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Satellite-Based Mobile Communications

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2.1 Introduction

Mobile satellite communications began in 1976 with the launch by COMSAT of the MARISAT satellites to provide communications to ships at sea. The International Maritime Satellite Organisation (INMARSAT) was subsequently formed in 1979, and that organization now provides mobile satellite communications services to aircraft and land-based terminals. A number of national mobile satellite communications systems also serve the United States, Canada, Australia, and Japan with many more planned.

The spectacular growth of terrestrial mobile communications systems has provided a catalyst for efforts to provide global mobile communications through the use of mobile satellite communications systems in low-, medium-, and geostationary-Earth orbit.

Until now, second-generation terrestrial and satellite mobile communications systems have existed as two independent environments. However, these environments are beginning to combine to form a third-generation global mobile communications system in which terrestrial and satellite systems have complementary instead of independent roles and form a single universal integrated system.

This chapter addresses satellite mobile communications systems, that is, satellite systems providing telecommunication services directly to mobile end users.

2.1.1 A Brief History of Satellite Communications

In an article in *Wireless World* in 1945, Arthur C. Clarke proposed the idea of placing satellites in geostationary orbit around Earth such that three equally spaced satellites could provide worldwide coverage. However, it was not until 1957 that the Soviet Union launched the first satellite *Sputnik 1*, which was followed in early 1958 by the U.S. Army's *Explorer 1*. Both *Sputnik* and *Explorer* transmitted telemetry information.

The first communications satellite, the *Signal Communicating Orbit Repeater Experiment (SCORE)*, was launched in 1958 by the U.S. Air Force. *SCORE* was a delayed-repeater satellite, which received signals from Earth at 150 MHz and stored them on tape for later retransmission. A further experimental communication satellite, *Echo 1*, was launched on August 12, 1960 and placed into inclined orbit at about 1500 km above Earth. *Echo 1* was an aluminized plastic balloon with a diameter of 30 m and a weight of 75.3 kg. *Echo 1* successfully demonstrated the first two-way voice communications by satellite.

On October 4, 1960, the U.S. Department of Defense launched *Courier* into an elliptical orbit between 956 and 1240 km, with a period of 107 min. Although *Courier* lasted only 17 days, it was used for real-time voice, data, and facsimile transmission. The satellite also had five tape recorders onboard; four were used for delayed repetition of digital information, and the other for delayed repetition of analog messages.

Direct-repeated satellite transmission began with the launch of *Telstar I* on July 10, 1962. *Telstar I* was an 87-cm, 80-kg sphere placed in low-Earth orbit between 960 and 6140 km, with an orbital period of 158 min. *Telstar I* was the first satellite to be able to transmit and receive simultaneously and was used for experimental telephone, image, and television transmission. However, on February 21, 1963, *Telstar I* suffered damage caused by the newly discovered Van Allen belts. *Telstar II* was made more radiation resistant and was launched on May 7, 1963. *Telstar II* was a straight repeater with a 6.5-GHz uplink and a 4.1-GHz downlink. The satellite power amplifier used a specially developed 2-W traveling wave tube. Along with its other capabilities, the broadband amplifier was able to relay color TV transmissions. The first successful trans-Atlantic transmission of video was accomplished with *Telstar II*, which also incorporated radiation measurements and experiments that exposed semiconductor components to space radiation.

The first satellites placed in geostationary orbit were the *synchronous communication* (*SYNCOM*) satellites launched by NASA in 1963. *SYNCOM I* failed on injection into orbit. However, *SYNCOM II* was successfully launched on July 26, 1964 and provided telephone, teletype, and facsimile transmission. *SYNCOM III* was launched on August 19, 1964 and transmitted TV pictures from the Tokyo Olympics.

The International Telecommunications by Satellite (INTELSAT) consortium was founded in July 1964 with the charter to design, construct, establish, and maintain the operation of a global commercial communications system on a nondiscriminatory basis. The INTELSAT network started with the launch on April 6, 1965, of *INTELSAT I*, also called *Early Bird*. On June 28, 1965, *INTELSAT I* began providing 240 commercial international telephone channels as well as TV transmission between the United States and Europe.

A second global satellite system was established by Intersputnik, founded in 1971, to serve the 14 socialist countries that had not joined the INTELSAT consortium. In 1979, INMARSAT established a third global system. In 1995, the INMARSAT name was changed to the International Mobile Satellite Organisation to reflect the fact that the organization had evolved to become the only provider of global mobile satellite communications at sea, in the air, and on the land.

Early telecommunication satellites were mainly used for long-distance continental and intercontinental broadband, narrowband, and TV transmission. With the advent of broadband optical fiber transmission, satellite services shifted focus to TV distribution, and to point-to-multipoint and very small aperture terminal (VSAT) applications. Satellite transmission is currently undergoing further significant growth with the introduction of mobile satellite systems for personal communications and fixed satellite systems for broadband data transmission.

2.1.2 Types of Telecommunications Satellite Services

Because satellite communications cover the whole range of voice, data, and video transmission, telecommunication satellite services are normally classified into three types:

- *Fixed satellite service (FSS)* networks are mainly intended for long-distance operation of telecommunications networks. FSS satellites are employed to relay signals between large, complex, and expensive Earth stations, which are connected to the terrestrial telecommunications network.

- *Direct-broadcast satellite service (DBS)* networks transmit broadcast and TV signals from a large central Earth station, via a satellite to receive-only Earth stations. DBS receive stations either are distribution heads for cable TV or are located in homes for direct-to-home transmission.
- *Mobile satellite services (MSS)* networks are relayed via satellite between large fixed Earth stations and small mobile terminals fitted to a ship, an aircraft, or a vehicle. Increasingly, MSS networks are formed to relay communications to portable handheld terminals.

