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12 Satellite Communication Systems

Ahmad Khanifar

CONTENTS

This chapter portrays the evolutionary path of satellite communication systems into the new millenium. It emphasizes the new services and their effect on what is perceived to be the established technology. System designers will be faced with the enormous task of integrating satellite-based mobile communications with the existing terrestrial network.

The geostationary orbital latency associated with satellite-based communication networks can be an inconvenience on voice transmissions and will be untenable for real-time applications, such as video conferencing, as well as many other standard data protocols. Using satellites in low earth-orbit (LEO) appears to be the obvious remedy to this problem, as a typical LEO distance is an order of magnitude closer to earth than the geostationary orbit.

Just as networks on the ground have evolved from centralised systems built around a single mainframe computer to distributed networks of interconnected personal computers, space-based satellite networks are evolving from centralised networks relying on a single geostationary satellite to distributed networks of interconnected LEO satellites. With a distributed network, reliability can be built into the network rather than into the individual unit. In such a distributed architecture, the dynamic routing and the robust scalability should be comparable to the Internet, while adding the benefits of real-time capability and location-insensitive access.

The fixed satellite services (FSS) arena will continue to provide global voice communications as well as witness a widespread incorporation of business service applications. The technology envisioned to fulfill the forthcoming service demands is very small aperture antennas (VSAT).

The choice of orbits and the access schemes are the two areas that have a decisive impact on the performance of systems discussed in the preceding section. These systems are discussed in greater detail in the following pages.

12.1 INTRODUCTION

Over the next ten years, space communications will play an integral role in the development of a global information infrastructure, allowing video, audio, and data to be distributed irrespective of borders and restrictions. Satellites are the key element to intercontinental traffic, as well as to direct user connection, bypassing terrestrial means. The ever-growing need to provide higher capacity at lower cost is the main driving force in this field.

It has been nearly 50 years since trans-horizon communication via satellites was proposed as a theoretical possibility. Since then, the science fiction-like idea has come a long way to manifest itself as an established technology. Despite this tremendous progress, 1998 will be remembered as another milestone in the evolutionary path of this industry. It was a year when a number of systems offering seamless worldwide satellite telecommunication using a portable handset were commissioned. Before we discuss these complex systems and other counterparts, we will take a look at where it all started.

The concept of global telecommunication coverage using satellites was first suggested in an article in *Wireless World* by science fiction author Arthur C. Clark.[1]

> All these problems can be solved by the use of a chain of space-stations with an orbital period of 24 hours, which would require them to be at a distance of 42,000 Km from the centre of the earth. There are a number of possible arrangements for such a chain but that shown figure (1) is the simplest. The stations would lie in the earth's equatorial plane and would thus always remain fixed in the same spots in the sky, from the point of view of terrestrial observers. Unlike all other heavenly bodies they would never rise or set. This would greatly simplify the use of directive receivers installed on the earth.

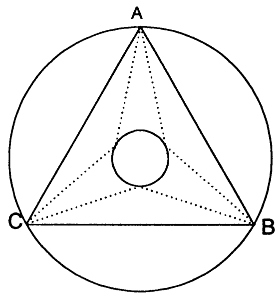

Figure 12.1 Arthur Clark's view of a Global Communications System

12.2 ORBITS

For the telecommunication coverage using a space vehicle, there are basically three orbital options: equatorial, polar, and inclined. Arthur Clark's vision of satellite communications was based on the circular equatorial orbit, but Figure 12.2 shows two more options, the circular polar orbit and the elliptically inclined orbit. There are merits for each in terms of earth coverage and the intended services.

12.2.1 Circular Equatorial Orbit (Geostationary)

A satellite in a circular orbit at 35,800 km has a period of 24 hours and appears stationary over a fixed point on the earth's surface, hence, it is referred to as geostationary. Such a satellite is visible from one third of the earth surface. Examples of telecommunication services using these orbits are the INTELSAT* and Eutelsat** satellites. Figure 12.3 shows a typical coverage area for different geostationary satellites.

The geostationary operation requires in-orbit stabilisation because the earth is not a perfect sphere and because of other perturbations, such as the earth's tidal

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* http://www.intelsat.int/

** http://www.eutelsat.com/home.html

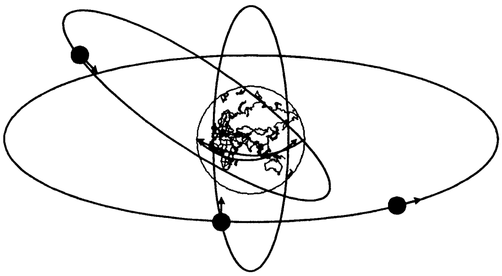

Figure 12.2 Three basic orbits

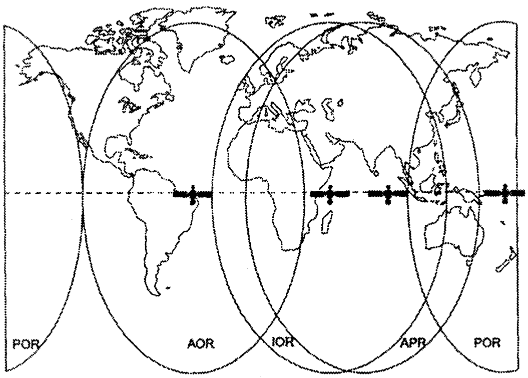

Figure 12.3 INTELSAT Global Network and Coverage Areas

motion and the gravitational forces of the moon and sun. An orbit that is inclined towards the equatorial plane produces a sinusoidal variation in the longitude. This is seen from earth as a motion around an ellipse with the period of 24 hours. An incorrect orbital velocity results in inaccurate altitude and drifts to the east or west. The east-west position of a satellite has to be corrected continuously over its operational lifetime, which typically is 10–15 years. Positioning is regularly corrected to within ±0.1°. The north-south positioning poses a greater demand on fuel reserves; to save fuel some satellite operators, including INTELSAT, allow their satellites to drift, resulting in an inclination angle of up to 3°. This, in turn, can typically extend the operational life of the satellite by as many as 3 years.

12.2.2 Circular Polar Orbit

The circular polar orbit is the only orbit plane that can provide full global coverage, including the polar regions, by a single satellite. For nearly all telecommunication systems where the instantaneous transfer of information is required, full global connectivity can be achieved with a series of satellites in circular polar orbit phased in an appropriate order. Until recently, this type of orbit has been used primarily for military, navigation, or meteorologic applications, but in the past few years a number of polar orbiter systems have been proposed and are being deployed for telecommunication applications. The Iridium constellation (to be discussed later) is a prime example and is due to become operational shortly after the time of this writing.

12.2.3 Elliptically Inclined Orbit

The elliptically inclined orbit offers unique properties that have been used by some communication satellite systems, notably a former Soviet Union domestic system called Molniya. Inclined orbits can provide visibility to higher northern and southern latitudes, but they require the earth station to track the satellite continuously. In addition, inclined orbits usually require at least three satellites, suitably phased to be spaced along the orbit, to provide continuity of service. The former USSR preferred to put its communication satellites into an eccentric orbit with an inclination of about 63° and a period of 12 hours. The main reason for this was geographical. Because all of the Soviet Union land area is in the northern hemisphere, extending from mid-latitude to the poles, and all of its launch sites are at relatively high northern latitudes, it takes considerably less energy to put a satellite into inclined orbit than into an equatorial one. A typical Molniya orbit may have an eccentricity of about 7, making an apogee of about 40,000 km and a perigee of about 500 km so that on alternate orbits, the apogee is above the former Soviet Union states. Because the height at apogee is close to a geosynchronous altitude, the satellite moves relatively slowly through the sky, spending a large fraction of its orbital period in this part of the sky. A typical Molniya satellite spends up to about 8 hours over the eastern part of the former Soviet Union republics.

The problem with the highly eccentric orbit is that the perigee is at a relatively low altitude. Consequently the drag due to the earth's atmosphere slows the satellite, thus reducing the height of the perigee. The satellite's lifetime is therefore reduced, and the spacecraft re-enters the atmosphere and burns up. As a result, over the years the Soviet Union has had to launch in excess of 100 Molniya satellites to maintain coverage. This type of orbit will be used in upcoming satellite systems such as Archimedes, a pan-European satellite broadcast system.

12.3 FREQUENCY

A communication satellite may be considered a distant repeater whose function is to collect the minute impinging electromagnetic field and retransmit the amplified frequency-converted carriers in the downlink towards the intended parts of the earth. With limited output power and a path loss on the order of 200 dB, the signal levels from the satellite are expected to be very weak at the ground receivers, hence any natural phenomena to facilitate the reception must be exploited.

