Satellite Systems Engineering in an IPv6 Environment

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Dedication

For Anna and the kids.
And for my parents, Gino and Angela
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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.
Preface

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.
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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, teledicine, 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
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LANs, WANs (ATM and MPLS), wireless (LAN and public hotspot), VoIP, network design/
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Over the years he has advised venture capitalists for investments of $150M in a dozen high-tech
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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

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* 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.)
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,
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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 1.2 Typical satellite orbits.
Introduction to Satellite Communications

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 \( (3 \times 10^8 \text{ m/s}) \), \( \lambda \) 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

![Image](AU7868_C001.indd)

Figure 1.3 Worldwide population of geostationary satellites (illustrative).
### Table 1.1  Key concepts related to orbits

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular orbit</td>
<td>A satellite orbit where the distance between the center of mass of the satellite and the center of mass of the earth is constant.</td>
</tr>
<tr>
<td>Clarke belt</td>
<td>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).</td>
</tr>
<tr>
<td>Collocated satellites</td>
<td>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.</td>
</tr>
<tr>
<td>Geostationary orbit/satellite</td>
<td>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.</td>
</tr>
<tr>
<td>Geosynchronous object</td>
<td>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.</td>
</tr>
<tr>
<td>Inclination</td>
<td>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.</td>
</tr>
<tr>
<td>Inclined orbit</td>
<td>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.</td>
</tr>
<tr>
<td>Orbit</td>
<td>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.</td>
</tr>
<tr>
<td>Orbital plane</td>
<td>The plane containing the center of mass of the earth and the velocity vector (direction of motion) of a satellite.</td>
</tr>
</tbody>
</table>

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

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* 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

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

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

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

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>
<thead>
<tr>
<th>Band</th>
<th>Characteristics</th>
<th>Considerations</th>
</tr>
</thead>
</table>
| 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

<table>
<thead>
<tr>
<th>xpdr</th>
<th>UP Center frequency (MHz)</th>
<th>UP Lower-end frequency (MHz)</th>
<th>UP Higher-end frequency (MHz)</th>
<th>DOWN Center frequency (MHz)</th>
<th>DOWN Lower-end frequency (MHz)</th>
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<td>3700</td>
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<td>4180</td>
<td>4160</td>
<td>4200</td>
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</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>xpdr</th>
<th>UP Center frequency (MHz)</th>
<th>UP Lower-end frequency (MHz)</th>
<th>UP Higher-end frequency (MHz)</th>
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</table>

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>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.</td>
</tr>
<tr>
<td>Frequency band</td>
<td>A range of frequencies used for transmission or reception of radio waves (e.g., 3.7–4.2 GHz).</td>
</tr>
<tr>
<td>Frequency spectrum</td>
<td>A continuous range of frequencies.</td>
</tr>
<tr>
<td>Hertz (Hz)</td>
<td>SI unit of frequency, equivalent to one cycle per second. The frequency of a periodic phenomenon that has a periodic time of 1 s.</td>
</tr>
<tr>
<td>Kelvin (K)</td>
<td>SI unit of thermodynamic temperature.</td>
</tr>
<tr>
<td>Msymbol/s</td>
<td>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.</td>
</tr>
<tr>
<td>Symbol</td>
<td>A unique signal state of a modulation scheme used on a transmission link that encodes one or more information bits to the receiver.</td>
</tr>
<tr>
<td>Watt (W)</td>
<td>SI unit of power, equal to 1 J/s.</td>
</tr>
</tbody>
</table>

Table 1.7  Frequency and wavelength of satellite bands

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Wavelength (m)</th>
<th>Typical antenna size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>0.081081081</td>
<td>1.2–4.8</td>
</tr>
<tr>
<td>4.2</td>
<td>0.071428571</td>
<td></td>
</tr>
<tr>
<td>5.925</td>
<td>0.050632911</td>
<td></td>
</tr>
<tr>
<td>6.425</td>
<td>0.046692607</td>
<td></td>
</tr>
<tr>
<td>11.7</td>
<td>0.025641026</td>
<td>0.6–2.4</td>
</tr>
<tr>
<td>12.2</td>
<td>0.024590164</td>
<td></td>
</tr>
<tr>
<td>12.7</td>
<td>0.023622047</td>
<td></td>
</tr>
<tr>
<td>18.3</td>
<td>0.016393443</td>
<td>0.3–1.2</td>
</tr>
<tr>
<td>18.8</td>
<td>0.015957447</td>
<td></td>
</tr>
<tr>
<td>19.7</td>
<td>0.015228426</td>
<td></td>
</tr>
<tr>
<td>20.2</td>
<td>0.014851485</td>
<td></td>
</tr>
<tr>
<td>27.5</td>
<td>0.010909091</td>
<td></td>
</tr>
</tbody>
</table>

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
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
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
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of supporting one or more communication channels [SAT200501]. In fact, a typical satellite will have 24 transponders: 12 to regenerate the consecutive 12–36 MHz frequency blocks that comprise the segments assigned for operation at the C band, Ku band, or Ka band (500 MHz total) for use in the \textit{vertical signal polarization} mode, and 12 for the frequency blocks that comprise the segments assigned to the \textit{horizontal signal polarization} mode. By utilizing

Figure 1.8  Basic functionality of various regenerators.