In 1996, the ITU defined the *Global Mobile Personal Communications by Satellite (GMPCS)* as comprising the following systems:

- *Geostationary Earth Orbit (GEO) MSS* are for voice and low-speed data mobile personal communications services.
- *Non-GEO (NGEO) MSS* are for narrowband mobile personal communications services excluding voice — because these are invariably based on low-Earth orbit (LEO) satellites, they are also called *Little-LEO.*
- *NGEO MSS* for narrowband mobile personal communications include voice, operating in LEO, medium-Earth orbit (MEO), or highly elliptical orbit (HEO) — also called *Big-LEO.*
- *GEO* and *NGEO FSS* offer fixed and transportable multimedia broadband services — also called *Super-LEO.*

This chapter focuses on MSS for personal communications and therefore considers the first three of these systems: GEO MSS, Little-LEO MSS, and Big-LEO MSS.

2.2 Satellite Orbit Fundamentals

2.2.1 Orbital Mechanics

An understanding of how orbits are chosen and what limitations they have for satellite performance is important in the design and use of a satellite system. Although the field of orbital mechanics is complex, a limited understanding is sufficient to consider the utility of various satellite orbits for MSS applications.

2.2.1.1 Kepler's Laws

Johann Kepler's three laws apply to the motion of satellites in elliptical orbits. Kepler developed these laws empirically, based on conclusions drawn from the extensive observations of Mars by Tycho Brahe (taken around the year 1600). They were originally defined in terms of the motion of the planets about the sun, but apply equally to the motion of natural or artificial satellites about Earth.

First Law

Kepler's first law states that the satellite will follow an elliptical path in its orbit around the primary body, in this case Earth, which is at one of the foci of the ellipse. As illustrated in Fig. 2.1, the point at which the satellite is closest to Earth is called the *perigee,* and the point that it is farthest away is called the *apogee.* In many cases, the orbits selected for use by communications satellites are circular, which is the special case of an ellipse when both foci are coincident.

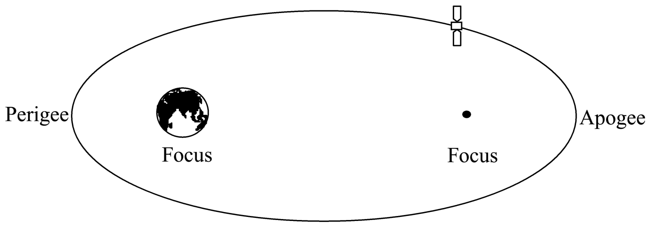

FIGURE 2.1 Illustration of Kepler's first law.

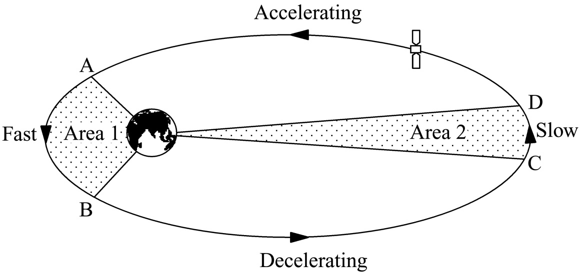

FIGURE 2.2 Illustration of Kepler's second law.

Second Law

Kepler's second law states that the line joining the satellite with the center of Earth sweeps out equal areas in equal times, as illustrated in Fig. 2.2. Area 1 is equal to area 2; the satellite sweeps out both areas in the same time. It follows that the satellite must move more quickly between points A and B than between points C and D.

Third Law

In his third law, Kepler stated that the cube of the mean distance of the satellite from Earth is proportional to the square of its period. Specifically, the orbit period of a satellite, T, at a height h above Earth's surface is

$$T = 2\pi\sqrt{\frac{(R+h)^3}{GM_e}} \text{ hours}$$

where Earth's radius R = 6,378,155 km, the gravitational constant $G = 6.67 \times 10^{-11}$ Nm^2/kg^2, and Earth's mass $M_e = 5.95 \times 10^{24}$ kg (neglecting the satellite mass).

2.2.2 Orbital Variations

Kepler's laws are sufficient to study simple satellite motion, but are not accurate enough to describe real satellites whose orbits are perturbed by Earth's gravitational anomalies and the effects of other bodies such as the sun and the moon. Earth is not a perfect sphere and the sun and the moon exert a gravitational pull on an orbiting satellite. These effects give rise to orbital perturbations and discrepancies between the motion predicted above and the actual motion of the satellite. Additionally, Earth's orbit and rotation must be taken into account to orient the satellite's orbit with respect to the stars.

2.2.2.1 Oblateness and Equatorial Ellipticity

Kepler's laws apply to bodies that are perfectly spherical. Earth is not a true sphere, with a flattening at the poles, and the equatorial circumference not quite circular. The distance from the center of Earth to the north or south poles is less than at the equator by about 20 km. This oblateness of Earth, together with the fact that the equator is not a circle, means that the direction of the force of gravity acting on an orbiting satellite is not toward the center of Earth but is slightly displaced. These effects cause satellites to drift and adjustments are typically required every few months to return them to a nominally geostationary position.

2.2.2.2 Lunisolar Perturbations

Although the effects of the gravitational forces from the moon, and to a lesser extent the sun, are small compared with Earth, there are noticeable perturbations to a geostationary satellite through an inclination of the orbit to the equator. This is evident whether or not the orbit is initially inclined. The energy required to correct for lunar–solar perturbations (perform *station-keeping*) is prohibitive for most satellite applications, although some satellites carry sufficient fuel for such corrections. The more usual approach for small geostationary satellites is to set the orbital inclination initially at 2° to 3°. The lunar–solar perturbation then causes the inclination to move through 0° and back to the initial angle in a period of 4 to 5 years, such that the angle of inclination remains small over the expected life of the satellite.

