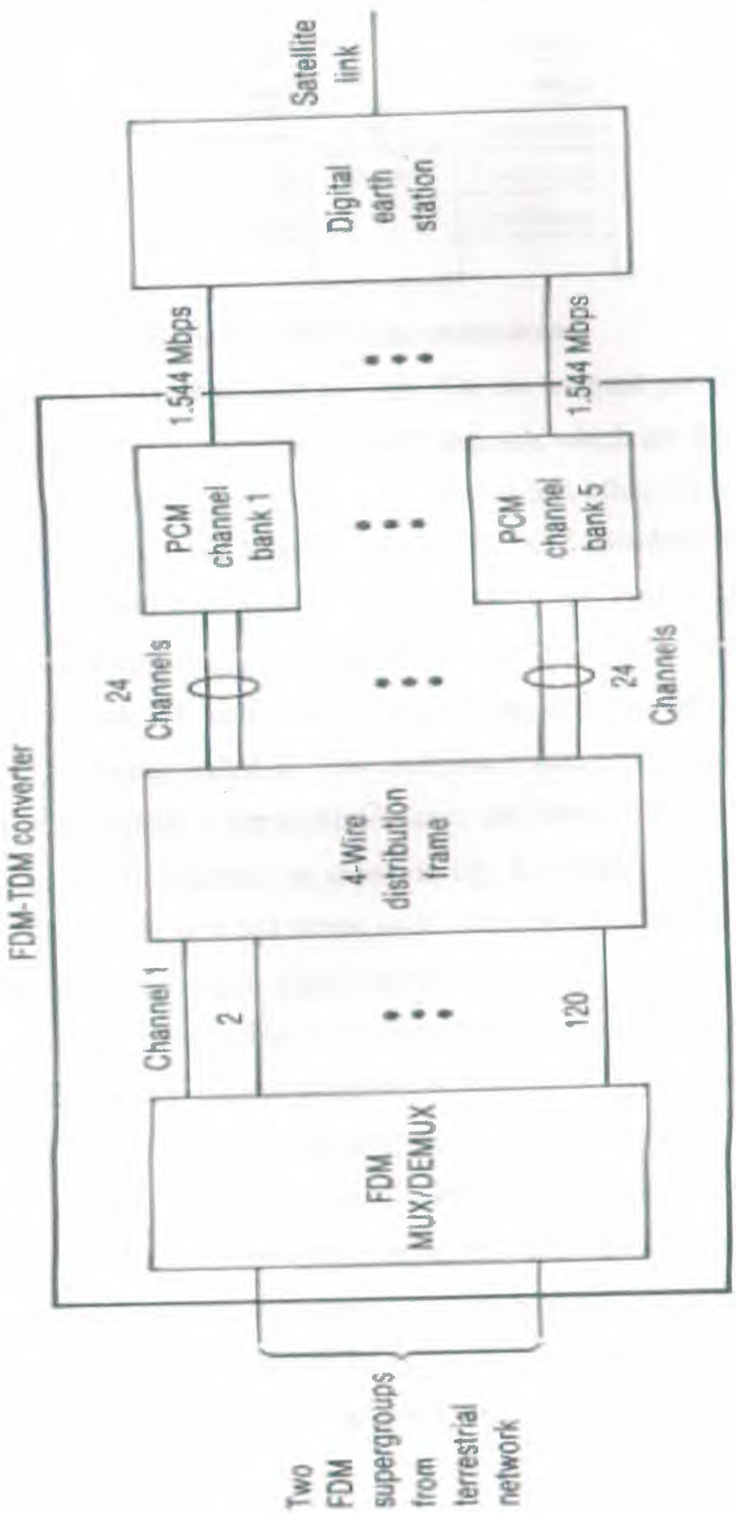


Figure 1.10 FDM-converter

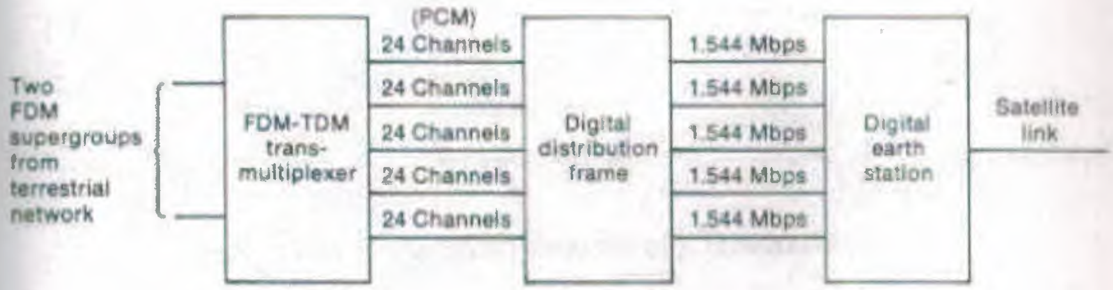


Figure 1.11 FDM-Tran multiplexer

and PCM channel banks connected back to back. On the transmit side the FDM super groups are demultiplexed to 120 individual speech channels which are then time division multiplexed and PCM-encoded by the chanel separate 1.544-Mbps T1 carriers. On the receive side, the five separate 1.544-Mbps T1 carriers are PCM-decoded and time division-demultiplexed into 120 individual speech channels which are then frequency division-multiplexed into two super groups. A four-wire distribution frame is used for the purpose of individual channel manipulation such as reordering, adding, deleting, and testing. A special type of FDM-TDM converter called a *Tran multiplexer* can interconnect FDM speech signals and TDM-PCM signals at the multiplex level and thus avoid breaking the signals down into individual speech channels, as shown in Fig. 1.11 where two super groups are converted to five T1 carriers at 1.544 Mbps each. With the use of a distribution frame, individual channels can be reordered, added, deleted, and tested. The fundamental element of a Tran multiplexer is shown in Fig. 1.12. FDM-TDM conversion is accomplished by removing any un- wanted out-of-band components from the FDM signal with an analog band pass alter (3 12 to 552 kHz for two super groups). The altered signal is passed through an A/D converter to produce a digital stream. The individual channel in this digital stream is processed by the digital signal processor via a real-time signal-processing algorithm. Tran multiplexer performance can be superior to that achievable with the conventional FDM-TDM conversion equipment shown in Fig.1.10, with approximately 2:1 and 5:1 reduction advantages in cost per voice channel and in size, respectively.

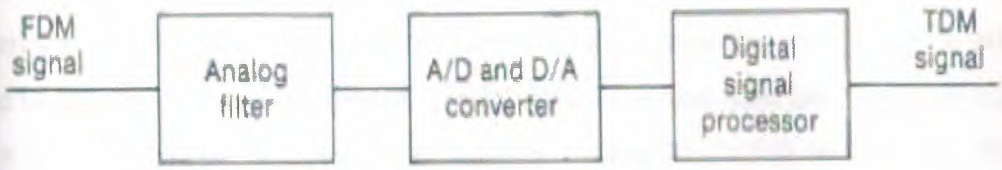


Figure 1.12 Fundamental elements of a Transmultiplexer.

1.5 Modulation

As mentioned in Sec. 1.2, modulation must be employed to transmit base band information over a band pass channel. In *analog modulation* such as frequency modulation, which is extremely popular in satellite communications, the signal-to-noise ratio at the output of the FM demodulator is an intuitive measure of how well the FM demodulator can recover the analog information signal from the received modulated carrier in the presence of additive white Gaussian noise (AWGN). The *output signal-to-noise ratio* is denned as the ratio of the average power of the analog information signal to the average power of the noise at the output of the demodulator. In *digital modulation,* the performance of the demodulator is measured in terms of the average probability of bit error, or the *bit error rate* as it is often called. The binary information, which consists of sequences of 1 and 0 digits, can be used to modulate the phase, frequency, or amplitude of a carrier. Consider the carrier A cos $(\omega_C t + \phi)$, where, A is the carrier amplitude, ω_C is the carrier frequency, and ϕ is the carrier phase. To transmit the binary digit or bit 1, ϕ is set to 0 rad, and to transmit the bit 0, ϕ is set to π radians. Thus 1 is represented by the waveform, A cos $\omega_c t$, and 0 is represented by the waveform A cos $(\omega c t + \pi) = -A \cos \omega_c t$. This type of discrete phase modulation is called phase-shift keying (PSK). Similarly, 1 can be transmitted by using the waveform A $\cos \omega_1 t$ and 0 transmitted by using the waveform, A $\cos \omega_2 t$,, where $\omega_1 \neq \omega_1$ .This type of digital modulation is called *frequency- shift keying* (FSK), where two waveforms at different carrier frequencies ω_1 and ω_2 are used to convey the binary information. The problem with digital modulation is that sometimes the binary digit 1 is transmitted but the demodulator decodes it as a 0, or vice versa, because of perturbation of the carrier by noise; this results in bit errors in the demodulation of the binary information. The average probability of bit error P_b is a convenient measure of the performance of the demodulator and is a function of the ratio of the energy per bit to the noise density, E_b/N_0, where the energy per bit E_b is the energy of the carrier during a signaling interval or bit duration T_b and $N_0/2$ is the noise power spectral density. When the base band information is transmitted at a rate of R bits per second, the bit duration is simply $T_b = 1/R$ seconds, and this is also the signaling interval of the waveform that represents a particular bit. For example, in PSK modulation,

$$s_1(t) = A \cos \omega_c t \qquad 0 \le t \le T_0$$

$$s_2(t) = -A \cos \omega_c t \qquad 0 \le t \le T_0$$

where $S_1(t)$ represents 1 and $S_2(t)$ represents 0. By definition we have

$$E_b = \int_0^{T_b} s_1^2(t)dt = \int_0^{T_b} s_2^2(t)dt = \int_0^{T_b} A^2 \cos^2 \omega_c t dt$$

Note that $E_b \approx A^2 T_b / 2$ when $\omega > 2\pi / T_b$ The quantity E_b / N_0 can be related to the average carrier power C, and the noise power N measured within the receiver noise bandwidth B. By definition, the average carrier power is

$$C = \frac{1}{T_b} \int_0^{T_b} E\left[s^2(t)\right] dt$$

where $S(t)$ is the carrier waveform during the signaling interval T_b and E [.] is the expected value. If all the carrier waveforms have identical energy E_0 during any signaling interval, then

$$C \frac{E_b}{T_b}$$

Recall that the power spectral density of noise is $N_0 / 2$ and that the noise bandwidth is B. Hence the noise power measured within the noise bandwidth for both positive and negative frequencies is

$$N = N_0 B$$

Therefore it is seen that the ratio of the energy per bit to the noise density can be expressed as

$$\frac{E_b}{N_0} = \frac{CT_b}{N / B} = T_b B \left(\frac{C}{N}\right)$$

where C / N is the average carrier-to-noise ratio. In satellite communications, it is the quantity C / N that is directly evaluated, as we will discuss in Chap.4. Once the CIN is known and the bandwidth of the receiver is selected, E_b / N_0 can be calculated, as well as the average probability of bit error P_0 which is a function of E_b / N_0.

1.6 Multiple Accesses

One advantage of communications satellites over other transmission media is their ability to link all earth stations together, thereby providing point-to-multipoint communications. A satellite transponder cab be accessed by many earth stations, and therefore it is necessary to have techniques for allocating transponder capacity to each of them. For example, consider a transponder with a bandwidth of 72 MHz. Assume that the bit duration-bandwidth product $T_b B$ in (1.5) is chosen to be 0.6; that is, every 0.6 Hz of the transponder bandwidth can be used to transmit 1 bps.(There are digital modulation schemes that can easily achieve $T_b B = 0.6$, which we will discuss in. Then the transponder capacity is 120 Mbps, which can handle about 3562 voice channels at 32 kbps, assuming the transponder efficiency is 95%. It is unlikely that a single earth station would have this much tragic; therefore the transponder capacity must be wisely allocated to other earth station. Furthermore, to avoid chaos, we want the earth stations to gain access to the transponder capacity allocated to them in an orderly fashion. This is called *multiple accesses.* The two most commonly used multiple access schemes are *frequency division multiple access* (FDMA) and *time division multiple access* (TDMA). FDMA has been used since the inception of satellite communication. Here each earth station in the community of earth stations that share the transponder capacity transmits one or more carriers to the satellite trans- ponder at different center frequencies. Each carrier is assigned a frequency band in the transponder bandwidth, along with a small guard band to avoid interference between adjacent carriers. The satellite trans- ponder receives all the carriers in its bandwidth, amplifies them, and re- transmits them back to earth. The earth station in the satellite antenna beam served by the transponder can select the carrier that contains the messages intended for it. FDMA is illustrated in Fig. 1.13. The carrier modulation used in FDMA is FM or PSK. In TDMA the earth stations that share the satellite transponder use a carrier at the same center frequency for transmission on a time division basis. Earth stations are allowed to transmit tragic bursts in a periodic time frame called the *TDMA frame*. During the burst, an earth station has the entire transponder bandwidth available to it for transmission. The transmit timing of the bursts is carefully synchronized so that all the bursts arriving at the satellite transponder are closely spaced in time but

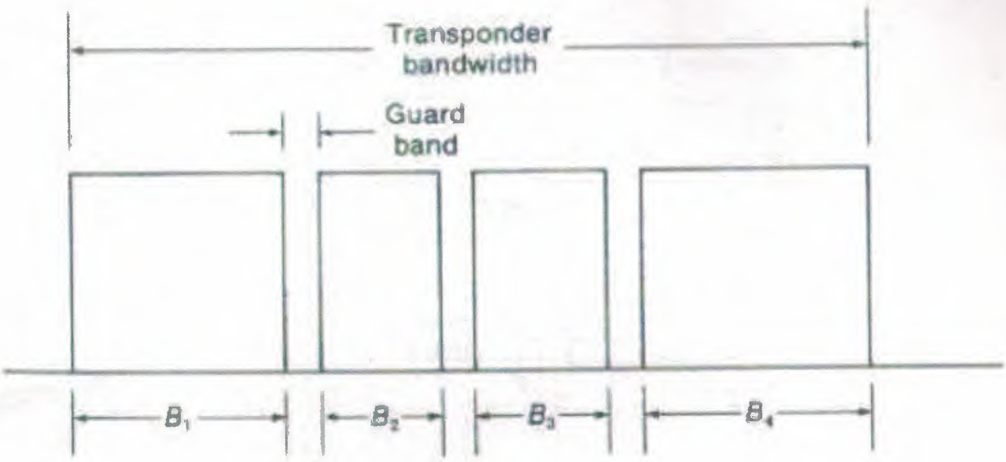


Figure 1.13 Concept of FDMA.B_m, Bandwidth resaved explicitly for station m,m = 1,2,3,4

do not overlap. The satellite transponder receives one burst at a time, amplifies it, and retransmits it back the satellite beam served to earth. Thus every earth station in by the transponder can receive the entire burst stream and extract the bursts intended for it. TDMA is illustrated in Fig.1.14. The carrier modulation used in TDMA is always a digital modulation scheme. TDMA possesses many advantages over FDMA, especially in medium to heavy tragic networks, because there are a number of efficient techniques such as demand assignment and digital speech interpolation that are inherently suitable for TDMA and can maximize the amount of terrestrial tragic that can be handled by a satellite transponder. For example, a 72-MHz transponder can handle about 178 1 satellite PCM voice channels or 3562 3z-kbps adaptive differential PCM channels. With a digital speech interpolation technique it can handle about twice this number, 3562 terrestrial PCM voice channels or 7124 3z-kbps adaptive differential PCM voice channels. In many TDMA networks employing demand assignment the amount of terrestrial traffic handled by the transponder can be increased many times. Of course these efficient techniques depend on the terrestrial traffic distribution in the network and must be used in situations that are suited to the characteristics of the technique. Although TDMA has many ad- vantages, this does not mean that FDMA has no advantages over TDMA. Indeed, in networks with many links of low traffic, FDMA with demand assignment is overwhelmingly preferred to TDMA because of the low cost of equipment, as we will discuss in. Besides FDMA and TDMA, a satellite system may also employ *random multiple access* schemes to serve a large population of users with bur sty (low duty cycle) tragic. Here each user transmits at will and, if a collision (two users transmitting at the same time, causing severe interference that destroys their data) occurs, retransmits at a randomly selected time to avoid collisions.

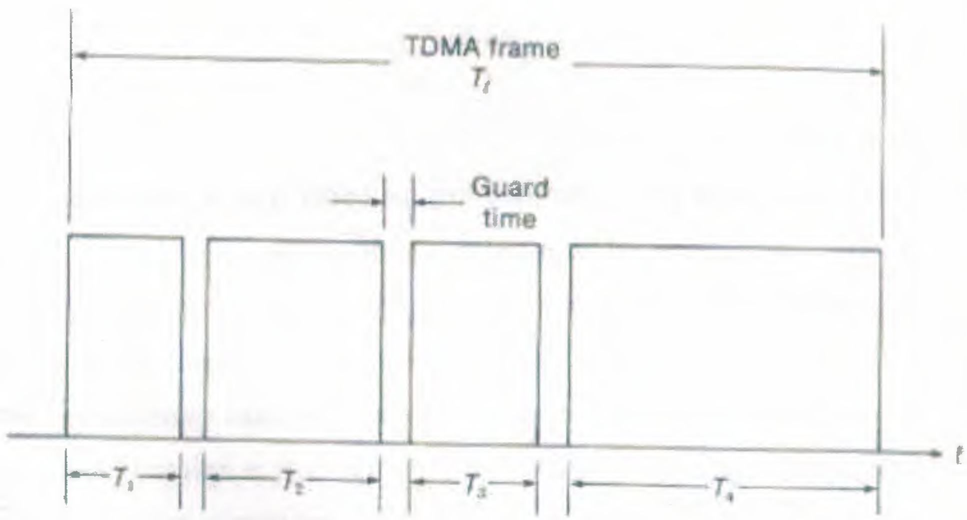


Figure 1.14 Concept of TDMA. T_m Time slot reserved explicitly for station *m,m = 1,2,3,4* very frame. The TDMA frame length T_f is also the frame period.

Another type of multiple access schemes is *code division multiple access,* where each user employs a particular code address to spread the carrier bandwidth over a much larger bandwidth so that the earth station community can transmit simultaneously without frequency or time separation and with low interference.

