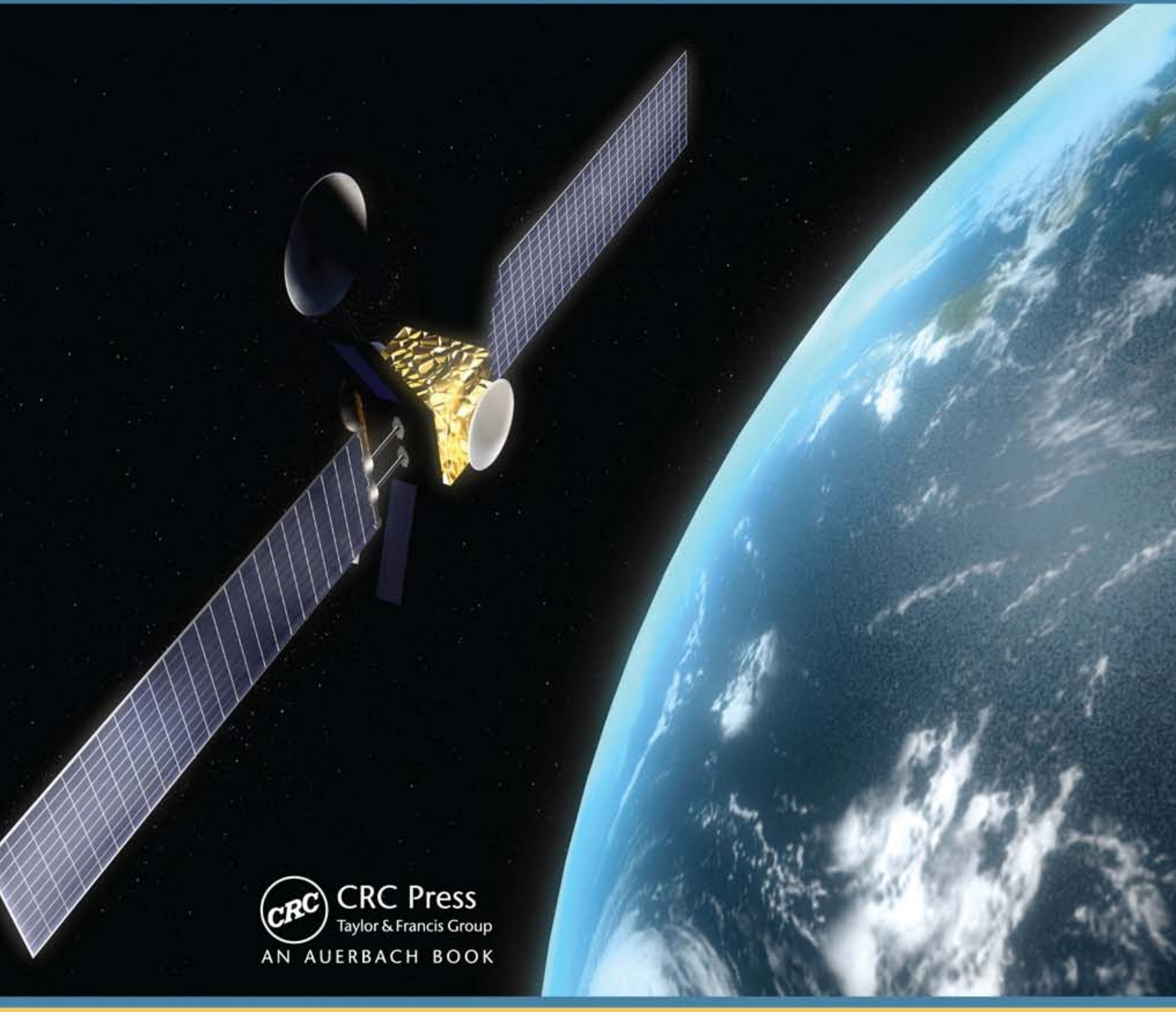
Satellite Systems Engineering in an IPv6 Environment



CRC Press
Taylor & Francis Group
AN AUERBACH BOOK

DANIEL MINOLI

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
AN AUERBACH BOOK

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Version Date: 20131120

International Standard Book Number-13: 978-1-4200-7869-5 (eBook - PDF)

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Dedication

For Anna and the kids.

And for my parents, Gino and Angela

Contents

Preface

This book provides a practical guide to satellite transmission engineering. Although there are a number of textbooks in the field, this book has two distinguishing features: (1) the focus is more on practical results and less on the actual derivation of the mathematical equations, and (2) usage of satellite transmission in an IPv6 environment is highlighted. This is the first book on the market to address the issue of satellite communications in IPv6 networks. Key aspects to consider include transmission theory, impairments, antennas' geometry/size, and reception techniques. Modulation is fundamental to any transmission system and high symbol-rate digital modulation in satellite transmission is now the norm. Multiplexing is also an important capability in any modern communication system. Multiplexing can take place at the physical layer, at the data-link layer, and at the packet layer. Many variables control the quality, bandwidth, and reliability of the received signal, such as transmit power, antenna/Low Noise Amplifier gain, antenna size, fade phenomena, and Forward Error Correction techniques, among others. A Link Budget Analysis determines the kind of tradeoffs that can be made to achieve engineering objectives. IPv6 is increasingly being deployed around the world. Because of intrinsic latency in satellite transmission, special considerations have to be taken into account for TCP traffic, in order to optimize throughput. As a corollary of multiplexing techniques, Very Small Aperture Terminals make use of statistical in-channel multiplexing to support a relatively large base of medium-throughput users, especially for data applications. All of these topics are discussed at a pragmatic level in this text.

There is now a global interest by (all) the telcos in Europe, Asia, and North America to enter the Internet Protocol TV (IPTV) distribution, and Digital Video Broadcast–Handheld (DVB-H), or OMA BCAST mobile video markets in order to replace revenues that have eroded to cable TV companies and wireless providers. Nearly all the traditional telcos worldwide are looking into these technologies at this juncture. Telcos need to compete with cable companies and IPTV, and DVB-H is the way to do it. In fact, even the cable TV companies themselves are looking into upgrading their ATM technology to IP. While these services are now starting out by using IPv4, IPv6 is just around the corner. Finally, government agencies looking to deploy IPv6 and also use satellite communication can benefit from this text.

After the Introduction, Chapter 2 covers electromagnetic propagation. Chapter 3 discusses basic antenna theory. Modulation and multiplexing techniques are discussed in Chapter 4. Chapter 5 covers Forward Error Correction. The critical topic of Link Budget Analysis is discussed in Chapter 6. IPv6 is discussed in Chapter 7. TCP/IPv6 issues are covered in Chapter 8. Considerations related to IPv6 support in satellite environments are surveyed in Chapter 9 and in Appendix A.