Figure 12.4 shows that sky noise is a minimum in the 2–10 GHz range. Consequently this band is favoured for satellite communications. As demand for capacity increased, higher frequencies of 14 GHz and 11/12 GHz (Ku-band) have also been utilised. Table 12.1 summarises the frequency allocations for various civilian applications.

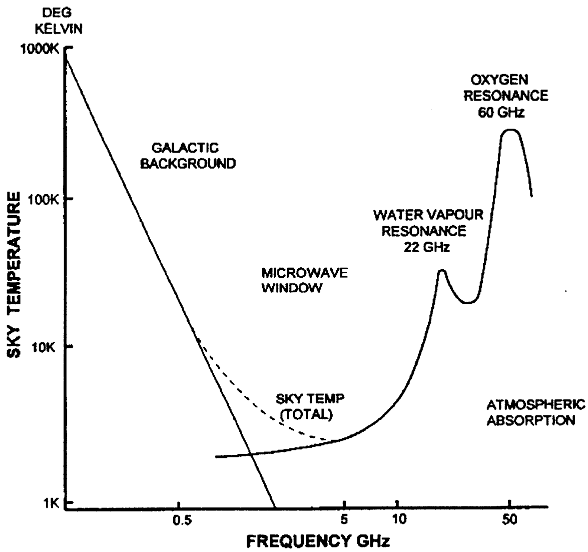

Figure 12.4 Sky-Noise and Frequency Bands

TABLE 12.1
Communications Satellite Frequency Allocations

Application	Downlink frequency (GHz)	Uplink Frequency (GHz)
	Fixed Services	
C-band (Commercial)	3.7–4.2	5.925–6.425
X-band (Military)	7.25–7.75	7.9–8.4
K-band (Commercial) Domestic	11.7–12.2	14–14.5
International	10.95–11.2	27.5–31
	Mobile Services	
Maritime	1.535–1.5425	1.635–f
Aeronautical	1.5435–1.58888	1.645–1.660
	Broadcast Services	
	2.5–2.535	11.7–12.75
	Telemetry, Tracking and Command	
	0.137–.138, .401–.402	1.525–1.54

12.4 MULTIPLE ACCESS

Multiple access is the method by which a number of ground stations may use a repeater (in this case a satellite) simultaneously. Frequency division multiple access (FDMA) and time division multiple access (TDMA) are widely used in commercial satellite applications. Code division multiple access (CDMA) has been used in military applications in the past because of its innate immunity to jamming, but, in recent years, it is being considered for both satellite and terrestrial mobile applications.

12.4.1 Frequency Division Multiple Access (FDMA)

FDM/FM/FDMA stands for frequency division multiplex (of base-band signals), frequency modulation (of carriers), and frequency division multiple access (in RF band). The transponder can be shared among several earth stations, which has been used in satellite telecommunication networks such as the INTELSAT series. Typically, the available bandwidth is in the order of 500 MHz shared between several transponders (nominally 12×36 MHz transponders). Each earth station is assigned a segment of this bandwidth, with sufficient guard band allocated between segments to ensure that one user will not interfere with an adjoining user. In C-band, the uplink band of frequencies transmitted to the satellite is 5925–6425 MHz; thus, a 6000 MHz carrier received by the satellite is retransmitted to the earth at 3775 MHz. The local oscillator (L.O.) frequency onboard the satellite in this case uses a frequency of 2225 MHz to down-convert the uplink frequency.

In such a network, although an earth station may transmit only one carrier to the satellite, it must be equipped to receive at least one carrier from each location with which it wishes to communicate. Some earth stations intercommunicate with dozens or more distant stations, so they require an equal number of receiver equipment. On the uplink, depending on the required capacity, they may transmit to all stations using only a single carrier. FDMA was widely used in the earlier INTELSAT network, and its main attractive feature is the simplicity; however, FDMA does not permit demand assignment, and it is not compatible with the widely used digital switching and multiplexing infrastructure.

12.4.1.1 SPADE

The SPADE (single-channel per carrier PCM multiple access demand assignment equipment) system was conceived to address the lack of flexibility in the FDMA networks. The SPADE system is capable of the following:

- providing efficient service to light traffic links
- handling overflow traffic from medium capacity pre-assigned links
- allowing the establishment of a communications link from any earth station to any other earth station within the same zone of command
- utilizing the satellite capacity efficiently by assigning circuits individually
- making optimum use of existing earth station equipment

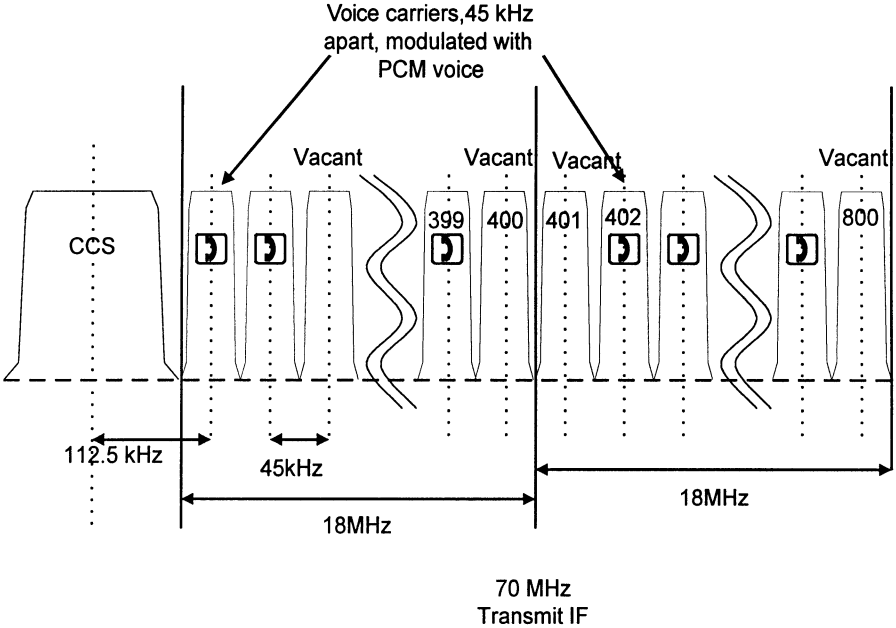

Figure 12.5 SPADE frequency plan

Figure 12.5 shows the frequency allocations of SPADE. At the center of the transponder bandwidth, a pilot frequency is used as a reference in receiving stations for automatic frequency control (AFC). On either side of the pilot, there are 400 carrier channels spaced 45 kHz apart, with a bandwidth of 45 kHz. At the extreme left a carrier, with a wider allocated bandwidth than the others, is used to carry the common signaling channel at 128,000 b/s. This channel is used to control the allocation of voice carriers to the earth stations.

The 36 MHz transponder frequency plan shown in Figure 12.5 is a pool of 397 usable two-way voice channels. A free channel can be taken by any earth station on demand. The 128 kb/s signaling channel is shared by all earth stations and uses TDMA. Each earth station is assigned a 1-ms slot every 50 ms, permitting it to transmit a burst of 128 bits.

In general, more information can be transmitted via a transponder if only one carrier is used. The more carriers to share a transponder, the lower the overall capacity.

As the number of carriers increases, more guard bands are needed. Furthermore, with more carriers, the level intermodulation noise is greater, because carriers tend to modulate one another caused by the non-linear characteristics of the travelling wave tube amplifiers (TWTAs), resulting in reduced output, as shown in Table 12.2.

Despite the outline presented in the above table, in certain applications, such as thin routes, or to accommodate traffic spillover, SPADE offers a higher efficiency than the fixed systems. This efficiency is because there is one voice

TABLE 12.2
FDMA System Throughput

No. of carrier / transponder	Carrier band MHz	No. of channels / Carrier	No. of channels / transponder
1	36	900	900
4	3 of 10 MHz	132	456
–	1 of 5 MHz	60	–
7	5	60	420
14	2.5	24	336

channel/carrier, and the carrier is switched off when no one is speaking (voice-activated channel). So, even when the channel is occupied, the carriers can be switched off half the time. In fixed systems, the carriers cannot be switched off when there is speech inactivity, because they are modulated by master groups or other blocks of speech channels.

12.4.2 Time Division Multiple Access (TDMA)

Time division multiple access (TDMA) circumvents many problems associated with the FDMA, and, because of its maturity and compatibility with digital switching, it is the most widely used access system in satellite and terrestrial mobile systems. Consequently, it is discussed in detail here.

In the TDMA scheme, each earth station is allowed to transmit a high-speed burst of bits for a brief period of time. The transmission time of the bursts are controlled so that no two bursts overlap. For the period of the burst, the full transponder bandwidth is available.