1.7 Frequency Reuse By Orthogonal Polarizations

One method of obtaining frequency reuse is to transmit two signals on the same frequency band (co channel) by placing each on orthogonal polarizations; thereby doubling the information capacity carried by the satellite. A fundamental requirement of dual-polarized transmission is to maintain a good level of isolation between two polarizations so that the co channel interference is acceptable. The polarization of a radiated electromagnetic wave is the curve traced by the end point of the instantaneous electric held vector as ob- served along the direction of propagation. Polarization may be classified as linear, circular, or elliptical (Fig. 1.15). If the vector oscillates along a line, the held is linearly polarized. if the vector remains constant in length but traces a circle, the held is circularly polarized. When the sense of rotation of the vector is counterclockwise (the wave direction is oil-the page), the held is right-hand circularly polarized. lf the rotation is clockwise, the field is left-hand circularly polarized. In general, the held may be elliptically polarized with either a fight- or a left-hand sense of rotation. A polarization ellipse is shown in Fig. 1.16. The wave associated with it travels in the +*z* direction (off the page). The instantaneous electric held can be described as follows:

$$ {}_{x}\hat{x} + \wp_{y}\hat{y} $$

$$ = E_1 \cos \omega t\, \hat{x} + E_2 \cos(\omega t + \Theta)\, \hat{y} $$

where E_1, E_2, , k, and *î* are the peak value, phase difference, x unit vector, and y unit vector of the *x* and y components of F, respectively. The tilt angle of the ellipse *T* is the angle between the x axis and the major axis of the ellipse. The axial ratio r of the ellipse is denned as the ratio of the electric held component along the major axis to that along the minor axis. When these components are in phase, *0* = 00, the wave is linearly polarized, and the orientation depends on the relative values of F1 and *Eg*. For example, if *Eg* = 0, then F = F1 cos *(a* k and the wave is horizontally polarized. When E'1 = 0, then g = *E2* costtt)/ + *ejî* and the wave is ver- tically polarized. Horizontal and vertical polarizations are two orthogonal linear polarizations. When *E3* = *Ek* and *0* = ::900, the polarization is circular, with the right-hand rotation corresponding to -900 and the left-

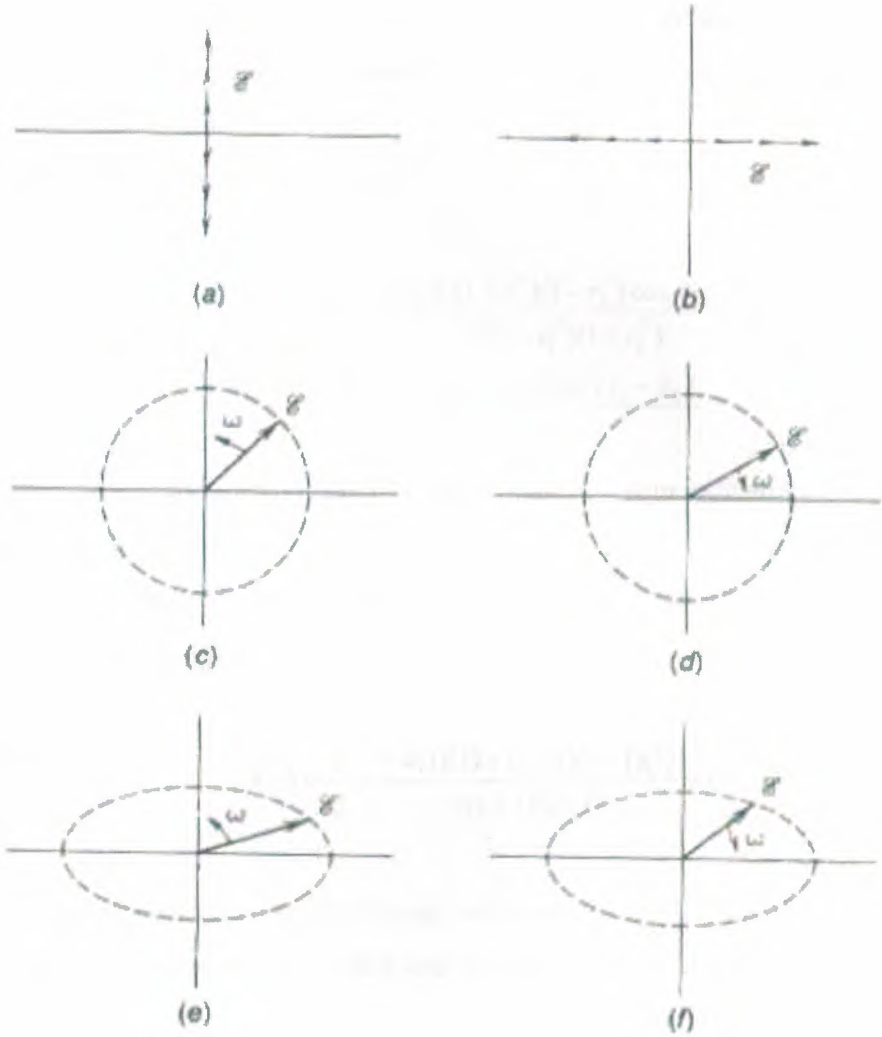


Figure 1.15 Types of polarization. (a) Linear vertical polarization. (b) linear horizontal polarization. (c) Right-hand circular polarization. (d) Left-hand circular polarization. (e) Right-hand elliptical polarization. (f) Left-hand elliptical polarization.

hand rotation corresponding to 90^0. Right- and left-hand circular polarizations are two orthogonal circular polarizations. In theory there is infinite isolation between orthogonal polarizations; that is, two signals in the same frequency band but each on orthogonal polarizations do not interfere with each other. A right-hand circularly polarized antenna absorbs the maximum amount of power from a right- hand circularly polarized wave and absorbs no power from a left-hand circularly polarized wave. A polarization mismatch factor p is normally employed to describe the coupling between polarizations. It varies between 1 and 0 and is equal to 1 when the two polarizations are the same or the antenna and the wave have the same polarization state. It is 0 when the two polarizations are orthogonal. For two general polarization ellipses

with axial ratios r_1 and r_2, p is given by

$$\begin{aligned} p(\pm) &= \frac{1}{2} + \frac{\pm 4r_1r_2 + (1-r_1^2)(1-r_2^2)\cos 2(\tau_1 - \tau_2)}{2(1+r_1^2)(1+r_2^2)} \\ &= \frac{(r_1 \pm r_2)^2 + (1-r_1^2)(1-r_2^2)\cos^2(\tau_1 - \tau_2)}{(1+r_1^2)(1+r_2^2)} \end{aligned} \tag{1.6}$$

The + sign indicates the some sense of rotation, and the - sign indicates the opposite sense of rotation.

As an example, consider right-hand and left-hand circular polarizations; thus rj = rz = 1 and c'j = n.

$$p(-) = \frac{1}{2} + \frac{-4(1)(1) + (1-1)(1-1)(1)}{2(1+1)(1+1)} = 0$$

$$p(+) = 1$$

Now consider horizontal and vertical linear polarizations; rj = rz = x and gj - 72 = +90% Dividing the numerator and denominator by rlrl and taking the limit gives

$$p = \frac{1}{2} + \frac{1}{2}\cos 2(\tau_1 - \tau_2) = \cos^2(\tau_1 - \tau_2) = 0$$

For two aligned linear polarizations, n = n, and thus p = cos: 0 = 1. In a satellite system using dual orthogonal polarizations as a means of signal discrimination, an important parameter in determination of the quality of the system is the *cross-polarization discrimination ratio*. It is denned as the ratio of the polarization mismatch factors of an incident

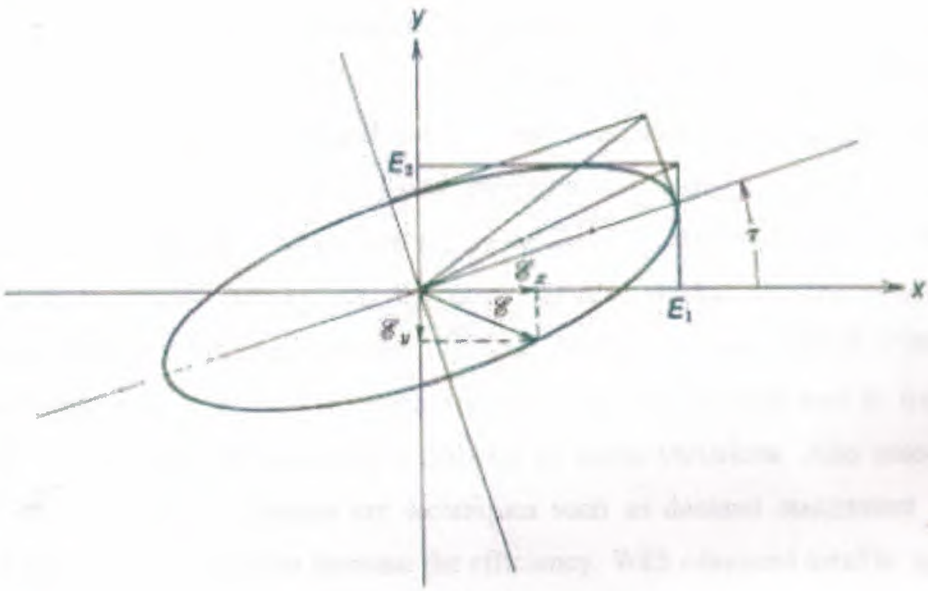


Figure 1.16 Polarization ellipse

wave, when measured at the antenna port having the same polarization state (copolarized), to that measured at the port having the orthogonal po- larization (cross-polarized). Thus

$$X = \frac{(r_1 + r_2)^2 + (1 - r_1^2)(1 - r_2^2)\cos^2(\tau_1 - \tau_2)}{(r_1 + r_2)^2 + (1 - r_1^2)(1 - r_2^2)\cos^2(\tau_1 - \tau_2)} \tag{1.7}$$

As an example consider the case where the wave is left-hand circularly polarized with an axial ratio of $rg = 1$ and the antenna with an axial ratio of rl = 1. The popularized port is designated as left-hand circular polarization, and T2 = 'r1. Then,

$$X = \frac{(r_1 + 1)^2}{(r_1 - 1)^2} = 10\log\frac{(r_1 + 1)^2}{(r_1 - 1)^2}\, dB$$

For an ideal antenna $r_l = 1$ and $X = \infty$. For an antenna with $r_l = 1.1$.

X=26.4 dB

1.8 Advent Of Digital Satellite Communication

The future trend in satellite communications is toward digital techniques. Frequency division multiplexing-frequency modulation-frequency division multiple access (FDM-FM-FDMA) has been the most popular analog technique used in commercial satellite systems because it has been held-proven and makes it easy to provide quality satellite links at a low cost. As the number of earth stations increases, the transponder capacity decreases markedly in a FDM-FM-FDMA system. In addition, FDM-FM-FDMA is inflexible in responding to tragic changes. On the other hand, a digital satellite system such as quaternary phase shift keying-time division multiple access (QPSK-TDMA) can accommodate a large number of earth stations with only a small loss in trans- ponder capacity. Furthermore, it can quickly respond to tragic variations. Also associated with digital satellite communications are techniques such as demand assignment and digital speech interpolation to further increase the efficiency. With advanced satellite systems with on- board switching and processing, multiple spot beams, and beam hopping, a digital system can serve a mixture of large, medium, and small earth stations with high efficiency. Unlike an analog satellite system, a digital satellite system can employ error-correction coding to trade bandwidth for power. Finally, the use of code-division multiple accesses (CDMA) for low data rate applications enable users to employ micro earth stations (0.5-m antenna) at an extremely low cost ($3000) to obtain premium quality services. The flexibility of digital satellite systems will make them even more promising when Integrated digital networks become fully implemented.

2. EARTH STATION

2.1 EARTH STATION ANTENNA

In Chap.1 we gave a functional description of the digital earth station shown in Fig. 2.4. In practice, an earth station is basically divided into two parts:

1. A RF terminal, which consists of an unconverted and a down converter, a high-power amplifier, a low-noise amplifier, and an antenna
2. A base band terminal, which consists of base band equipment, an encoder and decoder, and a modulator and demodulator.

The RF terminal and the base band terminal may be located a distance apart and connected by appropriate IF lines. In this chapter we will focus attention on a discussion of the RF terminal and will consider the base band terminal from a system point of view only because its subsystems will be discussed separately and in detail in subsequent chapters. The base band equipment will be discussed in the modulator and demodulator will be considered in; and the encoder and decoder will be covered.

The earth station antenna is one of the important subsystems of the RF terminal because it provides a means of transmitting the modulated RF carrier to the satellite within the uplink frequency spectrum and receiving the RF carrier from the satellite within the downlink frequency spectrum. The earth station antenna must meet three basic requirements:

1. The antenna must have a *highly directive gain;* that is, it must focus its radiated energy into a narrow beam to illuminate the satellite antenna in both the transmit and receive modes to provide the required uplink and downlink carrier power. Also, the antenna radiation pat- tern must have a low sideline level to reduce interference from unwanted signals and to minimize interference into other satellites and terrestrial systems.
2. The antenna must have a *low noise temperature* so that the elective noise temperature of the receive side of the earth station, which is proportional to the antenna temperature, can be kept low to reduce the noise power within the downlink carrier bandwidth. To achieve a low noise characteristic, the antenna radiation pattern must be controlled in such a way as to minimize the energy radiated into sources other than the satellite. Also, the ohmic losses of the antenna that contribute directly to its noise temperature must be

minimized. This includes the ohmic loss of the waveguide that connects the low-noise amplifier to the antenna feed.

3. The antenna must be *easily steered* so that a tracking system (if required) can be employed to point the antenna beam accurately toward the satellite taking into account the satellite's drift in position. This is essential for minimizing antenna pointing loss.

2.1.1 ANTENNA TYPES

The two most popular earth station antennas that meet the above requirements are the paraboloid antenna with a focal point feed and the Cassegrain antenna. Aparaboloid *antenna* with a focal point feed is shown in Fig. 2.1 This type of antenna consists of a ejector which is a section of a surface formed by rotating a parabola about its axis, and a feed whose phase center is located at the focal point of the paraboloid rejecter. The size of the antenna is represented by the diameter D of the ejector. The feed is 'p connected to a high-power amplifier and a low-noise amplifier through an *orthogonal mode transducer* (OMT) which is a three-port network. The inherent isolation of the OMT is normally better than 40 dB. On the transmit side the signal energy from the output of the high-power amplifier is / radiated at the focal point by the feed and illuminates the ejector which rejects and focuses the signal energy into a narrow beam. On the receive Side the signal energy captured by the ejector converges on the focal Point and is received by the feed which is then routed to the input of the

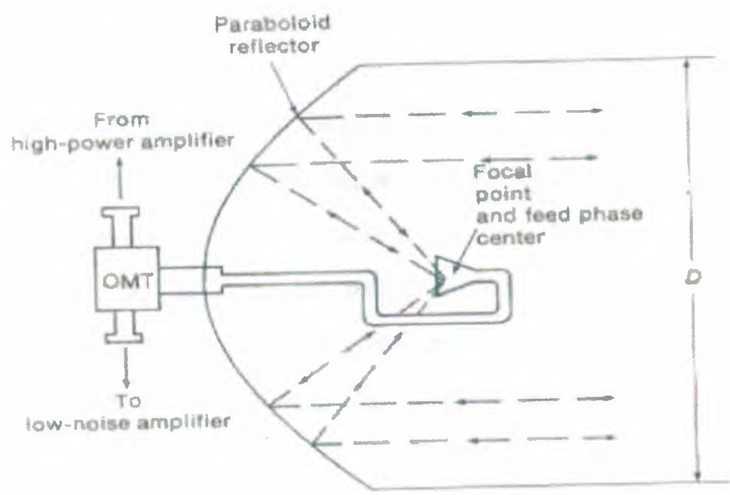


Figure 2.1 Parboloid antenna with a focal point feed.

low-noise amplifier. This type of antenna is easily steered and offers reasonable gain efficiency in the range of 50 to 60%. The disadvantage occurs when the antenna points to the satellite at a high elevation angle. In this case, the feed radiation which spills over the edge of the reflector (spillover energy) illuminates the ground whose noise temperature can be as high as 2900 K and results in a high antenna noise contribution. Paraboloid antennas with a focal point feed are most often employed in the United States for receive-only applications.

A *Cassegrain antenna* is a dual reflector antenna which consists of a paraboloid main reflector, whose focal point is coincident with the virtual focal point of a hyperboloid sub reflector, and a feed, whose phase center is at the real focal point of the sub reflector, as shown in Fig. 2.2. On the transmit side, the signal energy from the output of the high-power amplifier is radiated at the real focal point by the feed and illuminates the convex surface of the sub reflector which rejects the signal energy back as if it were incident from a feed whose phase center is located at the common focal point of the main reflector and sub reflector. The reflected energy is reflected again by the main reflector to form the antenna beam. On the receive side, the signal energy captured by the main reflector is directed toward its focal point. However, the sub reflector reflects the signal energy back to its real focal point where the phase center of the feed is located. The feed therefore receives the incoming energy and routes it to the input of the low-noise amplifier through the OMT. A Cassegrain antenna is more expensive than a paraboloid sub reflector and the integration of the three antenna elements-the main reflector, sub reflector, and feed-to produce an optimum antenna system. However, the Cassegrain antenna offers many advantages over the paraboloid antenna: low noise temperature, pointing accuracy, and flexibility in feed design. Since the spillover energy from the feed is directed toward the sky whose noise temperature is typically less than 31 K, its contribution to the antenna noise temperature is small compared to that of the paraboloid antenna. Also, with the feed located near the vertex of the antenna because of the addition of the main reflector, greater mechanical stability focal point feed in the very accurate pointing of high-gain narrow-beam antennas. To minimize the losses in the transmission lines connecting the high- power amplifier and the low-noise amplifier to the feed, a beam waveguide feed system may be employed. A Cassegrain antenna with a beam waveguide feed system is shown in Fig. 2.3. The beam waveguide assembly consists of four mirrors supported by a shroud and precisely located relative to the sub reflector, the feed, the elevation axis, and the azimuth can be achieved than with the paraboloid antenna. This increased stability permits axis. This mirror configuration ant as a RF feed and the sub reflector minimum loss while energy funnel between the and, as such, must be designed to achieve allowing the feed to be mounted in the concrete foundation at ground level. The shroud assembly ants as a shield against