Telephone carriers (telcos), equipment manufacturers, content providers, content aggregators, satellite companies, venture capitalists, and colleges and technical schools can make use of this text. The text can be used for a college course on satellite applications to video distribution, specifically IPv6, IPTV, DVB-H, and datacasting.

It is not the goal of this book to present an exhaustive view of the satellite field. There is a very extensive literature on the topic of satellite communications; however, this text looks at the issues from a forward-looking and pragmatic perspective.

Acknowledgments

The author would like to thank William B. McDonald, WBMSAT P.S., Inc., for his review of Chapters 1 through 4 of the manuscript.

Also thanking Mike Noon, SES Engineering.

About the Author

Daniel Minoli has many years of technical hands-on and managerial experience (including budget or PL responsibility) in networking, telecom, wireless, video, Enterprise Architecture, and security for global Best-In-Class carriers, service providers, and financial companies. He has worked at financial firms such as AIG, Prudential Securities, Capital One Financial and service provider firms such as Bell Telephone Laboratories, ITT, Bell Communications Research (now Telcordia), AT&T, Leading Edge Networks, Inc., and SES Engineering, where he is director of Terrestrial Systems Engineering. SES is the largest satellite communications company in the world. He also played a founding role in the launching of two companies through the high-tech incubator Leading Edge Networks, Inc., which he ran in the early 2000s: Global Wireless Services, a provider of secure broadband hotspot mobile Internet and hotspot VoIP services; and, InfoPort Communications Group, an optical and Gigabit Ethernet metropolitan carrier supporting Data Center/SAN/channel extension and Grid Computing network access services. For several years he has been session, tutorial, and now overall technical program chair for the IEEE ENTNET (Enterprise Networking) conference. ENTNET, part of IEEE Globecom, focuses on enterprise networking requirements for large financial firms and other corporate institutions.

At SES Engineering Mr. Minoli has been responsible for engineering satellite-based video, Internet, IPTV, and DVB-H systems. This includes overall engineering design, deployment, and operation of SD/HD encoding, inner/outer AES encryption, Conditional Access Systems, video middleware, Set Top boxes, Headends, and related terrestrial connectivity. At Bellcore/Telcordia he did extensive work on broadband, on video-on-demand for the RBOCs (then known as Video Dialtone); on multimedia over ISDN/ATM, and on distance learning (satellite) networks. At DVI he deployed a (satellite-based) distance learning system for William Patterson College. At Stevens Institute of Technology (where he was an adjunct professor) he taught approximately a dozen graduate courses on digital video. At AT&T he deployed large broadband networks to also support video applications, for example, video over ATM. At Capital One he was involved with the deployment of corporate video-on-demand over the IP-based intranet. As a consultant he handled the technology-assessment function of several high-tech companies seeking funding, developing multimedia, digital video, physical layer switching, VSATs, telemedicine, Java-based CTI, VoFR and VPNs, HDTV, optical chips, H.323 gateways, nanofabrication/(Quantum Cascade Lasers), wireless, and TMN mediation.

He has also written columns for *ComputerWorld, NetworkWorld*, and *Network Computing* (1985–2006). He has taught at New York University (Information Technology Institute), Rutgers University, and Stevens Institute of Technology (1984–2006). Also, he was a Technology Analyst at Large for Gartner/DataPro (1985–2001); based on extensive hands-on work at financial firms and carriers, he tracked technologies and wrote CTO/CIO-level technical scans in the area of telephony and data systems, including topics on security, disaster recovery, network management, LANs, WANs (ATM and MPLS), wireless (LAN and public hotspot), VoIP, network design/economics, carrier networks (such as metro Ethernet and CWDM/DWDM), and E-Commerce. Over the years he has advised venture capitalists for investments of $150M in a dozen high-tech companies. He has acted as expert witness in a (won) $11B lawsuit regarding a VoIP-based wireless air-to-ground communication system, and has been involved as a technical expert in a number of patent infringement proceedings.

Chapter 1

Introduction to Satellite Communications

Satellite communication plays, and will continue to play, a key role in commercial, TV/media, government, and military communications because of its intrinsic multicast/broadcast capabilities, mobility aspects, global reach, reliability, and ability to quickly support connectivity in open-space and/or hostile environments. At a different level, Internet Protocol version 6 (IPv6) is a technology now being deployed in various parts of the world that allows true explicit end-to-end device addressability. As the number of intelligent systems that need direct access expands to the multiple billions (e.g., cell phones, personal digital assistants (PDAs), appliances, sensors/actuators/Smart dust, and even body-worn biometric devices), IPv6 becomes an institutional imperative in the final analysis. The integration of satellite communication and IPv6 capabilities promises to provide a powerful networking infrastructure that can serve the evolving needs of government, military, IP-based television (IPTV), and mobile Digital Video Broadcast Handhelds (DVB-H) stakeholders, to name just a few.

This text provides a pragmatic assessment of satellite communication and engineering in an IPv6 environment and in light of newly evolving applications. Because the U.S. government is a major user of satellite systems and a proponent of IPv6, this text may be of interest to this community of users, among others. The satellites of the future will not only be signal regenerators in space but will contain onboard IP and IPv6 routers to facilitate intelligent traffic distribution; hence, it is important to understand the interplay and overlaying of IPv6 routing over a satellite-based transmission channel. The first part of the text (Chapters 1 through 6) focuses on traditional engineering issues, and the second part (Chapters 7 through 9) focuses on IPv6.

This chapter provides an introductory overview of the field, whereas chapters that follow provide more details on some key aspects of the technology, particularly those that have relevance to the IPv6 and related, or evolving, services. After this introduction, Chapter 2 covers electromagnetic propagation. Chapter 3 discusses basic antenna theory. Modulation and multiplexing techniques are discussed in Chapter 4. Chapter 5 covers Forward Error Correction (FEC). The critical topic of Link Budget Analysis is discussed in Chapter 6. IPv6 is discussed in Chapter 7. Transmission Control Protocol (TCP)/IPv6 issues are covered in Chapter 8. Initiatives and considerations related to IPv6 support in satellite environments are surveyed in Chapter 9 and Appendix A. There is an extensive body of literature on the topic of satellite communications (including such minor contributions as [MIN197901], [MIN197801], [MIN198601], and [MIN199101]); however, this chapter looks at the issues from a forward-looking but pragmatic perspective.