Figure 1.9  Basic architecture of a 3R regenerator.
transponders, commercial communication satellites perform the following functions:

- Receive signals from the ground station (uplink beam)
- Separate, amplify, and recombine the signals (the regeneration function)
- Transmit the signals back to (another) earth station (downlink beam)

Some advanced functions include digital signal processing and are called regenerative and nonregenerative onboard processors.

### 1.4 Satellite Transmission Chain

The ground segment of a satellite transmission chain consists of the earth stations (also known as ground stations) that are operating within a particular satellite system or network. Earth stations are typically connected to the end user’s equipment directly with local cabling or via a
terrestrial network. The ground segment supports either one or both of the following: (i) an uplink, (ii) a downlink. Figure 1.11 depicts an end-to-end link. A satellite link is comprised of the following elements:

\[
\text{Link} = \text{modulation equipment} + \text{upconversion equipment} + \text{amplification equipment} + \text{uplink transmission channel} + \text{frequency shift (conversion) equipment} + \text{downlink transmission channel} + \text{signal reception/antenna} + \text{amplification equipment} + \text{downconversion equipment} + \text{demodulation equipment}.
\]

The uplink is that portion of a satellite communications link that involves signal transmission from the ground and reception on board the satellite. The downlink is that portion of a satellite communications link that involves signal (re-)transmission from the satellite and reception on the ground. Downconversion is the process of converting the frequency of a signal to a lower

Figure 1.11  Satellite link (some details). LNA = low noise amplifier; HPA = high power amplifier; LNB = low noise block downconverter.
frequency; it is performed at the reception point to permit the recovery of the original signal. The opposite, upconversion, is the process of converting the frequency of a signal into a higher frequency; it is done at the point of transmission. Signal management on the ground is better handled at lower frequencies, and hence, the purpose/need for frequency conversion (to a higher frequency level for transmission and down to a lower frequency level at reception). The transponder is a repeater that takes in the signal from the uplink at a frequency $f_1$, amplifies it, and sends it back on a second frequency $f_2$.

An uplink system consists of the following subsystems (often in redundant mode):

- Network interface devices such as routers, encryptors, conditional access systems, and encapsulators.
- Modulators (devices that superimpose the amplitude, frequency, or phase of a wave or signal onto another wave—the carrier—which is then used to convey the original signal over the satellite link. QPSK and 8-PSK are typical, but other methods are also used. FEC is typically handled at this point in the chain.)
- Upconverters (devices for converting the frequency of a signal into a higher frequency; transceivers that take a 70/140/900 MHz signal and frequency and convert it to either C-, Ku-, or Ka-band final frequency)
- PA (power amplifiers), specifically high-power amplifiers (HPAs); for example, solid-state power amplifier (SSPA or a klyston). Transmit power amplifiers provide amplification of signals to be transmitted to the satellite (typically 750–3000 W for high end applications)

A downlink link includes the following components:

- Downconverters (devices for converting the frequency of a signal into a lower frequency; transceivers that take a C-, Ku-, or Ka-band signal and frequency and convert it to either 70-, 140-, or 900-MHz final frequency)
- LNA (low noise amplifier), LNB (low-noise block downconverter), or LNC (low noise converter)
- Modem (customer site)

The LNA amplifies the RF signal from the antenna and feeds it into a frequency converter, the output of which is typically the intermediate frequency (IF) of 70/140/900 MHz. It provides 50–60 dB of amplification. An LNA is more precise and stable, but more expensive than an LNB. The LNB amplifies the RF signal from the antenna and converts it to an L-band signal. An LNB provides 50–60 dB of amplification and also converts from one block of frequencies to another (what goes in comes out amplified and at a different frequency). The LNC is similar to an LNB, but it has a variable shift. It provides 50–60 dB of amplification and also converts a block of frequencies to a specific portion of that block of frequencies (what goes into the LNC comes out amplified and at a different frequency within a given range; often it uses a local oscillator to help in conversion). LNA/LNB/LNCs are typically used for one-way field antennas. See Figure 1.12 [MUC200202].

Antennas in a satellite environment are reflective systems, typically parabolic in shape. A highly directional antenna concentrates most of the radiated power along the antenna “boresight.” It follows that a high-gain antenna is very directional and needs to be pointed with reasonably high precision. As an example, at 12 GHz the pointing accuracy needed for a 1-m diameter dish is of the order of a degree or two of arc. The antenna uses a three-axis
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Figure 1.12  LNA/LNB/LNC operation (C-band example).

