2

Earth Station Design Philosophy

The previous chapter provided a historical perspective for the ground segment, laying out how earth stations were created and evolved into higher forms. As a radio communication facility, an earth station receives and, in many cases, transmits a properly formatted signal on a reliable and affordable basis. The first earth stations were designed as major facilities that could house the necessary electronic equipment. Like the radio telescopes and tropospheric scatter sites discussed in Chapter 1, these earth stations were impressive in their scale. They bear some resemblance to major earth stations in modern networks used as uplinks, concentration points, and network management centers. Subscriber terminals, on the other hand, must have fewer components and be simple to operate and maintain. A single-function design philosophy was pioneered with C-band backyard dish receivers and the first VSATs drawn from the consumer electronics and telecommunications equipment businesses. We next review basic earth stations and their functions as a foundation for the detailed design discussions in subsequent chapters.

2.1 The Major Earth Station

As the communication hub of literally every application system, major earth stations come in varying sizes and configurations to satisfy the requirements in one or more of the following functions:

- Telephone or telecommunication gateway, allowing remote user terminals or other gateways to gain access to public or private terrestrial networks including the PSTN and the Internet;
- Broadcasting uplink to originate video programming, audio (radio) programming, and data and other noninteractive forms of information;
- Hub in a star network, allowing remote user terminals to connect back to a central location to access a host computer, servers, telephone switching equipment, and private video transmission;
- Network control center, to process requests from remote terminals for service and satellite bandwidth, and to manage the overall satellite telecommunication network.

Because of the modulator and the flexible nature of any large earth station, we can use the generic block diagram provided in Figure 2.1 to explore the various subsystems. Probably the most essential and sensitive aspect is the RF terminal (RFT), which provides the critical direct interface to the space link. The RFT radiates in the assigned frequency band, under control or

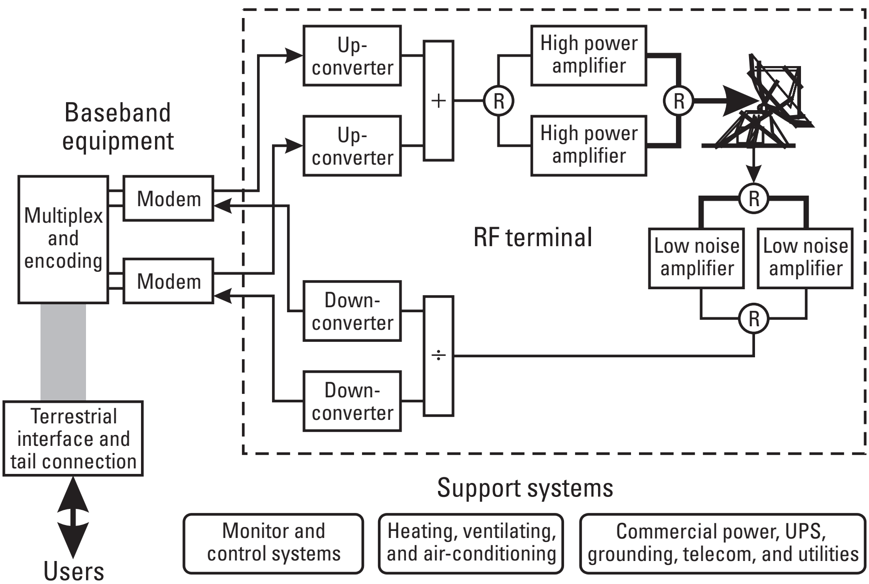

Figure 2.1 Operating elements of a major earth station, including RF terminal, baseband equipment, terrestrial interface and tail connection, and support systems.

direction of the satellite or ground segment operator. Connection to baseband equipment is at a standard intermediate frequency (IF), to simplify connecting different types of transmission equipment, whether analog or digital. The IF center frequency itself is determined by the RF bandwidth of the carrier on the link to the satellite. The actual RF frequency is established by the up converter and down converter, for transmit and receive, respectively. Typical IFs include:

- 70 MHz, supporting a usable bandwidth of 36 MHz (the typical transponder bandwidth at C-band) up to a maximum of 54 MHz (one of a number of bandwidths used at Ku-band);
- 140 MHz, supporting wider IF bandwidths, such as 110 MHz (the upper end of what has been used on some Ku-band satellites);
- 1550 MHz, allowing a total bandwidth of 500 to 1,200 MHz to be passed from the low noise block (LNB) converter on the antenna to internal electronics of the earth station.

The most visible element of an earth station is the outdoor antenna, which can take many forms and sizes to correspond to the application requirements illustrations (gain, beamwidth, and isolation). For GEO satellites, this antenna can remain essentially fixed on the satellite, moving only for initial alignment and if a different orbit position must be viewed. Non-GEO systems put much tougher requirements on this class of antenna to direct the beam at moving spacecraft. Satellites in inclined geosynchronous orbits place a requirement on the antenna for slow-rate tracking. Some or all of the remaining electronic equipment of the RFT is mounted to the antenna to reduce losses and, in the case of reception, reduce the noise temperature. All of these concepts are reviewed below and covered in detail in Chapter 3.

The electronic equipment of the RFT has not changed much in principle since the first systems were constructed. This is because all must perform the basic functions of translating the IF signal to the operating RF frequency, amplifying it to an adequate power level, and connecting it to the antenna (e.g., for the uplink). For reception (the downlink), the RFT collects and amplifies the signal, and then translates it in frequency to IF. Requirements for each of these components are determined through a detailed budgeting process, where the overall specifications of the earth station are allocated to components.

The elements of a compact RFT can be attached to the antenna structure (possibly the feed itself). In large installations with many high-power amplifiers and redundant systems, the RFT may be contained in its own shelter by the antenna, or installed in the earth station building itself. The latter reduces RF equipment maintenance difficulties but introduces more transmit waveguide loss. An exception might be where the antenna is mounted on the roof immediately above the HPAS.