1.1 Satellite Orbits

Satellite communication is a line-of-sight (LOS) one-way or two-way radio frequency (RF) transmission system that comprises a transmitting station (uplink), a satellite system that acts as a signal regeneration node, and one or more receiving stations (downlink). (See Figure 1.1.) Satellites can reside in a number of orbits. A geosynchronous (GEO) satellite* circles the earth at the earth's rotational speed and in the same direction of rotation, therefore appearing at the same position in the sky at a particular time each day. When the satellite is in the equatorial plane, it appears to be permanently stationary when observed from the earth's surface, so that an antenna pointed to it will not require tracking or (major) positional adjustments at periodic intervals of time (this satellite arrangement is also known as *geostationary*†,‡). The geostationary orbit is at an altitude of 35,786 km (22,236 mi.) from the earth's surface (42,164 km from the earth's center, the earth's radius being 6,378 km). See Figure 1.2.

The major consequence of the geostationary orbital position is that signals experience a propagation delay of no less than 119 ms on an uplink (longer for earth stations at northern latitudes or for earth stations looking at satellites that are significantly offset longitudinally compared with the earth station itself§), and no less than 238 ms for an uplink and a downlink or a one-way end-to-end transmission path. A two-way interactive session with a typical communications protocol, such as TCP, will experience this roundabout delay twice (no less than 476 ms) because the information is making two round trips to the satellite and back. One-way or broadcast (video or data) applications easily deal with this issue, as the delay is not noticeable to the video viewer or the receive data user. However, interactive data applications and voice backhaul applications typically have to accept (and adjust to) this predicament imposed by the limitations

* In this book, whenever we use the term *satellite,* we mean a geostationary communications satellite, unless noted otherwise by the context.

† In practice, the terms *geosynchronous* and *geostationary* are used interchangeably.

‡ A geostationary orbit is a circular prograde orbit (prograde is an orbital motion in the same direction as the primary's rotation) in the equatorial plane, with an orbital period equal to that of the earth; hence, a satellite in a geostationary orbit appears to be fixed above the surface of the earth, that is, it is at a fixed latitude and longitude.

§ Depending on the location of the earth station and the target satellite (which determines the look angle), the path length (and so the propagation delay) can vary by several thousand kilometers. (e.g., for a satellite at 101°W and an antenna in Denver, Co., the "slant" range is 37,571.99 km; for an antenna in Van Buren, ME, the range is 38,959.54 km.)

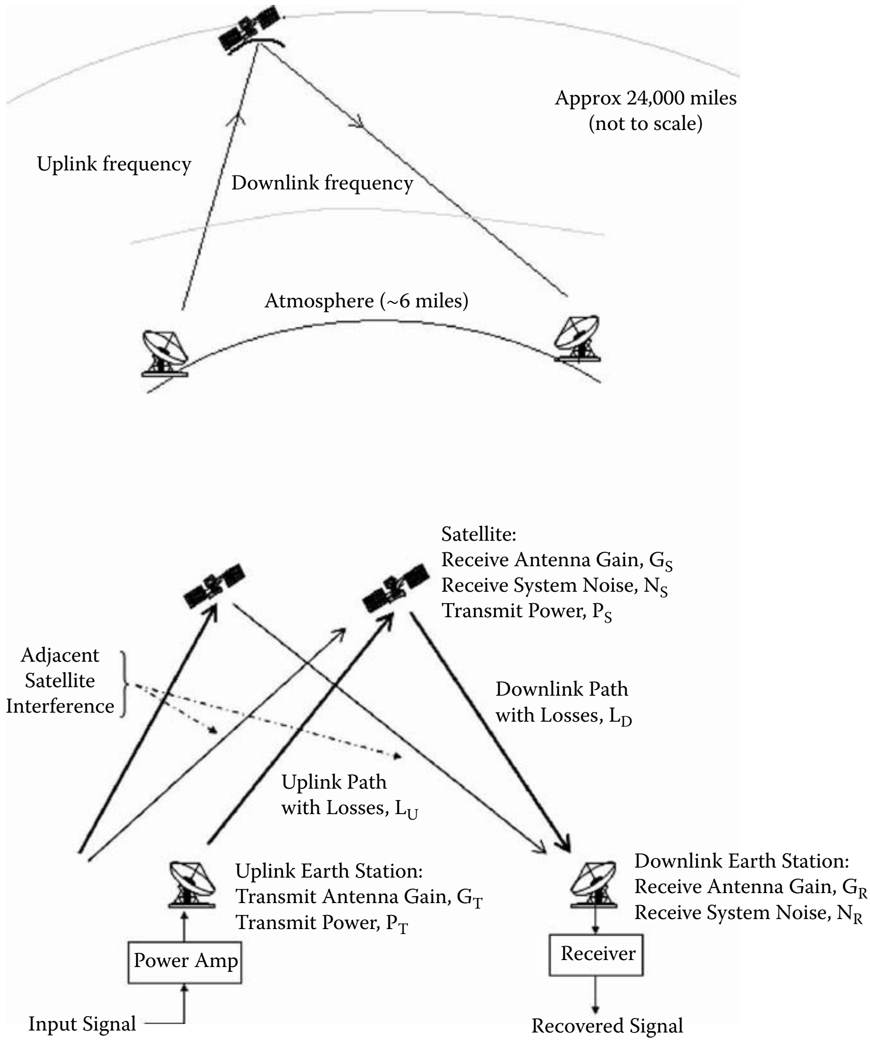

Figure 1.1 A typical satellite link.

of the speed of light, which is the speed that radio waves travel. Satellite delay compensation units and "spoofing" technology have successfully been used to compensate for these delays in data circuits. Voice transmission via satellite presently accounts for only a tiny fraction of overall transponder capacity, and users are left to deal with the satellite delay individually; only a few find it to be objectionable.

At the practical level, the orbit has a small nonzero inclination and eccentricity, which causes the satellite to trace out a small but manageable "figure eight" in the sky. Orbital positions are defined by international regulation as longitude values on the "geosynchronous circle," for example, 101°W, 129°W, and so on. Satellites are spaced at 2° or 3° to allow sufficient separation to support frequency reuse (see Figure 1.3). In actuality, an orbital position is a box of about 150 × 150 km,