Figure 1.13  Antenna pointing.
pointing system that one needs to adjust when pointing it to a satellite (see Figure 1.13 [LAU200701]):

- **Azimuth**—This is the magnetic compass direction (angle of sighting) at which one points the dish. It is a side-to-side adjustment. Azimuth is the angular distance from true north along the horizon to a satellite, measured in degrees.
- **Elevation**—This is the angle above the horizon at which one points the dish. This is an up-and-down adjustment.
- **Polarization**—The (linear) polarization or skew represents the feed’s alignment needed to capture the maximum signal from the satellite consistent with the satellite signal’s transmit signal orientation (polarization*). This is a rotational adjustment. Polarization prevents interference with signals on the same satellite at the same frequency but opposite polarization.

Antennas are addressed in detail in Chapter 3.

A Block Upconverter (BUC) takes the L-band signal and converts it to either the C- or Ku-band final frequency. This is typically used for two-way field antennas, and operates in the 5–25 W range for commercial applications (but can also operate at other power levels in special circumstances).

### 1.5 Satellite Services

Traditionally, satellite services have been classified in the following categories:

- **Fixed Satellite Service (FSS):** This is a satellite service between satellite terminals at specific fixed points using one or more satellites. Typically, FSS is used for the transmission of video, voice, and IP data over long distances from fixed sites. It makes use of geostationary satellites with fixed ground stations. Signals are transmitted from one point on the globe either to a single point (point-to-point) or from one transmitter to multiple receivers (point-to-multipoint). FSS may include satellite-to-satellite links (not commercially common) or feeder links for other satellite services such as the Mobile Satellite Service or the Broadcasting Satellite Service.

- **Broadcast Satellite Service (BSS):** This is a satellite service that supports the transmission and reception via satellite of signals that are intended for direct reception by the general public. The best example is Direct Broadcast Service (DBS), which supports the direct broadcast of TV and audio channels to homes or businesses directly from satellites. BSS/DBS make use of geostationary satellites. Unlike FSS, which has both point-to-point and point-to-multipoint communications, BSS is only a point-to-multipoint service. Therefore, a smaller number of satellites are enough to service the market.

- **Mobile Satellite Service (MSS):** This is a satellite service intended to provide wireless communication to any point on the globe. With the broad penetration of the cellular

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* Incorrect alignment results in picking up the undesired cross-pol (XP) signal, which will severely impact performance/quality of the intended signal.

† Some mobile applications are also possible with FSS, but the antenna system is generally very complex and expensive.
telephone, users have started to take for granted the ability to use the telephone anywhere in the world, including rural areas in developed countries. MSS is a satellite service that enhances this capability. It uses low earth orbit and medium earth orbit satellite systems.

- Maritime Mobile Satellite Service (MMSS): This is a satellite service between mobile-satellite earth stations and one or more satellites.
- Although not formally a service in the regulatory sense, one can add global positioning service/system (GPS) to this list; this service uses an array of satellites to provide global positioning information to properly equipped terminals.

### 1.6 Satellite Applications with IPv6 Implications

There are many traditional and emerging satellite applications. Major commercial applications include, but are not limited to, the ones listed here; each of these may need to support IPv6 modes in the not-too-distant future.

![Diagram of typical enterprise (two-way) (very small aperture terminal) satellite communications.](image)

**Figure 1.14** Typical (enterprise) (two-way) (very small aperture terminal) satellite communications.
Two-way enterprise (very small aperture terminal) satellite communications for intranet/Internet access connectivity (see Figure 1.14). Enterprise customers and/or government agencies may want to use IPv6 in the future (IPv4 is common today).

Video distribution to cable headends (see Figure 1.15). Cable TV companies may be interested in IPv6 environments in the future.

IPTV video distribution to telco headends (see Figure 1.16). Telephone companies may want to use IPv6 in the future, especially to support “Triple Play” or “Quadruple Play” (IPv4 is common today).

DTH video reception by consumers. Some ancillary applications may be able to make effective use of an IPv6 infrastructure.

1.7 Non-Geostationary Satellites
Up to now we have covered satellite systems in the geostationary orbits (aka as GEO); some other orbits/satellites of interest include low earth orbits (LEOs), medium earth orbits (MEO)
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(a) intermediate circular orbits (ICO), polar orbits, and highly elliptical orbits (HEOs). (See Figure 1.17.) This section has a brief overview of these systems, but they are not the focus of our coverage in this text.