In its simplest form, each station is allocated in turn an equal length burst. To be efficient, however, stations must be able to vary their transmission rate, so either the bursts will be of variable length or the scheme must permit some stations to transmit more often than others. TDMA also avoids the intermodulation problem by using a single carrier, and it is highly efficient in using satellite power. The uplink power amplifiers can be operated at full power which in turn means a more efficient use of uplink resources.

The input to the transponder thus consists of a set of bursts originating from a number of earth stations. This set is called the TDMA frame. There are two reference bursts (RB1 and RB2), traffic bursts, and guard time between bursts. The TDMA frame is the period between two reference bursts. Figure 12.6 shows this arrangement.

Every earth station receives the entire bit stream and extracts the bits addressed to it, therefore the entire system needs to be synchronized. Maintaining synchronization is a complex issue because several factors contribute to the need for frequent resynchronization in a TDMA-based satellite communication network.

The propagation channels to different earth stations are of different path lengths, so there is a variation in propagation times. Moreover, in each path the delay is not

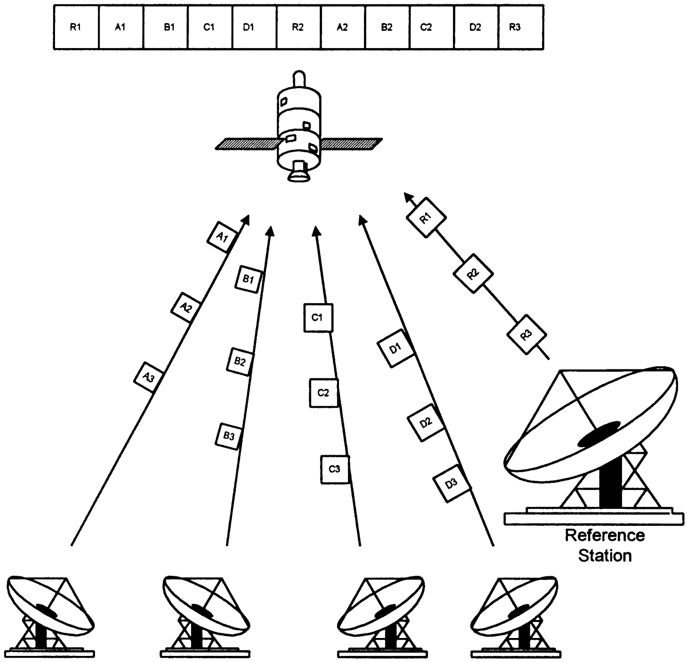

Figure 12.6 TDMA system using a reference station for burst synchronization

constant, as satellites tend to drift from their orbital station. In addition, the sun and moon create an oscillation in the satellite position (tidal oscillation) that is superimposed onto the long term drift. To circumvent these problems, each burst carries its own means of synchronization so that it can be transmitted and received in isolation. A burst starts with a synchronization pattern that permits the receiving modem to carry out the carrier and clock recovery.

12.4.2.1 Reference Burst

There are normally two reference bursts, RB1 (primary reference burst) and RB2 (secondary reference burst) which is added for reliability. The TDMA traffic stations take their timing reference from the primary reference burst.

12.4.2.2 Traffic Burst

Each station may transmit one or more traffic bursts / TDMA frame and may position them in the frame according to a burst time plan that coordinates traffic between stations. The length of the traffic bursts depends on the information it carries and can be changed if required. The location of the burst in the frame is referenced to the primary reference burst's time of occurrence. By detecting the primary reference burst, a traffic station can locate and extract the traffic burst intended for it. It can also derive the exact transmit timing of its own bursts.

12.4.2.3 Guard Time

A short guard time is used between bursts originating from several stations that access a common transponder to ensure that bursts never overlap. The guard time must be long enough to allow for transmission timing inaccuracies and the range variation of the satellite distance.

The TDMA frame length is normally selected to be in the 0.75–20 ms range, and it is usually a multiple of 0.125 ms, which is the sampling period of PCM (8 kHz). The frame length is chosen at the outset and remains constant for a TDMA system.

The structure of the traffic and reference bursts is shown in the Figure 12.7. The traffic burst contains the actual information bits and is preceded by the preamble. The reference burst contains only the preamble and no traffic data. The preamble normally consists of the carrier and clock recovery sequence (CCR), the unique word (UW), and the signaling channel.

12.4.2.4 Carrier and Clock Recovery Sequence

Each burst begins with a sequence of bits enabling the earth station demodulator to recover the carrier phase and regenerate the timing clock. The number of bits in the CCR depends on the carrier to noise ratio (C/N) and the acquisition range (carrier frequency uncertainty). Therefore, a high C/N and a small acquisition range require a short CCR and vice versa; typically, 300 to 400 bits for a120 Mbps TDMA system.

12.4.2.5 Unique Word

There are two unique words in TDMA bursts:

- the unique word that follows the CCR bits in the RB and is used to provide receive-frame timing that allows a station to locate the position of a TB in the frame.
- the unique word in the traffic burst that marks the time of occurrence of the traffic burst and provides receive-burst timing that allows the station to extract only the wanted sub-bursts within the traffic bursts.

The unique word is a sequence of ones and zeros selected to have good correlation properties to enhance its detection. At the demodulator, the unique word enters the unique word detector, which is a digital correlator (as discussed in Appendix A), where it is correlated with a strict pattern of itself. The maximum number of errors allowed in the unique word detection is called detection threshold. The unique word detection occurs at the instant of reception of the last bit of the UW. It marks receive-frame timing if the unique word belongs to the primary burst, or it marks receive-traffic burst timing if the unique word belongs to the traffic burst.

The position of every burst in the frame is defined with respect to receive-frame timing, and the position of every sub-burst in the traffic burst is defined with respect to receive-burst timing. Clearly, the accurate detection of the unique word is of utmost importance.

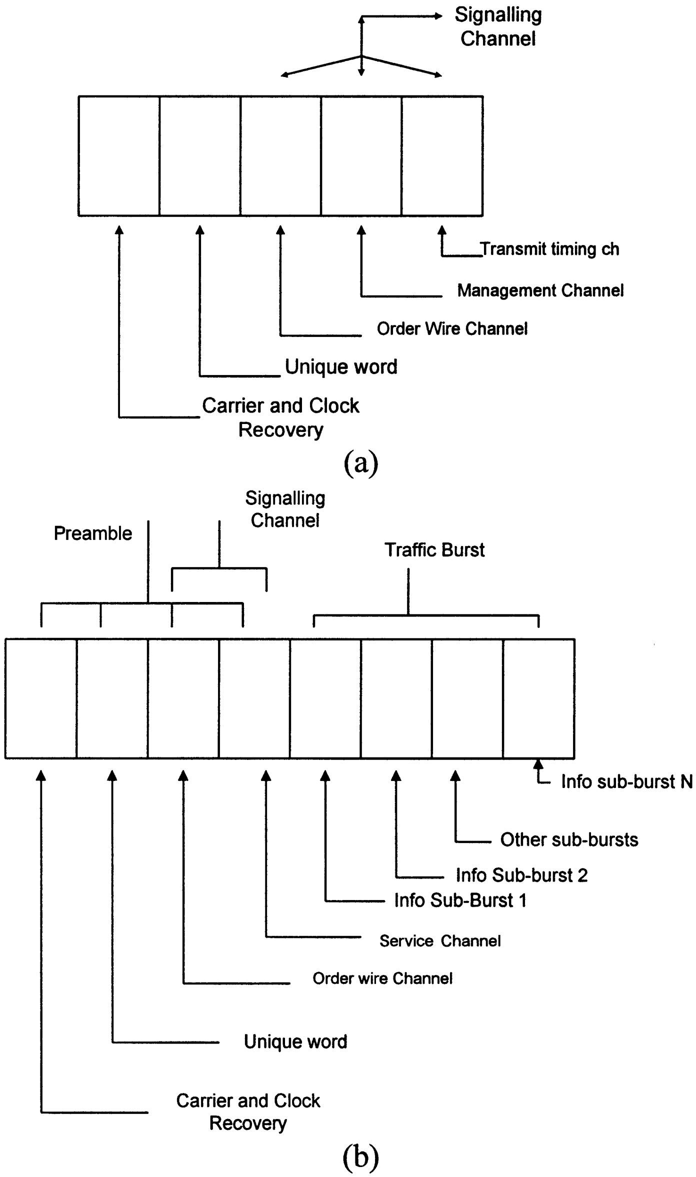

Figure 12.7 TDMA burst structure, (a) reference burst, (b) traffic burst

12.4.2.6 Traffic Data

The traffic data follows the preamble in a burst. The traffic data sub-burst is further subdivided into time slots addressed to the individual destination stations. The length of the traffic sub-burst depends on the type of services. The greater the fraction of frame time that is given over to traffic, the higher the efficiency.