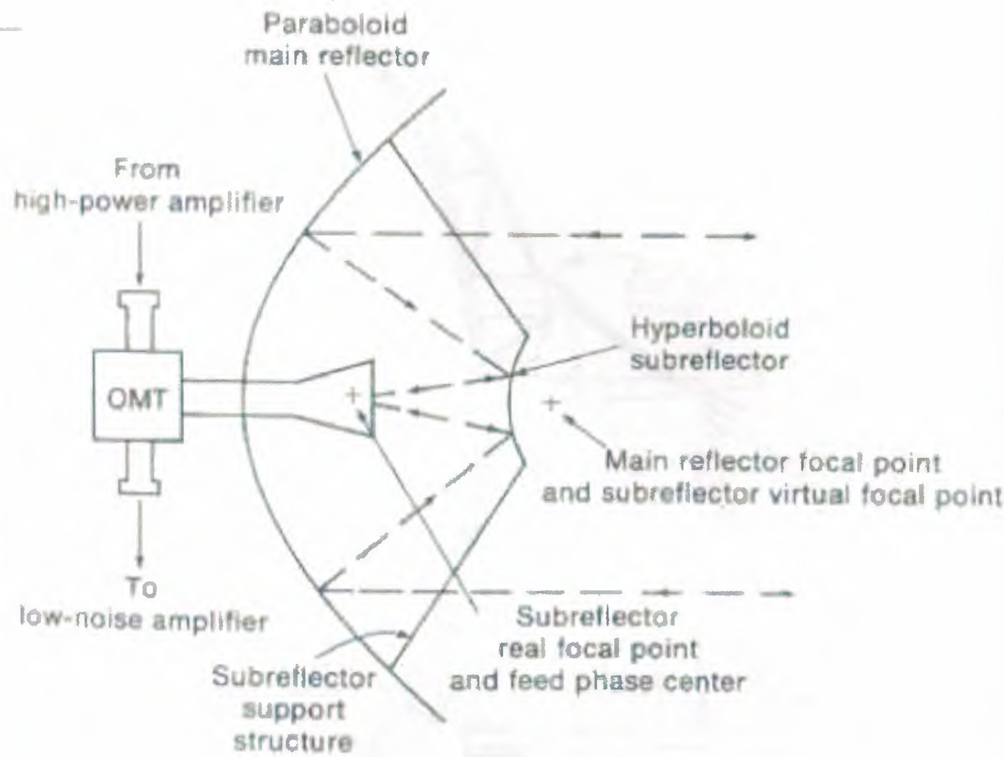


Figure 2.2 Cassegrain antenna

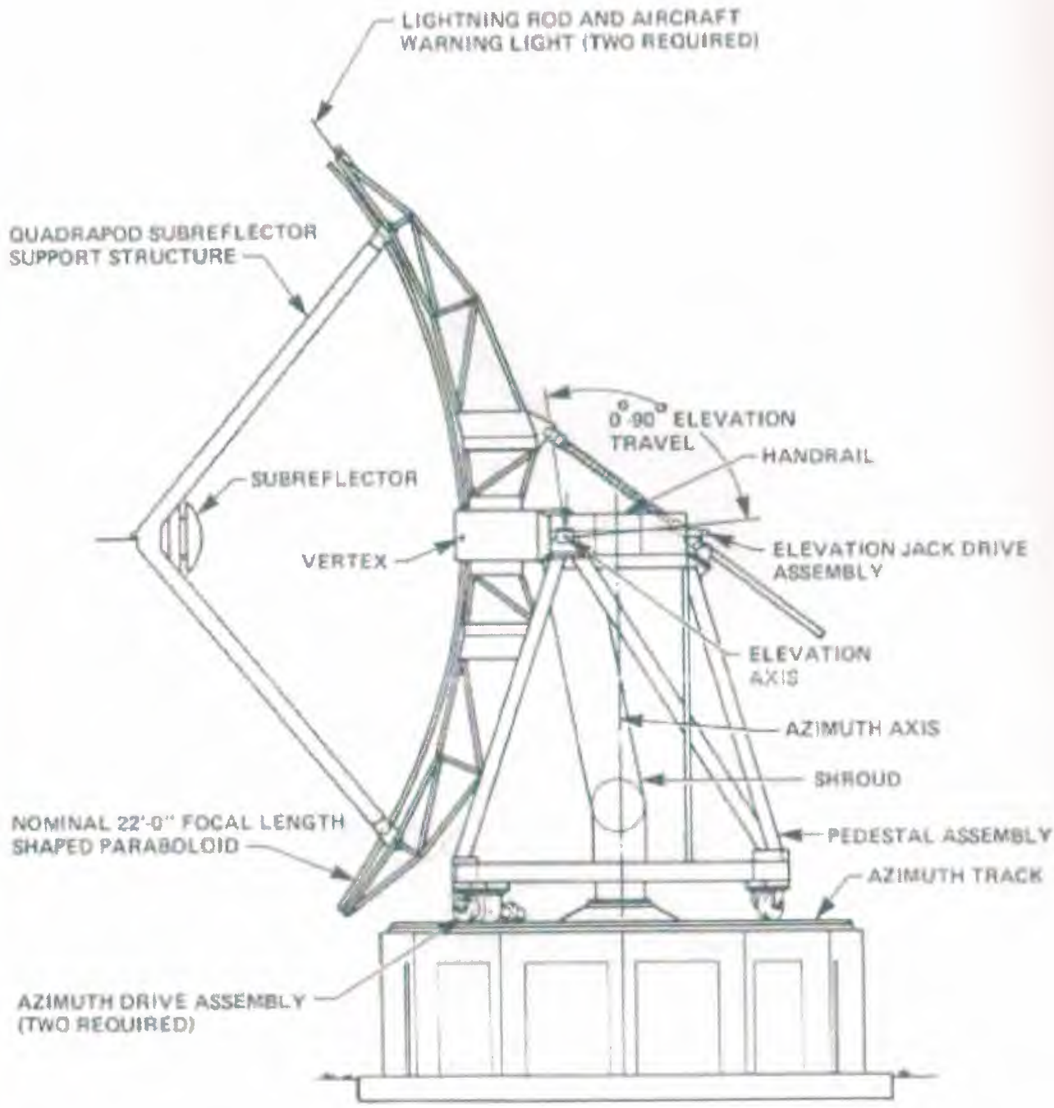
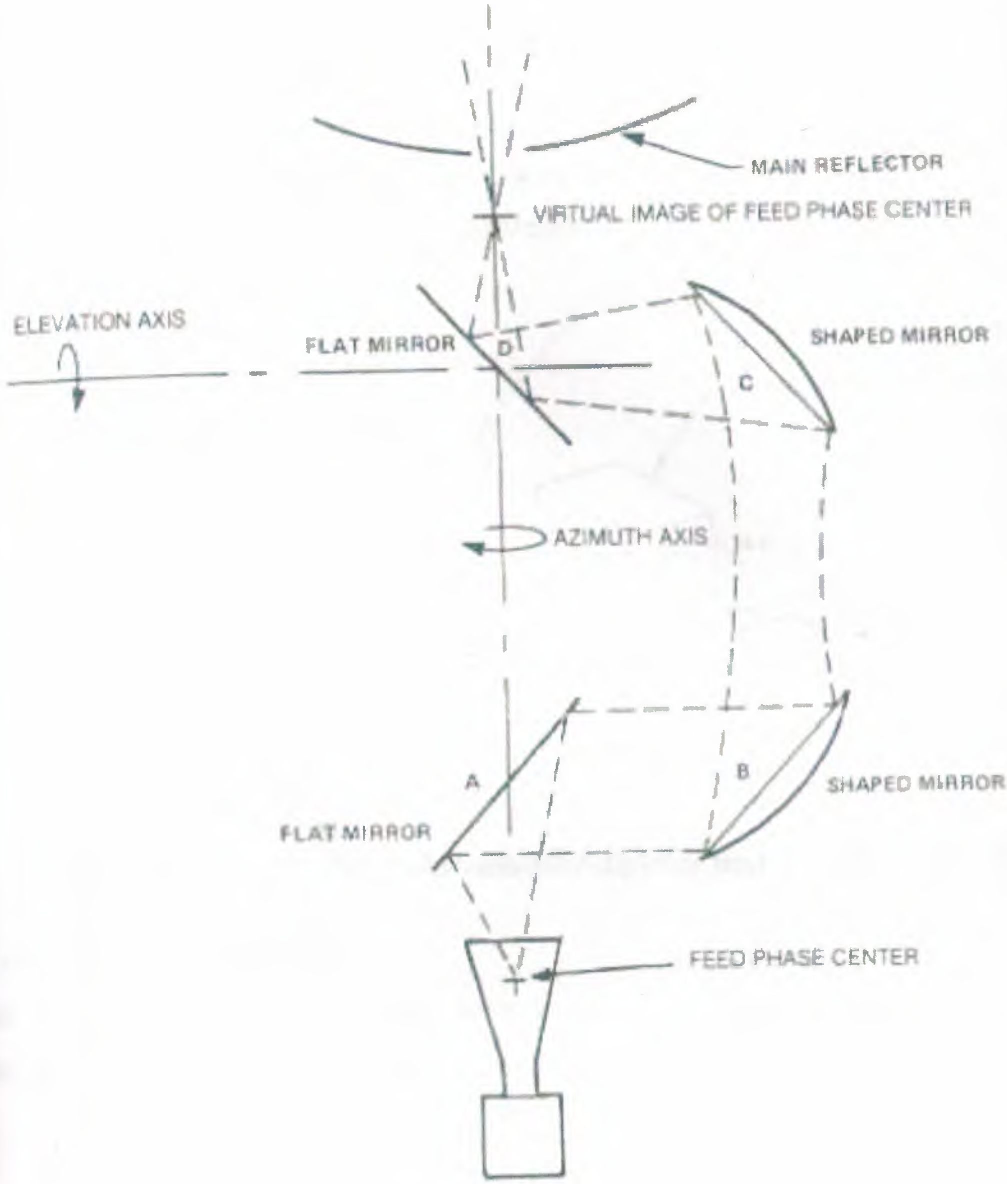


Figure 2.3 (a) Complete structure of a Cassegrain antenna. (b) Beam waveguide feed. (*Courtesy of GTE*)

ground noise and provides a rigid structure which maintains the mounting integrity of the mirrors when the antenna is subjected to wind, thermal, or other external loading conditions. The lower section of the shroud assembly is supported by the pedestal and rotates about the azimuth axis. The upper section of the shroud assembly is supported by the main reflector support structure and rotates about the elevation axis. As seen in Fig.3.3b the beam waveguide mirror system directs the energy to and from the feed and the reflectors. The configuration utilized is based on optics, though a correction is made for diffraction elects by using slightly elliptical curved mirrors. For proper shaping and positioning of the beam



waveguide mirrors, the energy from the feed located in the equipment room is refocused so that the feed phase center appears to be at the sub reflectors real focal point. In operation, mirrors A, B, C, and D move as a unit when the azimuth platform rotates. Mirror D is on the elevation axis and rotates also when the main reflector is steered during elevation. In this way, the energy to and from the beam waveguide system is always directed through the opening in the main reflector vertex. As mentioned in Chap. 1, modern communications satellites often employ dual polarizations to the same allow two independent carriers to be sent in frequency band, thus permitting frequency reuse and doubling the satellite capacity. Figure 3.4 shows a wideband OMT duplexer type of frequency reuse feed for a Cassegrain antenna that provides horizontal and vertical polarization for a Ku-band operation.

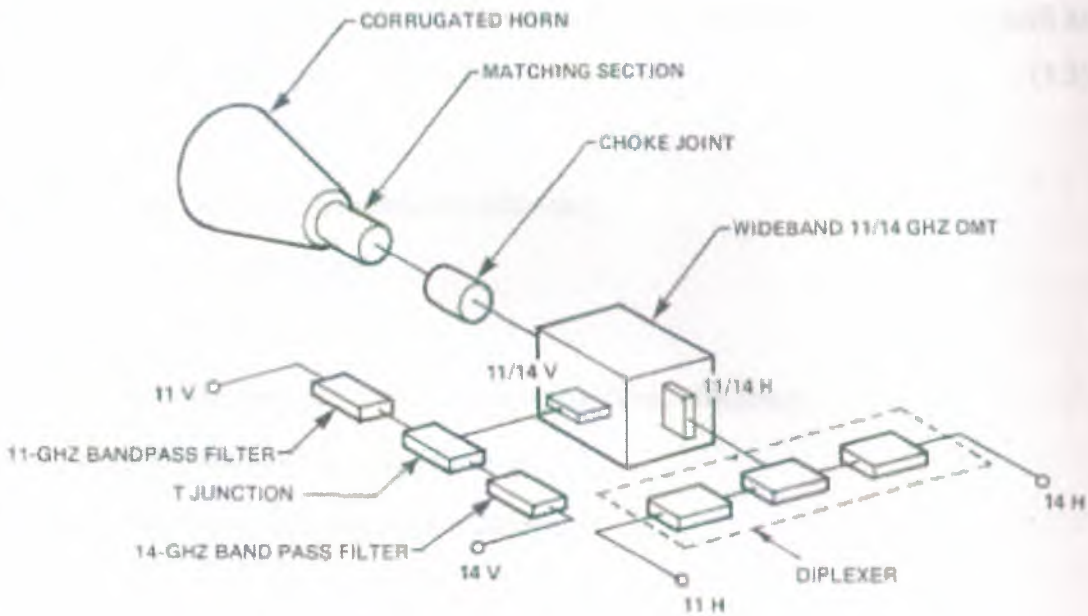


Figure 2.4 Wideband orthomode transducer-diplexer feed. (*Courtesy of GTE*)

2.1.2 ANTENNA GAIN

Gain is perhaps the key performance parameter of an earth station antenna because it directly affects the uplink and downlink carrier power. For an antenna, the gain is given by

$$G = \eta \frac{4\pi A}{\lambda^2} = \eta \frac{4\pi A f^2}{C^2} \tag{2.1}$$

where A = antenna aperture area (m2)

λ = radiation wavelength (m)

f = radiation frequency (Hz)

c = speed of light = 2.997925 X 10^8 m/s

η = antenna aperture efficiency ($\eta < 1$)

For a circular aperture, it follows that $A = \pi D^2/4$; therefore

$$G = \eta\left(\frac{\pi D}{\lambda}\right)^2 = \eta\left(\frac{\pi f D}{\lambda}\right)^2 \tag{2.2}$$

where D = antenna diameter (m).

The antenna efficiency η represents the percentage of the aperture area 24 that is used effectively in transmission or reception and is a product of various efficiency factors that reduce the antenna gain. Typical efficiency factors for a Cassegrain antenna such as the one shown in Fig. 3.3 *a* are $\eta = \eta_1\eta_2\eta_3\eta_4\eta_5\eta_6$ (3.3)

where η_1 = main reflector illumination efficiency

η_2 = spillover efficiency

η_3= phase efficiency

η_4= sub reflector and support structure blocking efficiency

η_5= feed system dissipating efficiency

η_6= reflector surface tolerance efficiency

The illumination efficiency, 1 is determined by the characteristic of the field distribution across the main reflector aperture. If it is uniform over the entire aperture area, then, η_1.=1 The spillover efficiency η_2 represents not only the energy spilled aver the edge of the main reflector but also the energy spilled over the edge of the sub reflector. To minimize the spillover loss, a feed with low sidelines in its radiation pattern is desired. To achieve this pattern, multiple modes are used in the design of the feed radiation section which is a horn. Furthermore, the feed angle subtended by the sub reflector is chosen so that the main beam of the feed radiation pattern intersects the sub reflector at a low level, minimizing the feed main beam spillover past the sub reflector. However, the low edge illumination of the sub reflector normally results in sharply tapered illumination across the main reflector aperture, resulting in a low illuminating efficiency, 1. With a Cassegrain antenna this condition can be improved substantially by deliberately altering the shape of the sub reflector to distribute the energy essentially uniformly nearly to the edge of the main reflector but then falling of very sharply. An illumination efficiency η_1, of 0.94 to 0.96 can be achieved in practice with a main reflector spillover efficiency of as high as 0.99. With good feed design, sub reflector spillover efficiency on the order of 0.98 can be realized. Thus a spillover efficiency of η_2= 0.97 can be achieved in a shaped system.

Distorting the shape of the sub reflector to achieve uniform illumination across the main reflector results in a phase error being introduced into the main reflector. This phase error results in energy being radiated in undesired directions, thus decreasing the gain and increasing the sideline level of the antenna. The phase efficiency Na identifies this gain loss. Most of this loss can be eliminated, however, by reshaping the main reflector to correct the phase error. In a well-designed Cassegrain antenna the phase efficiency pa can be on the order of 0.98 and 0.99 at the design frequency and remain on the order of 0.95 over 70% of the operating 500-MHz band. Blocking of the main reflector aperture by the sub reflector and sup- port structure results in an electively smaller aperture, hence a loss in the antenna gain. The sub reflector blocking efficiency is about 0.97, and that of the support structure is about 0.95 in a well-designed antenna. The dissipative loss of the feed system also reduces the antenna gain. Depending on the feed system structure the efficiency η_5 can be as high as 0.94. All the above-cited efficiency factors are primarily dependent on the main reflector and sub reflector geometries and the feed system structure and not on the operating frequency. In practice the main reflector and sub reflector cannot be built to the ideal shapes without some surface tolerance. These results in a scattering of energy in unwanted directions in a manner similar to that associated with the phase error. The surface tolerance may, in effect, be considered a special type of phase error which limits the maximum achievable gain G_M in the sense that, for a given surface tolerance and antenna diameter, increasing the operating frequency increases the antenna gain until it equals G_M. Further increasing the operating frequency will decrease the antenna gain. The surface tolerance efficiency η_6 imposes an upper limit on the maximum operating frequency, hence on the maximum antenna gain, and is fixed by current manufacturing technology. The reflector surface tolerance efficiency η_6 may be expressed [1] as

$$\eta_6 = \exp\left[-\left(\frac{4\pi\varepsilon}{\lambda}\right)^2\right]$$

$$= \exp\left[-\left(\frac{\varepsilon}{D}\right)^2\left(\frac{4\pi f D}{c}\right)^2\right] \qquad (2.4)$$

Where ε = rms reflector surface error (m) and ε / D = antenna surface tolerance. The factor $\left(\frac{4\pi f D}{c}\right)^2$ is in effect the mean-square phase error introduced by the surface error $\mathcal{E}$. The antenna surface tolerance $\mathcal{E} / D$ within current commercial technology is as follows:

$$10^{-3} \leq \frac{E}{D} \leq 10^{-4} \qquad D \leq 1.2\,\text{m}$$

$$2\times10^{-4} \leq \frac{E}{D} \leq 5\times10^{-5} \qquad 2.5\text{m} \leq D \leq 6\text{m} \tag{2.5}$$

$$10^{-4} \leq \frac{E}{D} \leq 2\times10^{-5} \qquad 9\text{m} \leq D \leq 24$$

The performance of a well-designed Ku-band 20-m Cassegrain antenna with a beam waveguide frequency reuse feed system is shown in Table 3.1.

2.1.3 ANTENNA POINTING LOSS

In the previous section we have discussed the gain of the antenna as given in (2.2). This is the peak or on-axis gain of the antenna which can be achieved if the antenna beam is pointed accurately toward the satellite. A loss in gain can occur if the antenna pointing vector is not in line with the

Table 2.1 Performance of a Ku-band 20-m Cassegrain antenna

antenna

Parameters	11.95 GHz	14.25 GHz
Illumination efficiency	0.96	0.94
Spillover efficiency		
Main reflector	0.99	0.99
Subreflector	0.96	0.98
Phase efficiency	0.98	0.98
Blocking efficiency		
Subreflector	0.97	0.97
Support structure	0.95	0.95
Feed system dissipative efficiency		
Basic feed	0.94	0.93
Diplexer	0.96	0.98
Beam waveguide	0.91	0.96
Surface tolerance efficiency		
Main reflector	0.87	0.83
Subreflector	0.97	0.97
Net antenna efficiency	0.57	0.54
Antenna gain (dB)	65.53	66.82

satellite position vector as shown in Fig. 3.5. The antenna pointing loss can be evaluated from the antenna gain pattern which is a function of the of-axis angle θ. For a paraboloid reflector with aperture diameter D, the normalized gain pattern for a *uniform aperture distribution* [2] is given by

$$G_{n,u}(\theta)=4\left|\frac{J_1(u)}{u}\right|^2 \tag{2.6a}$$

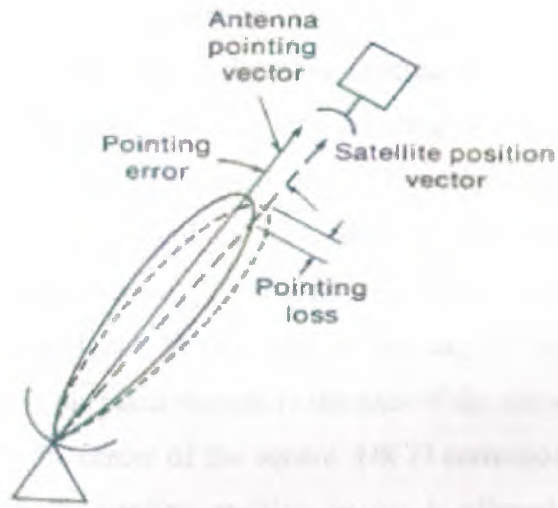


Figure 3.5 Antenna pointing error

Where

$$u=\frac{\pi D}{\lambda}\sin\theta \tag{2.6b}$$

and θ = off-axis angle and J_1 (•)= first-order Bessel function of the first kind (see Appendix 5B). If the aperture distribution is *parabolic* [the aperture held distribution is of the form $1 - (2_r / D)^2$, where r is the radial distance from the center of the circular aperture] , then the normalized gain pattern is given by

$$G_{n,p}(\theta)=64\left|\frac{J_2(u)}{u^2}\right|^2 \tag{2.7}$$

where J_2 (•) = second-order Bessel function of the first kind (see Appendix 5B).

The *half-power beam width* for a uniform aperture distribution is twice the value of θ at $G_{n,u}$ (θ) $=\frac{1}{2}$ 1, which is 1.02λ / D radians or 58.5λ/D degrees. For a parabolic aperture distribution, the half-power beam width is $1.27\lambda/D$ radians or 72.7:/D degrees. *In practice the antenna pointing accuracy is normally kept within one-third of the half-power beam width. For example, the half-power beam width of a 20-m* [illegible] antenna with uniform aperture distribution is 0.062° at 14.25 GHz. If the [illegible] error is kept within 0.020°, the normalized gain will be greater than $G_{n,u}$ [illegible] = 0.757 or, equivalently, the loss in gain will be less than -10 log 0.757 = 1.2 dB. Note that the normalized peak gain at $\theta = 0$ is unity (1). Because the earth station antenna is subjected to a wind loading elect and the satellite drifts in orbit, an antenna tracking system is necessary for a large-diameter antenna to minimize the pointing error. The antenna tracking system is a closed-loop pointing system; that is, the antenna pointing vector which is a function of the azimuth and elevation angles is derived from the received signal. One of the commonly used antenna tracking systems for earth stations is a step track which derives the antenna pointing vector from the signal strength of a satellite beacon signal. In this type of tracking the antenna is caused to move around the edge of a in the plane normal to the axis of the antenna beam as square pattern shown in Fig. 2.6. The center of the square *ABCD* corresponds to the assumed satellite position. Thus, if the satellite position vector is aligned with the antenna pointing vector, the amplitude of the beacon signal received at each of the four pointing positions *A, B, C,* and *D* will be equal. An error in elevation results in the of-axis angle θ for positions A and *B* differing from the off-axis angle θ for positions C and D. Since the received signal. amplitude is proportional to the square of the of-axis angle θ as indicated in (2.6a) or (2.7), by comparing the average amplitude at A and *B* with that of *C* and *D,* the difference in the offset angle or elevation angle error can be determined. Similarly, by comparing the average amplitude at A and *D* with that at *B* and *C,* the azimuth angle error can be determined. The step track system can provide a tracking accuracy of from $\frac{1}{5}$ to $\frac{1}{3}$ of the half-power beam width, which results in a pointing loss of between 0.5 and 1.5 dB. For better tracking accuracy, a monopoles tracking system must be employed. This type of tracking can provide a tracking accuracy of up 1/20 all of the half-power beam width. For a fixed earth station with a small antenna (a half-power beam width on the order of 0.2^0 or more), a program tracking system can be used. This is an open- loop pointing system where the antenna pointing vector is derived from the earth station position and the satellite ephemeris data.

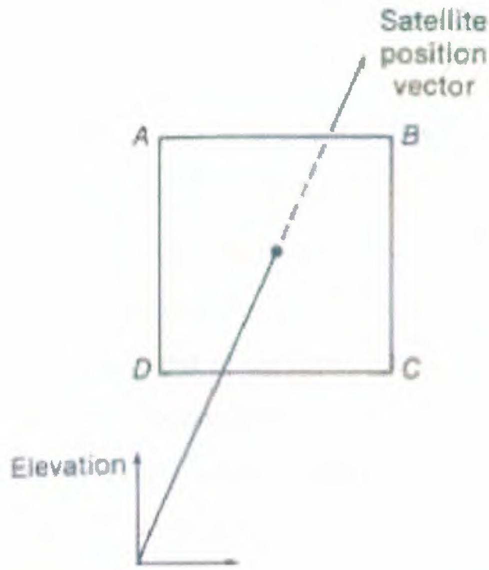


Figure 2.6 Principle of a step track.

The satellite ephemeris data is normally obtained from a *telemetry, tracking,* and *control* station (TT&C) and is stored in the memory of the tracking system. The satellite ephemeris data is updated periodically. The updated interval depends on the satellite station keeping characteristics.