As we saw earlier in the chapter, geostationary orbits are circular orbits that are oriented in the plane of the earth’s equator. A geostationary satellite completes one orbit revolution around the earth every 24 hr; hence, given that the satellite spacecraft is rotating at the same angular velocity as the earth, it overflies the same point on the globe on a permanent basis (unless the satellite is repositioned by the operator). In a geostationary orbit, the satellite appears stationary, that is, in a fixed position, to an observer on the earth. The maximum footprint (service area) of a geostationary satellite covers almost one-third of the earth’s surface; in practice, however, except for the oceanic satellites, most have a footprint optimized for a continent and/or portion of a continent (e.g., North America, or even continental United States). Non-GEO orbits are discussed next.
1.7.1 Low Earth Orbits (LEOs)

These are either elliptical or, more commonly, circular orbits that are at a height of 2000 km or less above the surface of the earth. The orbital periods at these altitudes vary between 90 min and 2 hr, and the maximum time during which a satellite in LEO is above the local horizon for an observer on the earth is up to 20 min. With LEOs there are long periods during which a given satellite is out of view of a particular ground station; this may be acceptable for some applications, for example, for earth monitoring. Coverage can be extended by deploying more than one satellite and using multiple orbital planes. A complete global coverage system using LEOs requires a large number of satellites (40–80) in multiple orbital planes and in various inclined orbits. Most small LEO systems employ polar or near-polar orbits. Due to the relatively large movement of a satellite in LEO with respect to an observer on the earth, satellite systems using this type of orbit need to be able to cope with Doppler shifts. Satellites in LEOs are also affected by atmospheric drag that causes the orbit to deteriorate (the typical life of an LEO satellite is 5–8 years, whereas the typical life of a GEO satellite is 14–18 years). However, launches into LEOs are less costly than to GEOs, due to their much lighter weight, and multiple LEO satellites can be launched at one time [GEO200101].

1.7.2 Polar Satellites

Polar orbits are LEOs that are in a plane of the two poles. Their applications include the ability to view only the poles (e.g., to fill in gaps of GEO coverage), or to view the same place on earth at the same time each 24-hr day. By placing a satellite at an altitude of about 850 km, a polar orbit period
of about 100 min can be achieved (for more continuous coverage, more than one polar orbiting satellite is employed.)

A special polar orbit that crosses the equator and every latitude at the same time each day is called a sun-synchronous (SS) orbit; this orbit can make data collection a convenient task. Satellites in polar orbits are mostly used for earth-sensing applications. Typically, such a satellite moves at an altitude of 1000 km. In an SS orbit, the angle between the orbital plane and the sun remains constant. This orbit can be achieved by an appropriate selection of orbital height, eccentricity, and inclination that produces a precession of the orbit (node rotation) of approximately 1° eastward each day, equal to the apparent motion of the sun; this condition can only be achieved for a satellite in a retrograde orbit. As noted, the SS low-altitude polar orbit is widely used for monitoring the earth because, each day, as the earth rotates below it, the entire surface is covered, and the satellite views the same earth location at the same time each 24-hr period. All SS orbits are polar orbits, but not all polar orbits are SS orbits. All polar orbits are LEOs [GEO200101].

A special SS orbit, called a dawn-to-dusk orbit, is where the satellite trails the earth’s shadow. Because the satellite never moves into this shadow, the sun’s light is always on it. These satellites can, therefore, rely mostly on solar power and not on batteries; they are useful for agriculture, oceanography, forestry, hydrology, geology, cartography, and meteorology.

**1.7.3 Medium Earth Orbits (MEO)/Intermediate Circular Orbits**

These are circular orbits at an altitude of around 10,000 km. Their orbit period is in the range of 6 hr. The maximum period a satellite in MEO is above the local horizon for an observer on the earth is in the order of a couple of hours. A global communications system using this type of orbit requires a small number satellites in two or three orbital planes to achieve global coverage. The U.S. GPS is example of a MEO system.

**1.7.4 Highly Elliptical Orbits (HEOs)**

These typically have a perigee (point in each orbit which is closest to the earth) at about 500 km above the surface of the earth, and an apogee (the point in its orbit which is farthest from the earth) as high as 50,000 km. The orbits are inclined at 63.4° to provide communications services to locations at high northern latitudes. The orbit period varies from 8 to 24 hr. Owing to the high eccentricity of the orbit, a satellite spends about two-thirds of the orbital period near the apogee, and during that time it appears to be almost stationary to an observer on the earth (this is referred to as apogee dwell). A well-designed HEO system places each apogee to correspond to a service area of interest. After the apogee period of orbit, a switchover needs to occur to another satellite in the same orbit to avoid loss of communications. Due to the relatively large movement of a satellite in HEO with respect to an observer on the earth, satellite systems using this type of orbit need to be able to cope with Doppler shifts. An example of an HEO system is the Russian Molnya system; it employs three satellites in three 12-hr orbits separated by 120° around the earth, with apogee distance at 39,354 km, and perigee at 1,000 km [GEO200101].