12.4.2.7 Frame Efficiency

The TDMA efficiency η is defined as

$$h = 1 + \frac{T_X}{T_f}$$

where T_X is the overhead portion of the frame. For n bursts in the frame,

$$T_x = n \cdot T_g + \sum_{i=0}^{n} T_{p,i}$$

where T_g is the guard time and $T_{n,i}$ = preamble of burst i.

Therefore, η can be improved by increasing the frame length. However, this increase in turn increases the size of buffer memory required. Furthermore, the frame length must be kept small compared with the maximum roundtrip delay of 274 ms (maximum path distance at 5° antenna elevation angle) to avoid adding a significant delay to the transmission of voice traffic. The frame length for voice traffic is normally selected as less than 20 ms.

12.4.2.8 TDMA Super-frame Structure

The burst position control is carried out by the reference station using the transmit timing channel, while coordination of traffic is carried out by the reference station's burst using the management channel. This, in turn, means that to control n stations in the network, there will be n messages in the transmit timing channel and n messages in the management channel of the reference burst. Furthermore, to improve the reliability of this operation, these control messages are sent using the 8:1 redundancy-coding algorithm (repeated 8 times). This procedure further reduces the frame efficiency. The same applies to the service channel of the traffic bursts.

To reduce the length of the preamble of the reference and traffic bursts, the reference station can send one message to each station per frame instead of n messages to the n stations per frame. To address n stations, therefore, the process takes n frames. In this way, n frames can be put into one group, called a super-frame.

12.4.2.9 Advanced TDMA

In multiple beam satellites, the antenna beam interconnections are normally fixed in the basic TDMA systems discussed so far. However, it is possible to increase the system capacity if a number of spot beam antennas are employed to provide spatial division, hence reusing the same frequency band. Narrow beam antennas provide high gain and power saving in the uplink and downlink channels. Satellite-switched TDMA (SS-TDMA) will then be required for the interconnection of upbeams with the downbeams. This is accomplished by dynamic switching using a microwave switch matrix onboard the satellite. During a SS-TDMA frame, the satellite switch is controlled by a sequence of states of various duration. The duration of a given

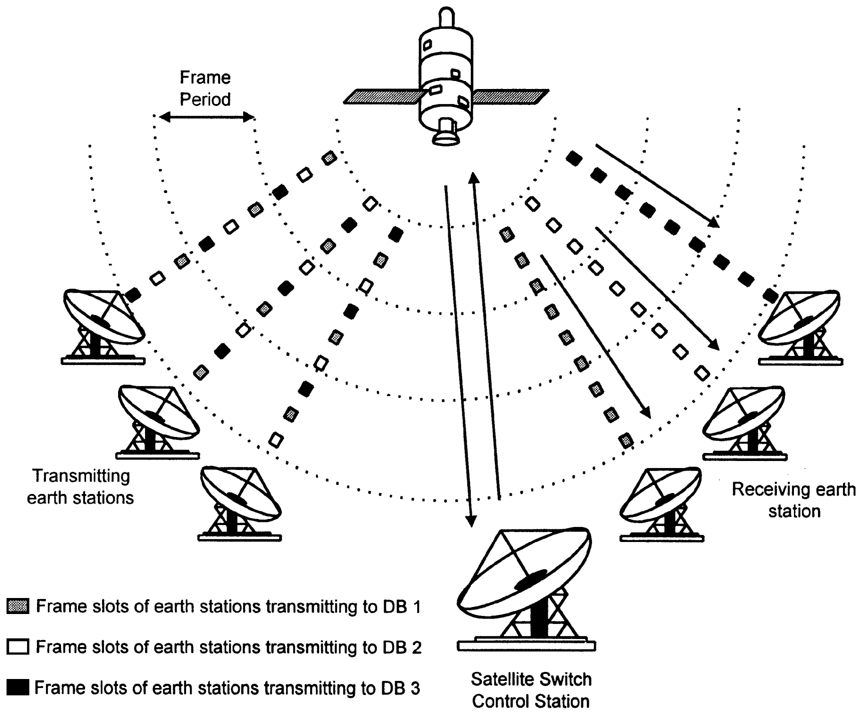

Figure 12.8 Satellite-switched TDMA

switch state is selected to accommodate a segment of the total traffic between the two earth stations. This arrangement is shown in Figure 12.8.

INTELSAT VI series of satellites have a number of transponders that are interconnectable using either static switch matrices or a subsystem which provides SS-TDMA. Two SS-TDMA networks are in operation, one in the Atlantic Ocean Region (AOR) and one in the Indian Ocean Region (IOR). The C-band frequencies are reused six times through two hemispherical beams and four zone beams using dual circular polarization and spatial isolation. The Ku-band frequencies are reused twice by the two spatially isolated spot beams, using orthogonal linear polarization.

Another advanced feature of SS-TDMA system is beam hopping, which is capable of offering satellite services to sparsely populated areas. Beam hopping is implemented by using phase array antennas onboard the satellite. The antenna steers its beam towards a particular spot for a new TDMA burst and dwells for the duration of the burst and the guard band. The information in the burst is stored in the uplink memory, then the beam is steered in the direction of the second burst, and the second burst is stored, and so on. The stored uplink bursts are demodulated and reconfigured for downlink transmission. A combination of SS-TDMA and beam-hopping TDMA allows the flexibility and provision of service for low, medium, and high bit rate requirements applicable to different traffic requirements.

12.4.3 CDMA

Unlike the FDMA or TDMA systems that have been widely used in fixed satellite services so far, the interest in a commercial application of Code Division Multiple Access (CDMA) started with the mobile satellite systems. In FDMA and TDMA, the user terminal discrimination is achieved through frequency or time separation of the relevant channel, whereas in CDMA the system relies on the signature sequence assigned to the individual user (terminal) to ensure signal separatability. This is particularly suitable for mobile satellite services. The individual user signature is used to spread the spectrum of the modulated carrier in a direct-sequence spread-spectrum (DS-SS) arrangement. The user signals are modulated with approximately orthogonal signature sequences. The modulation scheme used in the DS-CDMA is normally binary phase-shift keying (BPSK) or quaternary phase-shift keying (QPSK). Since the signature signal usually is at a much higher rate than the transmitted data, the transmission bandwidth is much higher. The spread-spectrum user signals are simultaneously transmitted using the same frequency band. In the receiving end, the composite incoming signal is correlated with the exact signature sequences of each user, thus reconstructing the information signals of the individual user. However, the residual correlation of the signatures produces interference.

The noise power in a correlation receiver can be calculated from Lutz[6]:

$$N_{tot} = N_0 + \alpha(1+k)\frac{(N_u - 1)E_b}{G}$$

where N_u is the number of active users in the satellite beam, G is the chip rate of the spread sequence. Further assumptions are Gaussian channels, no shadowing, asynchronous user signals, and discontinuous transmission (i.e., during speech pauses the signal transmission is interrupted). N_0 represents thermal noise and the second term describes the interference caused by other users, the signal of which is received with E_b. The interference is inversely proportional to G, the processing gain with typical values of 100 to 1000. α is speech activity of users and is normally taken as 0.5. The factor $(1 + k)$ accounts for the additional interference produced by users in the neighbouring cells, with k defined as the other cells' interference power divided by the user's cell interference power. In terrestrial CDMA, k is taken as 0.44. However, in satellite mobile systems, k may vary between 0.75 to 1.25 based on the type of orbit and the antenna beam contours. The CDMA links are normally interference-limited, i.e., the term N_0 can be ignored and the number of user per beam can be approximated to

$$N_u \approx \frac{G}{\alpha(1+k)} \cdot \frac{1}{\left(\frac{E_b}{N}\right)_{req}}$$

The term $(E_b/N)_{req}$ designates the required signal-to-noise for the link. Assuming $(E_b/N)_{req} = 5$ dB and a Gaussian channel, for BER of 10^{-6}, $\alpha = 0.5$ and $k = 1.2$, the number of user is given as

$$N_u \approx 0.29G = 0.29\frac{B_s}{Rb}$$

A similar treatment of a TDMA system with a bandwidth of B_s and a user bit rate of R_b using M-level modulation results as in Lutz[6]:

$$N_u = \frac{1}{C} \cdot \frac{B_s}{R_b} \cdot \frac{IdM}{1 + \frac{H+G}{I+P}IdM}$$

where H is the burst header, I and P are the user information and parity, and G is the guard time. Assuming a four-cell cluster, $P + I = 1000$ bits, $H = 100$ symbols, $G = 30$ symbols, and $M = 2$, the number of user within a cell becomes

$$N_u = 0.22\frac{B_s}{R_b}$$

A comparison of the above two systems suggests that CDMA may be more efficient than TDMA. However, the CDMA efficiency may not be fully achieved because of imperfect power control.