2.1.4 ELECTIVE ISOTROPIC RADIATED POWER

To express the transmitted power of an earth station or a satellite, the *effective isotropic radiated power* (EIRP) is normally employed. The earth station EIRP is simply the power generated by the high-power amplifier times the gain of the earth station antenna, taking into account the loss in the transmission line (waveguide) that connects the output of the high-power amplifier to the feed of the earth station antenna. If we let P_T denote the Input power at the feed of the antenna and G_T the transmit antenna gain, the earth station EIRP is simply

$$\mathbf{EIRP = P_T G_T} \tag{2.8}$$

For example, consider a 2-kW high-power amplifier and a 20-m Cassegrain antenna whose transmitted gain is 66.82 do at 14.25 GHZ as given in Table 3.1. If it is assumed that the loss of the waveguide that connects the high-power amplifier to the feed is 1 dB, then the earth station EIRP in decibel-wafts is (noting that P_T decibel-wafts are equivalent to 10 log P_T wafts).

EIRP = 33 + 66.82 - 1 = 98.82 dBW

The uplink carrier power, that is, the power of the carrier received at the satellite, is directly proportional to the earth station EIRP. This will be discussed.

2.1.5 ANTENNA GAIN-TO-NOISE TEMPERATURE RATIO

The antenna gain-to-noise temperature ratio G/T is a figure of merit commonly used to indicate the performance of the earth station the low-noise amplifier in relation to sensitivity in receiving the downlink carrier from the satellite. The parameter G is the receive antenna gain referred to the input of the low-noise amplifier. For example, if the input of the low-noise amplifier is connected directly to the output port of the feed system of the 20-m Cassegrain antenna whose performance is illus- trated in Table 3.1, then the receive antenna gain at 11.95 GHZ is 65.53 dB. If a piece of waveguide with a 0.53-dB loss is used to connect the input of the low-noise amplifier to the output port of the feed system, the receive antenna gain referred to the input of the low-noise amplifier is simply 65 dB. The parameter T is denned as the earth station system noise temperature referred also to the input of the low-noise amplifier. We have discussed the antenna gain previously, therefore in this section we will concentrate on determination of the earth station system noise temperature. The treatment of noise in communications systems is based on a form of noise called *white noise* whose shown in is includes thermal noise Fig. 2.7, and is bat over a large range of frequencies. White noise random characterizing as a Gaussian Process with a Zero mean, and it produced by the random motion of electrons in conducting media, solar noise, and cosmic noise. White noise corrupts the received signal in an additive fashion and is normally referred to as *additive white Gaussian noise* (AWGN) in the analysis of communications systems. The treatment of noise is outside the scope of this book, and it is recommended that the reader consult for a detailed study. (Appendix 3A gives a brief review of thermal noise.) In electrical communications systems, the power spectral density of white noise delivered to a matched load from a noise source is customarily expressed in watts per hertz (W/Hz) as

$$\frac{N_0}{2} = \frac{kT_s}{2} \tag{2 .9}$$

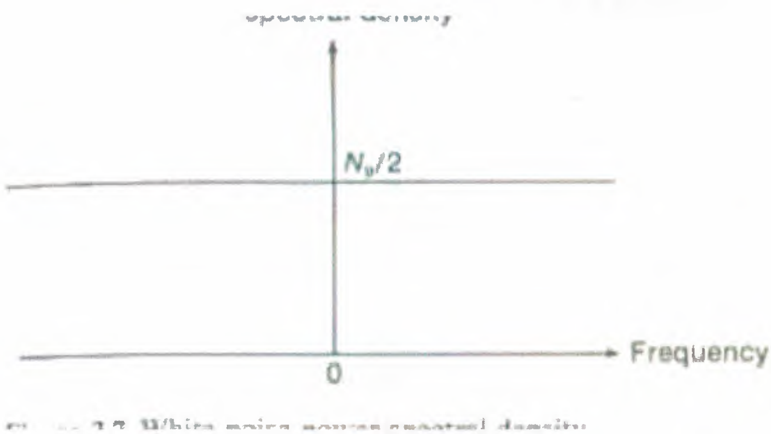


figure 2.7 White noise power spectral density

Where k is Boltzmann's constant (1.38 x 10^{-23} J/K) and T_s is the noise temperature of the noise source measured in kelvins. This means that, if this noise source is connected to the input of an ideal band pass alter with bandwidth B in hertz (Fig. 2.8) whose input resistance is matched to the source resistance, the output noise power in watts is simply

$$N = N_0 B = kT_s B \tag{2.10}$$

Since any passive or active two-port system, such as the waveguide that connects the input of the low-noise amplifier to the antenna feed, and the low-noise Amplifier itself have equivalent noise that contributes to the noise from the antenna, we must take into account their effects. Consider a two-port system with gain G and a noise source of temperature T_s connected to its input. The output noise power in a bandwidth B (Hz) is then

$$N = \mathrm{GkT}_s\mathrm{B} + N_n \qquad (2.1\ 1)$$

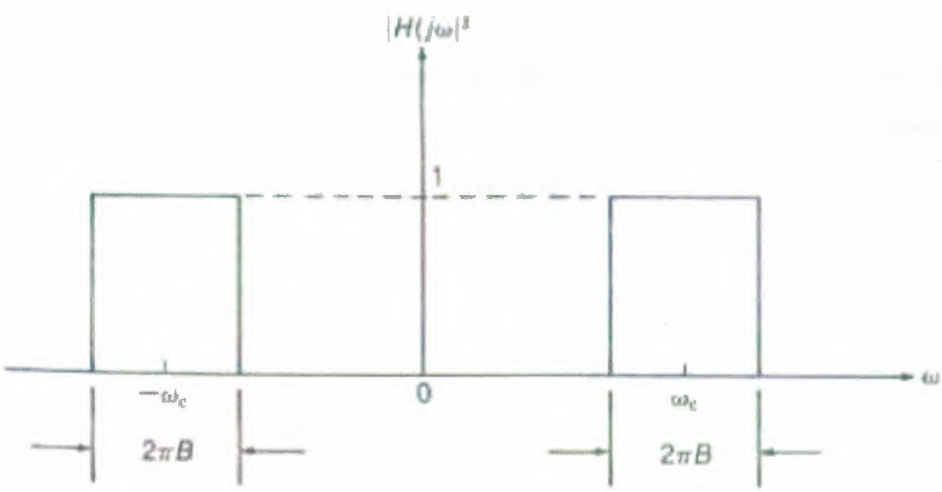


Figure 2.8 Ideal band pass filter.H(J ω),transfer function of band pass filter; ω_c , center frequency band pass filter; B, bandwidth of band pass filter in hertz.

where N_n is the output noise power produced by the internal noise sources in the system. Equation (3.11) can be written as

$$N = G\,kB\,(T_s + \frac{N_n}{GkB})$$

$$= GkB(T_s + F_e) \qquad (2.12)$$

where

$$T_e = \frac{N_n}{GkB} \qquad (2.13)$$

From (3.12) it is seen that N_n can be considered to be produced by a fictitious noise source of ***equivalent noise temperature*** T_e connected to the input of the system. Therefore we conclude that a noisy two-port system can be characterized by its equivalent noise temperature T_e. The parameter $T_s + T_e$ in (3.12) is denned as the system noise temperature referred to the input of the two-port system:

$$T = T_s + T_e \qquad (2.14)$$

In other words, we can model a noisy two-port system as a noiseless two- port system and account for the increased noise by assigning to the input noise source a new temperature T higher than Ts by Te. Note that $GT = G\,(Ts + Te)$ is simply the noise temperature measured at the output of the two-port system. Another measure of the internal noise generated by a two-port system is the noise figure F, defined as the output noise power of the system divided by the output noise power if the system is noiseless (i.e., all the internal noise sources are absent), assuming that the noise sources at the input is at the ambient temperature T_0 (T_0 is normally taken to be 290 K). By this definition the *noise figure F* is also the ratio of the signal-to-noise ratio at the system input to the signal-to-noise ratio at the system output. Thus F is simply the ratio of *N* in (2.11), with $Ts = T_0$ and GkT_0B which is *N* when $N_n = 0$:

$$F = \frac{GkT_0B + N_n}{GkT_0B}$$

$$= 1 + \frac{T_e}{T_0} \qquad (2.15)$$

From (2.15) it is seen that

$$T_e = (F-1)T_0 \qquad (2.16)$$

Now consider two 2-port systems M_1 and M_2 in cascade as shown in fig.2.9. Each system Mi is characterized by its gain G_1 and its equivalent noise temperature T_{ei} ,i =1,2. The noise source at the input of the cascaded system is assumed to have a temperature

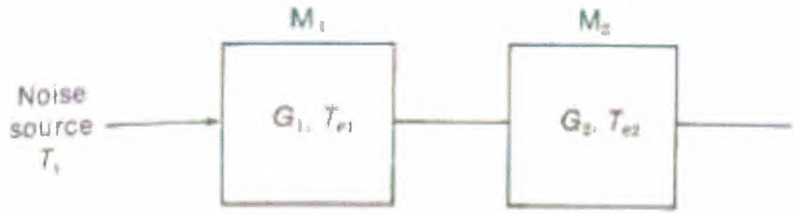


figure 2.9 Cascaded tow-port system for equivalent noise temperature analysis

T_s. The noise power N_1 at the output of system M_1 is given by (2.12)

$$N_1 = G_1\, kB(T_s + T_{ei}) \tag{2.17}$$

This is amplified by M_2 and appears at its output as

$$N_{12} = G_1\, G_2\, kB\, (T_s + T_{e1}) \tag{2.18}$$

Thus N_{12} is the noise power produced by the internal noise sources at M_1. From (2.13) the internal noise sources at M_2 is given by

$$N_2 = G_2\, kT_{e2}B \tag{2.19}$$

The total output noise power is simply the sum of N_{12} and N_2 :

$$N = N_{12} + N_2 = G_1\, G_2 kB(T_s + T_{e1}) + G_2\, kT_{e2}B$$

$$= G_1 G_2\, kB\, (T_s + T_{e1} + \frac{T_{e2}}{G_1}) \tag{2,20}$$

By comparing (2.20) and (3.12) it is seen that the cascaded system can be characterized by its gain G = G1G2, which is obvious, and its equivalent noise temperature

$$T_e = T_{e1} + \frac{T_{e2}}{G1} \tag{2.21}$$

Equation (2.21) demonstrates clearly the contribution of the, second system M_2 to the overall noise temperature. It is seen that, if the gain of the first system M_1 is large enough ($G_1 >> T_{e2}/T_{e1}$), then the second system contributes negligibly to the overall noise temperature. The results of (3.12) can be easily generalized to a cascade of *n* systems:

$$T_e = T_{e1} + \frac{T_{2e}}{G} + \frac{T_{e3}}{G_1 G_2} + \cdots + \frac{T_{en}}{G_1 G_2 \cdots G_{n-1}} \tag{2.22}$$

By using (3.15), the noise figure of *n* systems in cascade can be expressed as

$$F = F_1 + \frac{F_2 - 1}{G} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_n}{G_1 G_2 \cdots G_{n-1}} \tag{2.23}$$

Before proceeding to an evaluation of the earth station system noise low-noise amplifier, we pause here for a moment to make the following observation concerning the ohmic loss in a transmission line such as a waveguide, coaxial cable, or other device characterized by power loss rather than power gain. For such alossy two-port system, let $L > 1$ be the power loss (i.e., its gain $G = 1/L < 1$) and T_0 its ambient temperature; then the output noise is simply kT_0B. By using (3.12) with $T_s = T_0$ and $G = 1/L$, we have

$$kT_0B = \frac{1}{L} kB(T_0 + T_e)$$

which yields the equivalent noise temperature of a lossy two-port system:

$$T_e = (L - 1)T_0 \tag{2.24}$$

By comparing (3.24) and (3.16) it is seen that the noise figure of a lossy two-port system is

$$F = L \tag{2.25}$$

Now consider the receive side of the earth station, which consists of the antenna, the, the waveguide that connects the antenna feed low-noise amplifier, and the down converter casasde, as shown in Fig. 3.10. The antenna noise temperature is measured at the feed output and is denoted by T_A. The waveguide is characterized by its power loss $L_1 > 1$ (or power gain $G_1 = 1/L_1 < 1$) and its equivalent noise temperature $T_{e1} = (L_1 - 1)T_0$. The low-noise amplifier is characterized by its gain G_2 and its equivalent noise temperature T_{e2} of the cascaded low-noise amplifier and down converter is given by

(2.21) as

$$T_e = T_{e2} + \frac{T_{e3}}{G_2} \tag{2.26}$$

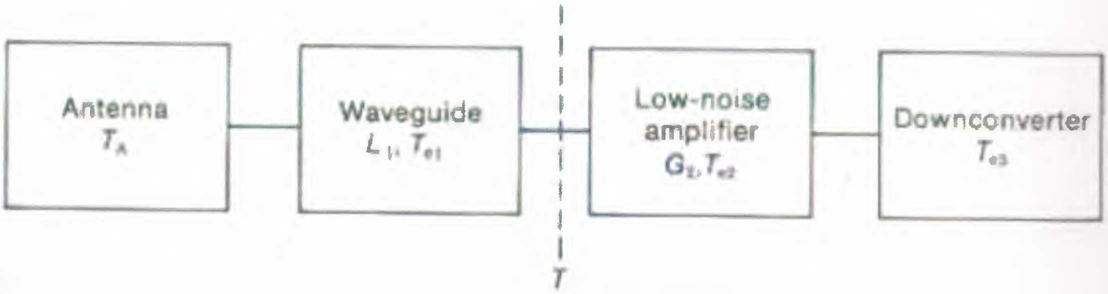


Figure 2.10 Receive side the earth station for system noise temperature evaluation

From (2.12) we note that the noise power at the output of the waveguide is given by

$$\begin{aligned} N &= G_1 kB(T_A + T_{e1}) \\ &= \frac{1}{L_1} kB\,[T_A + (L_1 - 1)T_0] \\ &= kB\left(\frac{T_A}{L_1} + \frac{L_1 - 1}{L_1} T_0\right) \end{aligned} \tag{2.27}$$

Thus the noise temperature T_s measured at the output of the waveguide is

$$T_s = \frac{T_A}{L_1} + \frac{L_1 - 1}{L_1} T_0 \tag{2.28}$$

From (2.14, (3.26), and (2.28), it is seen that the earth station system noise temperature referred to the input of the low-noise amplifier is simply

$$\begin{aligned} T &= T_s + T_e \\ T &= \frac{T_A}{L_1} + \frac{L_1 - 1}{L_1} T_0 + T_{e2} + \frac{T_{e3}}{G_2} \end{aligned} \tag{2.29}$$

Example 3.1 To illustrate evaluation of the antenna gain-to-noise temperature ratio, consider a 20-m Cassegrain antenna whose receive antenna gain is 65.53 dB at 11.95 GHZ as given by Table 3.1. The receive side of the earth station is characterized by the following parameters.

Antenna noise temperature: $T_A = 60$ K

Waveguide loss: L_1=1.072 (0.3 dB)

Low-noise amplifier

Equivalent noise temperature: $T_{e2} = 150$ K

Gain: $G_2 = 10^6$ (60 dB)

Down converter equivalent noise temperature: $T_{e3} = 11 \times 10^3$ K

Substituting all the above values into (2.29) yields the earth station system noise temperature referred to the input of the low-noise amplifier as ($T_0 = 290$ K):

$$T = \frac{60}{1.072} + \frac{0.072}{1.072}(290) + 150 + \frac{11 \times 10^3}{10^6}$$
$$= 225.5 \text{ K}$$

The antenna gain referred to the input of the low-noise amplifier is

$$G = 65.53 - L_1$$
$$= 65.53 - 0.3 = 65.23 \text{ dB}$$

Thus the antenna gain-to-noise temperature ratio in decibels perkelvin is

$$\frac{G}{T} = G\text{ (dB)} - 10 \log T$$
$$= 65.23 - 23.53$$
$$= 41.7 \text{ dB/K}$$

Based on the above analysis we can make the following remarks:

1. The higher higher the antenna gain, the higher the value of G / T, hence the higher downlink carder-to-noise ratio.
2. The lower the loss of the waveguide that connects the antenna feed to the input of the low-noise amplifier, the higher the value of G/T.
3. The lower the equivalent noise temperature of the low-noise amplifier, the higher the value of G/T. Also, its gain must be sufficiently large to reduce the noise contribution of the down converter.
4. The value of *GIT* is invariant regardless of the reference point. We choose the input of the low-noise amplifier because this is the point where the contribution of the low-noise amplifier is clearly shown.

2.1.6 G/F MEASUREMENT

One of the precision methods for measuring the antenna gain-to-noise temperature ratio G/T of the earth station is the radio star method. This measurement employs the Y factor denned as the ratio of the noise power received with the star accurately centered on the receive beam axis to the background noise power (when the star has drifted out of the beam):

$$Y=\frac{T+T_{star}}{T} \tag{2.30}$$

where T_{star} = effective noise temperature of star and T = system noise temperature. The receive antenna gain G is related to T_{star} [4] as follows:

$$kT_{star}=\frac{SG\lambda^2}{8\pi}=\frac{SGc^2}{8\pi f^2} \tag{2.31}$$

where S = flux density per 1-Hz bandwidth of radio star (W/m^2/Hz)

f = measurement frequency (Hz)

c = speed of light = 2.997925 X 10^8 m/s

k = Boltzmann's constant = 1.38 X 10^{-23} J/K

Substituting (3.30) into (3.31) yields

$$\frac{G}{T}=(Y-1)\frac{8\pi k}{S\lambda^2} \tag{2.32}$$

Equation (3.32) represents the ideal condition where there is no atmospheric loss and the radio star is a point source. The equation for a non ideal condition is given by

$$\frac{G}{T}=L_aL_s(Y-1)\frac{8\pi k}{S\lambda^2} \tag{2.33}$$

where L_a = atmospheric loss and L_s = correction factor for angular ex- tent of radio star.

Table 2.2 Typical one-way clear-air total zenith attenuation values, L_a (dB)[a]

Frequency (GHz)	Altitude (km) 0	0.5	1.0	2.0	4.0
10	0.053	0.047	0.042	0.033	0.02
15	0.084	0.071	0.061	0.044	0.023
20	0.28	0.23	0.18	0.12	0.05
30	0.24	0.19	0.16	0.10	0.045
40	0.37	0.33	0.29	0.22	0.135
80	1.30	1.08	0.90	0.62	0.30
90	1.25	1.01	0.81	0.52	0.22
100	1.41	1.14	0.92	0.59	0.25

[a]Mean surface conditions:21^{0}C,7.5 g/m^3 H_2O,U.S. std atoms., 45^{0}N, July

The atmospheric loss or attenuation Aa can be calculated from exist- ing data and is given by

$$L_a\,(\mathrm{dB}) = \frac{L'_a\,(\mathrm{dB}) + b_\rho\,(\rho_0 - 7.5\ \mathrm{g/m^3}) + c_T\,(21^\circ\mathrm{C} - T_0)}{\sin E} \tag{.34}$$

where $L_a^{`}$= zenith one-way attenuation for a moderately humid atmosphere (7.5) g/m$^3$surface water vapor) and a surface temperature of 21$^0$C; $L_a^{`}$ is plotted in Fig. 2.11 and given in Table 2.2

b_p = water vapor density correction coefficient; b_p is given in Table 2.3

C_T=temperature correction coefficient; C_T is given in Table 2.3

P_0=urface water vapor density (g/m^3). The factor $b_p(P_0$-7.5) 7.5 g/m^3) accounts for the difference between the local surface water vapor density and 7.5 g/m^3

Table 2.3 Water vapor density and temperature correction coefficients

Frequency (GHz)	Water vapor density Correction b_ρ	Temperature correction c_T
10	2.10×10^{-3}	2.60×10^{-4}
15	6.34×10^{-3}	4.55×10^{-4}
20	3.46×10^{-2}	1.55×10^{-3}
30	2.37×10^{-2}	1.33×10^{-3}
40	2.75×10^{-2}	1.97×10^{-3}
80	9.59×10^{-2}	5.86×10^{-3}
90	1.22×10^{-1}	5.74×10^{-3}
100	1.50×10^{-1}	6.30×10^{-3}

3. SOME ASPECTS OF THE IBPLEMENTATIQN OF AN INTEGRATED SPACE/TERRESTRIAL NETWORK

3.1 THE EVOLUTION OF THE TERRESTRIAL NETWORK

The Public Switched Telephone Network (PSTN) from which the integrated Digital Network (1DN) is emerging by a process of technological substitution, providing the backbone for the ISDN, is a dynamic "organism" subject to constant 1 lion These changes may alter not only the way information is treated but also the economic balance between the different trade-offs available to the network designer, and as a consequence its internal architecture.

Figure 3.1 shows what can be considered a model of a European national network? Table 1 shows some of its main macro-economic figures. To provide a reference, these values are compared with some available figures made public by several Telecommunication Administrations.

The introduction of cheaper transmission systems .and the extended traffic handling ability of Digital Switching Exchanges favors the recombination of a relatively large quantity of transit switching nodes into a lesser number of larger exchanges which are fully meshed in their interconnections.

