1 INTRODUCTION

This chapter describes the characteristics of satellite communication systems. It aims to satisfy the curiosity of an impatient reader and facilitate a deeper understanding by directing him or her to appropriate chapters without imposing the need to read the whole work from beginning to end.

1.1 BIRTH OF SATELLITE COMMUNICATIONS

Satellite communications are the outcome of research in the area of communications and space technologies whose objective is to achieve ever increasing ranges and capacities with the lowest possible costs.

The Second World War stimulated the expansion of two very distinct technologies—missiles and microwaves. The expertise eventually gained in the combined use of these two techniques opened up the era of satellite communications. The service provided in this way usefully complements that previously provided exclusively by terrestrial networks using radio and cables.

The space era started in 1957 with the launching of the first artificial satellite (Sputnik). Subsequent years have been marked by various experiments including the following: Christmas greetings from President Eisenhower broadcast by SCORE (1958), the reflecting satellite ECHO (1960), store-and-forward transmission by the COURIER satellite (1960), powered relay satellites (TELSTAR and RELAY in 1962) and the first geostationary satellite SYNCOM (1963).

In 1965, the first commercial geostationary satellite INTELSAT I (or Early Bird) inaugurated the long series of INTELSATs; in the same year, the first Soviet communications satellite of the MOLNYA series was launched.

1.2 DEVELOPMENT OF SATELLITE COMMUNICATIONS

The first satellites provided a low capacity at a relatively high cost; for example, INTELSAT I weighed 68 kg at launch for a capacity of 480 telephone channels and an annual cost of \$32 500 per channel at the time. This cost resulted from a combination of the cost of the launcher, that of the satellite, the short lifetime of the satellite (1.5 years) and its low capacity. The reduction in cost is the result of much effort which has led to the production of reliable launchers which can put heavier and heavier satellites into orbit (typically 5900 kg at launch in 1975, reaching 10 500 kg by Ariane 5 ECA and 13 000 kg by Delta IV in 2008). In addition, increasing expertise in microwave techniques has enabled realisation of contoured multibeam antennas whose beams adapt to the shape of continents, frequency re-use from one beam to the other and incorporation of higher

Satellite Communications Systems, Fifth Edition Gérard Maral, Michel Bousquet and Zhili Sun

power transmission amplifiers. Increased satellite capacity has led to a reduced cost per telephone channel.

In addition to the reduction in the cost of communication, the most outstanding feature is the variety of services offered by satellite communications systems. Originally these were designed to carry communications from one point to another, as with cables, and the extended coverage of the satellite was used to set up long distance links; hence Early Bird enabled stations on opposite sides of the Atlantic Ocean to be connected. However, as a consequence of the limited performance of the satellite, it was necessary to use earth stations equipped with large antennas and therefore of high cost (around $10 million for a station equipped with a 30m diameter antenna).

The increasing size and power of satellites has permitted a consequent reduction in the size of earth stations, and hence their cost, leading to an increase in number. In this way it has been possible to exploit another feature of the satellite which is its ability to collect or broadcast signals from or to several locations. Instead of transmitting signals from one point to another, transmission can be from a single transmitter to a large number of receivers distributed over a wide area or, conversely, transmission can be from a large number of stations to a single central station, often called a hub. In this way, multipoint data transmission networks and data collection networks have been developed under the name of VSAT (very small aperture terminals) networks [MAR-95]. Over 1 000 000 VSATs have been installed up to 2008. For TV services, satellites are of paramount importance for satellite news gathering (SNG), for the exchange of programmes between broadcasters, for distributing programmes to terrestrial broadcasting stations and cable heads, or directly to the individual consumer. The latter are commonly called direct broadcasting by satellite (DBS) systems, or direct-to-home (DTH) systems. A rapidly growing service is digital video broadcasting by satellite (DVB-S), developed in early 1991; the standard for the second generation (DVB-S2) has been standardised by the European Telecommunication Standard Institute (ETSI). These DBS systems operate with small earth stations having antennas with a diameter from 0.5 to 1 m.

In the past, the customer stations were Receive Only (RCVO) stations. With the introduction of two-way communications stations, satellites are a key component in providing interactive TV and broadband Internet services thanks to the implementation of the DVB satellite return channel (DVB-RCS) standard to the service provider's facilities. This uses TCP/IP to support Internet, multicast and web-page caching services over satellite with forward channel operating at several Mbit/s and enables satellites to provide broadband service applications for the end user, such as direct access and distribution services. IP-based triple-play services (telephony, Internet and TV) are more and more popular. Satellites cannot compete with terrestrial Asymmetric Digital Subscriber Line (ADSL) or cable to deliver these services in high-density population areas. However, they complement nicely the terrestrial networks around cities and in rural areas when the distance to the telephone router is too large to allow delivery of the several Mbit/s required to run the service.

A further reduction in the size of the earth station antenna is exemplified in digital audio broadcasting (DAB) systems, with antennas in the order of 10 cm. The satellite transmits multiplexed digital audio programmes and supplements traditional Internet services by offering one-way broadcast of web-style content to the receivers.

Finally, satellites are effective in mobile communications. Since the end of the 1970s, INMARSAT satellites have been providing distress signal services along with telephone and data communications services to ships and planes and, more recently, communications to portable earth stations (Mini M or Satphone). Personal mobile communication using small handsets is available from constellations of non-geostationary satellites (such as Iridium and Globalstar) and geostationary satellites equipped with very large deployable antennas (typically 10 to 15 m) as with the THURAYA, ACES, and INMARSAT 4 satellites. The next step in bridging the gaps between fixed, mobile and broadcasting radiocommunications services concerns satellite multimedia broadcast to fixed and mobile users. Satellite digital mobile broadcasting (SDMB) is based on hybrid integrated satellite–terrestrial systems to serve small hand-held terminals with interactivity.

1.3 CONFIGURATION OF A SATELLITE COMMUNICATIONS SYSTEM

Figure 1.1 gives an overview of a satellite communication system and illustrates its interfacing with terrestrial entities. The satellite system is composed of a space segment, a control segment and a ground segment:

— The *space segment* contains one or several active and spare satellites organised into a constellation.
— The *control segment* consists of all ground facilities for the control and monitoring of the satellites, also named TTC (tracking, telemetry and command) stations, and for the management of the traffic and the associated resources on-board the satellite.