12.4.4 Satellite Packet Communications

The access systems introduced so far are designed primarily for voice and data traffic with fixed or demand assignment. These systems use multiple access protocols such as FDMA, TDMA, or CDMA, and they are based on circuit-switched networks, which are efficient for voice/data transmission when messages are long in comparison to the time required to establish the link. Data traffic is somewhat different from voice traffic as its message length ranges from a few characters to hundreds of megabytes. This characteristic is referred to as bursty and results in a large peak-to-average ratio. Therefore, if fixed capacity allocation is used, each user must be assigned enough capacity to meet the peak transmission rate. Consequently, the resulting channel utilization will be low. To circumvent this problem, the data is formatted into fixed length packets, which are routed through shared communication resources by a sequence of node switches. Packet switching does not store packets for a prolonged period of time, and packets are discarded if difficulty arises in delivery, in which case they have to be retransmitted. As an implementation example, a shared satellite global beam offers full connectivity between users, eliminating the routing and switching. Each user can listen to its own message and receive automatic acknowledgement. This allows the implementation of a special multiple access protocol for the dynamic assignment of the satellite capacity.

12.4.4.1 Statistical Channels

Sharing of a common communication medium requires protocols governing the behavior of the group of users. Protocols enable the users to gain access to the central resource (transponder capacity). An example is the Aloha protocol, a random access scheme pioneered at the University of Hawaii for interconnection of terminals and computers via radio and satellite. Aloha has several refinements:

- Pure Aloha *(P-Aloha)*
- Slotted Aloha *(S-Aloha)*
- Aloha with Capture Effect *(C-Aloha)*
- Aloha with Capacity Reservation *(R-Aloha)*

P-Aloha — The P-Aloha scheme is simple and needs no sophisticated hardware. In essence, the users address the message packets in a TDMA frame in a purely random fashion. As a result of this unrestricted access freedom, message packets do collide and need to be retransmitted, reducing the throughput and transmission efficiency. Figure 12.9 shows the arrangement for the P-Aloha multiple access.

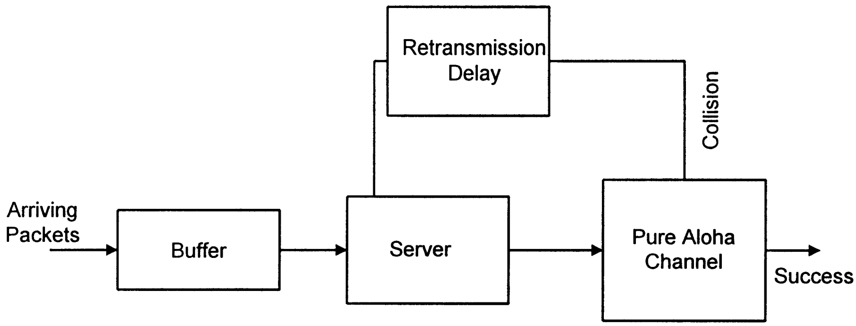

Figure 12.9 The Aloha multiple access protocol

S-Aloha — The S-Aloha technique decreases the probability of collision between packets by requiring that users transmit only at the beginning of discrete time intervals (slots). The S-Aloha channel has two disadvantages: the potential complexity of the synchronization and the limited packet length. Also, for users with small traffic load, the time between the end of a user transmission and the beginning of the next slot is wasted. The maximum throughput of S-Aloha is twice that of the P-Aloha.

C-Aloha — Improvement in capacity can be achieved if each user transmits at slightly different levels. If two packets with different signal levels collide, the stronger of the two is likely to capture the receiver and be transmitted without an error. The C-Aloha can yield a three-fold increase in capacity over P-Aloha. The performance of such a technique in satellite transponders may suffer from transponder nonlinearities.

R-Aloha — In a system where there are a few large and frequent users, it is possible to dedicate a portion of the channel on a fixed-assignment basis, leaving the remaining portion of the channel open to contention among many sporadic users. For example, if half of the channel is dedicated to a fixed-assignment basis of 80% utilization and the remaining half at 36.8 efficiency on S-Aloha mode, the overall channel efficiency becomes 58.4%. There are a variety of reservation protocols in use.

12.4.4.2 Very Small Aperture Terminals (VSAT)

The VSAT is the physical layer realization of an access system described in the preceding section. The system enables a large number of remote microterminals to have communication access to a central HUB, share a computing system, have access to a common database, and exchange e-mail, voice, and fax services. The network comprising a central HUB and remote terminals is characterized by its star topology. The network architecture is shown in Figure 12.10. The satellite links can be implemented in C-band, but they are mostly implemented in Ku band because of the wide bandwidth availability.

At the central HUB site, the inbound satellite links are typically at 56 Kb/s and the outbound link is typically at 256 Kb/s. The outbound carrier is different from the inbound link in two fundamental ways: it is at higher rate, allowing for multiple VSATs to receive a common outbound channel, and the outbound carrier uses continuous modulation enabling the VSAT terminals to use a low cost demodulator.

Direct VSAT-to-VSAT communication is not usually supported; however, VSAT-to-VSAT communications can be supported using a two–hop technique (VSAT-to-HUB-to-VSAT).

The VSAT terminals send data in packet form through a random access/time division multiple access (RA/TDMA) satellite channel with transmission delay of τ seconds. After processing, the host acknowledges the successful reception of the packet data via a broadcast TDM channel. A failure due to packet error or packet collision requires retransmission. This extra delay due to the retransmission loop introduces significant complexity in system design. The TDM frame from the HUB-station can be a combination of variable length data messages multiplexed at the HUB-site and broadcast to all remote stations in the network. A synchronization pattern is sent every frame to synchronize remote stations in the network. The synchronization pattern provides the start of the TDMA frames to all terminals.

The TDM frame structure is shown in Figure 12.11. Each message contains an address field that identifies the microstation for which the message is intended. All microstations receive the TDM stream and filter out the messages not intended for their own use. By using an appropriate addressing scheme, it is possible to broadcast a single message to all stations or to a specific station.

For inbound transmission from the microstations to the HUB, the TDMA carriers can be a S-Aloha shared by many microstations. The timing on the TDMA channel is divided into a series of contiguous frames and slots. Each frame is

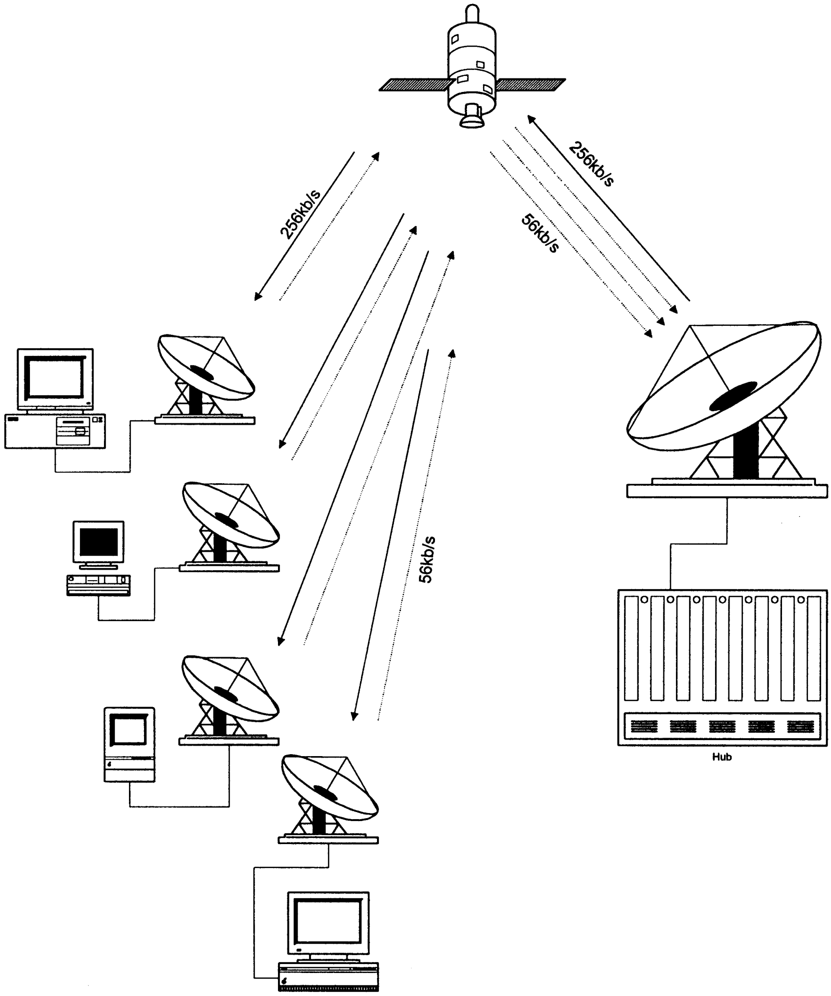

Figure 12.10 VSAT network configuration

comprised of N slots as shown in Figure 12.12. Remote terminals may transmit packets only within the slots, and a packet can never cross the slot boundaries. The size of a packet may vary, but the maximum size of a packet can never be greater than the size of slot. Packets are transmitted as bursts. The size of a slot and the number of slots in the frame will depend on the type of application. The slot period is software selectable.