2.2.2.3 Solar Radiation Pressure

For geostationary satellites, the effects of solar radiation pressure must also be considered. The effect increases with an increase in the size of the surface area of the satellite that is projected in the direction of the sun. This is the case for large powerful satellites that use large solar arrays. The net effect of the solar radiation pressure on a geostationary satellite is to increase the orbital eccentricity and to introduce a disturbing torque affecting the north–south axis of the satellite. Such perturbations are corrected periodically.

2.2.2.4 Atmospheric Drag

Low-orbit satellites suffer atmospheric drag from the friction caused by collision with atoms and ions. The effect of drag is to reduce the ellipticity of an elliptical orbit, making it more circular, and to cause a loss of altitude of a circular orbit. At very low orbital altitudes the friction causes excessive heat on a satellite that finally results in its loss by burning. The orbital lifetime of a satellite (limited by drag) is a complex function of initial orbit height, geometry and mass of the satellite, and ionospheric conditions. However, in predicting a satellite's life, the orbital life must be distinguished from the operational life. The latter is the period during which a satellite performs the planned mission successfully. Moreover, a satellite can continue to orbit for some time after ceasing to function. Conversely, a satellite on low orbit may well reach its orbital life well before its operational life would expire.

For example, the orbital life of a small satellite in a 400-km circular Earth orbit is typically a few months, whereas the orbital life of a similar satellite in an 800-km circular orbit could be several decades. In the case of the 400-km orbit, the functional life of the satellite is mainly governed by the orbital lifetime (except for the less likely situation where the satellite equipment fails earlier), whereas in the latter the functional life depends on the lifetime of the satellite equipment.

2.2.3 Types of Orbit

The height of a satellite above Earth is a major factor in its utility for use within a communications system. Satellite height determines the orbit period, the time that the satellite is visible to a ground station, the footprint (coverage area on Earth's surface), the propagation delay of signals to and from the satellite, and the path attenuation. Other physical influences include the two Van Allen radiation belts (Fig. 2.3);

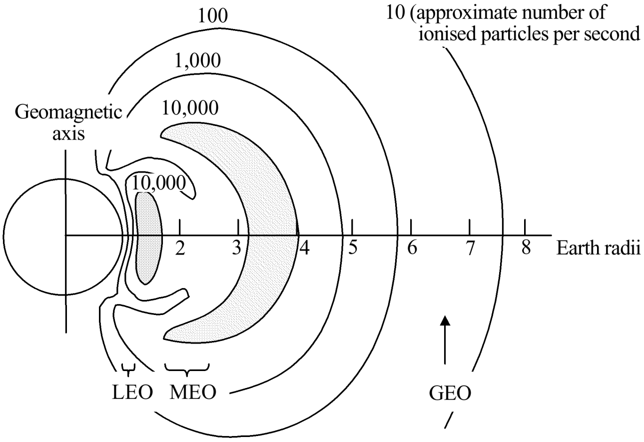

FIGURE 2.3 Satellite orbits and the Van Allen radiation belts.

peaks of radiation occur at altitudes of around 3,000 to 7,000 km and around 13,000 to 20,000 km where prolonged exposure can seriously shorten satellite lifetime. Additionally, altitudes lower than 400 km are uneconomical because of Earth's gravity and the drag of the atmosphere that reduces satellite lifetimes.

Four types of orbit are generally used for telecommunications satellites:

- *Low-earth orbit (LEO)* at heights of between 500 and 2,000 km
- *Medium-earth orbit (MEO)* between 5,000 and 15,000 km — also called *intermediate circular orbit (ICO)*
- *Geostationary earth orbit (GEO)* at 35,786 km
- *Highly elliptical orbit (HEO)* with an apogee that may be beyond GEO

2.2.3.1 Geostationary Earth Orbit

At geostationary altitudes, satellites have an orbital period equal to the period of rotation of Earth. Consequently, they remain in a fixed position in respect to a given point on Earth. An obvious advantage is they are available to all Earth stations within their shadow 100% of the time. The shadow of a satellite includes all Earth stations that have a line-of-sight (LOS) path to it and lie within the radiation pattern of the satellite antenna. At geostationary altitude, the satellite has coverage of 17.3° cone angle, or about 40% of Earth's surface. However, the polar areas are not covered.

Early launch vehicles did not have sufficient capacity to lift useful payloads into geostationary orbit so lower orbits were employed. As launch vehicles improved, GEO satellites became the most popular for telecommunications satellites because they have the following advantages:

- Only three satellites are needed to provide global coverage.
- Each satellite has a large footprint.
- Each satellite remains stationary with respect to Earth, minimizing the need for the terminal to track the satellite.
- The transmitted signal has only a small Doppler shift (affecting synchronous digital systems) caused by satellite movement.
- The technology required is well known after almost 40 years of operating geostationary satellites.