While the RF terminal design is dictated by the satellite link requirements, the baseband equipment is highly specialized and customized for the particular multiple access (ma) method and end-user service requirements. Because baseband equipment is composed of hardware elements performing signal encoding, multiplexing, and modulation, as well as the reverse of these functions, it is usually supplied as an integrated system. In recent years, much of the complex functionality is provided by a custom software component that runs on a dedicated computer or other processor. We find the greatest complexity, and along with it, flexibility, in time division multiple access (TDMA) baseband systems. Frequency division multiple access (FDMA) is usually simpler to configure and manage, since transmissions are kept apart in frequency. An exception to this rule is demand assignment (DA), wherein the channels are assigned dynamically on a call-by-call basis. In this instance, the baseband system requires a considerable degree of automation under software control. The remaining MA method, namely code division multiple access (CDMA), is likewise complex and specialized, with baseband highly customized as well.

The major earth station is in effect a production facility that must operate and be maintained by staff on a 24-hour-a-day basis. Necessary support functions for the generic earth station are indicated at the bottom of Figure 2.1 and summarized as follows:

- *Monitor and control (M&C) systems.* Earth stations can be operated locally by technical staff or, if the system allows it, remotely from a control center. A properly designed M&C system allows staff members to detect, troubleshoot, and resolve technical problems in a timely manner. Most allow operators to configure portions of the station for service and to change the functions being used by customers and subscribers. The facilities to do this are integrated into the equipment and overall station and some could be remoted to a control center by a specialized network.
- *Heating, ventilating, and air-conditioning (HVAC).* Much of the indoor equipment is similar in design and construction to high-quality computer systems, memory, and peripherals, and therefore

should be kept in a hospitable environment. This consists of maintaining temperature and humidity within the proper range for correct and long-life operation. Typical specifications are as follows:

- Temperature: 15° to 25° C
- Humidity: 30% to 70%
- Dust: A consideration in particularly dusty areas. Air should be filtered for particulate matter

- *Power and utilities.* Commercial prime power is typically rated according to the national standard in the particular country. More critical is the tolerance on this voltage, as some equipment might not have been provided with adequate power regulation.
- *Emergency safeguards* (fire, flood, earthquake, heavy wind). Potentially the most difficult and costly factors to address adequately. See applicable sections in Chapter 10.

2.2 User Terminals

While major earth stations have many of the same physical and electronic characteristics, such is not the case with a user terminal (UT), which is intended for a specific application. This is clearly illustrated by comparing a DBS home receiving system to a handheld GMPCS mobile telephone, which is like comparing a VCR to a cordless phone. What is important is that these devices must be simple to operate, reliable in service and function, attractive in appearance and design, and affordable in cost (all of this, of course, is relative). The UT is designed and manufactured like other consumer electronic products, using very large scale integration (VLSI), application-specific integrated circuits (ASIC), and special software programming in read-only memory (ROM). Also, advances in digital signal processing allows designers to convert complex modulation schemes and other algorithms into DSP implementations, which are repeatable in performance and much more cost effective than former analog designs. With manufacturing volumes now reaching hundreds of thousands, or even millions of units, it makes sense to use the latest technology and production systems. Considering first the typical VSAT, its RFT is provided as an integrated package of antenna, feed, and transmitter/receiver (transceiver). On the other end of the interfacility link (IFL) coaxial cable, which carries the IF signals and power for the RFT, is the indoor unit that contains the baseband and interface equipment. The indoor equipment of a conventional VSAT is functionally similar to that of the larger type of earth station used as the hub in this type of star network. However, the quantity of equipment, its bandwidth capability, and degree of redundancy are much less than what one would encounter in the typical large earth station. The indoor unit is contained in an enclosure about the size of a standard PC. Like a PC, it is possible to configure the indoor unit for a particular set of services and transmission features (such as protocol operation, MA, error correction, and control of channel assignment).

We could compare the DTV TV receiver to the common VCR found in most homes. A 45-to-60-cm offset-fed parabolic antenna is used to capture the signals, which are amplified and block translated to a 1 GHz IF in the LNB. The coaxial cable carries about 500 MHz of spectrum into the home to make all of the transponder channels available for demodulation. DC current to power the LNB is carried back over this cable. Within the set-top box, another down converter is tuned to the frequency of the carrier where the desired video channel is located. This assumes a multiple-channel-per-carrier (MCPC) time division multiplex (TDM) scheme such as used in DVD and DSS. The carrier is demodulated down to a single bit stream allowing errors to be removed through forward error correction (FEC). After demultiplexing, the nearly error-free MPEG data is converted back to the appropriate analog video format with stereo sound and other ancillary data (e.g., the electronic program guide and conditional access). Beginning in 2000, DTH receivers were appearing that also include an internal hard drive and control circuitry to allow watchers to pause, replay, and record programs for later viewing.

We complete our brief discussion of user terminals with the handheld GMPCS class of mobile telephone. There are some similarities with VSATs and DTH receivers, but the new demands for compactness require greater customization and miniaturization. Another consideration is battery operation for an extended period (e.g., 2 to 4 hours talk time, 24 to 48 hours standby). Many of the elements in the block diagram are familiar: transmit and receive operation as in a VSAT, inclusion of a digital modem, encryption, forward error correction and microprocessor control as in a DTH receiver, and simplified functional design as in both.

2.3 Design Principles

Earth stations and the ground segments that they comprise are created according to engineering principles established over the twentieth century. This gives us an excellent base with which to understand how these facilities and devices can be built and operated efficiently and cost effectively. The following discussion is an introduction to the topic, to be expanded greatly in coming chapters. We review the basic physical principles of microwave design, satellite and telecommunications systems engineering, and systems operations and maintenance. Readers wishing more fundamental background information may refer to the references at the conclusion of this chapter [1, 2, 3].