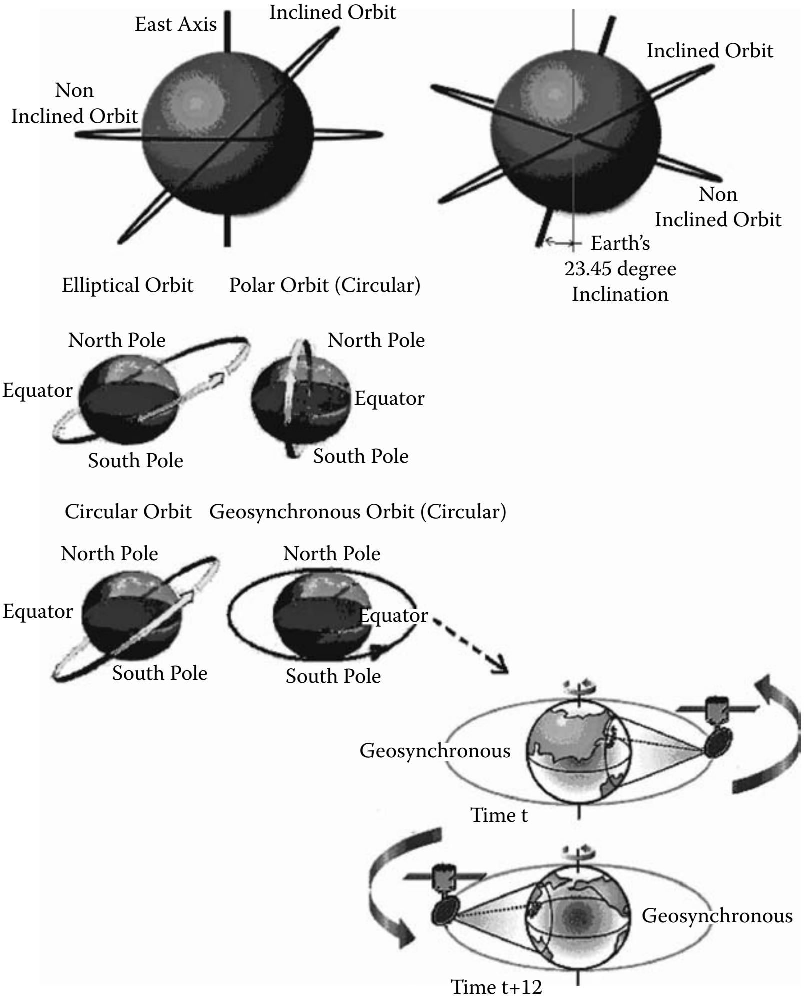

Figure 1.2 Typical satellite orbits.

within which the satellite is maintained by ground control. Table 1.1 lists some key concepts related to orbits [SAT200501]. Table 1.2 identifies some satellites that cover the United States. (A similar worldwide tabulation can also easily be compiled.)

1.2 Satellite Transmission Bands

The transmission channel of a satellite system is a radio channel using a direct-wave approach, operating at specific RF bands within the overall electromagnetic spectrum (see Figure 1.4 [MIN199101]). The frequency of operation is in the super high frequency (SHF) range (3–30 GHz), as defined in Table 1.3. Regulation and practice dictates the frequency of operation, the channel

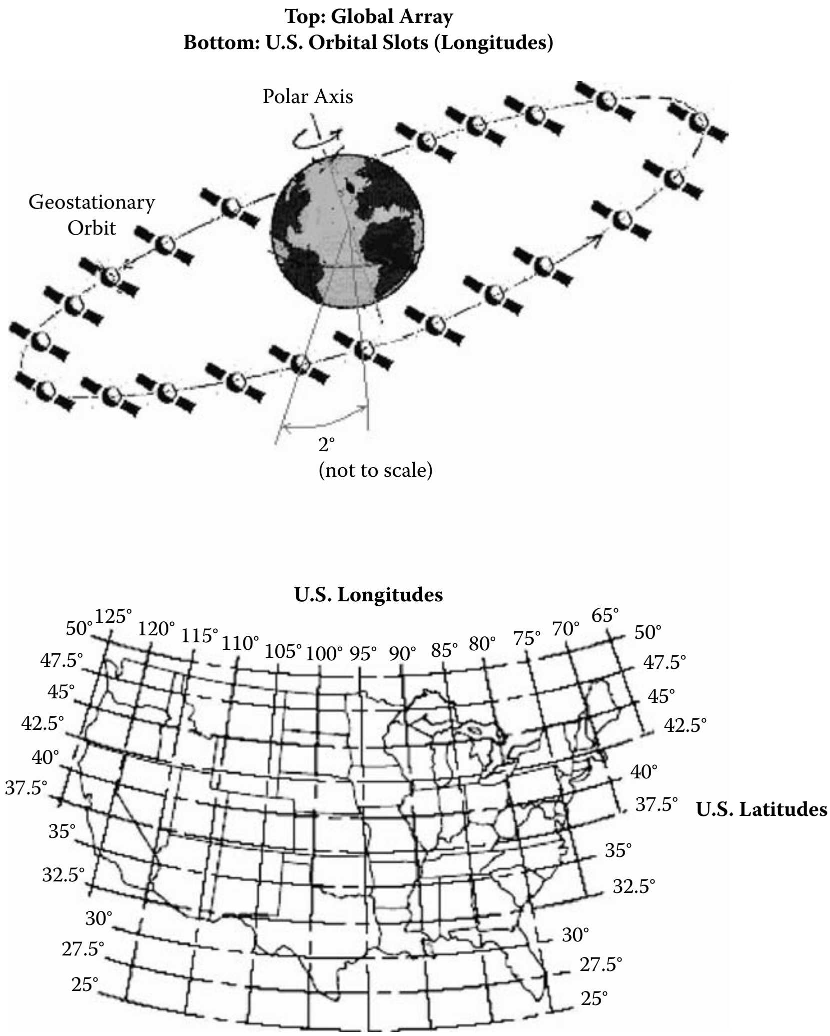

Figure 1.3 Worldwide population of geostationary satellites (illustrative).

bandwidth, and the bandwidth of the subchannels within the larger channel. Different frequencies are used for the uplink and the downlink. A satellite link is a radio link between a transmitting earth station and a receiving earth station through a communications satellite. A satellite link consists of one uplink and one downlink; the satellite electronics (i.e., the transponder) will remap the uplink frequency to the downlink frequency.

Note that $c = \lambda f$, where c is the speed of light (3×10^8 m/s), λ is the wavelength, and f is the frequency.