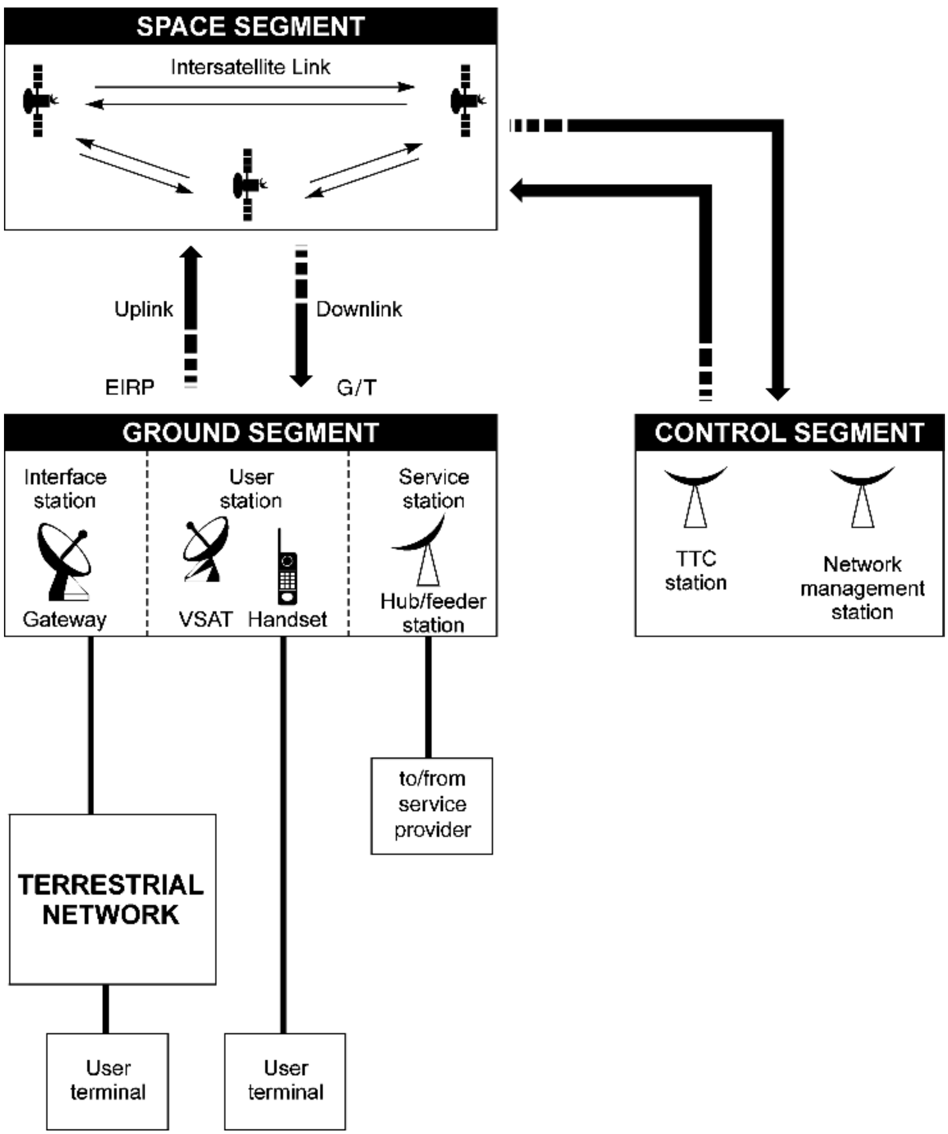

Figure 1.1 Satellite communications system, interfacing with terrestrial entities.

— The *ground segment* consists of all the traffic earth stations. Depending on the type of service considered, these stations can be of different size, from a few centimetres to tens of metres.

Table 1.1 gives examples of traffic earth stations in connection with the types of service discussed in Section 1.7. Earth stations come in three classes as illustrated in Figure 1.1: *user stations*, such as handsets, portables, mobile stations and very small aperture terminals (VSATs), which allow the customer direct access to the space segment; *interface stations*, known as gateways, which interconnect the space segment to a terrestrial network; and *service stations*, such as hub or feeder stations, which collect or distribute information from and to user stations via the space segment.

Communications between users are set up through *user terminals* which consist of equipment such as telephone sets, fax machines and computers that are connected to the terrestrial network or to the user stations (e.g. a VSAT), or are part of the user station (e.g. if the terminal is mobile).

The path from a source user terminal to a destination user terminal is named a simplex connection. There are two basic schemes: *single connection per carrier* (SCPC), where the modulated carrier supports one connection only, and *multiple connections per carrier* (MCPC), where the modulated carrier supports several time or frequency multiplexed connections. Interactivity between two users requires a duplex connection between their respective terminals, i.e. two simplex connections, each along one direction. Each user terminal should then be capable of sending and receiving information.

A connection between a service provider and a user goes through a hub (for collecting services) or a feeder station (e.g. for broadcasting services). A connection from a gateway, hub or feeder station to a user terminal is called a *forward* connection. The reverse connection is the *return* connection. Both forward and return connections entail an uplink and a downlink, and possibly one or more intersatellite links.

Table 1.1 Services from different types of traffic earth station

Type of service	Type of earth station	Typical size (m)
Point-to-point	Gateway, hub	2–10
	VSAT	1–2
Broadcast/multicast	Feeder station	1–5
	VSAT	0.5–1.0
Collect	VSAT	0.1–1.0
	Hub	2–10
Mobile	Handset, portable, mobile	0.1–0.5
	Gateway	2–10

1.3.1 Communications links

A link between transmitting equipment and receiving equipment consists of a radio or optical modulated carrier. The performance of the transmitting equipment is measured by its *effective isotropic radiated power* (EIRP), which is the power fed to the antenna multiplied by the gain of the antenna in the considered direction. The performance of the receiving equipment is measured by G/T, the ratio of the antenna receive gain, G, in the considered direction and the system noise temperature, T; G/T is called the receiver's *figure of merit*. These concepts are detailed in Chapter 5.

The types of link shown in Figure 1.1 are:

— the *uplinks* from the earth stations to the satellites;
— the *downlinks* from the satellites to the earth stations;
— the *intersatellite links*, between the satellites.

Uplinks and downlinks consist of radio frequency modulated carriers, while intersatellite links can be either radio frequency or optical. Carriers are modulated by baseband signals conveying information for communications purposes.

The link performance can be measured by the ratio of the received carrier power, C, to the noise power spectral density, N_0, and is denoted as the C/N_0 ratio, expressed in hertz (Hz). The values of C/N_0, for the links which participate in the connection between the end terminals, determine the quality of service, specified in terms of *bit error rate* (BER) for digital communications.

Another parameter of importance for the design of a link is the bandwidth, B, occupied by the carrier. This bandwidth depends on the information data rate, the channel coding rate (forward error correction) and the type of modulation used to modulate the carrier. For satellite links, the trade-off between required carrier power and occupied bandwidth is paramount to the cost-effective design of the link. This is an important aspect of satellite communications as power impacts both satellite mass and earth station size, and bandwidth is constrained by regulations. Moreover, a service provider who rents satellite transponder capacity from the satellite operator is charged according to the highest share of either power or bandwidth resource available from the satellite transponder. The service provider's revenue is based on the number of established connections, so the objective is to maximise the throughput of the considered link while keeping a balanced share of power and bandwidth usage. This is discussed in Chapter 4.