**1.8 Glossary of Key Satellite Concepts and Terms**

Table 1.8 provides a basic satellite glossary for the concepts covered in this chapter from a variety of industry sources (including [SAT200501], [ANS20001], [EUT200701], and [GEO200101] among others).
### Table 1.8 Basic satellite glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifier</td>
<td>A highly linear device designed to increase the amplitude (power) of a signal. In an earth station, the main amplifier is often called the high-power amplifier (HPA); for a very small aperture terminal (VSAT) antenna, the amplifier may be included in the Block Upconverter (BUC). Although a variety of power values are available, HPAs typically range from 500 to 3000 W; BUCs range from 5 to 25 W for commercial applications. Other amplifiers are used throughout the earth station to amplify various stages of the signal.</td>
</tr>
<tr>
<td>Antenna</td>
<td>A passive device for transmitting or receiving radio waves. In commercial satellite communication, the antenna almost invariably consists of a parabolic reflector and a feed horn. On the receiving link, the reflector focuses radio waves onto the feed horn; the feed horn detects the signal and converts it into an electrical signal. On the transmitting side, the reflector concentrates the radio waves emitted by the feed horn into a narrow beam that is aimed at the satellite.</td>
</tr>
<tr>
<td>Antenna aperture</td>
<td>The effective area of an antenna capable of radiating or receiving RF energy. In a typical parabolic antenna, this dimension is equivalent to the diameter of the main reflector.</td>
</tr>
<tr>
<td>Antenna efficiency</td>
<td>Also known as radiation efficiency, the ratio of the power applied to an antenna to the power actually radiated by the antenna, stated as a percentage.</td>
</tr>
<tr>
<td>Apogee</td>
<td>Point in a satellite orbit (especially for highly elliptical ones) that is farthest from the earth.</td>
</tr>
</tbody>
</table>
| Attenuator                  | In electrical systems, a resistive network that reduces the amplitude of a signal without appreciably distorting its waveform. Electrical attenuators are usually passive devices. The degree of attenuation may be fixed, continuously adjustable, or incrementally adjustable. Fixed attenuators are often called pads, especially in telephony.  
*Note*: The input and output impedances of an attenuator are usually matched to the impedances of the signal source and load, respectively. The amount by which the signal power is reduced is usually expressed in dB [ANS200001]. |
| Availability                | The ratio of the total time a functional unit is capable of being used during a given interval to the length of the interval.  
*Note*: An example of availability is 100/168 if the unit is capable of being used for 100 hr in a week.  
*Note*: Typical availability objectives are specified in decimal fractions, such as 0.9998 [ANS200001]. |
| Band pass filter            | A filter that ideally passes all frequencies between two nonzero finite limits and blocks all frequencies not within the limits.  
*Note*: The cutoff frequencies are usually taken to be the 3-dB points. The band pass filter allows only a specified range of frequencies to pass from input to output, rejecting all signals at lower or higher frequencies. |
<p>| Block Upconverter (BUC)     | Transmitter device that combines signal upconversion and power amplification in a single unit. The BUC is typically located directly at the antenna output, or relatively close to it. |</p>
<table>
<thead>
<tr>
<th><strong>Table 1.8</strong> Basic satellite glossary (Continued)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Broadcast Satellite Service (BSS)</strong></td>
</tr>
<tr>
<td><strong>C band</strong></td>
</tr>
<tr>
<td><strong>Coax(ial) cable</strong></td>
</tr>
<tr>
<td><strong>Dawn-to-dusk orbit</strong></td>
</tr>
<tr>
<td><strong>Demodulation</strong></td>
</tr>
<tr>
<td><strong>Demodulator</strong></td>
</tr>
<tr>
<td><strong>Descrambler</strong></td>
</tr>
<tr>
<td><strong>Digital-to-analog converter (DAC)</strong></td>
</tr>
<tr>
<td><strong>Dish</strong></td>
</tr>
<tr>
<td><strong>Downconverter</strong></td>
</tr>
<tr>
<td><strong>Dual feed</strong></td>
</tr>
<tr>
<td><strong>Dual-band feed</strong></td>
</tr>
<tr>
<td><strong>Earth station antenna</strong></td>
</tr>
<tr>
<td>Term</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Effective isotropic radiated power (EIRP)</td>
</tr>
<tr>
<td>End-of-life (EOL)</td>
</tr>
<tr>
<td>F/D ratio</td>
</tr>
<tr>
<td>Feed horn (feed)</td>
</tr>
<tr>
<td>Filter</td>
</tr>
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<td>Fixed Satellite Service (FSS)</td>
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<td>Focal length</td>
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<td>Frequency reuse</td>
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<tr>
<td>G/T</td>
</tr>
<tr>
<td>Geostationary orbit (GEO)</td>
</tr>
<tr>
<td>Global positioning (service/) system (GPS)</td>
</tr>
<tr>
<td>High power amplifier (HPA)</td>
</tr>
<tr>
<td>Highly elliptical orbits (HEOs)</td>
</tr>
<tr>
<td>Hybrid satellite</td>
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</tbody>
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(Continued)
<table>
<thead>
<tr>
<th><strong>Intermediate frequency (IF)</strong></th>
<th>A frequency that a carrier frequency is translated to in the process of reception or transmission of the signal. Intermediate frequencies are found between a modulator and an upconverter, or between a downconverter and a demodulator. Typical intermediate frequencies are 70 MHz, 140 MHz, and L band 950–1450 MHz.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Isotropic antenna</strong></td>
<td>A theoretical point source of radiation used as a reference antenna when calculating antenna gain.</td>
</tr>
<tr>
<td><strong>Ka band</strong></td>
<td>The third and most recent band of frequencies authorized for satellite communications. It occupies roughly from 20 to 30 GHz in the radio spectrum. This band is the most susceptible to rain fade of all the three satellite bands.</td>
</tr>
<tr>
<td><strong>Kelvin (Kelvin scale)</strong></td>
<td>The Kelvin scale is a measure of temperature where the lowest value is absolute zero, the point where all molecular motion stops. Because all electrical devices contribute noise to a system based upon their temperature, noise contribution in satellite systems is expressed in Kelvins.</td>
</tr>
<tr>
<td><strong>Klystron</strong></td>
<td>A power amplifier tube used to amplify microwave energy (provided by an RF exciter) to a high power level. A klystron is characterized by high power, large size, high stability, high gain, relatively narrow bandwidth, and high operating voltages. Electrons are formed into a beam that is velocity modulated by the input waveform to produce microwave energy. A klystron is sometimes referred to as a linear beam tube because the direction of the electric field that accelerates the electron beam coincides with the axis of the magnetic field. [AMS200001].</td>
</tr>
<tr>
<td><strong>Ku band</strong></td>
<td>The second band of frequencies authorized for satellite communications. It occupies roughly from 10 to 14.5 GHz in the radio spectrum. This band is more susceptible to rain fade than C band.</td>
</tr>
<tr>
<td><strong>L band</strong></td>
<td>An intermediate frequency (IF), typically employed at an earth station to route traffic between various points over coaxial/waveguide facilities. The frequency range covers the 950–1450 MHz spectrum. Note that over-the-air L-band ranges are (slightly) different and are defined by various regulatory agencies. Satellite signals (at C-band and Ku-band frequencies) are downconverted to L band in the focal point of many dish antennas by the LNB for further distribution within the electronics subsystem or the earth station. At C band, the downconversion is typically as follows: 4200–950 MHz; 4180–970 MHz; 4160–990 MHz, and so on up to 3700–1450 MHz. At the Ku band, the downconversion is typically as follows: 11700–950 MHz; 11720–970 MHz; 11740–990 MHz, and so on, up to 12200–1450 MHz. The upconverter handles the opposite function.</td>
</tr>
<tr>
<td><strong>Line amplifier</strong></td>
<td>An amplifier in a transmission line that boosts the strength of a signal level.</td>
</tr>
<tr>
<td><strong>Line splitter</strong></td>
<td>An active or passive device that divides a signal into two or more signals containing all the original information. A passive splitter feeds an attenuated version of the input signal to the output ports; an active splitter amplifies the input signal to overcome the splitter's loss.</td>
</tr>
</tbody>
</table>
Table 1.8 Basic satellite glossary (Continued)