The RA/TDMA channel is a contention channel and needs to be synchronized to the start of each frame (SOF) and the start of each slot instant. Each slot on the TDMA channel may be either a random access TDMA, or a demand assigned (DA/TDMA) slot. A RA/TDMA slot is a contention slot and is available to all

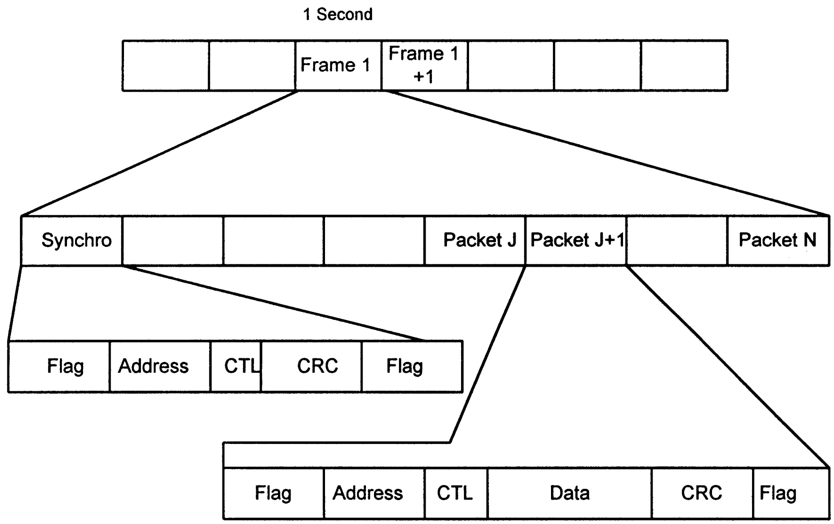

Figure 12.11 TDM frame structure

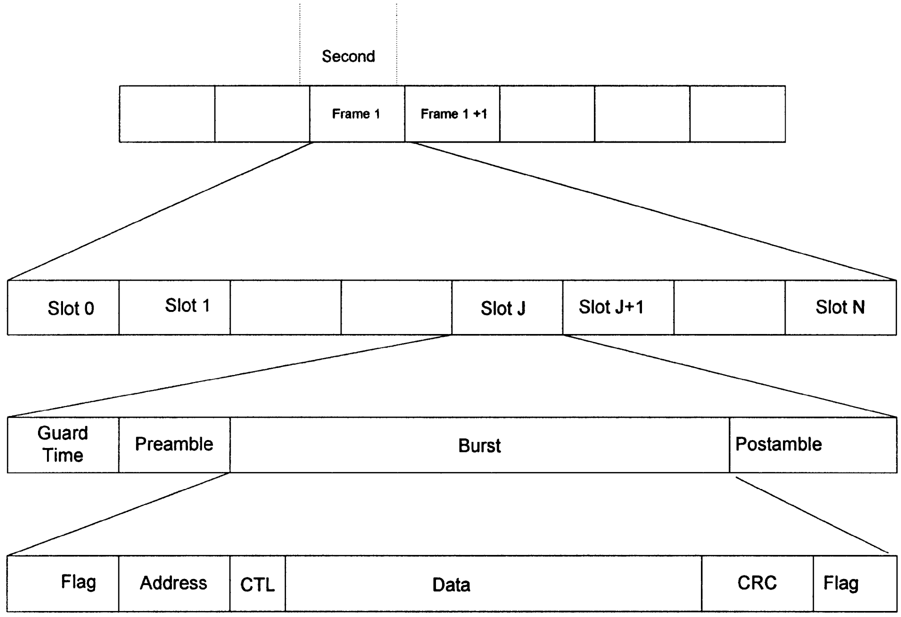

Figure 12.12 TDMA frame description

microstations for transmission of their packet. AD/TDMA slot is a slot dedicated to a single remote station. Normally there is no contention on DA/TDMA slots. The HUB broadcasts a slot map that defines the RA/TDMA and the DA/TDMA slots in each TDMA frame.

All microstations must receive this map and may transmit in the permitted slots.

The VSAT terminal is characterized by its low cost and small sized antenna, normally 0.6 to 1.8 meters in diameter for Ku band systems. Other characteristics include ease of installation and maintenance.

12.5 MOBILE SATELLITE COMMUNICATIONS

Fixed-satellite services (FSS) have been the primary application of communication satellites since commercial operation was started by INTELSAT. More recently, FSS has been used for the implementation of large numbers of VSAT networks throughout the globe. However, since 1980, the interest in the use of satellite communications for mobile applications has grown dramatically. The growing interest in mobile satellite systems (MSS) has been driven by the same factors that led to changes in the entire telecommunications industry: availability of the technology and deregulation. The main features of MSS include the following:

- large service area and limited capacity
- global coverage
- appropriate for rural service provision
- appropriate for layered architectures
- complementary to terrestrial networks

MSS has proved to be the largest new growth area in satellite communications. Table 12.3 shows some representative MSS that are in operation or will be in operation over the next 5 years.

TABLE 12.3
The Satellite-Mobile Systems

Name	Organisation	Features	Start of Service
ICO	Inmarsat	MEO	–
Iridium	Motorola	66 LEO Sat	1998
GlobalStar	Loral/Qualcomm	48 LEO Sat	1999
Teledesic	Motorola	288 LEO Sat	2003

The current generation of MSS have geosynchronous satellites with ground mobile terminals varying in size from portable briefcase-sized transceivers to a standard 'A' INMARSAT station with dish antennas of one meter in diameter. Future MSS will use handheld telephone or laptop ground terminals and the satellite networks will be made up of a fleet of LEO (low-earth circular orbiters, 400–1000 miles in altitude) or MEO (medium-earth orbits, 5000–7000 miles in altitude) with either polar or inclined orbits. In addition to handheld terminals, these MSS will also serve mobile ground terminals such as aircraft, shipboard, and land vehicles.

The next few years will see increasing levels of integration between satellite and terrestrial cellular communication networks. The primary purpose of MSS is not to substitute but to complement the terrestrial mobile communication networks; indeed, most ground terminals have the capability of functioning with both networks. Iridium[7] is currently operational, and Globalstar [8] and ICO[9] are at an advanced stage of development and due to start commercial mobile communication services in 1999 and 2000, respectively. With these systems fully deployed, business travellers can circumvent the incompatibility between terrestrial mobile networks in operation around the globe. The incompatibility problem appears to endure even in the third generation of mobile networks that are currently being developed, hence the necessity for the MSS complementary role.

Figure 12.13 shows the basic system architecture. Each satellite covers a circular area on the earth's surface that increases with increasing orbit height and a decreasing minimum elevation angle. The choice of orbital planes and satellite phasing within the orbits must guarantee continuous coverage of the service area. The number of required satellites is determined by the orbit height and minimum satellite elevation angle.[10]

Direct communication via satellite, using a handheld terminal with low transmit power and omni-directional antenna, requires a high antenna gain or spot-beam antenna onboard the satellite. In each constellation, the coverage area of each satellite is composed of a large number of beams, allowing frequency reuse within the coverage area and, therefore, increasing the bandwidth efficiency of the system. The gateway to the fixed terrestrial network is comprised of fixed earth stations and mobile switching centres (MSC). Call routing and mobility management is achieved by use of databases, such as the home location register (HLR) and the visitor location register (VLR). The network control centre (NCC) allocates, among other tasks, spot-beam frequencies and devises routing tables to the satellites in the network.