In a satellite system, several stations transmit their carriers to a given satellite, therefore the satellite acts as a network node. The techniques used to organise the access to the satellite by the carriers are called multiple access techniques (Chapter 6).

1.3.2 The space segment

The satellite consists of the *payload* and the *platform*. The payload consists of the receiving and transmitting antennas and all the electronic equipment which supports the transmission of the carriers. The two types of payload organisation are illustrated in Figure 1.2.

Figure 1.2a shows a *transparent* payload (sometimes called a 'bent pipe' type) where carrier power is amplified and frequency is downconverted. Power gain is of the order of 100–130 dB, required to raise the power level of the received carrier from a few tens of picowatts to the power level of the carrier fed to the transmit antenna of a few watts to a few tens of watts. Frequency conversion is required to increase isolation between the receiving input and the transmitting output. Due to technology power limitations, the overall satellite payload bandwidth is split into several sub-bands, the carriers in each sub-band being amplified by a dedicated power amplifier. The amplifying chain associated with each sub-band is called a *satellite channel*, or transponder. The bandwidth splitting is achieved using a set of filters called the *input multiplexer* (IMUX). The amplified carriers are recombined in the *output multiplexer* (OMUX).

The transparent payload in Figure 1.2a belongs to a single beam satellite where each transmit and receive antenna generates one beam only. One could also consider multiple beam antennas. The payload would then have as many inputs/outputs as upbeams/downbeams. Routing of carriers from one upbeam to a given downbeam implies either routing through different satellite channels, *transponder hopping*, depending on the selected uplink frequency or *on-board switching with transparent on-board processing*. These techniques are presented in Chapter 7.

Figure 1.2b shows a multiple beam *regenerative* payload where the uplink carriers are demodulated. The availability of the baseband signals allows *on-board processing* and routing of information from upbeam to downbeam through *on-board switching at baseband*. The frequency conversion is achieved by modulating on-board-generated carriers at downlink frequency. The modulated carriers are then amplified and delivered to the destination downbeam.

Figure 1.3 illustrates a multiple beam satellite antenna and its associated coverage areas. Each beam defines a *beam coverage area*, also called *footprint*, on the earth surface. The aggregate

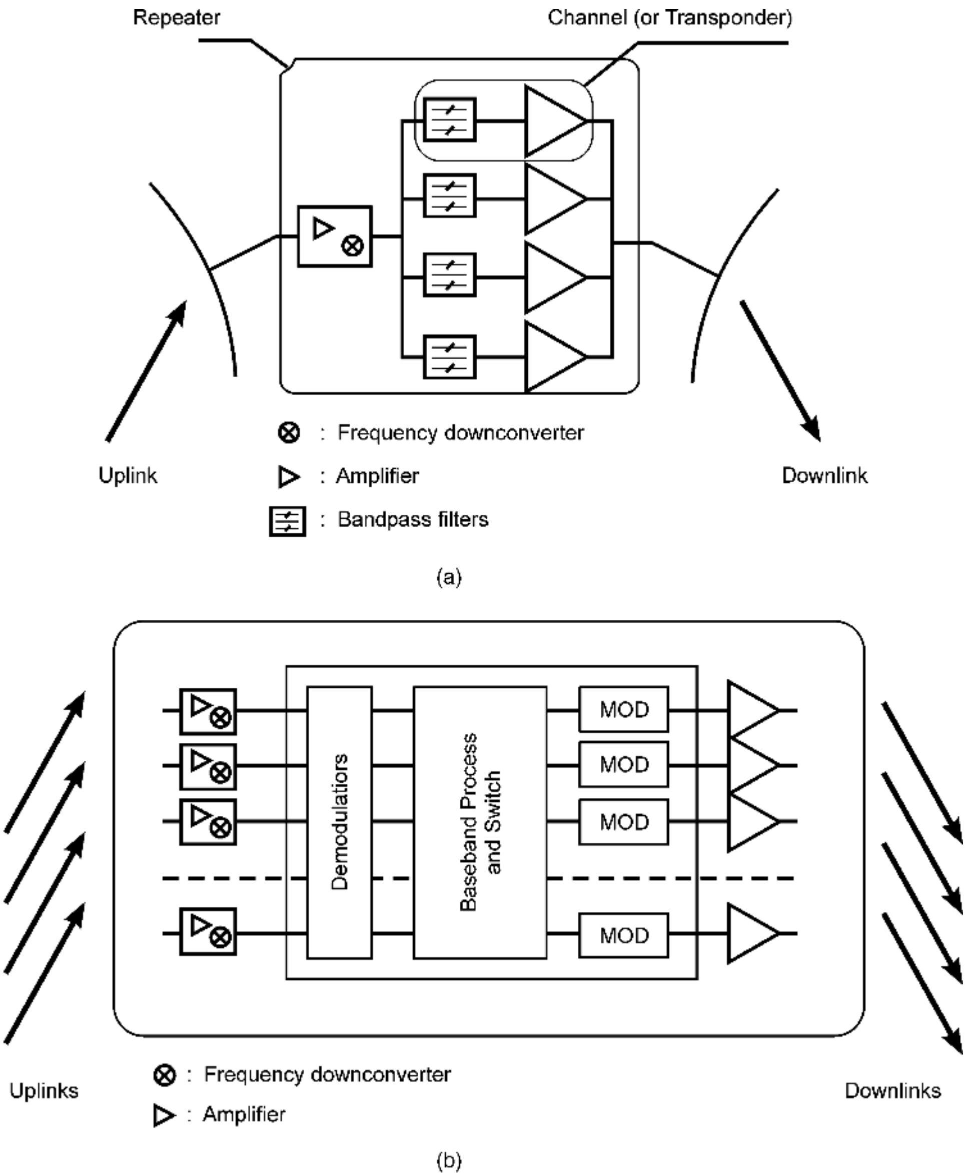

Figure 1.2 Payload organisation: (a) transparent and (b) regenerative.

beam coverage areas define the *multibeam antenna coverage area*. A given satellite may have several multiple beam antennas, and their combined coverage defines the *satellite coverage area*.

Figure 1.4 illustrates the concept of instantaneous system coverage and long-term coverage. The *instantaneous system coverage* consists of the aggregation at a given time of the coverage areas of the individual satellites participating in the constellation. The *long-term coverage* is the area on the earth scanned over time by the antennas of the satellites in the constellation.