However, for mobile communications, GEO systems have the following major problems:

- High latency — round-trip delay of 250 ms leading to a total of 500 ms for a two-way conversation
- Poor coverage beyond 75° to 80° north and south of the equator
- High path attenuation (mostly from free-space loss) requiring high-power transmitters and large antennas at both the satellite and the mobile terminal
- Large losses resulting from shadowing by buildings in the urban environment
- Limited number of orbital slots available above each country

2.2.3.2 Low-Earth Orbit

LEOs have an altitude of 500 to 1000 km and move over Earth's surface at velocities ranging from 6 to 8 km/s. In contrast to terrestrial mobile communications systems, LEO networks have a highly dynamic network topology. Handover occurs, not only because of movement of mobiles but also because of the satellites passing over the terminals. Because a single LEO cannot provide a communications link for more than a short period, constellations of LEOs are required to provide continuous coverage. The LEO concept was first considered in the 1960s for transoceanic communications using passive reflectors. However, cost and technological constraints restricted large-scale use of LEO systems until the 1990s, when interest in their use grew because of advances in technology coupled with the growing cost of placing GEO satellites into orbit, the congestion of the geostationary orbit, and the development of low-cost launchers.

Reasons why LEO systems are more suited to personal communications services include

- They can make use of small handheld terminals because they require less power and use small omnidirectional antennas.
- They can make more efficient reuse of frequencies.
- They have minimum propagation delay — even at a maximum LEO height of 1000 km, the latency is less than 3.3 ms for each uplink and downlink leading to a total of 13 ms for a two-way conversation.
- They are below the Van Allen belts.
- They are less subject to shadowing than GEO systems.
- They can provide communications coverage of the entire globe.
- They have low satellite launching costs because satellites can be injected directly into orbit, with the ability to launch several satellites in one launch.

However, the use of LEO systems does have some difficulties, such as

- A large number of satellites are required to provide the same coverage as GEO systems.
- To provide uninterrupted communications, frequent handover is required between satellites because of the speed at which the satellite is traveling across the ground.
- Satellites spend considerable time covering empty space (such as oceans and deserts).
- Satellites have a shorter lifetime because of orbital decay.
- Satellite lifetimes are also limited to 5 to 7.5 years because the satellite spends time in eclipse by Earth, providing a significant demand on battery power.

2.2.3.3 Medium-Earth Orbit

MEO — also called intermediate circular orbits — orbit between 5,000 and 15,000 km above Earth's surface. At those altitudes, a terminal would only see the satellite for slightly longer than 1 h, requiring approximately ten satellites in two planes (each plane inclined at 45° to the equator) for complete global coverage. MEOs have larger footprints than LEOs and require fewer satellites to provide the same coverage. However, they require larger, more capable payloads (larger antennas and higher power transmitters) to cater to increased transmission losses.

MEO systems are generally better suited to personal communications services than GEO and have the following advantages when compared with other orbits:

- They are between the Van Allen belts.
- Latency of 17 to 50 ms for each uplink and downlink leads to a total of 67 to 200 ms for a two-way conversation.
- Only a few satellites are required to cover the whole Earth, and each satellite has a relatively large footprint.
- Intersatellite handover is not as frequent as for LEO systems.
- Fewer eclipse cycles than LEO allow longer battery lifetimes of more than 7 years.
- Lower cosmic radiation leads to longer expected lifetimes.
- Higher average elevation angle from terminal to satellite reduces shadowing of LOS.
- Shorter slant ranges require less power than GEO systems, resulting in smaller satellites and mobile terminals.

However, the MEO systems also have some disadvantages, including

- Doppler frequency offsets are larger than for GEO because of higher relative satellite motion, but lower than for LEO.
- Although fewer satellites are required than for LEO, the trade-off between number of satellites and latency is generally considered suboptimum.
- Satellites spend considerable time covering empty space.

TABLE 2.1 Comparison of Satellite Systems as a Function of Orbit

Characteristic	LEO	MEO	GEO
Satellite height (km)	600–1,500	9,000–11,000	35,800
Orbital period (hr)	1–2	6-8	24
Number of satellites	40–80	8–20	2–4
Two-way propagation delay (ms)	10–15	150–250	480–540
Satellite life (years)	3–7	10-15	10–15
Elevation angle	Medium	Best	Good
Visibility of satellite	Short	Medium	Permanent
Handheld terminal	Possible	Possible	Restricted
Handover	Frequent	Infrequent	None
Cost of satellite	Maximum	Minimum	Medium
Gateway cost	Highest	Medium	Lowest
Network complexity	Complex	Medium	Simplest
Radio frequency output power	Low	Medium	High
Propagation loss	Low	Medium	High

2.2.3.4 Highly Elliptical Orbit

HEO satellites have an apogee that may be beyond GEO. Unlike GEO, HEO systems also cover the polar regions, which is why a HEO orbit was chosen for the Molniya system to provide coverage of the former Union of Soviet Socialist Republics. Molniya has a period of 12 h, 8 of which provides coverage of the operational region — for continuous coverage three satellites are required. HEO systems have the advantages of

- Coverage of the polar regions with a small number of satellites
- Lower launching costs
- Higher elevation angle for ground stations
- Lower atmospheric loss

However, HEO systems have significant disadvantages such as

- Requirement for continual tracking of the satellite by Earth station
- Extensive eclipse periods
- Signal fading
- More complex control of the satellites and Earth stations

2.2.4 Orbit Selection

The selection of orbit is effectively dictated by the specifications of the ground terminal. If the terminal is to be handheld, satellites need to be in LEO — or at least MEO — so that the terminal can use low powers and a small omnidirectional antenna. However, at these lower altitudes, the satellite footprint is significantly reduced and a number of satellites are required depending on the altitude.

Table 2.1 summarizes the satellite systems as a function of orbit. Further design trade-off issues are discussed in later sections when specific systems are described.

2.3 Satellite Radio Path

In the radio path between the terminal and the satellite, the major attenuation tends to be caused by free-space loss. There is a multipath component, although this tends to be somewhat different from terrestrial paths. Doppler frequency shift is a significant factor in all types of orbit, although it is most significant in low-Earth orbits where the satellite has the highest speed across the ground. Propagation between the satellite and the ground is also influenced by a number of factors that depend on the polarization of the wave.