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link budget</td>
<td>A collection of the various system parameters of a satellite link that is used to determine either the link performance from a fixed set of system parameters or some aspect of the system parameters given particular link performance criteria.</td>
</tr>
<tr>
<td>Local oscillator (LO)</td>
<td>A single-frequency reference signal that is used by a mixer to convert a communications signal to a higher or lower frequency band.</td>
</tr>
<tr>
<td>Low earth orbits (LEO)</td>
<td>Either elliptical or, more commonly, circular orbits that are at a height of 2000 km or less above the surface of the earth. The orbit period at these altitudes varies between 90 min and 2 hr, and the maximum time during which a satellite in LEO orbit is above the local horizon for an observer on the earth is up to 20 min [GEO200101].</td>
</tr>
<tr>
<td>Low-noise amplifier (LNA)</td>
<td>A low-noise device that receives and amplifies satellite signals at the output of the antenna feed horn; an LNA does not change the frequency of the received signal. LNAs are designed to contribute a minimum amount of noise to the signal received from the satellite to minimize the overall system noise temperature.</td>
</tr>
<tr>
<td>Low-noise block downconverter (LNB)</td>
<td>A low-noise device that receives and amplifies satellite signals at the output of a feed horn while also performing other functions such as signal detection, high-gain low-noise amplification, and frequency conversion. The frequency conversion downconverts a block of frequencies to a lower intermediate frequency range (typically in the L band). The feed horn is often integrated with LNB in a single mechanical unit.</td>
</tr>
<tr>
<td>Maritime Mobile Satellite Service (MMSS)</td>
<td>A satellite service between mobile satellite earth stations and one or more satellites.</td>
</tr>
<tr>
<td>Medium earth orbits/intermediate circular orbits (MEO/ICOs)</td>
<td>Circular orbits at an altitude of around 10,000 km. Their orbital period is around 6 hr.</td>
</tr>
<tr>
<td>Mixer</td>
<td>A nonlinear device in which two or more input signals are combined to generate a single output signal.</td>
</tr>
<tr>
<td>Mobile Satellite Service (MSS)</td>
<td>A satellite service intended to provide wireless communication to any point on the globe.</td>
</tr>
<tr>
<td>Modulator</td>
<td>A device that superimposes a signal (intelligence) onto a wave or signal (called a carrier), which is then used to convey the original signal via a transmission medium. Modulation techniques include amplitude modulation, frequency modulation, or phase modulation. For satellite applications, phase shift keying (PSK) is fairly common.</td>
</tr>
<tr>
<td>Offset antenna/feed</td>
<td>A parabolic antenna that has its feed horn offset from the center of the reflector in an effort to improve the performance of the antenna and reduce unwanted signals from adjacent satellites. Offset antennas can be easily modified to accept dual or multiple feeds, allowing them to receive signals from more than one satellite.</td>
</tr>
<tr>
<td>Perigee</td>
<td>Point in a satellite orbit (especially for highly elliptical ones) that is closest to the earth.</td>
</tr>
</tbody>
</table>
### Table 1.8 Basic satellite glossary (Continued)