The coverage area should encompass the *service zone*, which corresponds to the geographical region where the stations are installed. For real-time services, the instantaneous system coverage

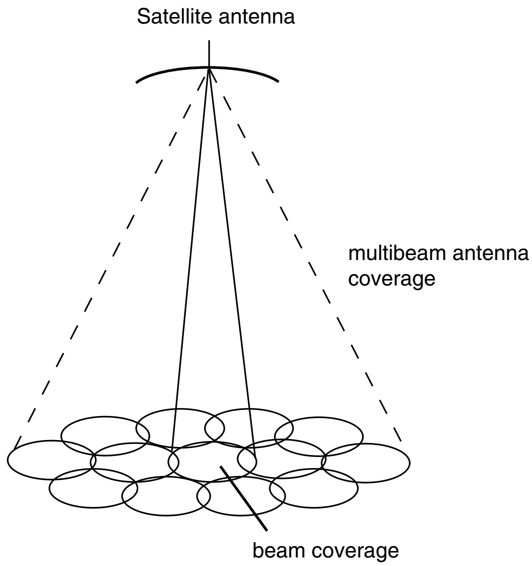

Figure 1.3 Multiple beam satellite antenna and associated coverage area.

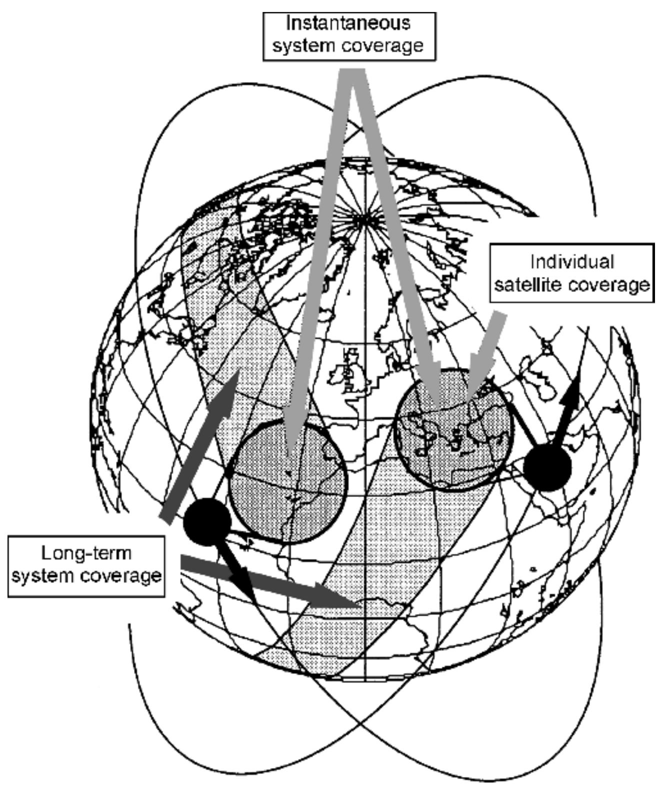

Figure 1.4 Types of coverage.

Table 1.2 Platform subsystem

Subsystem	Principal functions	Characteristics
Attitude and orbit control (AOCS)	Attitude stabilisation, orbit determination	Accuracy
Propulsion	Provision of velocity increments	Specific impulse, mass of propellant
Electric power supply	Provision of electrical energy	Power, voltage stability
Telemetry, tracking and command (TTC)	Exchange of housekeeping information	Number of channels, security of communications
Thermal control	Temperature maintenance	Dissipation capability
Structure	Equipment support	Rigidity, lightness

should at any time have a footprint covering the service zone, while for non-real-time (store-and-forward) services, it should have long-term coverage of the service zone.

The platform consists of all the subsystems which permit the payload to operate. Table 1.2 lists these subsystems and indicates their respective main functions and characteristics.

The detailed architecture and technology of the payload equipment are explained in Chapter 9. The architecture and technologies of the platform are considered in Chapter 10. The operations of orbit injection and the various types of launcher are the subject of Chapter 11. The space environment and its effects on the satellite are presented in Chapter 12.

To ensure a service with a specified availability, a satellite communication system must make use of several satellites in order to ensure redundancy. A satellite can cease to be available due to a failure or because it has reached the end of its lifetime. In this respect it is necessary to distinguish between the reliability and the lifetime of a satellite. *Reliability* is a measure of the probability of a breakdown and depends on the reliability of the equipment and any schemes to provide redundancy. The *lifetime* is conditioned by the ability to maintain the satellite on station in the nominal attitude, and depends on the quantity of fuel available for the propulsion system and attitude and orbit control. In a system, provision is generally made for an operational satellite, a backup satellite in orbit and a backup satellite on the ground. The reliability of the system will involve not only the reliability of each of the satellites but also the reliability of launching. An approach to these problems is treated in Chapter 13.

1.3.3 The ground segment

The ground segment consists of all the earth stations; these are most often connected to the end-user's terminal by a terrestrial network or, in the case of small stations (Very Small Aperture Terminal, VSAT), directly connected to the end-user's terminal. Stations are distinguished by their size which varies according to the volume of traffic to be carried on the satellite link and the type of traffic (telephone, television or data). In the past, the largest were equipped with antennas of 30 m diameter (Standard A of the INTELSAT network). The smallest have 0.6 m antennas (receiving stations from direct broadcasting satellites) or even smaller (0.1 m) antennas (mobile stations, portable stations or handsets). Some stations both transmit and receive. Others are receive-only (RCVO) stations; this is the case, for example, with receiving stations for a broadcasting satellite system or a distribution system for television or data signals. Figure 1.5 shows the typical architecture of an earth station for both transmission and reception. Chapter 5 introduces the characteristic parameters of the earth station which appear in the link budget calculations. Chapter 3 presents the characteristics of signals supplied to earth stations by the user terminal either directly or through a terrestrial network, the signal processing at the station (such as source coding and compression, multiplexing, digital speech interpolation, channel coding, scrambling