Frequencies above about 30 MHz can pass through the ionosphere and therefore can be utilized for communicating with satellites. (Frequencies below 30 MHz are reflected by the ionosphere at certain stages of the sunspot cycle.) However, commercial satellite services use

Table 1.1 Key concepts related to orbits

Circular orbit	A satellite orbit where the distance between the center of mass of the satellite and the center of mass of the earth is constant.
Clarke belt	The circular orbit (geostationary orbit) at approximately 35,786 km above the equator, where the satellites travel at the same speed as the earth's rotation and thus appear to be stationary to an observer on earth (named after Arthur C. Clarke, who was the first to describe the concept of geostationary communication satellites). *Note*: Sir Arthur C. Clarke died on March 19, 2008, at the age of 90.
Collocated satellites	Two or more satellites occupying approximately the same geostationary orbital position such that the angular separation between them is effectively zero when viewed from the ground. To a small receiving antenna, the satellites appear to be exactly collocated; in reality, the satellites are kept several kilometers apart in space to avoid collisions. Different operating frequencies and/or polarizations are used.
Geostationary orbit/ satellite	The orbit of a geosynchronous satellite, which lies in the plane of the earth's equator. A satellite orbiting the earth at such speed that it permanently appears to remain stationary with respect to the earth's surface.
Geosynchronous object	An object orbiting the earth at the earth's rotational speed and in the same direction of rotation. The object appears at the same position in the sky at a particular time each day but will not appear stationary if it is not orbiting in the equatorial plane.
Inclination	The angle between the plane of the orbit of a satellite and the earth's equatorial plane. An orbit of a perfectly geostationary satellite has an inclination of 0.
Inclined orbit	An orbit that approximates the geostationary orbit but whose plane is tilted slightly with respect to the equatorial plane. The satellite appears to move about its nominal position in a daily "figure-of-eight" motion when viewed from the ground. Spacecrafts (satellites) are often allowed to drift into an inclined orbit near the end of their nominal lifetime to conserve on-board fuel, which would otherwise be used to correct this natural drift caused by the gravitational pull of the sun and moon. North–south maneuvers are not conducted, allowing the orbit to become highly inclined.
Orbit	The path described by the center of mass of a satellite in space, subjected to natural forces, principally gravitational attraction, but occasional low-energy corrective forces exerted by a propulsive device to achieve and maintain the desired path.
Orbital plane	The plane containing the center of mass of the earth and the velocity vector (direction of motion) of a satellite.

much higher frequencies. The range 3–30 GHz represents a useful set of frequencies for geostationary satellite communication; these frequencies are also called *microwave frequencies*.* Above about 30 GHz, the attenuation in the atmosphere due to clouds, rain, hydrometeors, sand, and

* From 30 to 300 GHz, the frequencies are referred to as *millimeter wave*; above 300 GHz, optical techniques take over; these frequencies are known as *far infrared* or *quasi optical*.

Table 1.2 Partial list of geostationary satellites that cover the United States/North America

Satellite name	*Location*	*Notes*
SES-Americom 6	72 W	
SES-Americom 9	83 W	
SES-Americom 3	87 W	
Intelsat Americas 8	89 W	
Galaxy 11	91 W	
Intelsat Americas 6	93 W	
Galaxy 3C	95 W	
Galaxy 16	99 W	
SES-Americom 4	101 W	
DirecTV Television	101 W	Primary and additional programming: 110 and 119
SatMex5	117 W	
Dish Network Television	119 W	Primary and additional programming: 61.5, 110, and 148
Galaxy 10R	123 W	
Horizon 1	127 W	
Intelsat Americas 7	129 W	

Note: W stands for West, which refers to the longitude West of Greenwich, England. For example, 101°W L = 259°EL.

dust makes a ground-to-satellite link unreliable. (Such frequencies may still be used for satellite-to-satellite links in space, although these applications have not yet developed commercially [JEF200401]).

The actual frequencies of operation of commercial (U.S.) satellites are*

- C band: 3.7–4.2 GHz for downlink frequencies, and 5.925–6.425 GHz for uplink frequencies (Extended C band operates at frequencies of 5.850–6.425 GHz and 3.625–4.200 GHz, respectively.)
- Ku band: 11.7–12.2 GHz for downlink frequencies, and 14–14.5 GHz for uplink frequencies
- Broadcast satellite service: 12.2–12.7 GHz for downlink frequencies
- Ka band: 18.3–18.8 GHz and 19.7–20.2 GHz for downlink frequencies, and 27.5–31 GHz for the uplink frequencies

See Table 1.4 for details about frequency bands. These bands are further subdivided into smaller channels that can be independently used for a variety of applications. Table 1.5 depicts a typical subdivision of the C band into these channels, which are also called colloquially "transponders." (*Transponder* as a proper term is defined later in the chapter.) The nominal subchannel bandwidth is (typically) 40 MHz, with a (typical) usable bandwidth of 36 MHz. (Also see Figure 1.5.) Similar frequency allocations have been established for the Ku and Ka bands. Many satellites simultaneously support a C-band and a Ku-band infrastructure. (They have dedicated feeds and transponders for each band.) Most communications systems fall into one of three

* The international set of microwave bands is as follows: L band (0.39–1.55 GHz); S band (1.55–5.20 GHz); C band (3.70–6.20 GHz); X band (5.20–10.9 GHz); and K band (10.99–36 GHz).

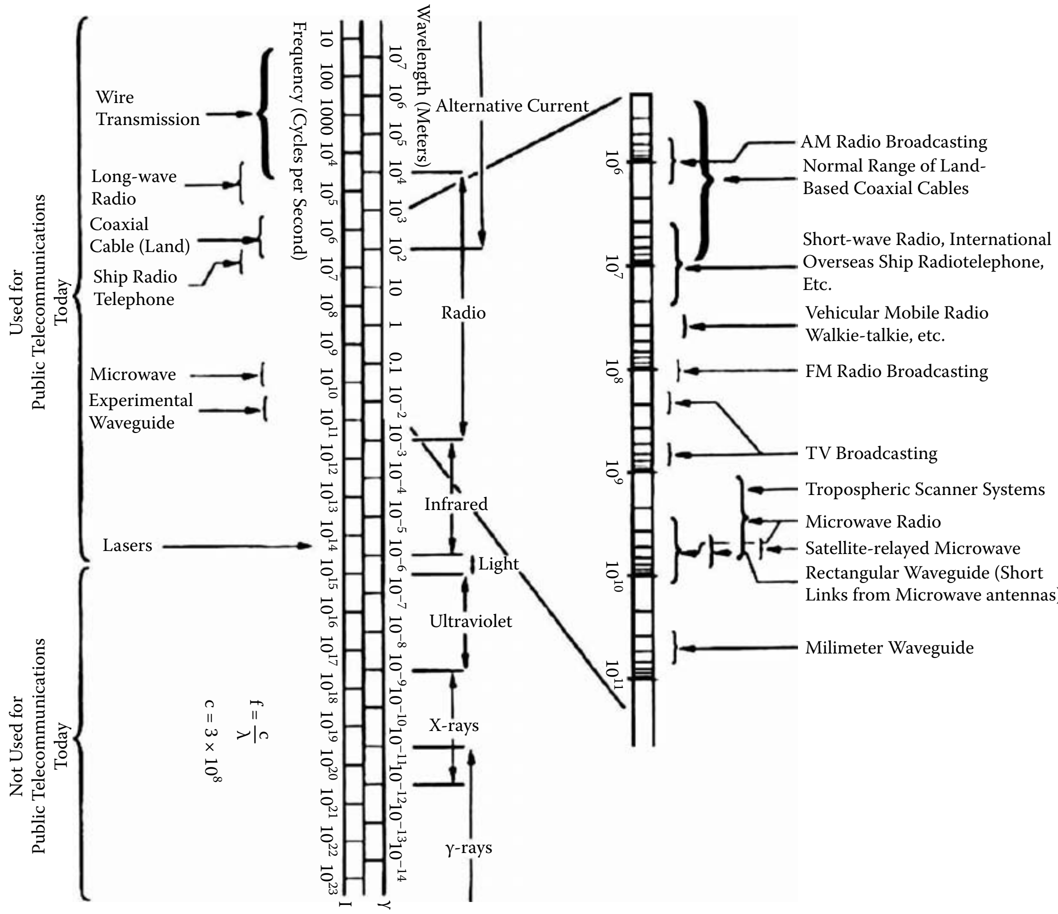

Figure 1.4 Electromagnetic spectrum.