2.3.1 Microwave Systems Engineering

Communication between the RFT and the satellite is governed by the basic principles of electromagnetic wave propagation. This spectrum of radiation covers everything from AM radio to light, but we are interested in microwave frequencies between about 1 and 50 GHz (the segment above 30 GHz is more aptly called millimeterwave). As Figure 2.2 indicates, the microwave spectrum is broken up into the familiar L, S, C, X, Ku, and Ka bands actively used in commercial and military satellite communications. These are applied to the different services, namely:

- *Fixed Satellite Service* (FSS), intended for communication among fixed locations on the earth by public telecommunication operators (direct reception by the public is not intended, but is employed throughout the world as another application of this band). Services tend to be broadband in nature (e.g., greater than 100 kbps and typically in the range of 1 to 200 Mbps) due to the RF bandwidth available and the link performance of fixed directional antennas on the ground. Originally allocated for GEO satellites, at least one non-GEO constellation has been granted noninterfering access to this spectrum through subdivision of the allocation.

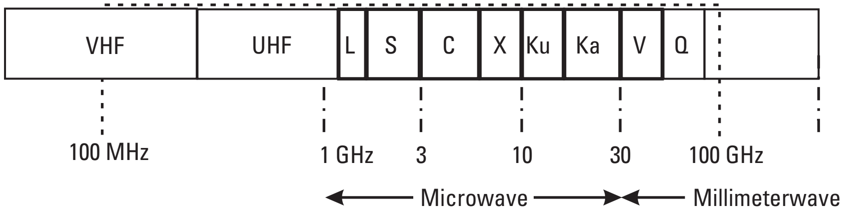

Figure 2.2 Designation of microwave and millimeterwave bands using letter abbreviations (scale is logarithmic and boundaries are approximate).

- *Broadcasting Satellite Service* (BSS), the bands intended for direct reception of broadband information by the public. The Ku-band BSS segment has been assigned into channels and orbit positions for use by individual nations according to a predetermined plan. This service is fundamentally reserved for GEO satellites, although entry is being allowed for at least one non-GEO satellite system within this same spectrum.
- *Mobile Satellite Service* (MSS), the bands around L and S band, which are available for communication with mobile earth stations, including ships, aircraft, vehicles, and persons. The Inmarsat system was established at L-band with GEO satellites followed by domestic satellites for land-mobile services. The public later assigned L and S bands to non-GEO satellite networks for GMPCS applications, although these were slow to gain general acceptance at the time of this writing.

Since many readers are familiar with the basic property of electromagnetic wave propagation in free space, the following is a summary of radio engineering principles, demonstrating their simplicity in mathematical terms. The key elements in the associated RF link are shown in Figure 2.3. For the

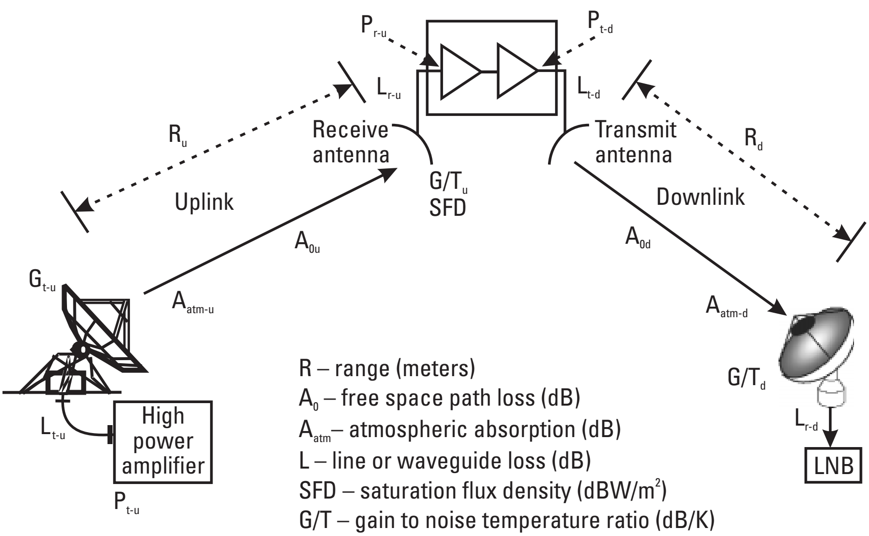

Figure 2.3 Key elements and terms for the uplink and downlink.

typical microwave link on a space-to-earth (downlink) or earth-to-space (uplink) path, the free space loss can be expressed in dB as:

$$A_0 = 183.5 + 20 \log F + 20 \log (R/35{,}788)$$

where F is the frequency in GHz, and R is the range in km.

The factor 20 in front of the log provides the squaring of both the frequency and range in the equation, and the denominator of R (e.g., 35,788) is the mean altitude of GEO. This formula, however, adjusts automatically for any range, including that of a LEO system at, say, 1,000 km.

Another important principle is that the performance of the microwave link can be predicted using the power balance equation, namely:

$$P_r = P_t - L_t + G_t - A_0 - A_{atm} + G_r - L_r$$

where P_r is the power reaching the receiver; P_t is the transmitted power; L_t is the waveguide loss between the transmitter and the transmitting antenna; G_t is the gain of the transmitting antenna; A_0 is the free space loss; A_{atm} is the sum of all atmospheric losses; G_r is the gain of the receiving antenna; and L_r is the waveguide loss between the receiving antenna and the receiver. The receiver is the first low noise amplification stage of the earth station or satellite, depending on whether this is the downlink or uplink, respectively. Transmitted power, P_t, is provided by a high power amplifier (HPA) within the sending end of the link. The most important single element on each end, other than the LNA or HPA, is the antenna used to either radiate the signal into space or to capture it on the receive side. As readers are aware, the performance of the antenna in terms of gain and beamwidth is governed by its effective area (the physical area of the antenna, adjusted downward by the aperture efficiency).