2.3.1 Path Loss in a Satelllite Link

2.3.1.1 Free-Space Loss

The major loss in an Earth-satellite path is free-space loss, L_{FS}, which is given by

$$L_{FS} = -92.44 - 20\log d_s f \ (\mathrm{dB})$$

where d_s is the slant range in kilometers and f is in gigahertz.

Figure 2.4 shows the significant increase in free-space loss as the altitude is increased from LEO to GEO altitudes (for a zenith path at 2 GHz).

2.3.1.2 Atmospheric Absorption

Losses occur in Earth's atmosphere as a result of energy absorbed by atmospheric gases. Absorption at any frequency is a function of temperature, pressure, humidity of the atmosphere, and elevation angle of the satellite. Absorption increases with frequency, as elevation angle is reduced and as propagation path is increased. Specific frequency bands have high absorption; the first absorption band, caused by water vapor, is centered around 22.2 GHz, whereas the second band, caused by oxygen, is centered around 60 GHz.

2.3.1.3 Ionospheric Effects

Radio waves traveling between satellites and Earth stations must pass through the ionosphere, which is the upper region of Earth's atmosphere that has been ionized by solar radiation. The free electrons of this layer are not uniformly distributed but form layers. Furthermore, clouds of electrons (known as *traveling ionospheric disturbances*) may travel through the ionosphere and give rise to fluctuations in the signal that can only be determined on a statistical basis. The effects include *scintillation*, *absorption*, *variation in the direction of arrival*, *propagation delay*, *dispersion*, *frequency change*, and *polarization rotation*. All these effects decrease as frequency increases, most in inverse proportion to the frequency squared, and only the polarization rotation and the scintillation effects are of major concern for satellite communications. Other effects are negligible at the frequencies of main interest for satellite communication, except for a small fraction of time under events such as solar flares.

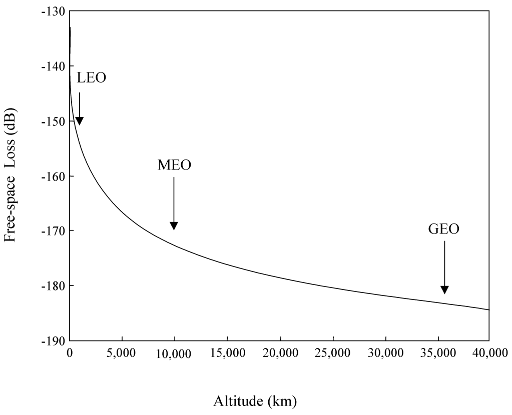

FIGURE 2.4 Free-space loss vs. altitude for a zenith path for a 2-GHz signal.

Polarization Rotation

The radio path between the satellite and the ground is affected by a number of factors that depend on the polarization of the wave. Because the relative geometry of the path is time varying, linear polarization may be difficult to orient, particularly for handheld terminals that may be operated in random orientation. Additionally, the signal is subjected to varying degrees of Faraday rotation, particularly at low frequencies. Both these effects can be overcome by the use of circular polarization in personal communications systems. However, circular polarization is still sensitive to diffraction and reflection of the signal resulting from obstacles in the path, because both reflection and diffraction are polarization sensitive.

Ionospheric Scintillation

Ionospheric scintillations are rapid variations in the amplitude, phase, polarization, or angle of arrival of radio waves. They are caused by small-scale refractive index variations in the F region of the ionosphere caused by local concentrations of ionization. The main effect of scintillations is fading of the signal. The fades can be quite severe, and they may last up to several minutes.

Ionospheric scintillation decreases in proportion to the inverse square of the frequency. Major scintillation is confined to frequencies below about 4 GHz. However, in extreme conditions such as magnetic storms, scintillation can cause problems up to 7 GHz.

Maximum levels of scintillation are observed in a region around the equator. Scintillation also increases in conditions of high solar activity and has a diurnal variation with high sunspot numbers; the peak levels occur approximately 1 to 2 h after sunset. It is interesting to note that, unlike tropospheric scintillation, ionospheric scintillation is independent of the elevation angle of the radio path.

When scintillation is expected at locations of interest, a link margin is provided to mitigate the effect. Link margins of several decibels could be required to achieve high link reliabilities for poorly sited Earth stations and operations below 3 to 4 GHz. At 4 GHz, attenuation resulting from ionospheric scintillation may vary from 0.5 to ~10 dB for 0.1% of the time, depending on the location and the level of solar activity.

2.3.1.4 Attenuation from Hydrometers

Hydrometer is a general term referring to condensed water vapors in the atmosphere, which includes rain, hail, ice, fog, cloud, and snow. All types of hydrometers produce transmission impairments. However, raindrops produce, by far, the maximum attenuation by absorbing and scattering radio waves.

Rain attenuation is a function of *rain rate* (measured in millimeters per hour) in the region of an Earth station. The *specific attenuation*, α, can then be calculated:

$$\alpha = aR_p^b \quad \left(\mathrm{dB\ km^{-1}}\right)$$

where R_p is the rain rate that would be exceeded p percentage time of the year, and a and b are coefficients that depend on frequency and polarization.

Clouds and fog are suspended water droplets, usually less than 0.1 mm in diameter. Attenuation in the radio path depends on the liquid water content of the atmosphere along the propagation path. The liquid content of fog is generally low and the attenuation from fog is negligible for satellite communications. Hail, ice, and snow have little effect on attenuation because of the low water content. However, ice can cause depolarization and subsequent polarization loss.