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar satellites</td>
<td>LEOs orbits that are in a plane of the two poles. Their applications include the ability to view only the poles (e.g., to fill in gaps of GEO coverage), or to view the same place on earth at the same time each 24-hr day. Polar orbits are typically used by LEO communications satellites as well as research, weather, and spy satellites.</td>
</tr>
<tr>
<td>Polarization</td>
<td>Transmission approach where radio waves are restricted to certain directions of electrical and magnetic field variations, where these directions are perpendicular to the direction of wave travel. By convention, the polarization of a radio wave is defined by the direction of the electric field vector. Four senses of polarization are used in satellite transmissions: horizontal linear polarization, vertical linear polarization, right-hand circular polarization, and left-hand circular polarization.</td>
</tr>
<tr>
<td>Rain zone (aka precipitation zone)</td>
<td>Rain is precipitation that falls to earth in drops more than 0.5 mm in diameter. Rainfall is the amount of precipitation of any type, primarily liquid. It is usually the amount that is measured by a rain gauge. To aid in calculating the effect of precipitation loss, the world is divided into precipitation zones or rain climatic zones, each of which has a numerical value defined by the International Telecommunication Union (ITU), used in the calculation of a link budget.</td>
</tr>
<tr>
<td>Satellite receiver</td>
<td>A receiver designed for satellite reception. It receives modulated signals from an LNA or LNB and converts them into their original form.</td>
</tr>
<tr>
<td>Scrambler</td>
<td>A device that renders a signal unintelligible; of interest for modern communication is the process of encryption that has high cryptographic strength.</td>
</tr>
<tr>
<td>Solid-state power amplifier (SSPA)</td>
<td>A high-power amplifier using solid-state technology (i.e., transistors). Originally used for low- and medium-power applications; however, reliable medium- to high-power SSPA technology has emerged and is used routinely at earth stations and on spacecraft.</td>
</tr>
<tr>
<td>Splitter</td>
<td>A device that takes an input signal and splits it into two or more identical output signals, each a replica of the input signal (typically, with reduced amplitude, for example, −3 dB, but active devices can also operate at 0 dB loss).</td>
</tr>
<tr>
<td>Spread spectrum</td>
<td>(1) Telecommunications techniques in which a signal is transmitted in a bandwidth considerably greater than the frequency content of the original information. <strong>Note:</strong> Frequency hopping, direct-sequence spreading, time scrambling, and combinations of these techniques are forms of spread spectrum. (2) A signal-structuring technique that employs direct sequence, frequency hopping, or a hybrid of these, which can be used for multiple access and/or multiple functions. This technique decreases the potential interference to other receivers while achieving privacy and increasing the immunity of spread-spectrum receivers to noise and interference. Spread spectrum generally makes use of a sequential noise-like signal structure to spread the normally narrowband information signal over a relatively wide band of frequencies. The receiver correlates the signals to retrieve the original information signal [ANS200001].</td>
</tr>
</tbody>
</table>
Table 1.8 Basic satellite glossary (Continued)