12.5.1 Frequency

The spectrum allocated by WARC-92 and 95 for the MSS falls mainly in the L-band and divided into the following categories:

- aeronautical mobile satellite services (AMSS)
- maritime mobile satellite services (MMSS)
- land mobile satellite services (LMSS)

Frequencies around 140 and 400 MHz can be used for MSS data systems. After the year 2000, additional frequency bands at 1.980–2.025 GHz (uplink) and

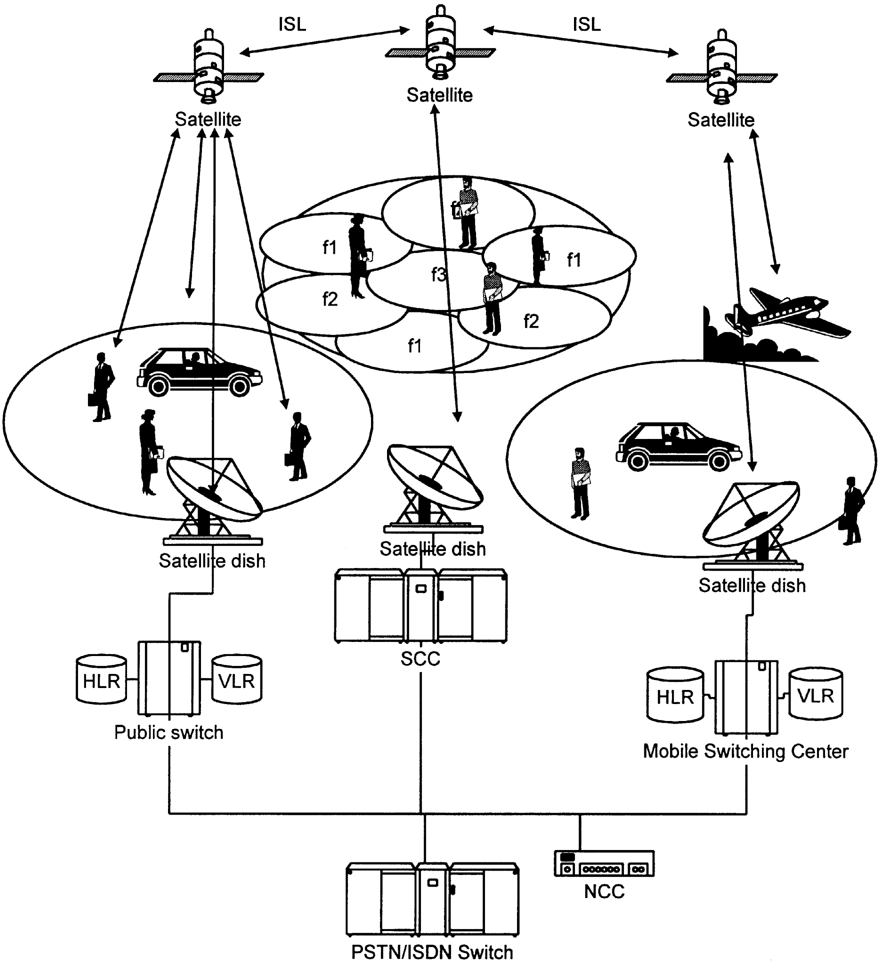

Figure 12.13 Satellite-mobile system architecture

2.160–2.200 GHz (downlink) may be used as intended by the ICO[9] system. Higher frequencies at 15 GHz and 20/30 GHz are foreseen for the feeder links. Intersatellite links may operate at 23 GHz, 60 GHz, or at optical bands. Table 12.4 shows the allocated bands.

12.5.2 Low Earth Orbit (LEO)

System Concept: Low earth orbits at 700–1500 km avoid the large propagation loss and delay associated with geostationary orbits. However, many LEO satellites are needed for continuous coverage of the earth's surface.

TABLE 12.4
The Allocated Frequency Band for Mobile Satellite Communications

1.6/2.4 GHz and 1.6/2.4 GHz bands approved by WARC 92		
Uplink	**Bandwidth**	**Downlink**
1610 MHz	16.5 MHz	2483.5 MHz
1626.5	34 MHz	1500
		1525
1660.5 MHz		1559 MHz

12.5.2.1 Globalstar (Commercial Service Planned for September 1999)

The Globalstar network is based on a joint venture between Loral and QUALCOMM. The access system is CDMA, and the system uses 48 satellites in 8 inclined orbits at 1414 km. Figure 12.14 shows the system configuration.

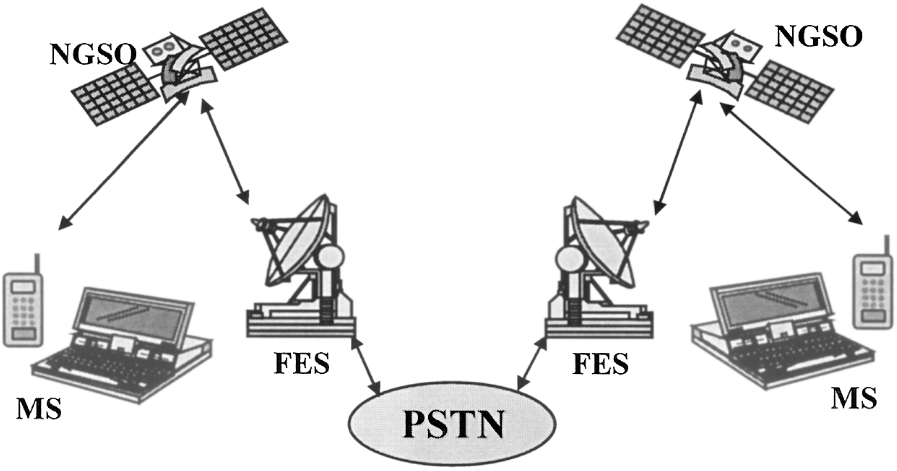

Figure 12.14 GlobalStar network configuration

The service is meant to be totally transparent to the user, whether provided by the Globalstar or the terrestrial network and is fully integrated into the terrestrial network. A Tri-mode handset, which will automatically switch between the terrestrial analogue system (AMPS), the digital cellular system (DAMPS), or the Global satellite network is being developed for the North American market. The system specifications are given and summarised in Table 12.5.

TABLE 12.5
GlobalStar System Configuration

Orbital characteristics		Frequency	
Orbit	Inclined circular	Mobile uplink	1610–1625 MHz
Altitude	1414 km	Mobile downlink	2483–2500 MHz
Orbital period	≅ 2 hours	Feeder uplink	6484–6541.5 MHz
Inclination	52°	Feeder downlink	5158.5–5216.0 MHz
No. of orbital planes	8		
No. satellites per plane	6		

12.5.2.2 Iridium (Operational)

The Iridium system is based on 66 satellites that are grouped in 6 orbital planes, each containing 11 active satellites and one spare satellite. The orbits are circular at the height of 783 km at an inclination angle of 86°. The separation between satellites in each orbit is 32.7°. The satellites in adjacent planes travel out of phase and are located at half-satellite spacing. Collision avoidance is built into the orbital planing, and the closest approach between the satellites is 223 km.

Satellites in planes 1, 3, and 5 cross the equator in synchronisation, while satellites in planes 2, 4, and 6 also cross in synchronisation, but out of phase with those in planes 1, 3, and 5. The first and last planes are counter-rotating. The separation between the corotating planes is 31.6°, which allows 22° separation between the first and last planes. This closer separation is needed because the earth's coverage under the counter-rotating planes is not as efficient as corotating planes.

Two-way communication links exist between each satellite and its nearest neighbour ahead and behind and to the nearest satellites in the adjacent planes.

The satellite antenna beam footprints are similar to the cells encountered in terrestrial cellular mobile systems with one major difference: unlike the fixed cellular network, the beams (cells) move relative to the mobile subscriber.

The orbital period for the Iridium satellites is approximately 100 minutes. Taking the average earth radius of 6371 km, the surface speed is

$$\frac{2 \times 6371 \times \pi}{100} \cong 400 km/\min \textit{ or over } 15000 \textit{ miles/h}$$

Therefore, satellites are travelling at a much greater velocity than that normally encountered by the terrestrial mobiles (cars included) which may be considered as stationary relative to the satellite.

A 48-beam antenna pattern is used from each satellite, with each beam under a separate control. This arrangement is shown in Figure 12.15.

At the equator, for example, overlap of patterns will be minimal and all beams may be on, while at high latitudes considerable overlap occurs and certain beams can be switched off. It is also possible to switch off the beams where their operation

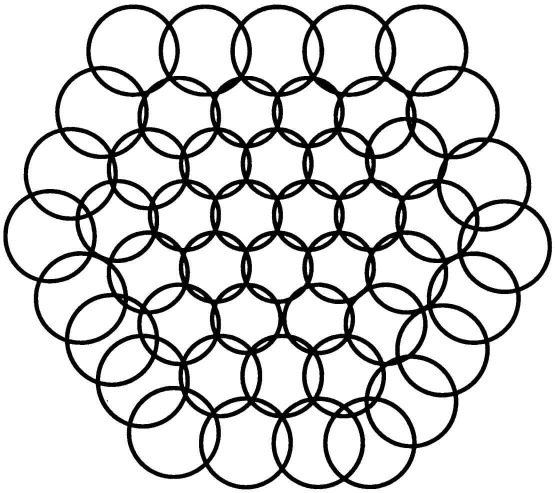

Figure 12.15 Iridium antenna foot-print

is prohibited by the telecommunication administrations. The beam switching is referred to as cell management. The access system for Iridium is TDMA, and dual mode handsets compatible with terrestrial DAMPS are commercially available.