Only a small link margin is required below 2 GHz to accommodate the additional loss introduced by rainfall. However, at higher frequencies such as 20 to 30 GHz, the rainfall loss is very significant, especially at low elevation angles where an additional link margin of tens of decibels may be required.

2.3.1.5 Multipath Propagation

Unlike terrestrial communications, there are few multiple paths in the earth–satellite path. However, depending on the elevation of the satellite, the path can be obstructed by buildings and trees. From 0° to 20° elevation, the signal propagation is similar to that of terrestrial mobile communications systems in that it suffers frequent multipath effects and significant blockage from obstacles. Above 20°, few multiple paths exist and the signal can generally be considered to be in free space. Unfortunately, most radio paths in personal communications are generally to LEO and MEO heights so that the typical maximum elevation of the satellite is not far above the lowest design elevation angle. The signals at the mobile terminal consist of a direct ray and a Rayleigh distribution of reflected rays with various amplitudes and phases. The resulting distribution may be modeled by the Rice distribution.

Mitigation effects for multipath include the selection of coding and modulation techniques that are able to provide robust operation in a multipath fading environment. A common time-domain strategy is to use convolutional coding and interleaving. Alternatively, a frequency-domain approach is to use convolutional coding and a spread-spectrum technique. ARQ schemes are used to ensure that lost data is retransmitted. The use of high-gain antennas can also significantly reduce multipath.

2.3.1.6 Doppler Shift

The signal transmitted from the satellite is subject to a Doppler shift that results from motion of the satellite as well as the movement of the ground station because of the rotation of Earth. The received signal therefore has the frequency:

$$f_r = f_t \pm f_d = f_t \pm \frac{v_r f_t}{c}$$

where f_r is the received frequency, f_d is the Doppler shift, and v_r is the relative velocity of the satellite relative to the receiver. Note that the Doppler shift is affected by whether the satellite is approaching or receding, which results in the ambiguous ± sign.

2.3.2 Frequency Selection

Table 2.2 lists the frequency bands allocated to satellite transmission. Commercial MSS systems predominantly operate in L-band, although systems will use C-band as well as Ka-band for satellite control and connection to gateways. As discussed earlier, lower frequencies experience lower attenuation. To minimize the power that must be generated onboard the satellite, the downlink frequency is chosen to be lower than the frequency for the uplink.

L-band is very useful for mobile communications because long wavelengths can penetrate many structures and less powerful transmitters are required. L-band is also the least affected by rain because rain attenuation is negligible in this band. However, L-band does suffer from ionospheric scintillation, which results in a split of the signal into direct and refracted paths. L-band also uses circular polarization to reduce the effect of Faraday rotation. S-band suffers less than L-band from ionospheric effects. However, it suffers slightly higher atmospheric attenuation from rain.

Ku-band has medium wavelengths that can penetrate many obstacles and provide high bandwidths. The band requires smaller antennas, but is more affected by rain attenuation.

Ka-band frequencies provide large amounts of available spectrum and high bandwidths. However, powerful transmitters are required and the short wavelengths are subject to strong rain fade — large rain attenuation creates a major technical challenge.

TABLE 2.2 Frequency Bands Allocated to Satellite Transmission

Frequency Band	Frequency (Uplink/Downlink)	User	Service
UHF	400/225 MHz	Military	Mobile
L-band	1.6/1.5 GHz	Commercial	Mobile
S-band	3/2 GHz	Commercial	Satellite control
C-band	6/4 GHz	Commercial	Fixed
X-band	8/7 GHz	Military	Fixed/mobile
Ku-band	14/12 GHz	Commercial	Fixed
Ka-band	30/20 GHz	Commercial	Fixed
Ka-band	44/20 GHz	Military	Fixed/mobile

2.4 Multiple Access Schemes

Whenever access to a satellite is required for a number of Earth stations, it is necessary to employ a multiple-access scheme to allow for a distinct separation between the uplink and downlink transmissions to and from each Earth station. Three *multiple access* schemes are commonly used: *frequency division multiple accessing* (*FDMA*), *time division multiple accessing* (*TDMA*), and *code division multiple accessing* (*CDMA*). Each scheme has its own characteristics, advantages, and disadvantages.

With FDMA, each Earth station is assigned specific uplink and downlink frequency bands within an allotted satellite channel bandwidth. That is, Earth station transmissions are separated in the frequency domain. Each terminal may operate independently with its own carrier, bandwidth, modulation, coding, and data rate. Antenna size varies for each terminal, based on individual link budget calculations. The disadvantages of FDMA include the requirement to reduce the transponder power by approximately one half to minimize intermodulation products. Precise control is also required over uplink power.

With TDMA, all Earth stations use the same carrier frequency and each station transmits a short burst of information during a specific time slot (epoch) within a TDMA frame. The bursts must be synchronized so that each station's burst arrives at the satellite at a different time. That is, transmissions from different Earth stations are separated in the time domain. TDMA is generally superior to FDMA because intermodulation distortion is lower and the full downlink power is available to all users. The main disadvantage is the requirement of accurate timing and synchronization.

With CDMA (sometimes called spread-spectrum multiple access), all Earth stations transmit within the same frequency band and, for all practical purposes, have no limitation on when they may transmit. Signal separation is accomplished by spread-spectrum techniques where each user has a unique code that is used to generate a pseudorandom sequence that is used to spread out the transmission to occupy the entire bandwidth. That is, users are separated by a unique code. At the receiver, the spread signal is despread by applying the same code to the received data. Although CDMA provides high immunity to jamming and has a low probability of interception, it is expensive and can cater to only a limited number of users.