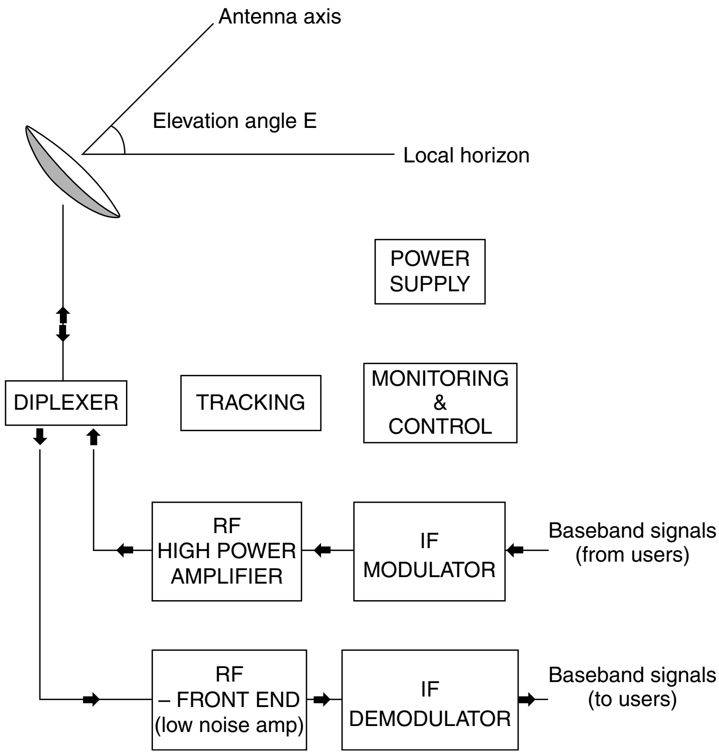

Figure 1.5 The organisation of an earth station. RF = radio frequency, IF = intermediate frequency.

and encryption), and transmission and reception (including modulation and demodulation). Chapter 8 treats the organisation and equipment of earth stations.

1.4 TYPES OF ORBIT

The orbit is the trajectory followed by the satellite. The trajectory is within a plane and shaped as an ellipse with a maximum extension at the apogee and a minimum at the perigee. The satellite moves more slowly in its trajectory as the distance from the earth increases. Chapter 2 provides a definition of the orbital parameters.

The most favourable orbits are as follows:

— Elliptical orbits inclined at an angle of 64° with respect to the equatorial plane. This type of orbit is particularly stable with respect to irregularities in terrestrial gravitational potential and, owing to its inclination, enables the satellite to cover regions of high latitude for a large fraction of the orbital period as it passes to the apogee. This type of orbit has been adopted by the USSR for the satellites of the MOLNYA system with period of 12 hours. Figure 1.6 shows the geometry of the orbit. The satellite remains above the regions located under the apogee for a time interval of the order of 8 hours. Continuous coverage can be ensured with three phased satellites on different orbits. Several studies relate to elliptical orbits with a period of 24 h (TUNDRA orbits) or a multiple of 24 h. These orbits are particularly useful for satellite systems for communication with mobiles where the masking effects caused by surrounding obstacles such as buildings and trees and multiple path effects are pronounced at low elevation angles (say less than 30°).

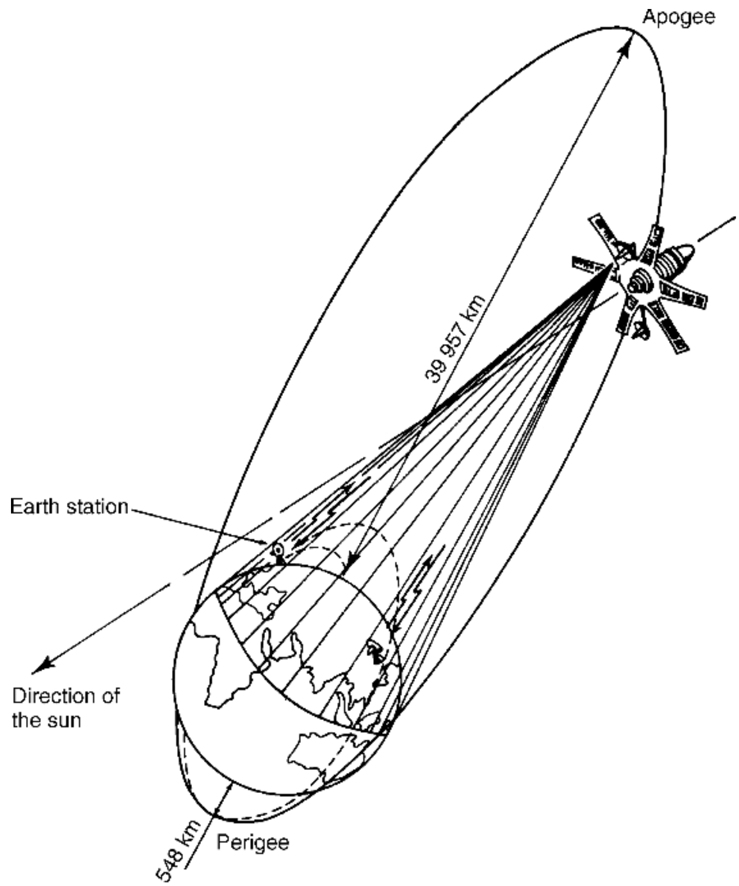

Figure 1.6 The orbit of a MOLNYA satellite.

In fact, inclined elliptic orbits can provide the possibility of links at medium latitudes when the satellite is close to the apogee with elevation angles close to 90°; these favourable conditions cannot be provided at the same latitudes by geostationary satellites. In the late 1980s, the European Space Agency (ESA) studied the use of elliptical highly inclined orbits (HEO) for digital audio broadcasting (DAB) and mobile communications in the framework of its Archimedes programme. The concept became reality at the end of the 1990s with the Sirius system delivering satellite digital audio radio services to millions of subscribers (mainly automobiles) in the United States using three satellites on HEO Tundra-like orbits [AKT-08].

— Circular low earth orbits (LEO). The altitude of the satellite is constant and equal to several hundreds of kilometres. The period is of the order of one and a half hours. With near 90° inclination, this type of orbit guarantees worldwide long term coverage as a result of the combined motion of the satellite and earth rotation, as shown in Figure 1.7. This is the reason for choosing this type of orbit for observation satellites (for example, the SPOT satellite: altitude 830 km, orbit inclination 98.7°, period 101 minutes). One can envisage the establishment of store-and-forward communications if the satellite is equipped with a means of storing information. A constellation of several tens of satellites in low altitude (e.g. IRIDIUM with 66 satellites at 780 km) circular orbits can provide worldwide real-time communication. Non-polar orbits with less than 90° inclination, can also be envisaged. For instance the GLOBALSTAR constellation incorporates 48 satellites at 1414 km with 52° orbit inclination.