categories: bandwidth efficient, power efficient, or cost efficient. Bandwidth efficiency describes the ability of a modulation scheme to accommodate data within a limited bandwidth. Power efficiency describes the ability of the system to reliably send information at the lowest practical power level. In satellite communications, both bandwidth efficiency and power efficiency are important [AGI200101].

Figure 1.6 depicts a two-way satellite link. The end-to-end (remote to central point) link makes use of a radio channel, as described previously, for the transmitting station uplink to the satellite; additionally, it uses a downlink radio channel to the receiving station (this is also generally called the inbound link). The outbound link from the central point to a remote point also makes use of a radio channel comprised of an uplink and a downlink.

From an application's perspective, the link may be point-to-point (effectively, where both ends of the link are peers), or it may be point-to-aggregation-point, for example, for handoff to a corporate network or to the Internet. Some applications are simplex, typically making use of an outbound link; other applications are duplex, using both an inbound and outbound link.

Table 1.3 Traditional classification of radio frequencies

Frequency band	*Frequency range*	*Propagation modes*	*Systems/uses/characteristics*
ELF (Extremely low frequency)	Less than 3 KHz	Surface wave	Worldwide, military, and submarine communication
VLF (Very low frequency)	3–30 kHz	Earth-ionosphere guided	Worldwide, military, and navigation
LF (Low frequency)	30–300 kHz	Surface wave	Stable signal, distances up to 1500 km
MF (Medium frequency)	300 kHz–3 MHz	Surface/sky wave for short/long distances, respectively	Radio broadcasting. Long-distance sky-wave signals are subjected to fading
HF (High frequency)	3–30 MHz	Sky wave, but very limited, short-distance ground wave also	3–6 MHz: Continental; 6–30 MHz: Intercontinental. Land and ship-to-shore communications
VHF (Very high frequency)	30–300 MHz	Space wave	Close to line-of-sight over short distances; broad-casting and land mobile
	30–60 MHz	Scatter wave	Ionospheric scatter over 900–2000 km distances
UHF (Ultrahigh frequency)	300 MHz–3 GHz	Space wave	Essentially line-of-sight over short distances; broad-casting and land mobile
	Above 300 MHz	Scatter wave	Tropospheric scatter over 150–800 km distances
SHF (Super-high frequency)	3–30 GHz	Space wave	The "workhorse" microwave band; Line-of- sight; terrestrial and satellite relay links
EHF (Extremely high frequency)	30–300 GHz	Space wave	Line-of-sight millimeter waves. Space-to-space links, military uses, and possible future use

Increasingly, satellite communications make use of digital modulation. Modulation is the process of overlaying intelligence (say, a bit stream) over an underlying carrier so that the information can be relayed at a distance. Demodulation is the recovery from a modulated carrier of a signal having the same characteristics as the original modulating signal. The underlying analog carrier is superimposed with a digital signal, typically using 4- or 8-point phase shift keying (PSK) techniques, or 16-point quadrature amplitude modulation (QAM). In addition, the original signal is fairly routinely encrypted and invariably protected with forward error correction (FEC) techniques. These topics are discussed in Chapters 4 and 5.

As noted, different frequencies are used for the uplink and downlink to avoid self-interference, following the terrestrial microwave transmission architecture developed by the Bell System in the

Table 1.4 Satellite band details

Band	*Characteristics*	*Considerations*
C band (6 GHz uplink and 4 GHz downlink)	• Relatively immune to atmospheric effects • Popular band, but on occasion it is congested on the ground (see note at right) • Bandwidth (~500 MHz/36 MHz transponders) allows video and high data rates • Provides good performance for video transmission • Proven technology with long heritage and good track record • Common in heavy rain zones	• Requires large antennas (3.8–4.5 m or larger, especially on the transmit side) • Large footprints • Best-performing band in the context of rain attenuation • Potential interference due to terrestrial microwave systems
Ku band (14–14.5 GHz uplink and 11.7–12.2 GHz downlink)	• Moderate to low cost hardware • Highly suited to VSAT networks • Spot beam footprint permits use of smaller earth terminals, 1–3 m wide, in moderate rain zones	• Attenuated by rain and other atmospheric moisture • Spot beams generally focused on land masses • Not ideal in heavy rain zones
DBS band (12.2–12.7 GHz downlink)	• Simplex • Multiple feeds for access to satellite neighborhoods • Small Receive Only antennas	• Attenuated by rain and other atmospheric moisture
Ka band (18.3–18.8 GHz and 19.7–20.2 GHz downlink)	• Microspot footprint • Very small terminals, much less than 1 m • High data rates are possible: 500–1000 Mbps	• Rain attenuation • Obstruction interference due to heavy rainfall (black out)

1940s and 1950s. In systems using the C band, the basic parameters are 4 GHz in the downlink, 6 GHz in the uplink, and 500 MHz bandwidth over 24 transponders using vertical and horizontal polarization (a form of frequency reuse discussed later on), resulting in a transponder capacity of 36 MHz, or 45–75 Mbps, depending on the modulation and FEC scheme. Table 1.6 depicts some key physical parameters of relevance to satellite communication [SAT200501]. C-band has been used for several decades and has good transmission characteristics, particularly in the presence of rain, which typically affects high-frequency transmission. Generally, C-band links are used for TV and video distribution to headends and for military applications, among others. A number of antenna types are utilized in satellite communication, but the most commonly used narrow beam antenna type is the dish reflector antenna. C-band receive dishes for broadcast-quality video reception are typically 3.8–4.5 m in diameter. The size is selected to optimize reception under normal (clear sky) or medium-to-severe rain conditions; however, smaller antennas of 1.5–2.4 m