2.5 Mobile Satellite Communications Systems

As discussed earlier, the ITU GMPCS defines three systems for the provision of MSS for personal communications as follows:

- GEO MSS — satellites operating in geostationary orbit providing voice and low-speed data mobile personal communications services
- Little-LEO — NGEO MSS for narrowband mobile personal communications services excluding voice, generally operating in LEO
- Big-LEO — NGEO MSS for narrowband mobile personal communications including voice, operating in LEO, MEO, or HEO

The next section briefly describes the major MSS systems for personal communications.

2.5.1 Geostationary Earth Orbit Mobile Satellite Services Systems

This section briefly gives a short outline of major GEO MSS systems, which use satellites in geostationary orbit to provide voice and low-speed data mobile personal communications.

INMARSAT was created in 1979 with approximately 40 members and has grown to more than 81 member countries. In 1990, INMARSAT launched four satellites into geostationary orbit and launched a fifth satellite in 1998. The new satellites are capable of providing spot beams to increase capacity by more than 20 times over earlier generations. The main advantage is that the increased power and sensitivity of the newer satellites has allowed a significant reduction in the size of the earth terminals, which are now little bigger than a laptop computer. Although INMARSAT provides a number of services, the most mobile is the INMARSAT-M terminal, which is briefcase sized and can provide global digital 6.8-kbps voice and 2.4-kbps fax and data.

Agrani is Afro-Asian Satellite Communications (ASC). Agrani is expected to cover 54 countries — Turkey to Singapore and Byelorussia to Somalia including the Middle East, India, and much of China. Two GEO satellites provide mainly voice, but also provide fax, data, and messaging for fixed and mobile users. The first satellite (expected in 2002) will mainly cover the Indian region, with the second extending coverage across Africa.

The American Mobile Satellite Corporation (AMSC) satellite provides coverage of the United States and regions of U.S. coastal waters, providing voice, messaging, and data services.

The Asian Cellular Satellite System (ACes) *Garuda-1* satellite was successfully launched in February 2000. ACes covers most of Asia from Pakistan to Japan, including southern China and all Association of Southeast Asian Nation (ASEAN) countries and provides mobile and fixed voice, data, fax, and paging.

Euro-African Satellite Telecommunications (EAST) is planned to provide a range of services including narrowband communications to handheld user terminals and higher bandwidth services to VSAT antennas. *Optus MobileSat II* comprises the Australian Optus B1 and B3 satellites and ground stations in Perth and Sydney. Over 1500 mobile terminals operate in the D-band with uplinks and downlinks at 1.6 and 1.5 GHz, respectively. These enable users to communicate from any location on the Australian mainland and 200 km out to sea. Both voice and low-rate data communications are provided.

Thuraya plans to provide high-powered GEO satellites that will cover a footprint of 99 countries throughout Europe, North and Central Africa, the Middle East, Central Asia, and the Indian Subcontinent. The first satellite was launched in October 2000. *Thuraya* will provide voice, fax, data, messaging, and global positioning system (GPS) within handheld and vehicular telephones that will integrate both satellite and cellular communications. A second satellite is planned to provide backup and expansion; a third satellite may follow if required. Other planned GEO MSS systems include: *Africom*, *APMT,* and *Cyprus GEM*.

2.5.2 Little-Low-Earth Orbit Systems

Little-LEO systems are non-GEO (NGO) MSS for narrowband mobile personal communications services excluding voice. Advances in antenna design, signal reception, and miniaturization have allowed the deployment of small LEO systems that can support data transmission at 100 to 300 bps. These systems operate at a frequency below 1 GHz and are only appropriate for nonvoice, store-and-forward messaging.

2.5.2.1 OrbComm

OrbComm was granted a license by the U.S. Federal Communications Commission (FCC) in 1994 and the first two satellites were launched in April 1995. OrbComm provides mobile tracking, remote monitoring, and commercial and personal messaging services. The final OrbComm constellation will consist of 48 small (40 kg) satellites in LEO with a planned life of approximately 4 years. Space-to-ground communications is via very high frequency (VHF): 148 to 150.05 MHz uplink and 137 to 138 MHz downlink. Terminals will transmit at a burst rate of 2.4 kbps and receive at a burst rate of 4.8 kbps giving an effective throughput of 300 bps.

Messages will be sent via OrbComm satellites to gateway stations on Earth, which will either forward the message directly to the destination via terrestrial networks, or store it for access on demand. Although the effective throughput is low, global coverage is provided.

2.5.2.2 Other Systems

VITAsat is managed by Volunteers in Technical Assistance (VITA), a U.S. nonprofit organization dedicated to bringing technical assistance to the developing world. It has entered into agreements permitting usage of two already-orbiting satellites (*HealthSat-2* and *UoSAT-12*) to bring low-cost e-mail services to rural and isolated areas of developing countries.

Leo One Worldwide has announced a little-LEO data-messaging system based on 48 satellites at 950 km in eight orbital planes inclined at 50°. The system will provide data rates of 2.4 to 9.6 kbps for the subscriber uplink and 2.4 kbps for the subscriber downlink. Gateway uplinks and downlinks will operate at 50 kbps. Other systems proposed include *E-Sat*, and *GEMnet*.

2.5.3 Big-Low-Earth Orbit Mobile Satellite Services Systems

Big-LEO systems are NGEO MSS for narrowband mobile personal communications including voice, operating in LEO, MEO, or HEO. These systems operate between 1 and 3 GHz and provide the full range of mobile services including voice and data. They are generally more complex than little LEOs and more satellites are deployed.