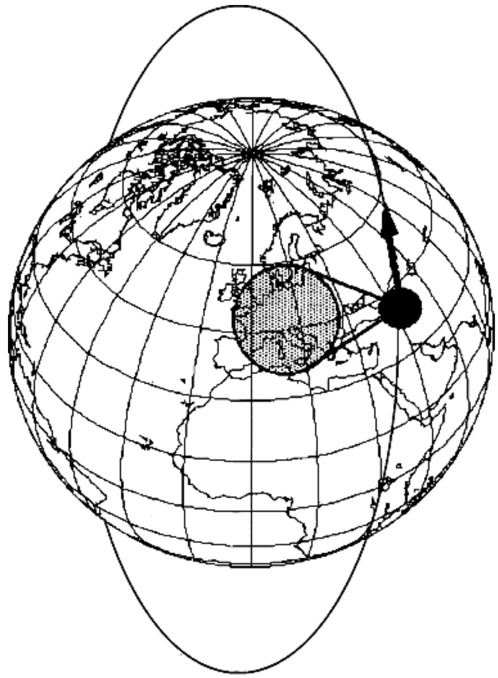

Figure 1.7 Circular polar low earth orbit (LEO).

— Circular medium earth orbits (MEO), also called intermediate circular orbits (ICO), have an altitude of about 10 000 km and an inclination of about 50°. The period is 6 hours. With constellations of about 10 to 15 satellites, continuous coverage of the world is guaranteed, allowing worldwide real-time communications. A planned system of this kind was the ICO system (which emerged from Project 21 of INMARSAT but was not implemented) with a constellation of 10 satellites in two planes at 45° inclination.
— Circular orbits with zero inclination (equatorial orbits). The most popular is the geostationary satellite orbit; the satellite orbits around the earth in the equatorial plane according to the earth rotation at an altitude of 35 786 km. The period is equal to that of the rotation of the earth. The satellite thus appears as a point fixed in the sky and ensures continuous operation as a radio relay in real time for the area of visibility of the satellite (43% of the earth's surface).
— Hybrid systems. Some systems may include combinations of orbits with circular and elliptical orbits. Such a design was envisaged for the ELLIPSO system.

The choice of orbit depends on the nature of the mission, the acceptable interference and the performance of the launchers:

— The extent and latitude of the area to be covered; contrary to widespread opinion, the altitude of the satellite is not a determining factor in the link budget for a given earth coverage. Chapter 5 shows that the propagation attenuation varies as the inverse square of the distance and this favours a satellite following a low orbit on account of its low altitude; however, this disregards the fact that the area to be covered is then seen through a larger solid angle. The result is a reduction in the gain of the satellite antenna which offsets the distance advantage. Now a satellite following a low orbit provides only limited earth coverage at a given time and limited time at a given location. Unless low gain antennas (of the order of a few dB) which provide low directivity and hence almost omnidirectional radiation are installed, earth stations must be equipped with satellite tracking devices which increase the cost. The geostationary satellite thus appears to be particularly useful for continuous coverage of extensive regions. However, it does not permit coverage of the polar regions which are accessible by satellites in inclined elliptical orbits or polar orbits.

— The elevation angle; a satellite in an inclined or polar elliptical orbit can appear overhead at certain times which enables communication to be established in urban areas without encountering the obstacles which large buildings constitute for elevation angles between 0° and approximately 70°. With a geostationary satellite, the angle of elevation decreases as the difference in latitude or longitude between the earth station and the satellite increases.

— Transmission duration and delay; the geostationary satellite provides a continuous relay for stations within visibility but the propagation time of the waves from one station to the other is of the order of 0.25 s. This requires the use of echo control devices on telephone channels or special protocols for data transmission. A satellite moving in a low orbit confers a reduced propagation time. The transmission time is thus low between stations which are close and simultaneously visible to the satellite, but it can become long (several hours) for distant stations if only store-and-forward transmission is considered.

— Interference; geostationary satellites occupy fixed positions in the sky with respect to the stations with which they communicate. Protection against interference between systems is ensured by planning the frequency bands and orbital positions. The small orbital spacing between adjacent satellites operating at the same frequencies leads to an increase in the level of interference and this impedes the installation of new satellites. Different systems could use different frequencies but this is restricted by the limited number of frequency bands assigned for space radiocommunications by the Radiocommunication Regulations. In this context, one can refer to an 'orbit-spectrum' resource which is limited. With orbiting satellites, the geometry of each system changes with time and the relative geometries of one system with respect to another are variable and difficult to synchronise. The probability of interference is thus high.

— The performance of launchers; the mass which can be launched decreases as the altitude increases.

The geostationary satellite is certainly the most popular. At the present time there are around 600 geostationary satellites in operation within the 360° of the whole orbital arc. Some parts of this orbital arc, however, tend to be highly congested (for example above the American continent and Europe).

1.5 RADIO REGULATIONS

Radio regulations are necessary to ensure an efficient and economical use of the radio-frequency spectrum by all communications systems, both terrestrial and satellite. While so doing, the sovereign right of each state to regulate its telecommunication must be preserved. It is the role of the International Telecommunication Union (ITU) to promote, coordinate and harmonise the efforts of its members to fulfil these possibly conflicting objectives.

1.5.1 The ITU organisation

The International Telecommunication Union (ITU), a United Nations organ, operates under a convention adopted by its member administrations. The ITU publishes the Radiocommunication Regulations (RR), which are reviewed by the delegates from ITU member administrations at periodic World/Regional Radio Conferences (WRC/RRC).

From 1947 to 1993 the technical and operational matters were administrated by two committees: the CCIR (Comité Consultatif International des Radiocommunications) and the CCITT (Comité

Consultatif International Télégraphique et Téléphonique). The International Frequency Registration Board (IFRB) was responsible for the examination of frequency-use documentation submitted to the ITU by its member administrations, in compliance with the Radiocommunication Regulations, and for maintaining the Master International Frequency Register (MIFR).

Since 1994 the ITU has been reorganised into three sectors:

— The Radiocommunications Sector (ITU-R) deals with all regulatory and technical matters that were previously handled respectively by the IFRB and the CCIR.
— The Telecommunication Standardisation Sector (ITU-T) continues the work of the CCITT, and those studies by the CCIR dealing with the interconnection of radiocommunications systems with public networks.
— The Development Sector (ITU-D) acts as a forum and an advisory structure for the harmonious development of communications in the world.

The abundant and useful technical literature previously published in the form of reports and recommendations by the CCIR and the CCITT have now been reorganised in the form of ITU-R and ITU-T series recommendations.

1.5.2 Space radiocommunications services

The Radiocommunication Regulations refer to the following space radiocommunications services, defined as transmission or reception of radio waves for specific telecommunications applications:

— Fixed Satellite Service (FSS);
— Mobile Satellite Service (MSS);
— Broadcasting Satellite Service (BSS);
— Earth Exploration Satellite Service (EES);
— Space Research Service (SRS);
— Space Operation Service (SOS);
— Radiodetermination Satellite Service (RSS);
— Inter-Satellite Service (ISS);
— Amateur Satellite Service (ASS).