Table 1.5 Typical subchannel ("transponder") allocation for C-band satellites

xpdr	*UP Center frequency (MHz)*	*UP Lower-end frequency (MHz)*	*UP Higher-end frequency (MHz)*	*DOWN Center frequency (MHz)*	*DOWN Lower-end frequency (MHz)*	*DOWN Higher-end frequency (MHz)*	*POL*
				By xpdr			
1	5945	5925	5965	3720	3700	3740	V
2	5965	5945	5985	3740	3720	3760	H
3	5985	5965	6005	3760	3740	3780	V
4	6005	5985	6025	3780	3760	3800	H
5	6025	6005	6045	3800	3780	3820	V
6	6045	6025	6065	3820	3800	3840	H
7	6065	6045	6085	3840	3820	3860	V
8	6085	6065	6105	3860	3840	3880	H
9	6105	6085	6125	3880	3860	3900	V
10	6125	6105	6145	3900	3880	3920	H
11	6145	6125	6165	3920	3900	3940	V
12	6165	6145	6185	3940	3920	3960	H
13	6185	6165	6205	3960	3940	3980	V
14	6205	6185	6225	3980	3960	4000	H
15	6225	6205	6245	4000	3980	4020	V
16	6245	6225	6265	4020	4000	4040	H
17	6265	6245	6285	4040	4020	4060	V
18	6285	6265	6305	4060	4040	4080	H
19	6305	6285	6325	4080	4060	4100	V
20	6325	6305	6345	4100	4080	4120	H
21	6345	6325	6365	4120	4100	4140	V
22	6365	6345	6385	4140	4120	4160	H
23	6385	6365	6405	4160	4140	4180	V
24	6405	6385	6425	4180	4160	4200	H
				By frequency			
2	5965	5945	5985	3740	3720	3760	H
4	6005	5985	6025	3780	3760	3800	H
6	6045	6025	6065	3820	3800	3840	H
8	6085	6065	6105	3860	3840	3880	H
10	6125	6105	6145	3900	3880	3920	H
12	6165	6145	6185	3940	3920	3960	H
14	6205	6185	6225	3980	3960	4000	H
16	6245	6225	6265	4020	4000	4040	H
18	6285	6265	6305	4060	4040	4080	H
20	6325	6305	6345	4100	4080	4120	H
22	6365	6345	6385	4140	4120	4160	H
24	6405	6385	6425	4180	4160	4200	H
1	5945	5925	5965	3720	3700	3740	V
3	5985	5965	6005	3760	3740	3780	V
5	6025	6005	6045	3800	3780	3820	V

(*Continued*)

Table 1.5 Typical subchannel ("transponder") allocation for C-band satellites

xpdr	*UP Center frequency (MHz)*	*UP Lower-end frequency (MHz)*	*UP Higher-end frequency (MHz)*	*DOWN Center frequency (MHz)*	*DOWN Lower-end frequency (MHz)*	*DOWN Higher-end frequency (MHz)*	*POL*
7	6065	6045	6085	3840	3820	3860	V
9	6105	6085	6125	3880	3860	3900	V
11	6145	6125	6165	3920	3900	3940	V
13	6185	6165	6205	3960	3940	3980	V
15	6225	6205	6245	4000	3980	4020	V
17	6265	6245	6285	4040	4020	4060	V
19	6305	6285	6325	4080	4060	4100	V
21	6345	6325	6365	4120	4100	4140	V
23	6385	6365	6405	4160	4140	4180	V

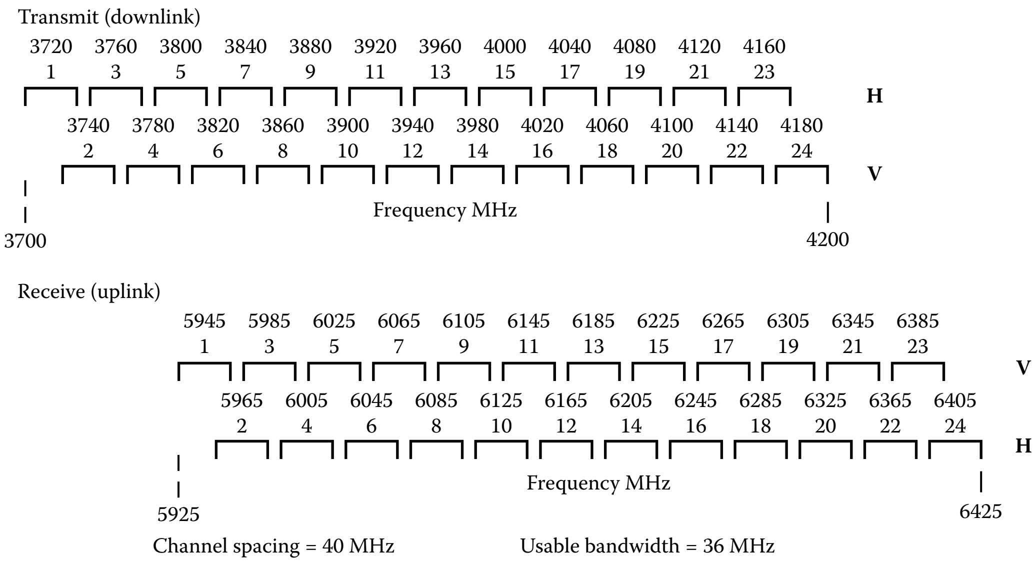

Figure 1.5 Subchannel ("transponder") allocation for C-band satellites.

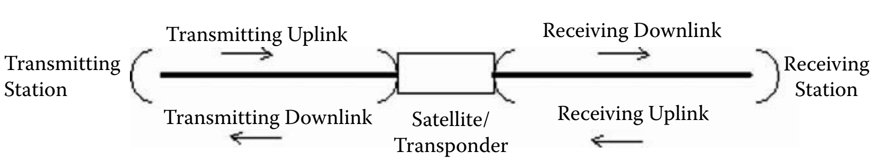

Figure 1.6 A satellite (radio) (microwave) link.

Table 1.6 Some key physical parameters of relevance to satellite communication

Frequency	The number of times that an electrical or electromagnetic signal repeats itself in a specified time. It is usually expressed in cycles per second (hertz [Hz]). Satellite transmission frequencies are in the gigahertz (GHz) range.
Frequency band	A range of frequencies used for transmission or reception of radio waves (e.g., 3.7–4.2 GHz).
Frequency spectrum	A continuous range of frequencies.
Hertz (Hz)	SI unit of frequency, equivalent to one cycle per second. The frequency of a periodic phenomenon that has a periodic time of 1 s.
Kelvin (K)	SI unit of thermodynamic temperature.
Msymbol/s	Unit of data transmission rate for a radio link, equal to 1,000,000 symbol/s. Actual channel throughput is related to the modulation scheme employed.
Symbol	A unique signal state of a modulation scheme used on a transmission link that encodes one or more information bits to the receiver.
Watt (W)	SI unit of power, equal to 1 J/s.

can also be used, depending on the intended application, service availability goals, and satellite footprint. For two-way transmission, the same size and considerations apply (although larger antennas can also be used in some applications, especially at major earth stations); availability, acceptable bit error rate, satellite-radiated power, and rain mitigation goals drive the design/size of the antenna and ground transmission power.