Figure 3.2 shows the architecture that may result from the redesign of the network incorporating the new trade-offs. There, a relatively large number of sector exchanges (i.e. local transit exchanges) will be eliminated, their functions being taken up by a few larger exchanges at regional (district) level. For instance, modernization plan: of British Telecom tall for the substitution of about 450 transit exchanges by about 55. In Italy, the change is more dramatic: nearly 1500 sartorial exchanges and 250 district exchanges will be substituted by 109 new exchanges.

Other important feature of the technological substitution if that the interconnection between the new transit exchanges is meant to be fully meshed. Further, the transit exchanges in the Italian case are subdivided in two Sublevels both serving directly local areas but the higher allowing the overflow of the lower. This will be so since the routes of the lower mesh will be relatively thin and therefore very inefficient in terms of Erlangs/circuit if no overflow was permitted.

The implementation of the network does not require a physically fully meshed physical network. To illustrate that, Figure 3 shows the expected network architecture in the UK.

The evolution of the network will occur progressively until well into the 21st century. The cost of this evolution is staggering. In Europe 500 Billion ECU will be spent in the next 15 years by Telecommunication Administrations. In this scenario the availability of a technology that may offer new flexibility of future telecommunication networks deserves full attention by the network planners.

	FR	G	IT	SP	UK	MODEL
INHAJITANTS	56 M	60 M	57 M	37 M	58 M	50 M
- no. of lines	22 M	25 M	17 M	10 M	20 M	16 M
SWITCHING (no. of units)						
- local exchange	6000	6000	13000		6300	5000
- sector exchanges	1800	525	1400		400	500
- P+S transit exchanges	75	8168	21230		40	50
TRANSMISSION (no. of trunks)						
- local trunks	500 K	1000 K	480 K	250 K	420 K	500 K
- local distance (>100 km) (R+N) trunks	125 K	250 K	120 K	62.5 K	105 K	100 K
- international	12.5 K	14.2 K	6.5 K	5 K	12.6 K	10 K
TRAFFIC (Erlangs busy hour)						
- local	692	1 M	536	280	464	500 K
- inter-urban (trunk)	173 K	250 K	134 K	70 K	116 K	125 K
- international	9 K	13 K	3.8 K	2.6 K	6.6 K	8 K

Table 3.1 Some Figures Of The European Networks

3.2 ADVANCED SATELLITE SYSTEM CONCEPTS

The emergence of optical fibre system: and the full awareness of the functionality of satellite systems coincide in pushing the application of satellite links in trucking roles towards lower layers of the transmission hierarchical structure. There its dynamic bandwidth assignment properties and its flexibility of use can be shown to full advantage.

The implications of this deeper integration in the terrestrial network are manyfold. Perhaps its most immediate consequence is the proliferation of earth stations. It becomes therefore paramount to reduce radically the cost per earth

FIGURE 1 - PRESENT STRUCTURE
OF TELECOM NETWORKS IN EUROPE

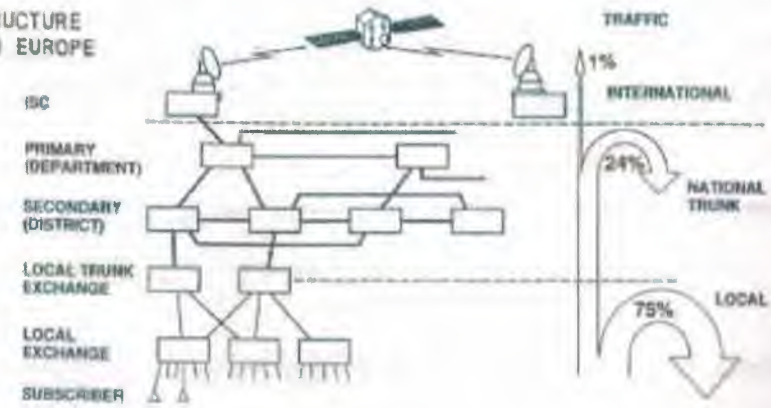


FIGURE 2 - ARCHITECTURE
OF FUTURE NETWORKS

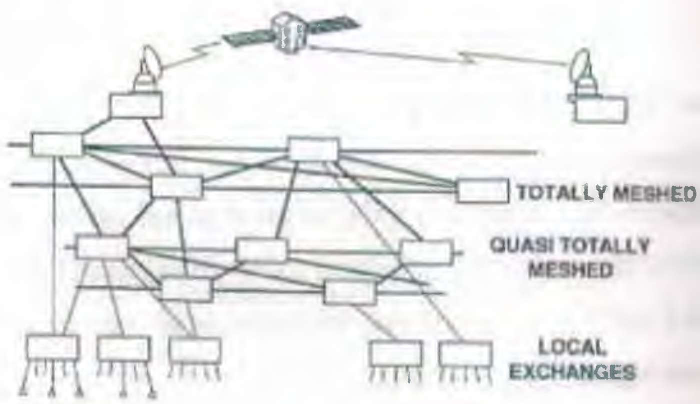


FIGURE 3 - PLANNED UK
HIGH ORDER TRUNK NETWORK

station if the overall satellite system is meant to be competitive. Further, the penetration to lower hierarchical levels calls for an increase of the traffic handling capacity of the system. at is not the same to share part of the few thousand Erlangs of international European traffic than getting involved in dealing with a part of the hundreds of thousands of Erlangs of the long distance national trunks.

These requirements converge in defining the satellite system with multiple lower earth station cost and frequency reuse for in spot beam antennas for creased system capacity.

To maintain the interconnectivity between any pair of beams, switching on the satellite becomes mandatory. And to maintain the burst efficiency, a single burst per transmit station is required, leading to TST/SS-TDMA system.

Since the traffic distribution throughout Europe is far from uniform (the relation between the traffic served by two spots of the same size may be as large as 200:1), the optimization of the bandwidth assignment calls for the use of beam hopping techniques and eventually dual frequency band utilization (14/12 and 30/20 GHz). Further system expansion without duplication of the earth segment cost may be provided by means of inter-satellite Links, which can also cater for the interconnection of the system with other equivalent systems in other regions of the world.

To provide an element of reference, some system concepts have been combined from several studies and papers. The resulting system characteristics are shown in Figure 4 and Table 2. It is interesting to contrast the potential capacity of such a system 64-128 thousand, 32 Kbit/s circuits, with the current total amount of international European circuits *% 15* thousand (of which a substantial amount corresponds to high usage routes). This shows the extent to which a single satellite system may satisfy both international and national traffic demand.

In the evolutionary network scenario described previously, the advanced satellite system can complement the functionality of terrestrial systems to achieve a harmonious development. The areas in which satellite system functionality is specially relevant are:

(i) Optimal digitalization strategy

The deployment of an advanced satellite system may be the most expeditious mechanism to ensure the adequate provision of digital connectivity (or even' access) to the whole European continent. This may ensure that the less developed regions are not left to the pressure of a very limited demand.

(ii) Optimal economic design of the network

The flexibility incorporated by the advanced satellite system concepts allows the dynamic reconfiguration of the network. This leads to optimal design of thin routes and the adaptation of the network to variable patterns of utilization e.g. seasonal variations of population.

Further, the availability of reassign able transmission plant may be used to realize investments on the network in the measure they are required. This avoids for instance the necessity to equip large
amounts of circuits well in advance of their utilization. The resulting network may be much closer to the traffic demand with the subsequent savings.

(iii)Improved operational features

The availability of circuits on demand allows the use of the satellite system as back-up to the terrestrial system. The ability to pool from a common resource implies that the redundancy arrangements which the satellite offers is one for no while with terrestrial means this would in general one for ones or two.
Further, the residence of the network in the face of unexpected events which cause either disruption of services or instantaneous surge of traffic in specific points is substantially improved.

(iv)Optimal provision of new network services

The deployment of a satellite system would allow the provision of services like point-to-multipoint broadcast, broadband without having to redesign a substantial part of the backbone network on this account.

TABLE 3.2 - REFERENCE SYSTEM CHARACTERISTICS

SATELLITE SYSTEM CHARACTERISTICS

Access and Process	TST/SS-TDMA
Capacity (DSI dependent)	64000 - 128000 circuits
No. of Transponders	32 x 8 RHz
Frequencies	14/12, (30/20) GHz
Frequency Re-use	x5, x7
Rates of operation	131, 33, 8 Mbit/s
Flexibility on Traffix	large traffic, spot beams at 20-30 GHz,
Assignment (spot size = 0.7^0)	small traffic low rate and beam-hopping
Spacecraft Cost Estimate	
(1 of 5 including launch)	= 200 M ECU

EARTH SEGQENT CHARACTERISTICS

System	TDMA
Assignment	on demand
Terrestrial Interface	G732, n x 2 Mbit/s
Rates of operation	131, 33, 8 Mbit/s
No. of Circuits/system	4000. 1000, 250
Antenna Sizes	8, 5, 3m
ES Costs	400 - 300 - 250 K ECU

MASTER CONTROL CHARACTERISTIC;

Signaling	CCITT no. 7
Reconfigurability	dynamic on demand
Clock Synchronization	Master on ground plesiochronous
	I/F to ground networks

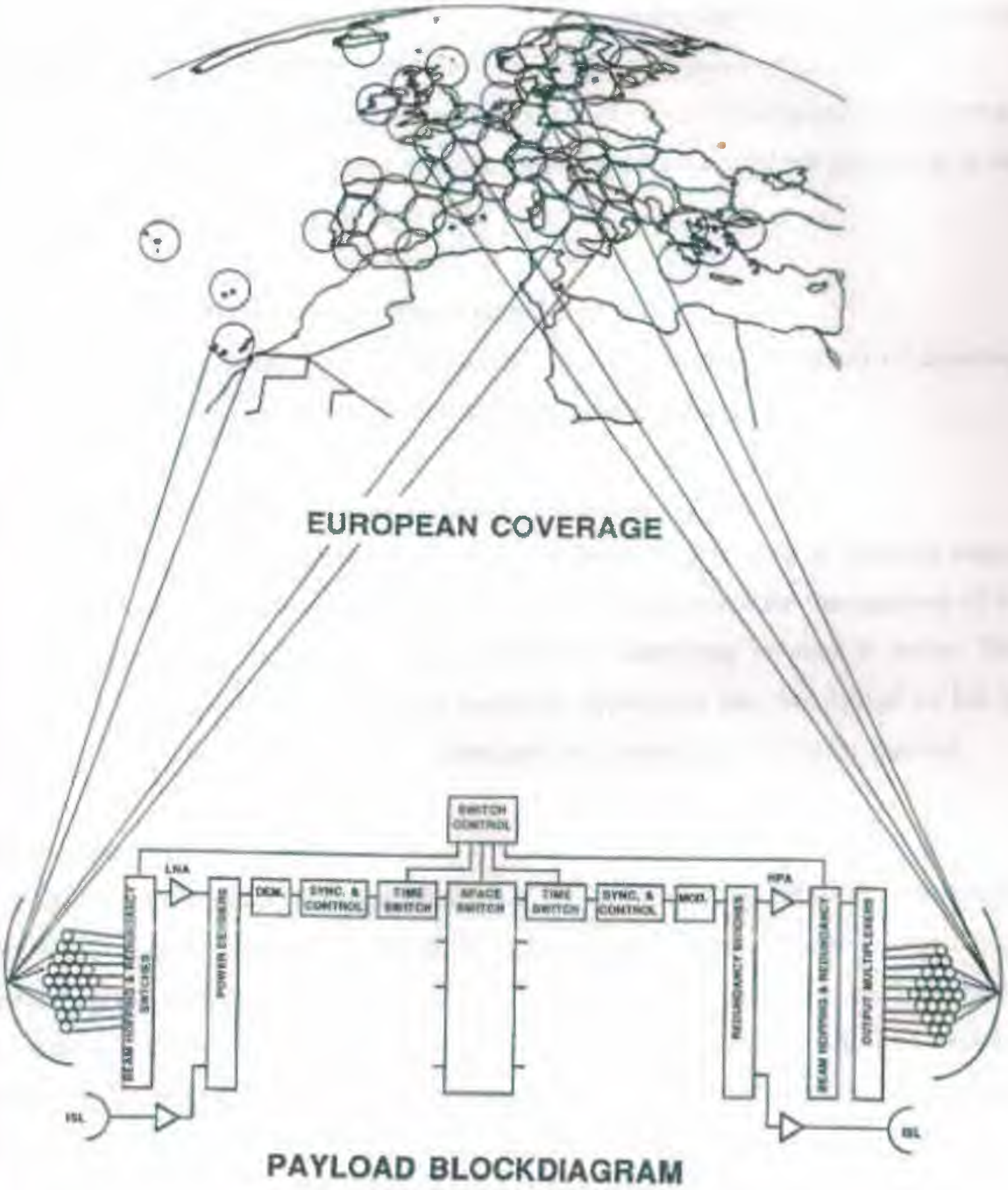


Figure 3.4 Example of advanced system configuration

3.3 THE PROBLERS OF THE INTEGRATION

Some of the technological aspects of the system proposed are very new and therefore may require in orbit demonstration to validate their feasibility.

However, the really difficult issues of the integration are precisely in the borderline now so diffused between the satellite system and the terrestrial network, without pretending to be exhaustive, we have identified the following:

Technical:

(i) Need of optimization of the process of network design.

Awareness of the availability of a "flexibility" tool in the implementation of dynamic networking would result in a more economical and robust planning.

(ii) Implementation of network management techniques.

No network management techniques are currently being used or even in planning stages throughout Europe. Fortunately the satellite system can implement the management of its own resources independently from the, fact that the underlying network is statue. The satellite system can be configured for a particular application and then would be left to rearrange itself between certain limits dynamically as a consequence of traffic demand.

(iii) Performance.

CCITT Recommendation G821 sets up, even if very peculiarly, the limits of performance for "standard 64 kbit/s ISDN channels. For many people, this is the key issue of the integration of satellites in the ISDN [18, 19]. Ye recognized its importance and especially the impact it may have on the system design if the 20-30 GHz band is used. It is however clear that this is a purely technological issue. The price of this specification has not been assessed yet.

(iv) System reliability.

The satellite system needs to be designed so as to ensure the grade of service and robustness required from public networks. The analysis of the redundancy required in several subsystems is currently being studied under ESA contract.

(v) Signaling.

The satellite system benefits from the introduction of the CCITT no. 7 signaling system, at are the nervous system of the network that will allow the reassignment of resources. It further provides the vehicle to convey administrative information which may be paramount in an international system. The best way to interact with the CCITT no. 7 network and the role of the master control terminal as either signaling point, signaling transfer point is the object of yet another ESA contract.

(vi) Provision of new services.

It is obvious that the satellite may be the vehicle to provide some new services to areas that otherwise may have to wait decades to get them, e.g. multipoint, broadband. However, the way to implement these services over the satellite and especially on the terrestrial tails is yet to be studied.

Economic:

A very important problem on the road ahead of the integrated system concept if the demonstration of the economic viability of the proposed solution. While the advantages listed are easy to perceive, they appear in many cases very difficult to evaluate.

In a companion paper to this conference [20], a simplified economic analysis is presented. It compares the cost of implementing the meshed connections of the second sublevel of the transit networks using satellites and optical fibre systems.

Other organizations have reported some analysis applicable to specific national applications (211. Further. ESA has funded a study by ESCO which is currently running and which some preliminary information has been used when writing this paper. Its final results are expected later this year.

Political:

The deployment of an integrated system may be performed in relatively trouble-free waters if it is done as a national system. On the other hand, given the relatively short European distances, it may be economically more attractive to deploy it at European scale. This implies that future generations of the European regional system (EUTELSAT 111 EUTELSAT 1V) could be allowed to have direct access to the national transit networks, while this path may be full of difficulties, since it may collide with the national systems, it presents at the same time the political opportunity to increase the cohesion of Europe in telecommunications networks. Further, its planned introduction might just oblige national Telecommunication Administrations to harmonize and standardize the different national systems. That in it would be an achievement.

3.4WIDE AREA NETWORKING BY INTERCONNECTING LANS AND MANS VIA SATELLITE

3.4.1 LAN INTERNETWORKING ISSUES

Organizations use multiple types of LANS to meet special application, security, and organizational growth and maintenance requirements. Market studies indicate that the North American LAN market will grow by about 20% annually for the next five years. Although office LANS will continue to remain as the largest percentage of share, factory and medical application LANS are expected to experience highest growth over this period. About 39% of the installed LANS are within a building floor, 27% within a building and 34% outside the premises. About 30% of the business communication takes place at inter-corporate level and about 20% at the inter-site intra-corporate level. This means nearly 50% of business communication i& with the agencies outside the premises.

3.4.2 LIMITATIONS OF INTERCONNECTION FACILITIES.

Lack of established Standards for the LANS as well as the interface units has made the task of interconnection very complicated. Further, analysis of applications indicate that the message length, terminal activity and data rate of user terminals each vary up to three orders of magnitude. Therefore, the LAN and inter-LAN traffic will vary even over a wider dyadic range.

Currently private lines are most commonly used to physically link local facilities to wide area network. Private circuit charges are fixed and are not traffic-adaptive. Other disadvantages of private lines are; rising costs, delays in acquiring facilities, and inability to reroute traffic around faulty link or nodes. Although dial-up services to some extent can be cost effective, they have inherent security drawbacks. In addition to speed constraints, terrestrial facilities are not economic or flexible for interconnection, reconfiguration and growth adoption.

3.4.3 BACKBONE NETWORK TO INFORMATION SERVICES

Providing LAN user the capability to access nationally communication power. In due and internationally, will course these primary vehicle to convey information services to the end-user. This will aid the decision process and enhance the productivity at all levels. Thus, formation of a wide area network by interconnecting LANS and MANS will provide the end-user the capability to utilize enormous communication, computing and information services. The value of such a powerful network will increase as more and more information and computing services become accessible. It is the authors' view that such a powerful, flexible, traffic-sensitive backbone network can be realized using satellite technology.

3.5 SATELLIITE-BASED WAN

3.5.1 NETWORK CONCEPT

The configuration of a satellite-based WAN is shown in Fig 1. First, multiple LANS at a location can be interconnected with appropriate gateways or bridges. They in turn can be linked to the nearest MAN by cable, fibre optic, or microwave digital radio links. The MANS of different locations are then linked through a high bit rate satellite link. LAN clusters which do not have or require immediate access to MAN can have on premises low bit rate satellite earth stations.

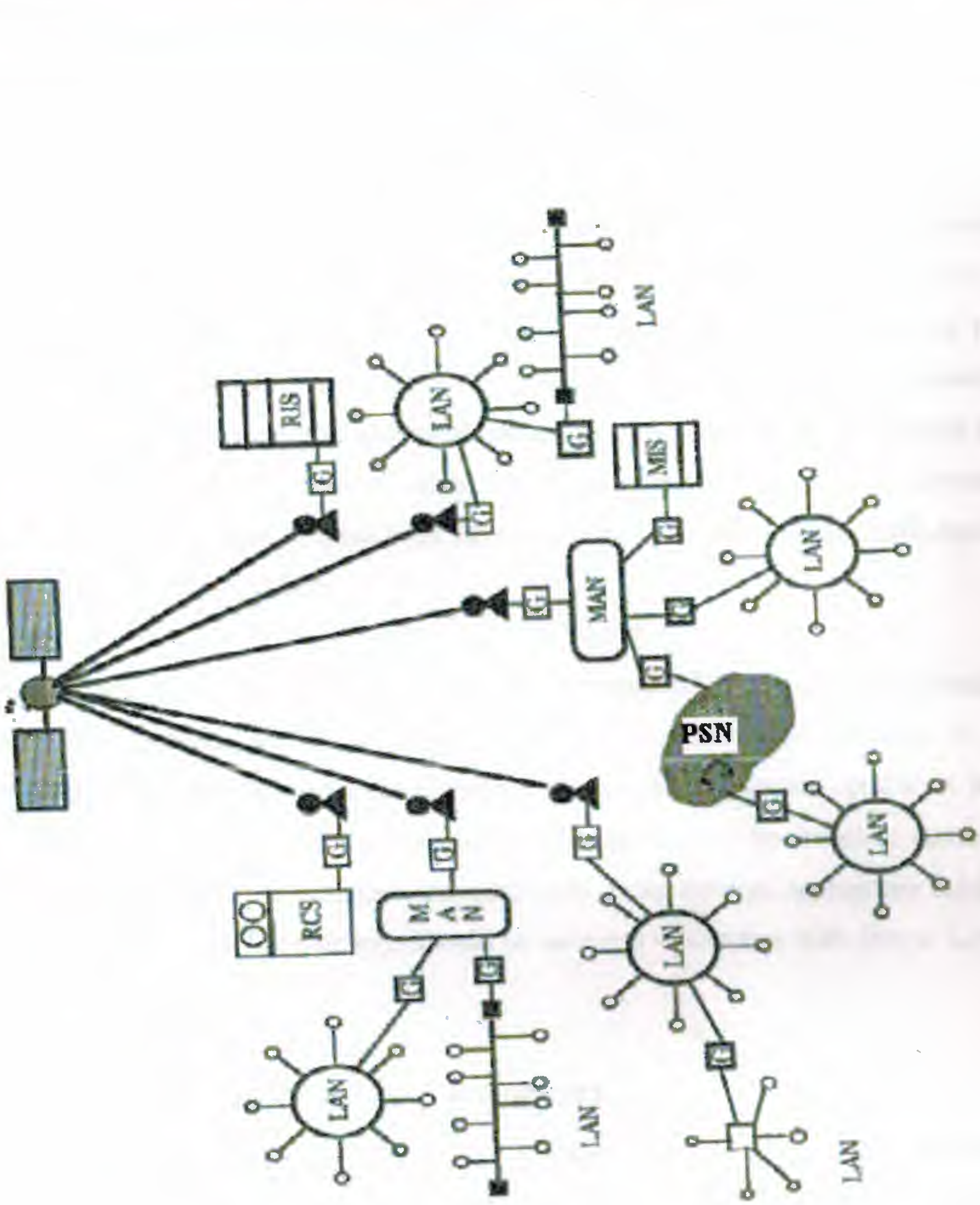


Figure 3.1 Wide Areas Networking VIA Satellite

Computing and information services centers can be linked to the network with appropriate gateways, satellite resource allocation and network management can be controlled by a Hub Station (centralized) or distributed among the network nodes. A number of factors will determine the type of satellite network required. These include, the number and type of LANS, MANS and terminals, terminal activity, application and the overall traffic characteristics. Satellite network can be designed to maximize flexibility and minimize transmission costs be appropriately segregating the inter-pi-AN traffic on the basis of message type (datagram, stream, etc.), traffic volume, delay tolerance and bit integrity (low-error, error-free). A TDMA type system with traffic-adaptive access protocol capability will be suitable. Currently there are systems (very small aperture terminal-VSAT network) which will support random access Aloha, reservation Aloha, demand or pre-assigned virtual channels at different bit rates. Message transfer delays for delay'-sensitive traffic can be minimized either by additional coding, or by separate high performance low bit rate channels or low bit rate terrestrial feed-back channels. A detailed innovative satellite network design can be done with the knowledge of a well defined traffic model. However, this is not pursued here.