For the typical parabolic reflector type of antenna illuminated by a feedhorn of some type, the on-axis gain of the main beam can be calculated (as a ratio) from [4]:

$$G = \eta \frac{4\pi A}{\lambda^2}$$

where η is the aperture efficiency (λ), A is the physical area of the aperture in square meters, and λ is the wavelength in meters. We can express this formula for a parabolic reflector antenna in a convenient form as follows:

$$G = 10\log(110\eta F^2 D^2)$$

where G is the gain in dBi (e.g., gain relative to an isotropic radiator of 0 dB gain), F is the frequency in GHz, and D is the physical diameter in meters. This assumes a center-fed circular reflector antenna. For noncircular offset-fed reflector antennas (discussed in Chapter 3), it is a common practice to use a mean dimension and adjust for error in the value of η. An important parameter for a parabolic reflector antenna is the half-power (3 dB) beamwidth [5]:

$$\theta_{3dB} \approx \frac{70\lambda}{D}$$

or equivalently for F in GHz and D in meters:

$$\theta_{3dB} \approx \frac{21}{FD}$$

Proper operation of the antenna in the system depends on the polarization of the electric component of the wave, which can be either linear or circular. Since most systems employ frequency reuse in the same beam, it is vital to provide adequate polarization isolation, measured as the difference in dB between the desired and undesired polarizations. For linear polarization, this amounts to proper rotational alignment of the feedhorn, while for circular it is inherent in the feedhorn design itself. The other important characteristic with respect to interference is sidelobe isolation. The following practical formula has become a specification for the maximum expected sidelobe level, in dBi:

$$G(\Theta) = 29 - 25\log(\Theta)$$

where Θ is the angle measured between the main beam and the sidelobe direction. This formula was originally adopted by the U.S. Federal Communications Commission and has become a global standard for frequency coordination between GEO satellite networks. A version of the formula originally adopted by the International Telecommunication Union (ITU) permits 3 dB greater sidelobe level:

$$G(\Theta) = 32 - 25\log(\Theta)$$

The FCC version provides greater confidence of satisfactory operation and would allow closer spacing of satellites as well (in fact, it was adopted back when the FCC wanted to reduce orbit spacing from 4 to 2 degrees).

The effective isotropic radiated power (EIRP) and the gain-to-noise-temperature ratio (G/T) are important figures of merit for earth stations as they establish the RF link performance. The transmit parameter, *EIRP*, is composed of the first three variables in the power balance equation:

$$EIRP = P_t - L_t + G_t$$

expressed in dBW (i.e., dB relative to one watt). From this relationship we see that EIRP can be improved by increasing either P_t or G_t, or by reducing the loss L_t.

The earth station *G/T* is the other figure of merit, i.e.,

$$G/T = 10 \log (G_r - L_r - T_{sys}), \text{ in dB/K}$$

where T_{sys} is the combined receiving system noise temperature in Kelvin. *G/T* has the curious units of dB/K. To compute T_{sys}, we must know the noise temperature of the earth station receiver (assuming this is the downlink) along with the losses associated with the antenna. The following is the basic formula for computing the system noise temperature:

$$T_{sys} = T_a/l_r + (1 - 1/l_r) \bullet 290 + T_{re}$$

where T_a is the antenna temperature (e.g., the cosmic and background noise picked up by the antenna feed and reflector), l_r is the receive waveguide loss expressed as a ratio greater than 1 (e.g., $l_r = 10^{Lr/10}$), and T_{re} is the receiver equivalent noise temperature, e.g., the familiar noise temperature rating of the LNA or LNB, as appropriate.

The purpose of using *G/T* as a figure of merit for an earth station is that we can directly apply it to the link budget to provide a measure of carrier to noise. We see that

$$C/T = EIRP - A_0 - A_{atm} + G/T$$

where *C/T* is the carrier-to-noise-temperature ratio, in dBW/K. Noise power density (N_0 in watts per hertz of bandwidth) is proportional to noise temperature, with the proportionality constant being Boltzmann's constant. We then have the following relationship for carrier to noise density as a ratio:

$$C/N_0 = C/kT$$

where k is Boltzmann's constant (1.380622×10^6 watts/Hz-K).

C/T is converted into carrier-to-noise ratio (C/N) by taking into account the bandwidth of the RF signal that the link supports. The following formula is expressed in dB:

$$C/N = C/T - 10 \log k - 10 \log B$$

where k is Botzmann's constant (note that $10 \log k = -228.6$ dBW/K/Hz) and B is the carrier occupied bandwidth in Hz which is determined by the data rate in bps, R_d, and type of modulation (i.e., $B \approx 0.6 \bullet R_d$ for quadrature phase shift keying [QPSK]).

Because the atmosphere is complex, A_{atm} is really a combination of several losses caused by individual constituents (e.g., oxygen, nitrogen, water vapor, and rain). Specific losses due to air and rain are illustrated in Figures 2.4 and 2.5, respectively [5]. We see that clear air loss is generally well under 1 dB while rain attenuation above about 12 GHz ranges from 2 dB to over 20 dB, depending on the frequency and rain rate. Rain rate, in turn, is a statistical factor produced by the local climate; e.g., we can expect intense heavy rain (resulting in extreme rain attenuation at peak times) in tropical climates like Java, and little rain attenuation during dry months in arid climates like California.