Enterprise applications tend to make use of the Ku band because smaller antennas can be employed, typically in the 0.6–2.4 m range (depending on application, desired availability, rain zone, and throughput, among other factors). Newer applications, typically for direct-to-home (DTH) video distribution, look to make use of the Ka band, where antenna size can range from 0.3–1.2 m. (See Table 1.7.) Spread-spectrum techniques and other digital signal processing are

Table 1.7 Frequency and wavelength of satellite bands

Frequency (GHz)	*Wavelength (m)*	*Typical antenna size (m)*
3.7	0.081081081	1.2–4.8
4.2	0.071428571	
5.925	0.050632911	
6.425	0.046692607	
11.7	0.025641026	0.6–2.4
12.2	0.024590164	
12.7	0.023622047	
18.3	0.016393443	0.3–1.2
18.8	0.015957447	
19.7	0.015228426	
20.2	0.014851485	
27.5	0.010909091	

being used in some applications to reduce the antenna size by reducing unwanted signals (e.g., either in the uplink with spread spectrum, or in the downlink with adjacent satellite signal cancellation using digital signal processing).

Related to the issue of orbits, note that, as stated, there are multiple satellites in the geostationary orbit, typically every 2° on the arc, and even collocated at the "same" location, when different operating frequencies are used (as depicted in Figure 1.3). Effectively, satellite systems may employ cross-satellite frequency reuse via space-division multiplexing; this implies that a large number of satellites (even neighbors) make use of the same frequency operating bands as long as the antennas are highly directional. Some applications (e.g., direct broadcast to homes) or jurisdictions (non-U.S.) allow spacing at 3°; higher separation reduces the technical requirements on the antenna system but results in fewer satellites in space.

Unfortunately, unless the system is properly "tuned" by following all applicable regulations and technical guidelines, adjacent satellite interference (ASI) can occur. A transmit earth station can inadvertently direct a proportion of its radiated power toward satellites that are operating at orbital positions adjacent to that of the wanted satellite. This can occur because the transmit antenna is incorrectly pointed toward the wanted satellite, or because the earth station antenna beam is not sufficiently concentrated in the direction of the satellite of interest (e.g., the antenna being too small). This unintended radiation can interfere with services that use the same frequency on the adjacent satellites. Interference into adjacent satellite systems is controlled to an acceptable level by ensuring that the transmit earth station antenna is accurately pointed toward the satellite and that its performance (radiation pattern) is sufficient to suppress radiation toward the adjacent satellites. In general, a larger uplink antenna will have less potential for causing adjacent satellite interference but will generally be more expensive and may require a satellite tracking system. Similarly, a receive earth station can inadvertently receive transmissions from adjacent satellite systems, which then interfere with the wanted signal. This happens because the receive antenna, while being very sensitive to signals coming from the direction of the wanted satellite, is also sensitive to transmissions coming from other directions. In general, this sensitivity reduces as the antenna size increases. As for a transmit earth station, it is also very important to accurately point the antenna toward the satellite to minimize ASI effects [FOC200701]. As noted, spread-spectrum techniques and other digital signal processing are being used in some advanced (but not typical) applications to reduce unwanted signals (e.g., with spread spectrum, or with ASI cancellation using digital signal processing).

The sharing of a channel (colloquially, a "transponder") is achieved, at this juncture, using Time Division Multiple Access (TDMA), random access techniques, Demand Access Multiple Access (DAMA), or Code Division Multiple Access (CDMA) (spread spectrum). Increasingly, the information being carried, whether voice, video, or data, is IP based. Multiplexing techniques are covered in Chapter 4.

1.3 Satellite Signal Regeneration

In general, the information transfer function entails bit transmission across a channel (medium). Because there is a variety of media in use in communication, many of the transmission techniques are specific to the medium at hand. Functions include, but are not limited to, modulation, timing, noise/impairments management, and signal level management. In the context of

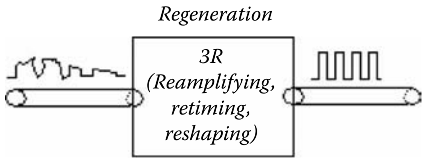

Figure 1.7 Regeneration as a general concept.

this book, the transmission channel is a radio channel. Typical transmission problems include the following:

- Signal attenuation (e.g., free space loss)
- Signal dispersion
- Signal nonlinearities (due to, e.g., amplification or propagation phenomena)
- Internal or external noise
- Cross talk (e.g., spectral regrowth), intersymbol interference, and intermodulation
- External interference and adjacent satellite interference

In general, some of these impairments, but not all, can be dealt with by using a regenerator. Regeneration is the function of restoring the signal (and/or bit stream) to its original shape and power level. These techniques are specific to the medium (e.g., radio channel, fiber channel, twisted-pair copper channel, and so on). Regeneration correctively addresses signal attenuation, signal dispersion, and cross talk; this is done via signal reamplification, retiming, and reshaping. Regeneration is generally considered a layer 1 function in the Open Systems Interconnection Reference Model (OSIRM). Figure 1.7 depicts a signal regeneration function pictorially. Regeneration and amplification are critical functions in satellite systems because the attenuation through space and the atmosphere is in the order of 200 dB (i.e., the power is reduced by 20 orders of magnitude).

Figure 1.8 depicts the basic building blocks of various regenerators. A "low-end" regenerator includes only the reamplification function. These are known as 1R regenerators. A "high-end" regenerator includes the reamplification, retiming, and reshaping functionalities. These are known as 3R regenerators. The functions of a 3R regenerator are (see Figure 1.9)

- Reamplification—increases power levels above the system sensitivity
- Retiming—suppresses timing jitter by optical clock recovery
- Reshaping—suppresses noise and amplitude fluctuations by decision stage

Regenerators are invariably technology specific. Hence, one has LAN repeaters (even if rarely used), Wi-Fi repeaters, copper-line (T1 channel) repeaters, cable TV repeaters, and optical regenerators (of the 1R, 2R, or 3R kind). Figure 1.10 depicts a regenerator in the satellite environment; this regenerator is the satellite transponder. The term *satellite transponder* refers properly to a transmitter–receiver subsystem on board the satellite that uses a single high-power amplification chain and processes a particular range of frequencies (the *transponder bandwidth).* There are many transponders on a typical satellite, each being capable