2.5.3.1 Iridium

The first fully functioning big-LEO system was Motorola's Iridium, which was probably the most complex of the MSS personal communications systems, providing worldwide voice, data, facsimile, and paging. Iridium satellites perform onboard processing, not only to translate a waveform frequency and retransmit it, but also to process the waveform down to baseband. This allows the satellites to support a variety of packet-oriented services, including routing, flow control, and error detection and correction.

The Iridium space segment consists of 72 satellites arranged in six orbital planes with 11 active and 1 spare satellite per plane at an altitude of 780 km. Satellites were expected to have a life of 5 to 7 years. Each satellite had 48 spot beams, each of which could be shared four ways using time division — the L-band, TDMA-TDD system provided 230 simultaneous conversations per satellite.

Iridium is the only big LEO to use intersatellite links to obviate the need to downlink traffic to hub stations on Earth. Each satellite has four cross-links; one forward within a plane, one backward within a plane, and two across planes. Cross-links operate at 25 Mbps at frequencies between 22.55 and 23.55 GHz. Although onboard processing and satellite cross-links increase flexibility, the advantages are offset by an increase in complexity and satellite weight (500 kg) leading to a satellite cost of U.S. $62 million.

Iridium phone calls are made through the shortest route including the satellite constellation to the terrestrial gateway closest to the destination. Intersatellite links and onboard satellite switching are used to route calls back to a satellite that can "see" a ground terminal. To provide global coverage, 12 ground stations are employed.

Despite meeting most planning deadlines, Iridium failed to attract sufficient subscribers to avoid bankruptcy and, in March 2000, the service was closed. Plans to bring the constellation of satellites down in a controlled reentry were aborted in late 2000 when the assets of Iridium LLC were acquired by Iridium Satellite LLC. The new owner does not see Iridium as a mass consumer service and intends to concentrate on industrial markets and specialized segments.

2.5.3.2 Globalstar

Globalstar has adopted a much simpler approach than Iridium and has employed satellites as a bent pipe with the same technology as used in GEO-based systems. The Globalstar system has 48 satellites twice as high as Iridium at an altitude of 1414 km inclined at 45° and 135° to the equator. Satellites have a lifetime of 5 to 15 years, weigh 704 lb, and have a capacity of 2800 full-duplex circuits. The constellation has eight orbital planes and covers from 70° south to 70° north. Globalstar signals go up to the nearest satellite and down from there to a terrestrial gateway that the satellite can see and are then passed on to existing fixed and cellular telephone networks; the satellite must be in sight of a ground station to complete a call. Complex intersatellite routing is avoided by having 38 ground stations worldwide.

Globalstar offers voice, SMS, roaming, positioning, facsimile, and data. Satellites have six spot beams using L-band CDMA; the full constellation can provide 28,000 simultaneous voice and data channels at 4.8 kbps.

2.5.3.3 Ellipso

Ellipso provides UHF CDMA voice, messaging, and positioning services through 17 satellites. Two inclined, elliptical orbital planes (with an apogee of 2903 km and a perigee of 425 km), each with five satellites effectively providing a LEO system in the Southern Hemisphere and a MEO system in the

Northern Hemisphere. Ellipso will also launch seven of its satellites into two slightly inclined circular planes around the equator to supplement services in the tropics.

The Ellipso ground segment employs 12 ground control stations (GCSs), deploying them near regional fiber hubs for networking efficiency. Each GCS typically tracks and uses two satellites while acquiring a third. The GCS also determines the position of subscriber terminals for administrative, billing, and application purposes.

2.5.3.4 Intermediate Circular Orbit

The Intermediate Circular Orbit (ICO) system was developed as a spin-off from INMARSAT (originally called INMARSAT-P, or Project 21). ICO provides full Earth coverage with ten satellites at 10,355 km arranged in two planes of five satellites in each plane. Satellites have an orbital period of 6 h with each satellite being visible from one point on Earth's surface for typically about 20 min. Twelve ground stations, called *satellite access nodes (SANs)*, are linked by high-speed terrestrial networks. ICO terminals are dual-mode (satellite and terrestrial) handsets and all operations are through existing cellular networks. ICO signals go from ground station to satellite to ground station with users at each end connecting through cellular and land networks. Each ICO satellite has a capacity of around 4500 voice channels using S-band CDMA.

The original ICO system suffered a number of early problems including launch failures during which one satellite was lost. ICO has emerged from bankruptcy with investment from ICO-Teledesic. NewICO has a planned service start date of 2003.

2.5.3.5 Constellation ECCO

The Constellation ECCO system will consist initially of one plane of 12 satellites (11 operational and 1 spare) in circular orbit around the equator, at an altitude of 2000 km. The satellites will transmit directly to mobile and fixed-site users in the 2483.5 to 2500 MHz band and receive directly from these users in the 1610 to 1626.5 MHz band. The system will provide phone and data services to all areas between the tropics.

Each satellite will have 24 antenna beams that collectively cover one eleventh of the equatorial belt. Each of the first-generation satellites will be able to support up to 192,000 subscribers and the whole system will be able to support as many as 1,392,000 subscribers. The design lifetime of these satellites is a minimum of 5 to 7 years.

2.5.3.6 Other Systems

Other planned big-LEO systems include *Movisat*, *MSAT*, and *Satphone*.

2.6 Summary

Over the next few years, a large number of consortia have launched, or are preparing to launch, constellations of satellites that will provide continuous, global phone and data services to mobile terminals. Most systems will be launched into LEO where there are considerable advantages to be gained over higher orbits. Because of the lower altitude, mobile terminals can be small personal handsets with low antenna gain and low-output power. These systems hold the promise of achieving third-generation mobile communications systems of integrating terrestrial and satellite networks providing a similar interface to a small handheld terminal.

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