2.3.2 Modem Design

The fact that digital communication has taken over satellites as the primary mode of information transmission is not surprising, since many important innovations in digital communications, such as TDMA and digital voice compression, were first applied to satellite links [6, 7]. As the title of this section suggests, the key earth station component for sending and receiving data is the modem. Readers are familiar with voice-band modems used to send and receive faxes and to connect to the Internet over the public switched telephone network (PSTN). This term is a contraction of modulator/demodulator, reflecting the fact that it provides the dual function of converting a data stream into a modulated carrier, and vice versa. For satellite communication in particular, this is critical because the modem must optimize the transition

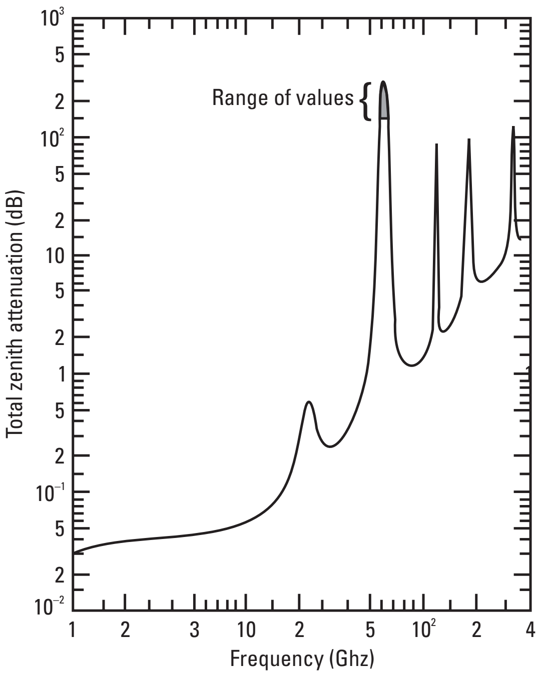

Figure 2.4 Typical atmospheric absorption (dB).

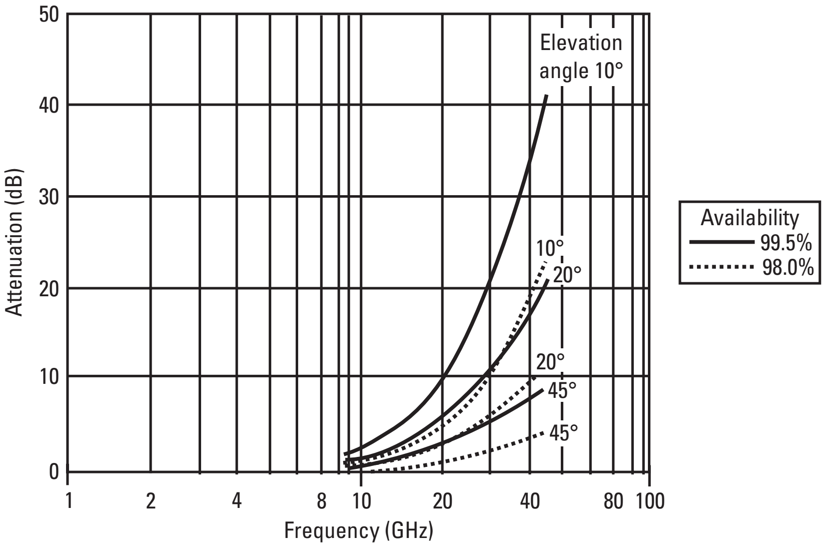

Figure 2.5 Rain attenuation versus frequency for 99.5% and 98% availability in a temperate climate.

between digital information and the analog carrier. The digital side interfaces with the data source after any preparatory processes like multiplexing, compression, and encryption. Often, the modem contains forward error correction (FEC) to reduce the required C/N for satisfactory bit error rate (BER) after the satellite link. The analog functions, to be described below, shape digital pulses to reduce the RF bandwidth, modulate the pulses onto the carrier, and in the case of higher order modulation like QPSK, 8 phase PSK, and 16 quadrature amplitude modulation (QAM) transform the waveform into signals that conserve bandwidth.

The data stream and associated modulated carrier for a biphase shift keying (BPSK) modem are shown in Figure 2.6 [8]. We see a 180-degree phase reversal whenever there is a transition from a zero to a one (or vice versa). Because this illustrates BPSK, the signal does not require the receiver to have an absolute phase reference in order to resolve the sense of the received bit. A block diagram of the modulator is provided in Figure 2.7 to show how nonreturn to zero (NRZ) data is modulated onto the sinusoidal carrier by a balance mixer, then amplified and bandwidth filtered to reduce the spectrum width. The last step is needed to suppress sideband energy and thereby control adjacent channel interference (ACI). Power amplifiers and other nonlinear devices positioned after this filter may re-create the

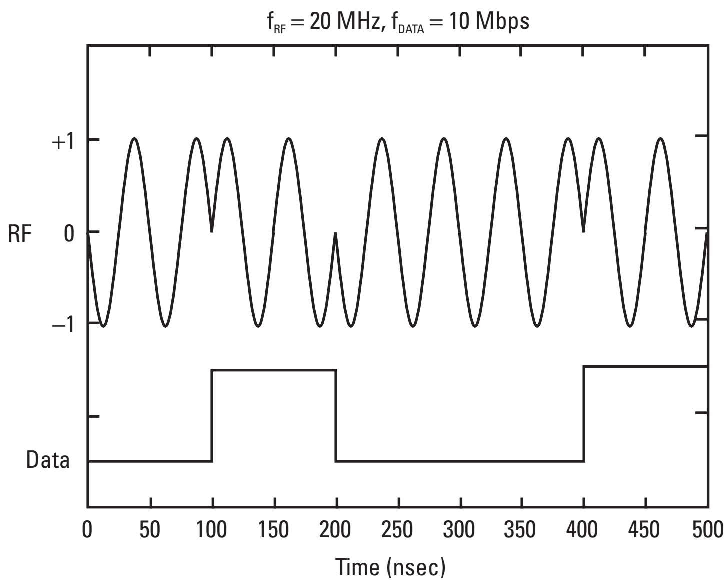

Figure 2.6 BPSK time domain waveforms.