Perhaps the most important element of a flexible satellite-based WAN is the earth station-to-earth station gateway and the associated interface processor. This gateway, at the satellite end, should be able to handle broadcast type satellite protocols, operate at wide range of bit rates, and tolerate differential delays. The gateway or the interface processor should be able to segregate messages and adaptively route through appropriate satellite facility. On the other side, the gateways should be universal to interface with diverse LANS and MANS.

3.5.2 INTER-LAN TRAFFIC ASSESSMENT.

The knowledge of inter-LAN traffic is very important to evolve an efficient and innovative satellite network (See Fig 1). Failing to locate any measured data in the open literature about the inter-l-AN traffic, we have attempted to make a parametric assessment. The inter-i-AN traffic is a function of a number of parameters; LAN speed, cable length, message length, number of active devices, average peak-hour device activity, application etc. An inter-corporate traffic of 2G% and intra-corporate traffic of 30% have been assumed for the traffic outflow based on a market survey. The LAN parameters assumed are: 1) Type = Ethernet; 2) Cable Length = 0.5KM; 3) Capacity = l0Mbps; 4) Channel Efficiency = 89%9
5) Packet Length = 10249 and
6) Average Device Activity = (1% - 20%).

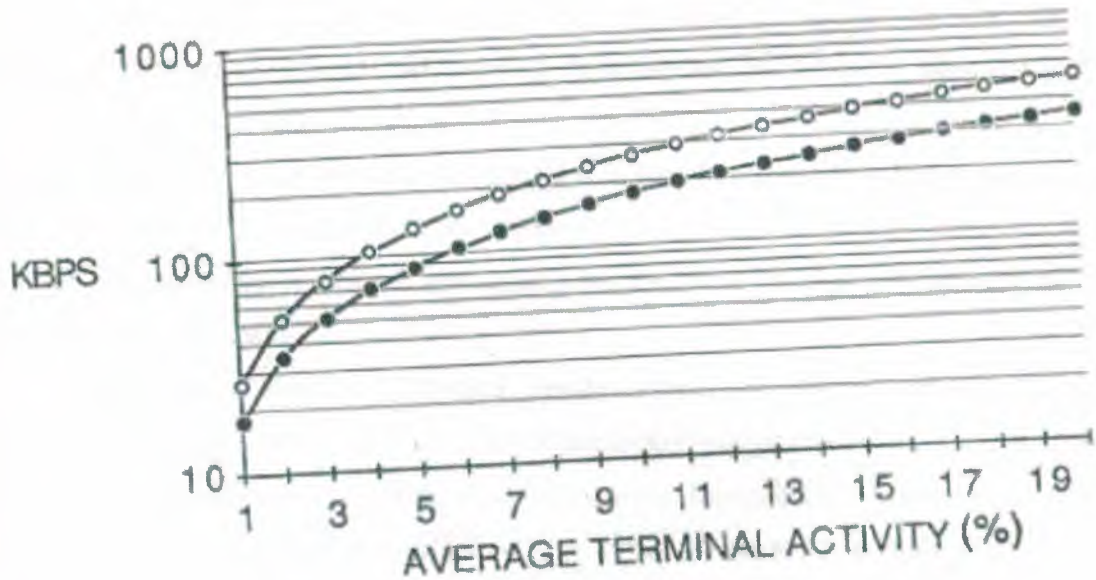


Figure 3.2 Inter-Lan Traffic Vs.Terminal Activity

In Figure 3.2 the peak hour average inter-l-AN traffic based on the assumptions above is drawn as a function of device activity for both the inter-corporate and intra-corporate cases.

3.6DATA TRANSFER OVER AN INTEGRATED COMMUNICATION NETWORK FOR AN ORBITAL INFRASTRUCTURE

3.6.1 DATA TRANSFER

This description of data transfer comprises two sub-topics, the first dealing with the problems of establishing an access procedure over the space-to-ground link, and the second dealing with end-to-end data transfer (this end-to-end data transfer includes data communication networks both on ground and on board, i.e., LAN's and/or WANs). For each of these sub-topics, the options are described and, where possible, more emphasis is given to the more adequate solution.

3.6.2 Access to the Space/Ground Link

Two methods of accessing the link are analyzed:

-Synchronous TDM (PCM) used in telephony (fixed-frame, fixed allocation of time slots to each channel, etc.). -Logical multiplexing (transmission resources are allocated according to traffic requirements).

The physical link over which the information is transferred shall multiples data originated by N sources and addressed to N destinations.

Four major evaluation criteria are considered for trade-off analysis between the above mentioned methods:

Synchronization technique: a classical synchronous TDM network relies on a centrally distributed clock such that the TX and RX are locked together at bit level. Logical channel multiplexing transmission relies on sync pattern recognition. Efficiency in terms of throughput; in synchronous TDM the number of bits is counted, and in a specific instant the destination of data is known (i.e., there is no need for in-band signaling and no overheads per information unit transmitted, on the other hand, out of band signaling is needed). In the case of logical multiplexing, in-band signaling is required since there is no correlation between the time clock and the data destination (this causes an increase in overheads).

. Efficiency in terms of flexibility; where synchronous TDM synchronization assumes that the time slot made free by one user is taken by another on the basis of statistical network traffic. This assumption works well in a large community of users (e.g., PTT users), but in fact would greatly limit efficiency in an environment where user data types are heterogeneous, and the number of users is limited.

Note: Heterogeneous means a slot allocated to a type of data (computer transaction), which cannot be easily reallocated to another type of data (e.g., video data). Statistical allocation of available slots does not work as well as for a small number of users.

Implementation of priority scheme; logical multiplexing allows for a very flexible solution to this problem by allocation a bandwidth on request to high priority users, thus maintaining nominal efficiency.

With synchronous TDM this is only possible through rigidly allocating a higher number of slots within the available bandwidth.

When comparing the advantages and draw and draw backs of these two proposed baselines in terms of user requirements, it appears that the logical multiplexing approach will offer better performance, and has the advantage of being compatible with existing link access procedures used in space systems for scientific satellites (Packet Telemetry Standard).

The present Packet Telemetry Standard at the level of a link access procedure has the following main features:

Frames have a fixed length, and consequently a fixed repetition rate, thus simplifying sync pattern recognition.

A logical channel (virtual circuit) identifier, which allows for real statistical multiplexing between frames.

. Each logical channel carries the data either of one single user (dedicated) or of a group of users (shared). Therefore, when a user is not active, the logical channel can be skipped, or reallocated to other users (thus providing the advantages of flexibility and optimum bandwidth usage). Control information carried in the frame header allows for sequence control lf all frames received, and of frames per logical channel.

. The frame error control field, implemented by the polynomial CRC and/or Reed-Solomon coding, is able to ensure the BER on the link is suitable for the required grades of services most required. This basic structure is adequate for the variety of classes of data already defined. Examining each basic class of data will give us the following details:

. Video high rate (user has large bandwidth requirement), may be allocated one dedicated logical channel with appropriate priority in order to meet the maximum allowed access delay.Audio (low rate and possibility of fragmentation of information); digital audio channel requires a nominal bandwidth of 64 Kblt/s, and assuming a transfer frame length of 10,000 bits, the number of bits per frame varies according to the channel data rate.

From an efficiency point of view, it would be ideal to wait for 10,000 bits to be generated in order to fill up one frame. However, it is reasonable to assume that the delay between successive audio samples should be in the order of 20 to 50 us, and therefore additional fragmentation of the audio information will be required. The result is that in each frame, a small number of audio bits will be available for transmission, thus decreasing efficiency. A possible solution to this problem is the sharing of the frame data field by audio channels and other users. This implies some difficulties, mainly in the area of signalling (channel allocation/deal location), and in influencing traffic which shares the virtual channel with audio. As a final consideration, we may say that both solutions (dedicated or synchronous insert) are technically feasible; the selection criteria are mains y linked to the frame repetition rate and the maximum acceptable audio sample length. In the case of asynchronous user data (computer data), users require a low data throughput compared to high rate payload, and therefore, in order to efficiency y use the link, users should share one single logical channel; this of course requires the implementation of higher level multiplexing. In the present Packet Telemetry Standard, this is supplied by the Source Packet, and the issue of adequacy of the source packet for such a function being applied to new users is addressed in some detail below.

3.6.3 TRANSFER OF DATA OVER THE INTERCONNECTED ENVIRONMENT

The method of accessing the link from space to ground and vice versa previously described is based on the assumption that all sources and destinations of data on board and on ground were physically local to the two end points *of* the link (LEO terminal and earth terminal). This assumption was made in order to simplify the global scenario of the communication network. In fact, the scenario is rather more complex because on-board users are interconnected to the LEO terminal, via an on-board LAN, as well as to ground users, via the decentralized control center network (where interconnection may be established via LANs, or via public wide area network). As a consequence, we can state that end-to-end data transfer takes place over interconnected sub-networks (in this respect the space-to-ground link is considered a sub-network). Refer to Figure3.3

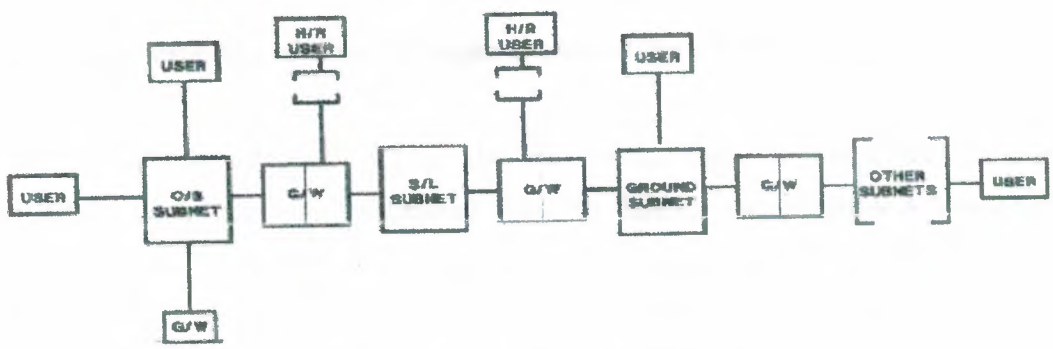


Figure 3.3 space-ground networks

G/H, Gateway

H/R USER, High Rate User

O/B SUBNET, On-Board Sub-Network

S/L SUBNET, Space Link Sub-Network

The data communication technique to be adopted for transferring information through this environment depends (among other things) upon the characteristics of the data generated by end users. The majority of end users on the Low Earth Orbit terminals is computer-based payloads with significant autonomy, requiring large amounts of software and therefore transfers of files. This type of data is of a "burst" nature (asynchronous with respect to accessing the network), and as based on interactive transactions between users. Hence, a transmission based on a data structure "packet" seems to be preferable to the synchronous distribution of data.

Given the structure of the interconnected environment already described, it is necessary to provide a mechanism capable of handling data transfer of this type. Two basic options can be considered for the implementation *of* this function:

(1) Data transfer takes place entirely via protocol; each user data unit is formatted in such a way as to provide full addressing capability throughout the system (datagram-like approach).

(2) Data transfer ls completely handled by management; in this case the user needs only to be known at the local network interface, and the communication management function facilitates delivery of data to the final destination.

There are advantages and disadvantages to each of these solutions:

(1) A fully data-driven protocol (e.g. the ISO 8473 Internet protocol) implies a 1arge overhead on each data unit transmitted (low efficiency), and provides a low grade of service in terms of reliability. In fact, such a system does not guarantee correct sequencing of the delivery of data units (without omission or duplication), and can also, in the event of link breakdown, create an unknown situation on the state of transmission that is the users responsibility for recovery from the instant of link interruption. All this is, of course, true in the case of connection-less service (datagram).

(2) The transfer by management solution certainly simplifies the highlighted problem but does imply a very heavy processing capability within the internal elements of the network. This can be a problem for the processing power required by the on-board processing unit, especially due to the relatively high data rates involved.

A possible alternative is a compromise between the two, and involves the establishment of an end-to-end logical link over which a relatively simple network protocol may be run according to requirements.

In such a case the logical path for data transfer is initially established by means of a connection request phase (signaling), and then data transfer takes place by means of data packets which can themselves use either a connection-less, or a connection oriental protocol according to the identified need. The basic principles of this solution are inspired by the switched virtual circuit service of the CCITT X25 recommendation; this solution combines the low overhead obtained and reliability in the transfer by management sol union, with the relatively simple protocol handling of the data driven approach.

The solution described above holds for those classes of data which:

* Can stand an asynchronous type of service by the network with a priory random access delay.

* Produce data at rates which can be effectively y handled by the present generation of data networks available both on ground and on-board.

There are some classes which, for either or both of the reasons listed above, are excluded from this classification:

* Audio data which requires asynchronous or quasi-synchronous transfer; this cannot be easily supported by present public data networks, and therefore requires special care in. transmission Video data with synchronized audio also falls into this category

* Payloads (including video cameras) whose generated data rates are far too high to be

handled by any on-board LAN or ground network; it is worth mentioning here that a SAR (Synthetic Aperture Radar) processor produces data in the order of up to 300Mbit/s, but multi-band optical IR Thematic cappers will go above 500 Mblt.

For these data classes, the interconnected environment described above can be simplified by making two basic assumptions:

(1) On-board, the physical connection between the user and the LEO terminal is via a point-to-point dedicated link (1.e., no on-board LAN).

(2) On ground, data transfer is assumed to terminate at the ground terminal (or at the user site when direct data distribution is considered).

Under this hypothesis the problem is reduced so as to provide fast and simple access to the space-to-ground link. The selected solution is to provide such user data With direct access to the data field of the Transfer Frame, where each high rate user is allocated one dedicated virtual channel (from an efficiency point of view, this is just fibbed by the high rates produced so that Virtual Channels can be efficiently filled. The requirements of synchronous transmission over the link are fulfilled by the implementation of a priority scheme; in this way virtual channels carrying synchronous data gain immediate access to the link when ready.

4. MOBILE SATELLITE NETWORKS

4.1 OPERATING ENVIRONMENT

Although cellular terrestrial mobile communication systems exist, they serve only the urban areas where base stations are located relatively close to mobile users. The cellular system is not economically possible for vehicular communications in rural or remote areas where the population density is low. Satellite technology has reached the point where vehicular communications between mobile users and base stations can be achieved with low cost. Such mobile *satellite* (MSAT) systems can complement existing cellular terrestrial mobile systems by extending the communication coverage from urban to rural areas. MSAT systems are not restricted to land coverage but can include aeronautical and maritime services as well. Some applications of MSAT telephone and data communications include transportation (coastal marine, rail, school buses, and public utilities), vehicle location and tracking, air telephone, land telephone, interactive data, public safety, and medicine. In the United States, land, aeronautical, and maritime MSAT services have recently been allocated frequency spectra in both L-band (1.6/1.5 GHz) and Ku-band (14/12 GHz). The frequency bandwidth for aeronautical and land mobile satellite services are 1646.5 to 1660.5 MHz for uplink and 1545 to 1559 MHz for downlink.

In this chapter we will discuss concepts of MSAT networks operating, in both L-band and Ku-band frequencies, and in Ku-band frequencies only. The propagation problems encountered in MSAT communications with low gain antennas such as multiparty and shadowing effects will also be presented.

In fixed satellite service systems such as VSAT systems, a ground terminal employs a high-gain directional antenna pointed directly at a geostationary satellite. Therefore, only the direct line-of-sight signal between the ground terminal and the satellite is collected by the ground terminal antenna. In MSAT communications, the mobile terminal employs a low-gain antenna of 3- to 6-dB gain (omni directional) or 10- to 14-dB gain (for steered antenna). These low- gain antennas collect the direct line-of-sight signal together with its specula ground reflection components in the vicinity of the mobile terminal and its multipath reflection components from hills, mountains, tees, buildings, etc. The last two components of the satellite signal are completely rejected by high- gain antennas in fixed satellite service systems. Figure3.1 shows the propagation model for MSAT communications. The rejected components of the direct signal may add up destructively and result in signal fading or attenuation. Furthermore, vehicles traveling along tree-lined roads may encounter shadowing of the direct line-of-sight signal, which results in even more severe signal fading. Therefore, an MSAT system must be designed to compensate for the degradation due to propagation effect. We will discuss propagation problems and modeling in detail in Sec. 3.4. Unlike axed satellite services which enjoy an

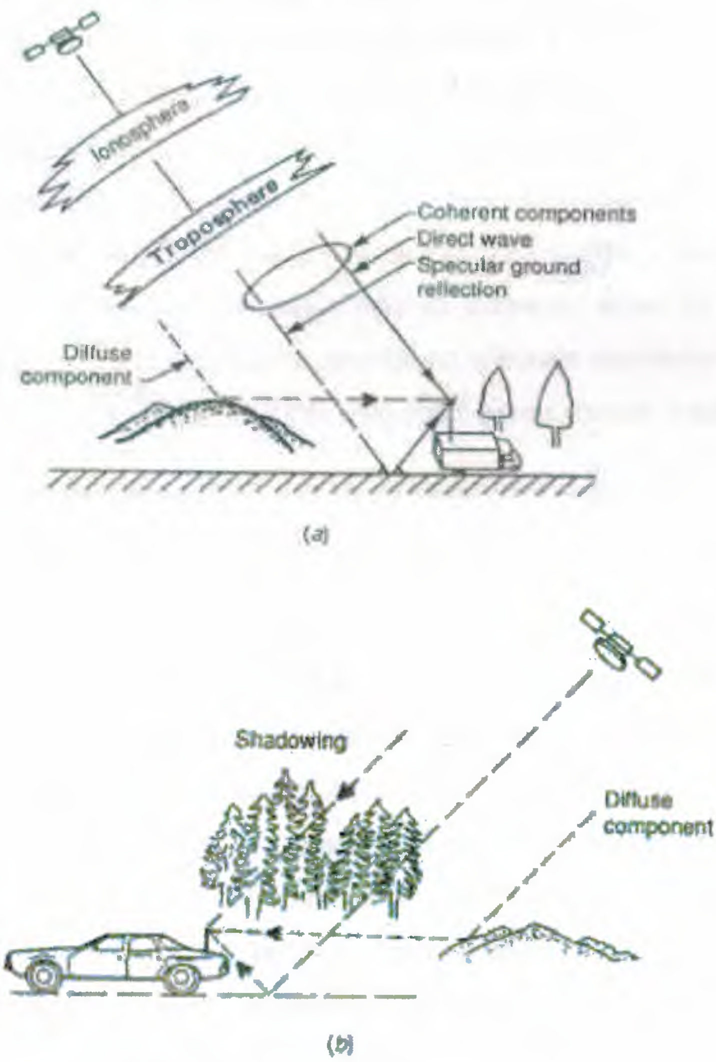


Figure 4.1 Mobile communication path.