1.5.3 Frequency allocation

Frequency bands are allocated to the above radiocommunications services to allow compatible use. The allocated bands can be either exclusive for a given service, or shared among several services. Allocations refer to the following division of the world into three regions:

— region 1: Europe, Africa, the Middle East, the former USSR;
— region 2: the Americas;
— region 3: Asia Pacific, except the Middle East and the former USSR.

For example, the fixed satellite service makes use of the following bands:

— Around 6 GHz for the uplink and around 4 GHz for the downlink (systems described as 6/4 GHz or C band). These bands are occupied by the oldest systems (such as INTELSAT, American domestic systems etc.) and tend to be saturated.

— Around 8 GHz for the uplink and around 7 GHz for the downlink (systems described as 8/7 GHz or X band). These bands are reserved, by agreement between administrations, for government use.
— Around 14 GHz for the uplink and around 12 GHz for the downlink (systems described as 14/12 GHz or Ku band). This corresponds to current operational developments (such as EUTELSAT, etc.).
— Around 30 GHz for the uplink and around 20 GHz for the downlink (systems described as 30/20 GHz or Ka band). These bands are raising interest due to large available bandwidth and little interference due to present rather limited use.

The bands above 30 GHz will be used eventually in accordance with developing requirements and technology. Table 1.3 summarises the above discussion.

The mobile satellite service makes use of the following bands:

— VHF (very high frequency, 137–138 MHz downlink and 148–150 MHz uplink) and UHF (ultra high frequency, 400–401 MHz downlink and 454–460 MHz uplink). These bands are for non-geostationary systems only.
— About 1.6 GHz for uplinks and 1.5 GHz for downlinks, mostly used by geostationary systems such as INMARSAT; and 1610–1626.5 MHz for the uplink of non-geostationary systems such as GLOBALSTAR.
— About 2.2 GHz for downlinks and 2 GHz for uplinks for the satellite component of IMT2000 (International Mobile Telecommunications).
— About 2.6 GHz for uplinks and 2.5 GHz for downlinks.
— Frequency bands have also been allocated at higher frequencies such as Ka band.

The broadcasting satellite service makes use of downlinks at about 12 GHz. The uplink is operated in the FSS bands and is called a *feeder link*. Table 1.3 summarises the main frequency allocation and indicates the correspondence with some usual terminology.

Table 1.3 Frequency allocations

Radiocommunications service	Typical frequency bands for uplink/downlink	Usual terminology
Fixed satellite service (FSS)	6/4 GHz	C band
	8/7 GHz	X band
	14/12–11 GHz	Ku band
	30/20 GHz	Ka band
	50/40 GHz	V band
Mobile satellite service (MSS)	1.6/1.5 GHz	L band
	30/20 GHz	Ka band
Broadcasting satellite service (BSS)	2/2.2 GHz	S band
	12 GHz	Ku band
	2.6/2.5 GHz	S band

1.6 TECHNOLOGY TRENDS

The start of commercial satellite telecommunications can be traced back to the commissioning of INTELSAT I (Early Bird) in 1965. Until the beginning of the 1970s, the services provided were telephone and television (TV) signal transmission between continents. The satellite was designed to complement the submarine cable and played essentially the role of a telephone trunk connection.

The goal of increased capacity has led rapidly to the institution of multibeam satellites and the re-use of frequencies first by orthogonal polarisation and subseqently by angular separation (see Chapter 5). Communication techniques (see Chapter 4) have changed from analogue to digital. The second-generation DVB-S2, although backward compatible with DVB-S, has made use of the many novel technologies developed in recent years, including modulation techniques of 8PSK, 16 and 32 APSK in addition to QPSK; efficient forward error correction (FEC) with new low-density parity check (LDPC) codes; adaptive coding and modulations (ACM); and performance close to the Shannon limit. This makes DVB-S2 30% more efficient than DVB-S. DVB-RCS can provide up to 20 Mbit/s forward link to user terminal and 5 Mbit/s return link from user terminal, which is comparable to ADSL technology. Multiple access to the satellite (see Chapter 6) was resolved by frequency division multiple access (FDMA). The increasing demand for a large number of low capacity links, for example for national requirements or for communication with ships, led in 1980 to the introduction of demand assignment (see Chapter 6) first using FDMA with single channel per carrier/frequency modulation (SCPC/FM) or phase shift keying (PSK) and subsequently using time division multiple access/phase shift keying (TDMA/PSK) in order to profit from the flexibility of digital techniques (see Chapter 4). Simultaneously, the progress of antenna technology (see Chapter 9) enabled the beams to conform to the coverage of the service area; in this way the performance of the link was improved while reducing the interference between systems.

Multibeam satellites emerged, with interconnection between beams achieved by transponder hopping or on-board switching using SSTDMA (satellite-switched time division multiple access). Scanning or hopping beams have been implemented in connection with on-board processing on some experimental satellites, such as Advanced Communications Technology Satellite (ACTS).

Multiple beam antennas of today may produce hundreds of beams. Indeed, this brings a twofold advantage: the link budget is improved to small user terminals thanks to the high satellite antenna gain obtained with very narrow beams; and the capacity is increased by reusing the frequency band allocated to the system many times.

Flexible interconnectivity between beams is required more than ever and may be achieved at different network layers by transparent or regenerative on-board processing. Regenerative payloads take advantage of the availability of baseband signals thanks to carrier demodulation. This is discussed in Chapters 7 and 9. Intersatellite links were developed for civilian applications in the framework of multisatellite constellations, such as IRIDIUM for mobile applications, and eventually will develop for geostationary satellites (Chapters 5 and 7). The use of higher frequencies (Ka band at 30/20 GHz) enables the emergence of broadband services, thanks to the large amount of bandwidth currently available, in spite of the propagation problems caused by rain effects (Chapter 5).

1.7 SERVICES

Initially designed as ‘trunks’ which duplicate long-distance terrestrial links, satellite links have rapidly conquered specific markets. A satellite telecommunication system has three properties which are not, or only to a lesser extent, found in terrestrial networks; these are:

— the possibility of broadcasting;
— a wide bandwidth;
— rapid set-up and ease of reconfiguration.

The preceding section describes the state of technical development and shows the development of the ground segment in respect of a reduction in the size of stations and a decreasing station cost. Initially a satellite system contained a small number of earth stations (several stations per country equipped with antennas of 15 to 30 m diameter collecting the traffic from an extensive area by means of a ground network). Subsequently, the number of earth stations has increased with a reduction in size (antennas of 1 to 4 m) and a greater geographical dispersion. The stations have become closer to the user, possibly being transportable or mobile. The potential of the services offered by satellite telecommunications has thus diversified.