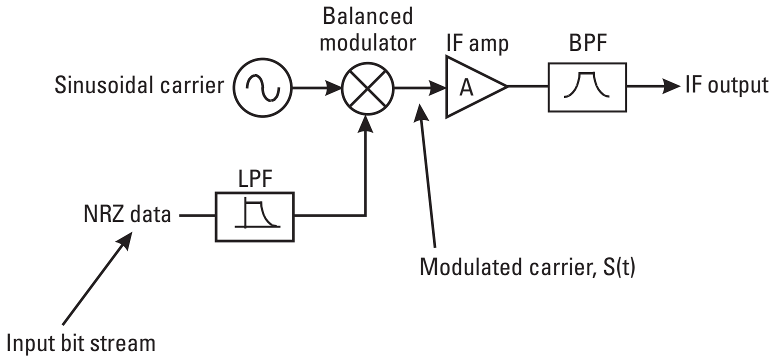

Figure 2.7 Simplified BPSK modulator block diagram.

sidebands and produce ACI in spite of any filtering at the input to the demodulator. The demodulator section (Figure 2.8) determines the final performance BER, which is the ratio of incorrectly received bits divided by the total received bits during a given time interval. These errors are introduced when the received bandwidth contains instantaneous peaks of noise and interference that cancel the desired signal. The problem is further complicated by distortion of the bit pattern itself by bandwidth limiting (which is necessary to reduce the total noise power) and channel impairments such as group delay and AM to PM distortion.

Digital communication link performance is largely determined by the ratio of signal to noise, measured by a parameter called the energy-per-bit-to-noise-density ratio (E_b/N_0):

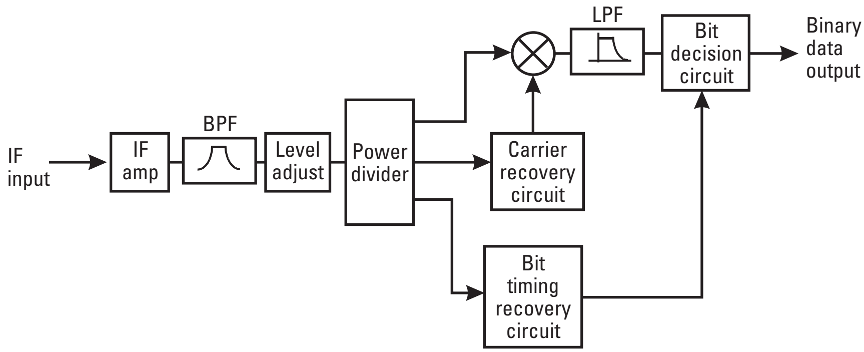

Figure 2.8 Simplified BPSK demodulator block diagram.

$$E_b/N_0 = C/N + 10 \log (B/R_b)$$

The factor B/R_b corrects for a bandwidth offset, namely that B is two sided and R_b is one sided. In a crude sense, E_b/N_0 is 3 dB greater than C/N, although the precise adjustment must account for other factors such as the number of levels (e.g., 4, 8, or 16) per symbol.

A theoretical plot of bit error rate (BER) versus E_b/N_0 is provided in Figure 2.9 for a typical modem performance curve under thermal noise (but excluding other factors such as adjacent channel interference (ACI) and intermodulation distortion (IMD)). Further improvement would be obtained from FEC as this reduces BER by several orders of magnitude at the expense of increasing bandwidth occupancy. However, this tradeoff is almost always favorable, because BER can be improved more effectively by adding FEC than by increasing EIRP.

2.3.3 Multiple-Access Control

Much attention in recent years has been focused on MA systems and the corresponding benefits to the technical performance of the system and ground

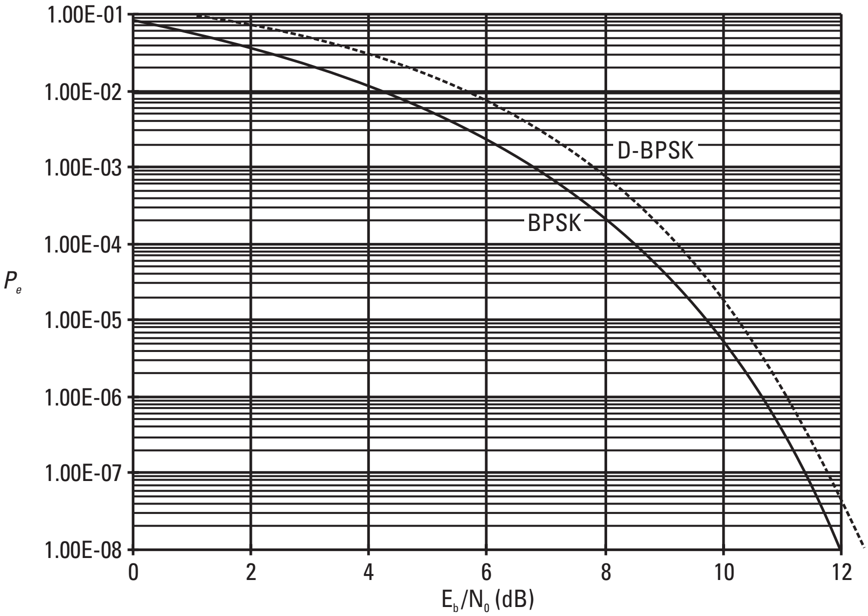

Figure 2.9 Theoretical probability of bit error (P_e) for BPSK and differential BPSK.

segment. The following, in conjunction with Figure 2.10, summarizes the three primary alternatives for multiple access:

- *Frequency division multiple access* (FDMA), where individual earth stations separate their transmissions from each other by uplinking them on different frequencies. This is the simplest MA technique, since stations transmit to the satellite without coordination and with minimal interaction. Single channel per carrier (SCPC) is that form of FDMA where each individual signal (voice conversation, TV program channel, or data stream) gets its own carrier within the satellite repeater. The alternative is to multiplex several channels into a carrier's baseband, which is called multiple channel per carrier (MCPC). In either case, loading of the transponder on a bent-pipe satellite repeater requires management of multiple carriers and the resulting RF intermodulation distortion (IMD). Due to the required amplifier output backoff of 3 to 5 dB, the capacity of the transponder is reduced by at least 50%.
- *Time division multiple access* (TDMA), where separation is achieved by having earth stations transmit their data as bursts at different times, according to a preset time frame. Thus, the transmissions

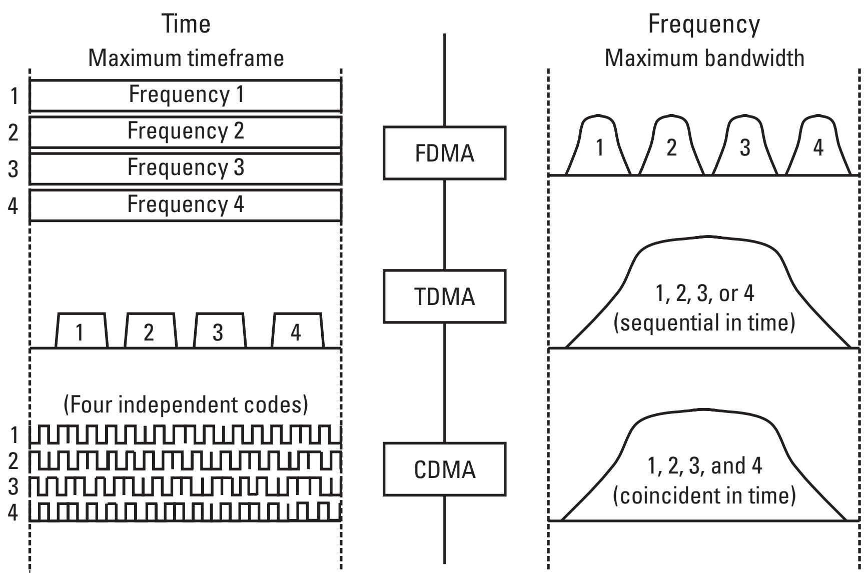

Figure 2.10 Time and spectrum illustrations of FDMA, TDMA, and CDMA, assuming four transmitting earth stations.

must be synchronized in time to prevent collisions among the transmissions when received at the satellite. An alternative form of TDMA, called ALOHA, allows earth station transmissions to be uncoordinated and so introduces the possibility of collisions and a corresponding requirement for automatic retransmission. In wideband TDMA, the burst transmissions at between 60 and 250 Mbps use the full bandwidth and power of the transponder, resulting in nearly 95% efficiency (allowing for the necessary synchronization overhead and guard time between bursts). Alternatively, TDMA networks can use lower data rates (between 64 Kbps and 15 Mbps) to share the capacity of a transponder in an FDMA mode and reduce the uplink power required from the earth station. The inherent digital feature of TDMA has made it the most popular multiple-access technique for VSAT networks.

- *Code division multiple access* (CDMA), where earth station transmissions are encoded using direct sequence spread-spectrum waveform. This is another popular technique obtained by mixing the user data with a very high-speed stream of bits from a pseudo-random noise (PN) generator. Several carriers may be transmitted on the same frequency but are separated by virtue of the different spreading codes. The information on any particular CDMA channel is recovered at the receiver by multiplying the incoming PN-modulated data by the original PN stream. Prior to data recovery, the CDMA receiver must synchronize to the spreading sequence and lock onto its precise timing (a technique called autocorrelation). CDMA has been made immensely popular by the success of IS-95, the digital cellular radio standard from Qualcomm that is based on this multiple-access mode [9].

The baseband characteristics, equipment configurations, software requirements, and management systems for these three MA techniques are very different. What is more, the particular design for a given supplier will likely be incompatible with that of another. An exception is for INTELSAT, Inmarsat, and EUTELSAT standards that have open architectures intended for use by multiple international operators. It would be necessary to examine, in detail, the corresponding elements of the earth station to uncover how the MA functions have been implemented. In simplified block diagrams, MA shows up as a box or a footnote, but in reality, the necessary logic can be dispersed throughout several elements. For example, the modem would appear as a single box in the diagram, but will differ in its internal design.

Shown in Figure 2.10 are the time and spectrum diagrams for the three MA methods, indicating how one transponder would be occupied by four earth station transmissions. In the FDMA time frame, all four transmissions are visible, with each at an independent frequency. There are three potential concerns with FDMA: IMD produced by a common satellite or earth station RF amplifier, ACI due to unfiltered out-of-band spectrum energy or error of the center frequencies (e.g., frequency tolerance), and transponder overdrive due to carrier power imbalance.

In wideband TDMA, the transmissions occur at different times but employ the full transponder bandwidth; separation is guaranteed by proper timing of the bursts and adequate guard times to prevent overlap. The fact that only one wideband spectrum is shown is not a concern, because the stations do not transmit at the same time (the spectrum illustration is, in effect, a snapshot taken when only one of the four stations is transmitting). A picture of narrowband TDMA would look like the FDMA case, since the burst occupies only a fraction of the total bandwidth. However, the picture is once again a snapshot in time, with several earth stations sharing the narrowband RF channel.