As a result of the small antenna foot print of the LEO satellite, a large number of gateway stations are required in systems without intersatellite links (ISL). Globalstar will use approximately 150 gateways all over the world. If ISLs are used, the number of gateways can be reduced, and their position can be chosen freely. The Iridium system, which uses ISLs, has plans for 11 gateway stations. Moreover, ISLs allow routing long distance calls within the satellite network, saving cost for terrestrial lines. The use of ISLs necessitates more signal processing and switching onboard the satellites to route the calls within the ISL network.

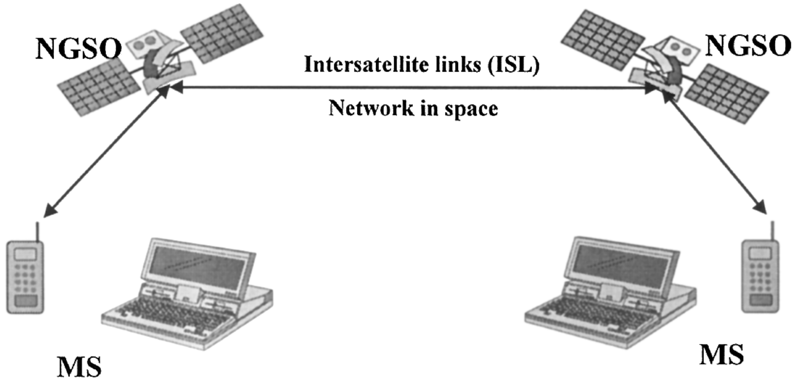

Figure 12.16 Iridium system architecture

12.5.2.3 Teledesic (Service Targeted for 2003)*

The Teledesic system* is proposed by a consortium formed by the major players in the satellite communications industry** and is building a global, broadband network using a constellation of LEO satellites. The commercial service is targeted for 2003. This system will create a network capable of worldwide access to telecommunications services, such as broadband Internet access, videoconferencing, high-quality voice, and other types of digital data.

The Teledesic Network will consist of 288 operational satellites, divided into 12 planes, each with 24 satellites. To make efficient use of the radio spectrum, frequencies are allocated dynamically and reused many times within each satellite footprint. Within any 100-km radius area, the Teledesic Network can support over 500 Mbps of data to and from the user terminals. The Network supports bandwidth-on-demand, allowing a user to request and release capacity as needed. The frequency of operation is at the high end of Ka-band (28.6–29.1 GHz uplink and 18.8–19.3 GHz downlink). The use of a high frequency band and a large number of LEO satellites (resulting high elevation look angles) enables the use of low-power terminals and small antennas.

The Teledesic Network is designed to support a very large number of simultaneous users. Most users will have two-way connections that provide up to 64 Mbps on the downlink and up to 2 Mbps on the uplink. Broadband terminals will offer 64 Mbps of two-way capacity. With such a bandwidth it would be possible to transmit a set of X-rays over the Teledesic Network in a few seconds.

Satellites in adjacent planes travel in the same direction except at the constellation seams, where ascending and descending portions of the orbits overlap.

12.5.3 Medium Earth Orbit (MEO) System Concept

Systems with satellites in medium earth orbits (10,000 km) provide links that avoid the large signal attenuation and delay associated with the geostationary orbits and still allow global coverage with a few (10–15) satellites. Since the required state-of-the-art satellite antennas are now available, and no ISLs are necessary, the technical risks of MEO systems are acceptable. An example of a MEO system is the ICO (Intermediate Circular Orbits)[9] system based on 10 satellites at an orbital height of 10,354 km.

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* www.teledesic.com

** Motorola, Boeing, and Matra Marconi Space form an international team who will develop the technology.

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APPENDIX

The unique word is a sequence of ones and zeros selected to have good correlation properties to enhance its detection. At the demodulator the unique word enters the unique word detector, which is a digital correlator as shown in the Figure 12.17, where it is correlated with a strict pattern of itself. The correlator consists of two *n*-stage shift registers where *n* is the length of the unique word. There are also *n* modulo-2 adders, a summer, and a threshold detector. Each stage in the shift register is applied to a modulo-2 adder whose output is a logical zero when the data matches the unique word in the same position. All the modulo-2 adder outputs are summed, and the sum is compared to a preset threshold in the detector. The maximum number of errors allowed in the unique word detection is called *detection threshold*. The unique word detection occurs at the instant of reception of the last bit of the UW. It marks the receive frame timing if the unique word belongs to the primary burst, or it marks the receive traffic burst timing if the unique word belongs to traffic burst.

Unique Word Detection (False or Miss!)

The accurate detection of the unique word is of utmost importance in a TDMA system, and the entire traffic burst is lost if the UW of a traffic burst is missed. It is also possible to have false detection which generates the wrong receive frame timing, consequently incorrect transmit frame timing, resulting in overlap with other bursts at the satellite.

Miss-detection probability — If ε represents the maximum number of errors allowed in a UW of length *n* bits and *i* is the actual number of errors in the unique word as received, then when $i < \varepsilon$, the received sequence is declared to be the unique word. If $i > \varepsilon$, the detected sequence *N* is declared not to be the unique word.

Let *p* represent the average probability of errors in the link (BER), the probability of a miss-detection is when $i > \varepsilon$ and is given as:

$$P_{miss} = \sum_{i=\varepsilon+1}^{N} \frac{N!}{i!(N-1)!} p^{i}(1-p)^{N-i}$$

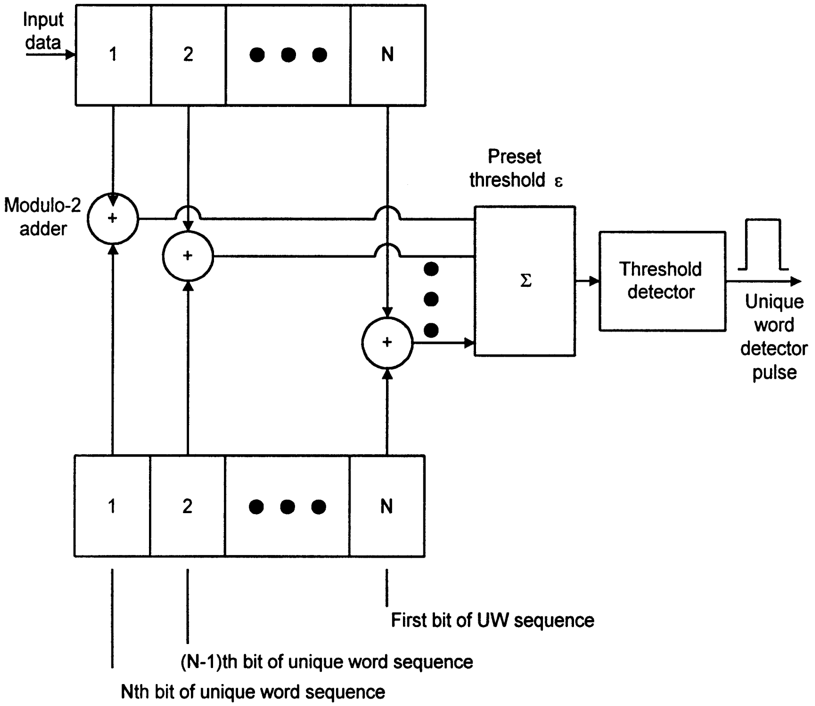

Figure 12.17 Unique word detector

This gives the average probability and it is not necessary to know the specific value of *i*.

UW false-detection probability — The false detection probability P_F is given by the probability that random data (bits 1 and 0 are assumed to be generated with equal probability) may accidentally match the stored UW pattern to the extent that the number of bits in disagreement does not exceed ε. For a UW of length *n*, there are 2^n combinations in which random data can occur, hence the probability of occurrence of one unique combination that corresponds to the stored UW is $1/2^n$, which is the situation of false detection probability when ε = 0. For a given value of ε, the total number of possible combinations in which ε or fewer errors can occur is

$$\sum_{i}^{\varepsilon} {}_N C_i$$

Thus, the probability that *n* random data bits will be detected as UW or false detection probability P_F is

$$P_F = \frac{1}{2^N} \sum_{i=O}^{\varepsilon} {}_N C_i$$

This is independent of link error probability.

In a typical link, the false detection probability is much higher than the probability of a miss. In practice, once frame synchronization has been achieved, a time window can be formed around the expected time of arrival for the UW, such that the correlation detector is in operation only for the window period, thus reducing the probability of miss-detection.