— Trunking telephony and television programme exchange; this is a continuation of the original service. The traffic concerned is part of a country's international traffic. It is collected and distributed by the ground network on a scale appropriate to the country concerned. Examples are INTELSAT and EUTELSAT (TDMA network); the earth stations are equipped with 15 to 30 m diameter antennas.
— 'Multiservice' systems; telephone and data for user groups who are geographically dispersed. Each group shares an earth station and accesses it through a ground network whose extent is limited to one district of a town or an industrial area. Examples are TELECOM 2, EUTELSAT, SMS, and INTELSAT (IBS network); the earth stations are equipped with antennas of 3 to 10 m diameter.
— Very small aperture terminal (VSAT) systems; low capacity data transmission (uni- or bi-directional), television or digital sound programme broadcasting [MAR-95]. Most often, the user is directly connected to the station. VSATs are equipped with antennas of 0.6–1.2 m in diameter. The introduction of Ka band will allow even smaller antennas (USAT, Ultra Small Aperture Terminals) to provide even larger capacity for data transmission, allowing multimedia interactivity, data-intensive business applications, residential and commercial Internet connections, two-way videoconferencing, distance learning and telemedecine.
— Digital audio, video and data broadcasting; the emergence of standards for compression, such as the MPEG (Motion Picture Expert Group) standard for video, has triggered the implementation of digital services to small earth stations installed at the user's premises with antennas of the order of a few tens of centimetres. For *television*, such services using the DVB-S standard are progressively replacing the former broadcasting of analogue programmes. Examples of satellite systems broadcasting digital television are ASTRA, HOT BIRD, DirectTV, ASIASAT, etc. For *sound*, several systems incorporating on-board processing have been launched in such a way as to allow FDMA access by several broadcasters on the uplink and time division multiplexing (TDM) on a single downlink carrier of the sound programmes. It avoids the delivery of the programmes to a single feeder earth station, and allows operation of the satellite payload at full power; This approach combines flexibility and efficient use of the satellite. Examples of such satellite systems are Worldspace, Sirius/XM-Radio. The ability of the user terminal to process digital data paves the way for satellite distribution of files on demand through the *Internet*, with a terrestrial request channel or even a satellite-based channel. This anticipates the broadband multimedia satellite services.
— Mobile and personal communications; despite the proliferation in cellular and terrestrial personal communication services around the world, there will still be vast geographic areas not covered by any wireless terrestrial communications. These areas are open fields for mobile and personal satellite communications, and they are key markets for the operators of geostationary satellites, such as INMARSAT, and of non-geostationary satellite constellations, such as IRIDIUM and GLOBALSTAR. The next step bridging the gaps between fixed, mobile and broadcasting services concerns satellite multimedia broadcast to fixed and mobile users, known as satellite digital mobile broadcasting (SDMB). Mobile TV services are available on terrestrial 3G networks in a point-to-point mode, not optimised to deliver the same content to many users at the same time. Smart overlay broadcast networks based on hybrid satellite–terrestrial mobile systems will efficiently provide end users with a full range of entertainment services with interactivity [WER-07]. A dedicated standard (DVB-SH) has been developed for these mobile broadcast applications.
— Multimedia services; these services aggregate different media, such as text, data, audio, graphics, fixed or slow-scan pictures and video, in a common digital format, so as to offer excess potential for online services, teleworking, distance learning, interactive television,

telemedicine, etc. Interactivity is therefore an embedded feature. They require an increased bandwidth compared to conventional services such as telephony. This has triggered the concept of an *information superhighway*. Satellites complement terrestrial, high-capacity fibre, cable-based networks with the following characteristics: use of Ka band, multibeam antennas, wideband transponders (typically 125 MHz), on-board processing and switching, a large range of service rates (from 16 kbit/s to 10 Mbit/s) and quasi-error-free transmission (typically 10^{-10} bit error rate).

1.8 THE WAY FORWARD

In the last 30 years, the satellite telecommunications landscape has changed significantly. Advances in satellite technology have enabled satellite telecommunications providers to expand service offerings. The mix of satellite telecommunications is continuously evolving. Point-to-point trunking for analogue voice and television was the sole service initially provided by satellites 30 years ago. In addition, telecommunications satellites today are providing digital audio and video broadcasting, mobile communications, on-demand narrowband data services and broadband multimedia and Internet services. The mix of service offerings will continue to change significantly in the future.

Satellite services can be characterised as either satellite relay applications or end-user applications (fixed or mobile). For *satellite relay applications*, a content provider or carrier will lease capacity from a satellite operator, or will use its own satellite system to transmit content to and from terrestrial ground stations where the content is routed to the end user. Relay applications accounted for around \$10 billion in 2000. *End-user satellite applications* provide information directly to individual customers via consumer devices such as small antenna (less than earth station) and hand-held satellite phones. End-user applications accounted for about \$25 billion in 2000. It was reported by the Satellite Industry Association on 11 June 2008 that the worldwide market in 2007 was \$123 billion; the average of annual growth was 11.5% from 2002 to 2007 and jumped to 16% in 2007; satellite services grew 18% in 2007 to \$37.9 billion, of which TV accounted for three quarters; launch was \$3.2 billion, up 19%; ground equipment was \$34.3 billion, up 19%; and satellite manufacture was \$11.6 billion, dipping slightly (reflecting a larger number of micro-satellites).

The DVB-S2 standard was published in March 2005 and it has been quickly adopted by industry. It is reported by the DVB forum that major broadcasters in Europe have started to use DVB-S2 in conjunction with MPEG-4 for High Definition Television (HDTV) services; examples include BSkyB in UK and Ireland, Premiere in Germany and Sky in Italy. It has also been deployed in America, Asia and Africa.

There are also many initiatives for satellites to deliver a range of multimedia services targeting fixed terminals at Ka band (Telesat Anik F2 multispot Ka band, Eutelsat Ka-Sat) [FEN-08], broadband mobile terminals on board planes, trains and ships at Ku or Ka band (satellite-on-the-move communications) [GIA-08], or fixed and mobile users with hybrid terrestrial/satellite systems at S-Band [SUE-08, CHU-08]. Satellite digital mobile broadcasting (SDMB) is a new service that is expected to show a significant growth in the years to come. Other initiatives include the provision of air traffic management services [WER-07].

Numerous new technologies are under development, in response to the tremendous demand for emerging global telecommunications applications. Improved technology leads to the production of individual satellites that are more powerful and capable than earlier models. With larger satellites (up to 10 000 kg) able to carry additional transponders and more powerful solar arrays and batteries, these designs will provide a higher power supply (up to 20 kW) to support a greater number of transponders (up to 150). New platform designs allowing additional capacity for station-keeping propellant and the adoption of new types of thrusters are contributing to increased service life for geostationary satellites of up to 20 years. This translates into an increased capacity from satellites with more transponders, longer lives, and the ability to transmit more data through increasing rates of data compression.

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