For the CDMA spectrum arrangement in Figure 2.10, the summation of signals from the four stations is because they transmit at the same time and may each utilize the full bandwidth. The way that the signals are separated at receivers is through the autocorrelation function previously mentioned. To provide independence, CDMA requires that different PN codes be used by each transmitting earth station; otherwise the receiver will not be able to separate the data. In practice, there is a limit to the number of simultaneous CDMA signals on the same frequency because unwanted transmissions appear as additional receiver noise. Also, RF power level in the satellite repeater and earth station receiver must be kept within a narrow range to prevent elevated carriers from producing more RF interference than can be tolerated on a system basis. CDMA has an advantage over TDMA and FDMA in that it can reject narrowband RFI that could appear in the occupied bandwidth.

The control of the earth station transmissions in a common MA ground segment is critical to the overall management of space segment resources and the delivery of effective user services. In FDMA, this management can be manual, using centralized network control, where operators can monitor transmissions and react quickly to problems. An automated demand assignment multiple access (DAMA) system would be under computer control and comparable to a first-generation analog cellular radio network—i.e., carrier frequencies are assigned temporarily for connections between pairs of earth stations, and then taken back for use by other stations when needed.

TDMA is the embodiment of a digital network via satellite. Also used in the digital advanced mobile phone system (D-AMPS) and global system for mobile communicaitons (GSM) cellular radio standards, this MA technique was originally pioneered on satellite for the INTELSAT system [6] [10]. The principle benefit is maximum usage of the available power and bandwidth without experiencing IMD. The control of burst transmissions within the time frame is provided through a synchronization system and traffic-control methodology exercised by a central network management facility (located at the hub station or one of the earth stations in the network). Control in a CDMA network is simplified in light of the fact that neither network frequency nor burst timing is critical to operation. However, there are still issues regarding the total loading of the transponder and control of individual power levels. These networks are designed with automatic schemes to adjust parameters dynamically, in response to traffic and power loading.

2.3.4 End-to-End Satellite Networks

The ground segment in satellite communication is not an end in itself, but rather is a piece of the overall delivery system for telecommunication or information services. Therefore, we must keep in mind that our satellite network does not stand on its own, and cannot operate in a vacuum (unlike the space segment). As shown in Figure 2.1, the typical earth station interfaces with a terrestrial segment in order to connect to the final user or, in many cases, an existing public network. The best example is a telephone gateway in an MSS network, where the satellite network connects calls that originated in the public switched telephone network (PSTN).

In many satellite applications, the user terminal is self-contained and does not need to interface with anything or anyone other than the end user. An example is an MSS user terminal in the form of a radio telephone instrument (e.g., a satellite cellphone). As long as the user understands how to operate the device, there is no additional end-to-end interface requirement. The other end of the communication link may still have to be transferred to the PSTN, in which case the MSS service must properly interoperate with existing public services. This can be an extremely difficult task, because of the multitude of operating conditions, types of calls, and differences that exist among forms of the PSTN in different countries (and sometimes within the same country).

There may still be interface requirements at the user terminal when the service must be connected to another device such as a PC or TV set. The PC must have the appropriate interface connector, signaling, and software to assure that the service works correctly. We mentioned previously that data networks using TCP/IP usually require some form of protocol spoofing to compensate for the variable error rate performance and added delay of the space link. With regard to the TV example, there are three international analog standards available (NTSC, PAL, and SECAM), and this is being expanded through the new digital TV (DTV) standards, which are all based on MPEG 2 but may not be identical in detail.

2.3.5 Satellite Systems Engineering and Operation

The daunting task of creating an effective satellite communication system involves many disciplines. The integration of the ground and space segments is crucial, as is the proper interfacing of the system with the user environment on the ground. We have specialists who deal with each of these elements and with the individual components of each element. But it is the job of the systems engineer to understand how all of the pieces work together to meet the overall requirements of the project and operation.

We refer here specifically to a satellite systems engineer, someone who understands the functionality of both the space and ground segments. This kind of expertise is not easy to come by, and in fact many who claim to be qualified are not. In many ways, it is the purpose of this (and the previous) book to create a foundation for entering the field of satellite systems engineering. Any ground segment project will, of necessity, require that the satellite systems engineering function be performed properly at every key step. Such performance draws heavily from generic systems engineering, but we cannot lose sight of the fact that we are talking about a satellite communication system. The first step in any systems engineering effort is to understand and define the requirements. In commercial satellite communication, this includes the purpose and strategy of the business that the system supports. Many system engineers work as part of business development because of the close coupling between the two functions during the formative phase. Because of the many tradeoffs that will be required as the design progresses, we must have a complete knowledge of the technology options and their characteristics (technical and financial).

In this author's experience, it is wise to enlist the talent and resources of outstanding analysts who can put the problem down on paper (and on computer) quickly and produce usable results. These studies form the foundation of the "trade space" for the project. By trade space we mean the collection of technology and performance options that we have considered in evaluating how to achieve the system objectives. Then we look at different ways to design the overall systems and their major components (e.g., the earth stations).

Any good systems engineer can do this, at least in principle. However, a satellite systems engineer is one who understands how the space segment is to be included. Through education and practical experience, the satellite systems engineer can investigate the best satellite design (whether GEO or non-GEO), frequency band, and MA method. By performing the link analyses and sizing exercises, he or she can find the optimum arrangement of earth stations in the overall network.

The operation of the ground segment and earth stations is another critical aspect of the overall system, since this determines the quality of service (QoS) and impacts the financial performance of the business as well. Examples of QoS factors include:

- System availability, measure in percent of time that the service is up and operating;
- Data throughput;
- Connection time (for connection-oriented services) and rate (accounting for frequency of busy signals and dropped calls);
- Information transfer delay (also called latency);
- BER as a function of time;
- Qualitative factors such as customer satisfaction rating.

Many of these factors are set by the design of the ground segment and are under the control of the systems and earth station engineers. However, others are the result of how well the ground segment is operated and maintained, which is something that depends on the people who perform these functions during its lifetime. The operation and maintenance (O&M) of ground segment and earth stations is a complex subject, which is treated in more detail in Chapter 11.

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