Figure 4.2 four-beam satellite coverage.

Allocated of about 500MHz bandwidth each at C-band, MSAT services at L-band are allocated a narrow bandwidth of only 14 MHz. Thus, an MSAT system must further be designed to efficiently utilize the L-band frequency spectrum. In order to reuse the frequency spectrum, the narrow band- width at L-band necessitates the use of a multiple beam satellite antenna such as the one shown in Fig. 13.2 for the L-band coverage of the United States. Present antenna technology permits frequency reuse by beams which are separated by more than a bam width to provide an adequate carrier-to-interference ratio. For the four-beam system in Fig. 13.2, the two outer beams (beams 1 and 4) can reuse the same frequency, and thus the capacity can be increased by a factor of $\frac{4}{3}$

4.2 MSAT NETWORK CONCEPT

In this section, the description of an MSAT network operating at both the 1 .6/1.5 GHZ 14/12-GHz bands is presented. Such a network shares many common features with the VSAT network described. Because MSAT mobile users are power-limited, an MSAT network is constrained to operate in a generalized star configuration which can have many semiautonomous hub stations. A11 communications links must be connected via a hub station; thus, the single- hop mode between a mobile terminal and a hub station as well as the double- hop mode between two mobile terminals via a hub station are possible. No direct connections between mobile terminals are possible in a power-limited MSAT network. The MSAT network configuration is shown in Fig. 13.3 and consists of the mobile terminals, the hub stations (base stations and gateways), and the *network control center* (NCC). The NCC and hub stations operate at 14/12 GHz and the mobile terminals operate at 1.6/1.5 GHz. Mobile terminals may include transportable terminals with antenna gain in the range of 15 to 22 dB . Vehicles must use lower gain antennas. Omnidirectional antennas such as the drooping dipoles can provide a

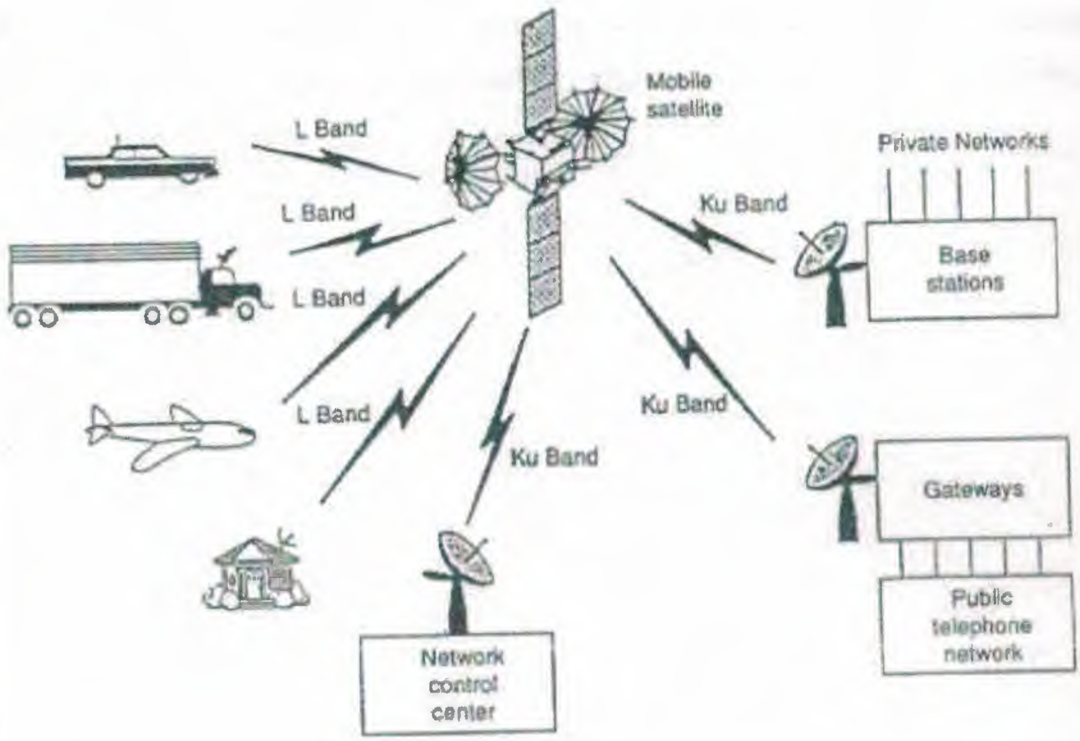


Figure 4.3 MSA network configurations.

Gain of 3 to 6 do for elevation angles between 20 to 60^0. Their advantages are their very low cost and simplicity. Their disadvantages are low gain and high susceptibility to multipath reflections. In addition, their wide beams prevent the orbital reuse of satellites, which may be needed if more than one orbital slot is required h demand. To alleviate these disadvantages, medium-gain to meet such antennas, such as the mechanically steered linear array, the mechanically steered planar array with an electronic sensor to determine the satellite position, or an electronically steered phase array, are used . Gain in. the range of 10 to 14 dB can be achieved for elevation angles between 20 to 60^0 with a full 360^0 in azimuth by beam steering. Furthermore, these medium-gain antennas can provide an antiatellite isolation of about 20 to 26 dB for two geostationary orbital slots for U.S. coverage that are separated by approximately 35^0. Figure 4.4 shows a mechanically steered planar array 4.4

show a mechanically steered planar array.

The hub stations in an MSAT network consist of two types: (1) base stations for terminations of private networks for dispatched operations such as trucking and (2) gateways for interconnections of telephone to other traffic on the public switched telephone networks. A hub station in an MSAT network is a passive station; that is, it does not participate in the access control to the network as does the hub station in a VSAT network. It merely serves as an interface between mobile terminals and private or public networks, or between mobile terminals

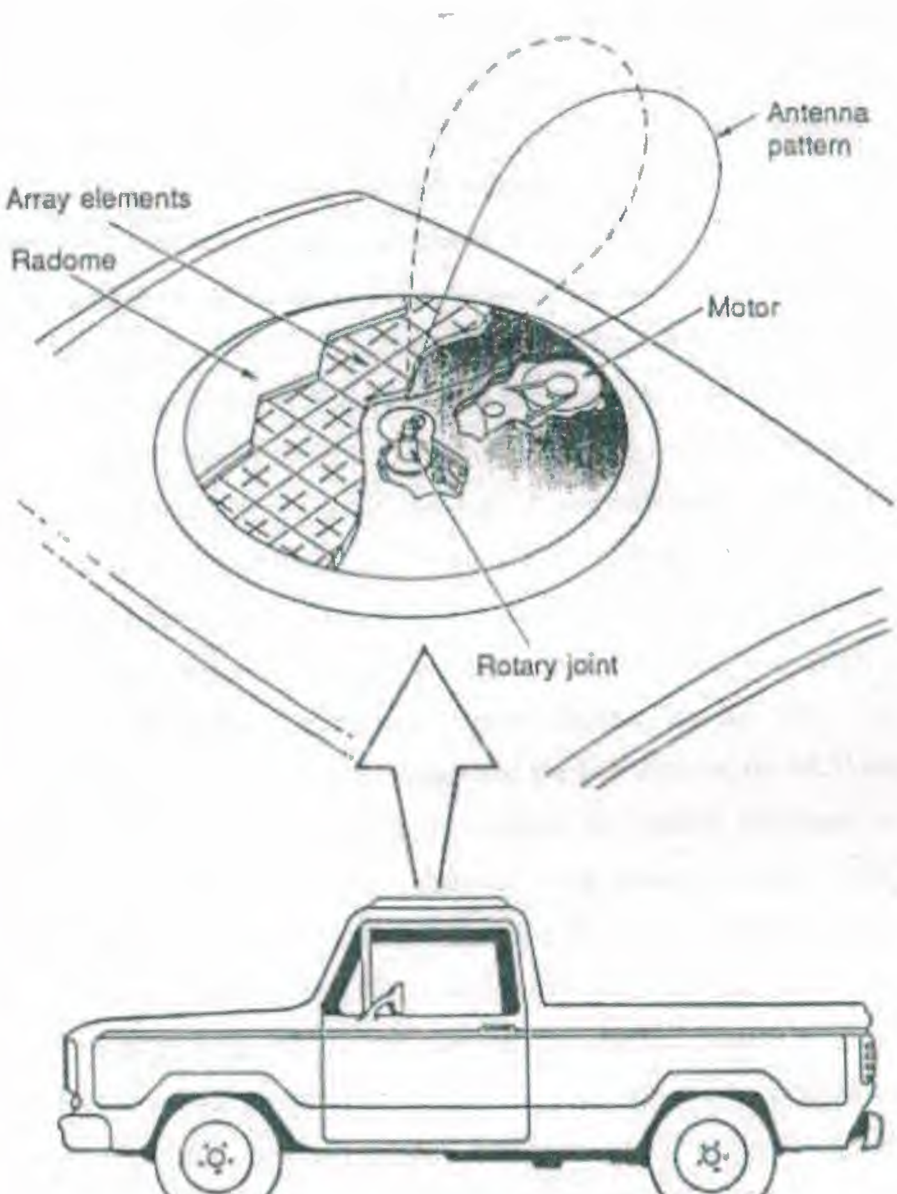


Figure 4.4 A mechanically steered planar array. (Courtesy of NASA JPL)

The NCC is the station that controls the access to satellite channels for the entire network. The NCC communicates with all mobile terminals and hub stations in an MSAT network. because of the limited bandwidth available at L-band (14 MHz) and because the traffic intensity at each mobile terminal is very low, fully variable demand assignment, must be used to improve the utilization of the satellite capacity. Two multiple access techniques that are suitable for an L/Ku-band MSAT network are FDMA and CDMA. TDMA requires too much power for a mobile terminal and, therefore, is inappropriate. Fully variable DA-FDMA is called *single-channel-per-carrier demand assign-met multiple access* (SCPC-DAMA). With SCPC-DAMA the satellite capacity

Is pooled and used on a single - channel-per-carrier basis. That is, for every channel assigned to a call, a carrier frequency is assigned to that channel. A Pair of frequencies is assigned to a duplex voice circuit (two channels). There- fore, a call can be blocked under only one condition--when no frequency pairs are available from the satellite capacity pool. The same concept applies to fully variable DA-CDMA where the satellite capacity is also pooled and used on a single-channel-per-spread spectrum code (SCPS-DAMA) basis. That is, when a channel is established, a *pseudo noise* (PN) code is assigned to that channel. Thus, a pair of PN codes is assigned to a duplex voice circuit. Channel blocking occurs only when there are no pairs of PN codes available from the pool. It is seen that an MSAT network employs centralized control DAMA via the NCC. To establish call connections between the mobile terminals and the hub stations, the NCC employs signaling circuits in both L- and Ku-bands. Call request by mobile terminals to the NCC is carried out via an L/Ku request channel using random access techniques, such as Aloha. The NCC signals the called hub station and receives the hub station response on a Ku/Ku signaling circuit. After the called party answers, the NCC sets up a duplex satellite circuit between the mobile terminal and the hub station via a Ku/L assignment channel for the mobile terminal and the Ku/Ku signaling channel mentioned above for the hub station. The NCC monitors the call duration using the Ku/Ku signaling circuit. Call request by the hub station to the NCC may be done via Ku-band Polling or TDMA signaling channel. The NCC signals the called mobile terminal On a Ku/L signaling circuit. When the mobile terminal acknowledges, the NCC assigns duplex satellite circuit via the Ku/L assignment channel for mobile terminals and the Ku/Ku signaling channel for the hub station. When SCPC-DAMA is used, the satellite capacity can be segmented into a common pool of 5-kHz channels, which is suitable for 4.8-kbps digitally encoded voice of near-soil quality (telephone) using linear predictive coding.

To obtain spectral efficiency, the trellis-coded modulation {TCM} technique discussed, is used. At L-band, a rate l6-state trellis-coded 8-DPSK with differential detection has been shown to be quite robust in a Rican fading channel (to be discussed in. Sec.4.4). This modulation scheme can achieve a bit error rate of 1 in 103 for an *Eb INZ* of about 10 do when the power ratio *K* between the direct component and the multiparty diffuse component of the received signal is 10 do (4). TCM is suitable for an MSAT network which is bandwidth-limited but not power-limited. If the network is power-limited but not bandwidth-limited, conventional QPSK or MFSK with low rate convolution code may offer the required lower *Ey IN?*AVA its some restrictions on mobile The use of FDMA, such as SCPC-D , pu communications at L-band. With one satellite (or multiple satellites which use Different frequency spectra of the allocated 14 MHz), omnidirectional antennas can be equipped for mobile terminals. If demand for mobile satellite communications increases to the point that orbital reuse with multiple satellites is necessary, medium-gain steered antennas must be employed and satellites using the some frequency spectrum must be separated by approximately 35^0. Orbital reuse thus limits the number of satellites that can provide coverage for North America and Alaska with SCPC-DAMA. The number of beams that these satellites can provide determines the MSAT capacity. For example, the four-beam system in Fig. 3.2 can increase its capacity by a factor of 4/3 if beams 1 and 4 reuse the same frequency spectrum. From the above discussion, it is seen that SCPC-DAMA is suitable for a bandwidth-limited system. For an MSAT network which is not bandwidth-limited but power-limited (a scenario similar to many VSAT networks described in Chap. 2), the use of SCPS-DAMA may alleviate the co channel interference and further improve the capacity. If the system is power-limited, the number of channels the network can handle depends on the satellite EIRP and not on the allocated bandwidth (14 MHz). With MFSK and direct sequence spreading (Chap. 1), one can achieve the same number of channels as SCPC-DAMA for the same satellite EIRP. For a multibeam power-limited system, SCPS-DAMA can greatly reduce the interference between adjacent beams. Consider the four-beam system in Fig. 13.2. With SCPS-DAMA, beams 1 and 3 can reuse the same frequency spectrum with a slight reduction in capacity (5 to 10 percent) due to interment interference and beams 2 and 4 can also reuse the same frequency spectrum (each beam can use 7 MHz of the allocated 14 MHz). Thus the satellite capacity is improved by a factor of 1.8 to 1.9 as compared to 4/3 for an SCPC-DAMA system. A problem may arise, though, in the use of spread spectrum techniques, namely, the propagation effects. It has been shown that for acceptable amplitude variations over the channel bandwidth (with constant amplitude modulation schemes), the multipath effects limit the usable bandwidth to a few tens of Kilohertz. The use of spread spectrum with wide bandwidth, as compared to narrowband SCPC-DAMA, will probably result in a much higher degradation due to signal amplitude variations. To further improve the satellite power allocated to each voice detectors to turn the carrier on or off. Since the voice activity factor is about 0.4, that is, the average talker speaks about 40 percent of the number of assigned satellite channels is active at any instant of time. Therefore the satellite power for each active channel is actually increased by a factor of 2.5. Tables 3.1 and show the link budged for an SCPC-DAMA MSAT network operating at L-and Ku-bands for the inbound link (mobile-to-hub) and outbound link (hub-to-mobile). In this example we consider two cases: (1) the

Modulation scheme is trellis-coded 8-DPSK and (2) the modulation scheme is QPSK with rate ½, constraint length 7 convocational codes, and Viterbi soft decision decoding. Also we assume the QPSK signal is filtered with a 40 percent cosine roll-off filter

Table 13.1 Satellite and hub station and mobile terminal parameters

Satellite	
Operating flux density (dBW/m^2)	
L-band (1.65 GHz)	−122 (−114)
Ku-band (14 GHz)	−92.1
Operating EIRP (dBW)	
L-band (1.55 GHz)	60
Ku-band (12 GHz)	38
G/T (dB/K)	
L-band	3
Ku-band	−3
Hub station (Ku-band)	
Transmit antenna gain (dB)	52
Receive antenna gain (dB)	50.7
Transmit power of all hub stations (dBW)	20
G/T (dB/K)	27
Mobile terminal (L-band)	
Transmit antenna gain (dB)	4 (12)
Receive antenna gain (dB)	4 (12)
Transmit power of all mobile terminals (dBW)	37
G/T (dB/K)	−20 (−12)

Note: Values in parentheses are for a medium-gain antenna.

1. Case1. The network can support a total of 3. 16 Mbps with mobile terminals using omni direction antenna. This is equivalent to approximately 658 active voice channels (4.8-kbps linear predictive coding voice). When using voice detectors, the network can support 658/0.4 = 1645 assigned voice channels since approximately 40 percent of them are active at any instant of time. If the mobile terminals use medium-gain antennas, the network can support 1256 active voice channels or 3140 assigned voice channels at any instant of time. This example shows that the representative network is power-limited, especially with omni directional antennas. The total bit rate of 3. 16 Mbps for 658 voice channels occupies a bandwidth of 3.29 MHz (5 kHz for each 4.8- kbps linear predictive coding voice channel). With medium-gain antenna mobile terminals, the network bit rate is 6 Mbps, which requires a bandwidth

Assume that the mobile terminals use omni directional antennas and that the satellite in this case has four-beam coverage as shown in Fig. 13.2. Thus, beams 1, 2, and 3 may be assigned a separate frequency band each. Beam 4 may reuse the frequency band of beam 1. Each beam is capable of handling approximately 658/4 = 164 active voice channels, which occupy a bandwidth of 0.82 MHz. The total bandwidth required by this four-beam satellite is 2.46 MHz. For a network with a medium-gain antenna, the required bandwidth for a four-beam satellite is approximately 4.68 MHz.14 is seen that the allocated bandwidth of 14 MHZ can accommodate, in the same

Table 13.2 Link budget for an L- and Ku-band SCPC-DAMA MSAT network

	Inbound	Outbound
Uplink		
Total EIRP (dBW)	41 (49)	72
Path loss (dB)	189	208.5
Gain of ideal 1-m² antenna (dB/m²)	25.8	44.4
Operating flux density (dB/m²)	−122 (−114)	−92.1
Transponder G/T (dB/K)	3	−3
Boltzmann's constant (dBW/K-Hz)	−228.6	−228.6
Total carrier-to-noise density ratio (dB-Hz)	83.8 (91.8)	89.1
Downlink (12 GHz)		
Operating satellite EIRP (dBW)	60	38
Path loss (dB)	188.4	206.6
Terminal or station G/T (dB/K)	−20 (−12)	27
Boltzmann's constant (dBW/K-Hz)	−228.6	−228.6
Total carrier-to-noise density ratio (dB-Hz)	80.2 (88.2)	87
Total interference and intermodulation C/I_0 (dB-Hz)	87	87
Total carrier-to-noise density ratio (dB-Hz)	78 (83.8)	82.8
Other losses (dB)	1	1
Total available C/N_0 (dB-Hz)	77 (82.8)	81.8
Link margin (dB)	2 (5)	5.8 (4)
Required trellis-coded E_b/N_0 at 10^{-3} BER with Rician fading of $K = 10$ dB (dB)	10	10
Total data rate (Mbps)	3.16 (6)	3.16 (6)
Required QPSK E_b/N_0 with Viterbi soft-decision decoding (rate ½, constraint length 7) at 10^{-3} BER with Rician fading of $K = 10$ dB (dB)	6.5	6.5
Total data rate (Mbps)	7.08 (13.49)	7.08 (13.49)

Note: Values in parentheses are for a medium-gain antenna.

Orbital slot approximately (1) five four-beam satellites for a total of 20 beams (0.82-MHz bandwidth for each beam) with an omni directional antenna and (2) three four-beam satellites for a total of 12 beams (1.56-MHz bandwidth for each beam) with a medium-gain antenna. The eve satellite omni directional antenna system can provide approximately 3290 active voice channels or 8225 assigned voice channels at any instant of time. The three satellite medium-gain antenna system can provide approximately 3768 active voice Channels or 9420 assigned voice channels at any instant of time. It is clear that the use of a medium-gain antenna as opposed to omni directional antennal requires two fewer satellites. Thus, it is likely that a user with a low-cost omni directional antenna terminal will pay a higher anytime charge than a user with a higher-cost medium antenna terminal.

2. Case 2. The above analysis clearly shows that the network is power-limited. Therefore, a higher capacity per satellite can be achieved with a conventional QPSK with a low rate convolutions code (rate 1/2, constraint length 7) that requires approximately 6.5 (18 in E_b / N_0 at a bit error rate of 1 in 10^3 as compared to $E_b / N_0 = 10$ dB for narrowband trellis-coded 8-DPSK. With mobile terminals employing omni directional antennas, the network can support 7.08 Mbps or, equivalently, 1475 active voice channels (4.8-kbps linear predictive coding voice) or 3687 assigned voice channels at any filtering. Instant of time. The occupied bandwidth is 9.91 MHZ with 40 percent cosine roll off altering. When a medium-gain antenna is equipped for mobile terminals, the satellite has enough power to support 13.49 Mbps (with some 3-dB gain in link margin for the inbound link and 1.8-dB loss in link margin for the- bound link). However, the required bandwidth is now up to 18.89 MHz, which exceeds the allocated bandwidth by 4.89 MHz. Therefore, with medium-gain antenna mobile terminals, the network is not power-limited but bandwidth-limited. In this case the network cans support to a 10-Mbps data rate, which occupies a bandwidth of 14 MHz. this is equivalent 2083active voice channels (4.8- kbps linear coding voice) or 5207 as- signed voice channels at any instant of time.

Now consider the four-beam satellite system in Fig. 4.2 and assume that the mobile terminals employ omni directional antennas. As analyzed above, the network can support 1475 active voice channels or approximately 369 active voice channels per beam. Thus each beam must be allocated a bandwidth of 2.48 MHz. The total bandwidth required by a four-beam satellite is therefore, equal to 7.44 MHz (beams 1 and 4 reuse the same frequency band). Thus, the allocated bandwidth of 14 MHZ can accommodate, at the same orbital slot, two four-beam satellites which can provide a total of 1920 active voice channels or 4800 assigned voice approximately channels. This capacity is equivalent to the capacity provided by a three four-beam satellite In this case, the networks can system using narrowband trellis-coded 8-DPSK as the modulation scheme with the saving of one satellite. Note that the use of trellis-coded 8-DPSK allows the addition of two more four-beam satellites to the network to increase capacity to 3290 active voice channels, while the use of coded QPSK limits the network to only two four-beam satellites for a total capacity of 1920 active voice channels.

With medium-gain mobile terminals, the network can employ, at a given orbital slot, only one four-beam satellite for a total of 2083 active voice channels. Thus, the system uses the fewest number of satellites but has no room for expansion unless satellites are separated by some 350 as required by medium-gain antenna isolation.

Table 4.3 summarizes the capacity of a multiple four-beam satellite MSAT network corresponding to a given orbital slot. It is clear that a narrowband modulation scheme allows more capacity than conventional coded QPSK in a multiple satellite network with a four-beam satellite antenna and allows even

Table 4.3 Capacity of a multiple four-beam satellite MSAT network at a given orbital slot

	Trellis-code 8-PSK	Coded QPSK
Maximum number of satellites	5 (3)	2 (1)
Number of active voice channels	3290 (3768)	1920 (2083)
Spectral efficiency (bps/Hz)	1.128 (1.29)	0.658 (0.714)

Note: Values in parentheses are for a medium-gain antenna.

more capacity with a complex satellite antenna that can provide more than four beams. Note that the use of medium-gain antenna for mobile terminals allows further orbital reuse of satellites by placing them about 35^0 apart.

4.3 CDMA MSAT NETWORK

In the previous section, we presented a technical advantage of spread spectrum CDMA multiple access technique over narrowband SCPC, that is, frequency reuse by multi beam satellite antenna (an improvement factor of 1.8 to 1.9 for CDMA and 4/3 for SCPC with a four-beam satellite antenna). In a CDMA system, capacity can be further improved by utilizing orthogonal circular polarizations for each beam. The inter user interference in one polarization is slightly increased by (1) the inter user interference in the opposite polarization attenuated by the cross-polarization discrimination ratio and (2) the multipath-reflected inter user interference in the opposite polarization which changes polarization and which appears at the full reflected power in the other polarization. Assuming 10-dB, cross-polarization discrimination ratio, case 1 implies an approximately 10 percent reduction in capacity for each polarization. Also assuming that on the average the power of the multipath-reflected signals is 10 do less than the power of the direct signal, case 2 implies an additional 10 percent reduction in capacity for each polarization. Thus, the net improvement in capacity with orthogonal circular polarizations is approximately 1.6. Note that polarization reuse cannot be applied to an SCPC system because the narrowband multipath-reflected signals, which change polarization, appear at full rejected power in the narrowband channel on the opposite polarization and severely interfere with reuse. In summary, both frequency reuse by multi beam satellite antenna and dual polarizations can theoretically improve a CDMA system capacity considerably. For four-beam converge the improvement factor is approximately 2.88 to 3.04.

In this section, some quantitative analysis of CDMA system capacity is carried out. As we have seen, both SCPC and CDMA are preferable access techniques for L/Ku-band MSAT networks. Since the first L/Ku-band satellite will not be launched until 1992 at the latest estimate, mobile satellite communication must be carried at the Ku-band, satellite will not be launched until 1992 at the latest estimate, mobile satellite communication it must be carried out at the Ku-band, which it must share with primary

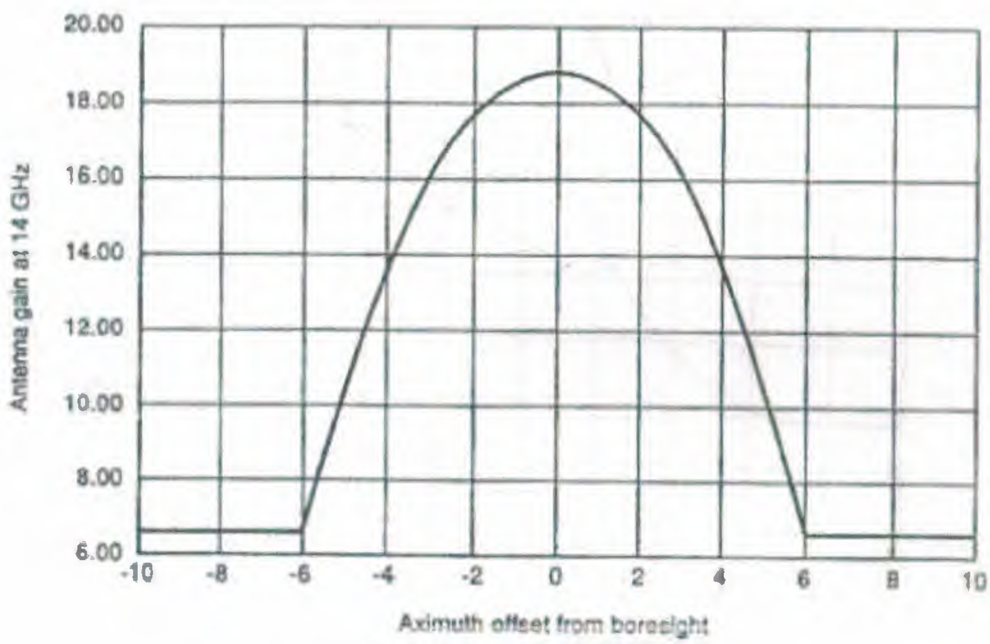


Figure 4.5 Typical gain of a steered antenna at 14 GHz

fixed satellite services such as those provided by VSAT networks. Thus mobile signals must be designed to operate existing systems. This necessitates the use of spread spectrum signals, especially for the inbound (mobile-to-hub) link, to reduce interference to adjacent satellites. Narrowband SCPC systems are unlikely to meet the FCC interference requirement for a large number of mobile terminals. Furthermore, spread spectrum signals can greatly attenuate narrowband signals from adjacent satellites on the outbound (hub-to-mobile) link while SCPC signals cannot. Most current mobile applications at Ku-band involve two-way massaging and position reporting. To reduce interference, these systems use medium-gain steered antenna. Figure 4.5 shows the gain of a steered antenna at 14 GHz. to comply with the FCC interference requirement, the total power spectral density of the inbound link must at least meet the requirement for a VSAT inbound link as shown in Fig.4.6 In the following discussion we will look at the spectral efficiency of a CDMA system which is denned as the ratio of the system bit rate to the spread bandwidth (bps/Hz). The following parameters can be denned.

C = user carrier power (W)
R_b = user bit rate (bps)
$k+1$ = number of simultaneous CDMA users
B_s = CDMA spread bandwidth (Hz)
$N_0/2$ = power spectral density of AWGN (W/Hz)
$J_0/2$ = power spectral density of inter user interference (W/Hz)

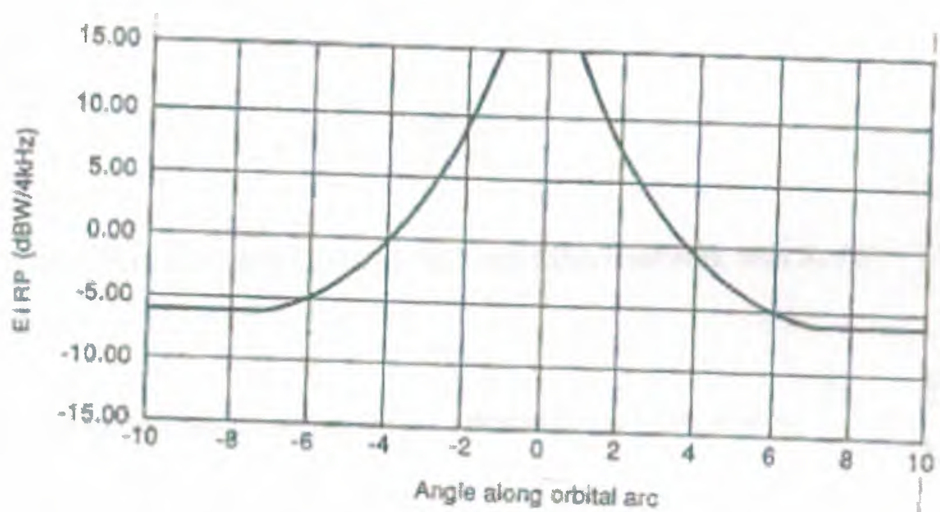


Figure 4.6 The VSAT inbound guideline as required by the FCC.

α = voice activity factor (= 0.4)

β = polarization and multipart reflection interference factor, $\beta > 1$

η = interleaf interference factor, $\eta > 1$

m = multibeam frequency reuse factor, $m > 1$

γB_s = CDMA noise bandwidth (Hz), $\gamma B_s < 1$

The spectral efficiency is thus given by 2m (k+1) R_b / B_s A factor of 2 accounts for two polarizations. Assuming equal user power, we have

$$J_0 = \alpha\beta\eta \frac{kC}{\gamma B_s} \tag{4.1}$$

Note that the power spectral density of inter user interference is reduced by the voice activity factor but is increased by polarization and multipath refection interference and by inter beam interference. Taking into account the AWGN of the channel the system E_b / N_0 after dispreading is

$$\frac{E_b}{N_0} = \frac{E_0}{N_0 + J_0} = \left[\left(\frac{E_0}{N_0}\right)^{-1} + \left(\frac{E_b}{J_0}\right)^{-1}\right]^{-1} \tag{4.2}$$

Thus

$$\frac{kR_b}{B_s} = \frac{\gamma}{\alpha\beta\eta}\left[\left(\frac{E_b}{N_0}\right)^{-1} - \left(\frac{E_b}{N_0}\right)^{-1}\right] \tag{4.3}$$

Hence

$$\frac{2m(k+1)R_b}{B_s} = \frac{2m\gamma}{\sigma\beta\eta}\left[\left(\frac{E_b}{N_0}\right)^{-1} - \left(\frac{E_b}{N_0}\right)^{-1}\right] + \frac{2mR_b}{B_s} \tag{4.4}$$

Example 4.1 Consider a CDMA four-beam MSAT network with R_b / B_s =1/255, β 1,2, η = 1.1, and = 2.

(a) Assume that inter-user interference dominates AWGN, that is, $\frac{E_b}{N_0} << \frac{E_b}{N_0}$, that no voice detectors, orthogonal circular polarizations, or frequency reuse is taken into account, and that γ is 0.8. Then

(a) Assume that inter-user interference dominates AWGN, that is, $\frac{E_b}{N_0} << \frac{E_b}{N_0}$, that no voice detectors, orthogonal circular polarizations, or frequency reuse is taken into account, and that γ is 0.8. Then

$$\frac{(k+1)R_b}{B_s} = 0.8\left(\frac{E_b}{N_0}\right)^{-1} + \frac{1}{255}$$

With convocational encoding and Viterbi soft-decision decoding (rate), constraint length 9, for example), one can obtain a bit error rate of 1 in 10^3 for an e%/Xo of about 4 do with wideband MFSK in a Rician fading channel (assuming the power ratio *K* between the direct component and the multipath diffuse components of the spread spectrum signal is 10 dB). This would yield a spectral efficiency of 0.32 bps/ilz. If *Eb INZ* = 12 dB, the spectral efficiency would be reduced to 0.27 bps/llz. '(b) lf voice activity detectors are employed, that is, (z = 0.4, then the spectral efficiency would be 0.8 bps/1l? (â% *Isz* -: *Eb INVj* and 0.67 bps/1l? with *E6lNz* = 12 dB. (c) If both voice activity detectors and multibeam frequency reuse *IT* = 1.1) are taken into account, then the spectral efficiency as calculated from (13.4) would be 1 .45 bps/1l; (db *l'Rz* <.: *Eb INS))* and 1 .23 bps/1l? With *Eb JND* = 12 dB. (d) If voice detectors, multibeam frequency reuse, and polarization reuse (# = 1 .2) are all employed, then the spectral efficiency is 2.43 bps/Hz (fb/.Vo < *EvINz4* and 2.05 bps/l!z with *Eb INZ* = 12 dB .system can theoretically achieve a high capacity but at the expense of satellite antenna complexity (dual polarization). By comparing this result with those shown in Table 3.3, we note that a CDMA system with only multibeam frequency reuse can achieve spectral efficiency comparable to that of narrowband SCPC. The above example also shows that the spectral efficiency of a CDMA system is also sensitive to the modulation scheme used, as rejected by the factor y. One should choose a modulation scheme such that the CDMA noise bandwidth is approximately the same as the spread bandwidth. Wideband MFSK with direct sequence spreading can provide sufficient uniform whitening of the inter user interference over disproved performance against a long-delay spread multipath, the amplitude variations over a large bandwidth will induce some adverse effects in a nonlinear satellite channel. This will negate some of the above advantages that CDMA enjoys over FDMA. For example, a 1.5-dB increase in the required *Ebl-h* due to amplitude variations and the nonlinear transponder effect reduces the spectral efficiency to 1.33 bps/ll; (assuming *Nz* = 12 dB) instead of 2.05 bps/Hz as in section (d) of the above Example. The choice between CDMA and narrowband SCPC for an MSAT network is likely to be a difficult one which may ultimately be determined by the receiver cost.

4.4 STATISTICS OF MOBILE PROPAGATION

In Sec. 4.1we have outlined the operating environment of a mobile satellite system. In this section, a more detailed discussion is provided. In theory, we may model the received signal by a mobile terminal, as in Fig 4.1, as the sum of diffuse component and tow coherent components, namely, the direct component and the coherently ground-reflected component. The direct component is the line-of –signal between the mobile terminal and the satellite. It is affected by the ionosphere and the troposphere and other natural or human-made obstacles on the earth's surface. For an elevation angle of 20^0 or more, the troposphere attenuation at L-band is normally less than 0.1 dB at can be ignored. The most important ionospheric effect is the Faraday Effect, which causes a rotation of the plane of polarization of the linearly polarized wave. The faraday rotion is inversely to the equare of the frequency. Maximum Faraday rotation is approximately 9^0 at 4 GHz and 4^0 at 6 GHZ .for mobile communications at L-band, the Faraday rotation is about 40^0 at 1.6 GHz, which makes circular polarization mandatory. Other effects that can attenuate the direct component are caused by human-made obstacles, such as overpasses, that can result in complete loss of signal, and shadowing by vegetation, which may cause partial signal fading. The ground-reflected component is a phase coherent wave reflected from the ground in the vicinity of the mobile terminal. A circularly polarized wave will look elliptical upon ground refection. Furthermore, it will also change its sense of polarization at incident angles above the Brewster angle (6 to 27^0). For mobile satellite communications in the United States, the elevation angle is between 20 and 60^0; therefore, the ground-rejected component will be of op-posit sense to the direct component and will be greatly attenuated by the mobile terminal antenna. For all practical purposes, the ground-reflected component is normally ignored. The diffuse component of the received signal represents the multipath reflection from the surrounding terrain. It arrives at an elevation of approximately 0^0 (i.e. , horizontally) to a first-order approximation , whereas the ground reflected component arrives at an elevation-E, where E is the elevation angle of the satellite as seen by the mobile terminal. The amplitude of the diffuse component is statistically characterized by a Rayleigh density function [8.9]. In summary, a satellite signal received by a mobile terminal can be approximated by a direct component (unshadowed or shadowed) and a diffuse component (Rayleigh distributed). If we let 7 be the random variable denoting the amplitude of the diffuse component, then the probability density of V is the Rayleigh density function given by

$$f_v(v)=\frac{2v}{\alpha}e^{-v^{2/\alpha}} \tag{4.5}$$

where v is the value assumed by the random variable 7 and a is the meansquare value of V (power of diffuse component).

When the direct component is unshadowed, the received satellite signal is Rice distributed with the following density function:

$$f_v(v)=\frac{2v}{\alpha}\exp\left[-\left(\frac{v^2}{\alpha}+k\right)\right]I_0\left(\frac{2v}{\sqrt{\alpha}}\sqrt{K}\right) \tag{4.6}$$

where a is the mean-square value of the diffuse component amplitude (power) and K is the ratio of the direct to diffuse power. K is typically in the range of 7 to 15 do for unshadowed mobile satellite signal. When the direct component is shadowed, its amplitude can be characterized

by a lognormal density function given by

$$f_v(v)=\frac{1}{\sqrt{2\pi\alpha v}}\exp\left[-\frac{(\ln v-\mu)^2}{2\alpha^2}\right] \tag{4.7}$$

where Jz is the mean of In v and &2 is the variance of In v. The combination of a shadowed direct component and a diffuse component can be statistically described by the following density function [12]:

$$f_v(v)=\frac{2v}{\sqrt{2\pi}\alpha v}\int_0^{\infty}\frac{1}{x}\exp\left[-\frac{(\ln v-\mu)}{2\alpha^2}-\frac{v^2+x^2}{\alpha}\right]I_0\left(\frac{2vx}{\alpha}\right)dx$$

$$\approx\begin{cases}\dfrac{1}{\sqrt{2\pi}\alpha v}\exp\left[-\dfrac{(\ln v-\mu)^2}{2\alpha^2}\right]\\ \dfrac{2v}{\alpha}\exp\left(\dfrac{-v^2}{\alpha}\right)\end{cases} \tag{4.8}$$

The above density functions are useful in modeling a mobile satellite path. For example, a maxed shadowed/unshadowed mobile path can be statistically characterized by a distribution function as

$$\Pr\{V\le v\}=\int_{-\infty}^{v}fv(v)dv$$

$$=\Pr\{V\le v|unshadwed\}(1-p)+\Pr\{V\le v|shadowed\}p \tag{4.9}$$

where p is the fraction of shadowing encountered by the direct component. The conditional distribution $\Pr\{V\le v|unshadwed\}$ can be obtained from the Rician

CONCLUSION

To design a satellite system for trucking applications was in the past no more difficult than to design the transmission system whose role it was meant to fulfill.

This is now changing rapidly. The evolution of the network, the emergence of very competitive alternatives, and the foreseen evolution of the satellite systems themselves call for a reappraisal of their role in the implementation of the backbone digital network. This reappraisal requires the investigation of many system problems which did not use to show up on the tables of satellite communications engineers. The problems are there. but the benefits that this integration may provide are very attractive. This is why ESA is actively studying every implication of these concepts.

In this project, the need for internetworking of LANS and some of the problems of the existing interconnection facilities were discussed briefly. A satellite based wide area network concept and inter-LAN traffic assessment issues were also discussed.

Given the major evaluation criteria as suggested earlier in the paper, the conclusion is that such a procedure provides a flexible ant efficient space telecommunication network capable of satisfying user requirements. In particular it would provide: minimum transmission delay, user access direct or via ISDN, flexibility in bandwidth-to-service allocation, further extensions.

REFERENCES

[1] Consultative Committee for Space Data Systems (CCSDS), Space Station: Application of CCSDS recommendations for Space Data System Standards to the Space Station Information System Architecture "Green Book".

[2] Telescience Requirements. Interactive Payload operations on Columbus, Report of Telescience User Team (ESTEC), 1987.

[3] Union Internationals des Telecommunications. Compete Consultative International Telegraphique et Telephonique, Tome III-Fascicule III.3, Tome III-Fascicule VIII.3, Tome VIII-Fascicule VIII.5.

[4] Hon vault, ESA, Future integrated Space Data System, AIAA/NASA International Symposium on Space information systems in the Space Station Era, Issue 22-23 1987, Washington, D.C.

[5] Kwei, TU, J.H. Johnson, Space Shuttle Communications and Tracking System, Proceedings of the IEEE, V01.75 No 3, March 1987.

[6] G.A. Beck, The NASA Advanced Communications Technology Satellite (ACTS).

[7] G. Maral, M. Bouquet, Satellite Communications Systems, alley Interference publication.

[8] A.M. Rutowski: The Role of Satellite Radio communication in ISDN. Telecommunications, June 1983.

[9] P. Amadesi, P. Haines, A. Pataeehini: Satellite Networks in the ISDN Era. Proceedings ICDSC-7, Munich. 1986.