<table>
<thead>
<tr>
<th>Term</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Sun-synchronous (SS) orbit</td>
<td>A special polar orbit that crosses the equator and each latitude at the same time each day; this orbit can make data collection a convenient task. Satellites in polar orbits are typically used for earth-sensing applications. Typically, such a satellite moves at an altitude of 1000 km [GEO200101].</td>
</tr>
<tr>
<td>System noise temperature</td>
<td>A value, expressed in Kelvins, that accounts for the noise contribution of all components in the earth station’s receive chain. Often depicted as $T_n$ or $T_{sys}$.</td>
</tr>
<tr>
<td>Traveling wave tube amplifier (TWTA)</td>
<td>A high-power amplifier based on vacuum-tube technology. Normally employed when high output power levels and wide bandwidths are required. Typically used on board satellites and often in earth stations.</td>
</tr>
<tr>
<td>Upconverter</td>
<td>A device for converting the frequency of a signal into a higher frequency.</td>
</tr>
<tr>
<td>Very small aperture terminal (VSAT)</td>
<td>A complete terminal (typically with a small 4–5 ft antenna) that is designed to interact with other terminals in a satellite-delivered data network, commonly in a “star” configuration through a hub. The term small aperture here actually refers to the occupied bandwidth of the VSATs’ transmitted carrier, which is typically only a few kHz wide. The VSAT terminal uses a special and often proprietary modulation, scrambling and coding algorithms; this allows the hub or network operator to control the system and present billing based on a data throughput or other form of usage basis. VSATs are utilized in a variety of applications and are designed as low-cost units. Commonly, several VSAT networks are operated through the same hub (shared services), which reduces the initial installation/setup costs [BAR200101].</td>
</tr>
<tr>
<td>Waveguide</td>
<td>A material medium that confines and guides a propagating electromagnetic wave, a transmission line. At microwave frequencies, a waveguide normally consists of a hollow metallic conductor, usually rectangular, elliptical, or circular in cross section, usually a pipe about 1 × 2 in. This type of waveguide may, under certain conditions, contain a solid or gaseous dielectric material [ANS200001]. It is typically used in earth stations to connect HPAs to the antenna.</td>
</tr>
</tbody>
</table>

References

Satellite Systems Engineering in an IPv6 Environment


[MUC200201] K. Muchorowski, CEENET Workshop 2002, Satellite Communications, NetSat Express, muchor@ceenet.org

References

1 Chapter 1. Introduction to Satellite Communications

[MUC200201] K. Muchorowski, CEENET Workshop 2002, Satellite Communications, NetSat Express, muchor@ceenet.org

Chapter 2. Electromagnetic Propagation and Reception


[BLA200701] K. Blattenberger, Free Space Loss, RF Café Website, Mt. Airy, NC.


Appendix 2A: Maxwell Equations

This section provides a brief overview of Maxwell’s Equations (not the easiest topic to discuss) and is based principally on reference [JEF199901]. The basic terms were defined in Section 2.2. All magnetic fields B form closed loops. Loops of B are linked with loops of current density J or displacement current density (∂D/∂t). Electric field lines either begin or end on charges, or else they also form closed loops. In a radiating situation, the currents, charges, fields, and potentials are all time varying. If one assumes a sinusoidal variation with time having angular frequency ω, then a general radiation problem can be solved by Fourier superposition of the solutions at different values of the angular frequency ω. There are four of Maxwell’s Equations plus a charge continuity equation that define electromagnetic theory: div D n = ρ
div B n = 0 curl E n = −(∂D/∂t)B curl H n = (∂D/∂t)D + J
and the continuity equation for charge: div J n + (∂ρ/∂t) = 0

These are written formally as follows: \( \nabla \cdot D = \rho \\ \ \ \ \ \nabla \cdot B = 0 \\ \ \ \ \nabla \times E = -\frac{\partial}{\partial t}B \\ \ \ \ \nabla \times H = \frac{\partial}{\partial t}D + J \\ \ \ \ \nabla \cdot J = \frac{\partial \rho}{\partial t} = 0 \)

where the divergence (div), curl (curl), and gradient (grad) are defined in vector differential calculus. In broad terms, the gradient represents the “slope” of a scalar field along the direction of maximum change; the gradient is a vector. The divergence represents the flow out of a small volume per unit volume, and is a scalar. The curl represents the rotation of a field around a point; for a magnetic field forming closed loops, it is the limit of the size of the field multiplied by the
perimeter of the loop divided by the area of the loop, as the loop shrinks to nothing. The curl is a vector because it has an associated axis of circulation or direction in space. A high-level explanation of these equations is as follows: Lines of \( \mathbf{n} \mathbf{D} \), electric induction, are proportional to the electric field and “diverge” away from a region containing charge density \( \rho \). If there is a surface charge \( \sigma \) (coulombs per square meter), then close to the charge sheet there is an electric induction field \( \mathbf{D} = \mathbf{\sigma} \). Lines of \( \mathbf{n} \mathbf{B} \) never diverge from anything, and form closed loops. Electric field lines that form closed loops encircle a changing magnetic field. Lenz’s law applies; the electric field, if it drove a current, would do so in such a way as to reduce the changing magnetic field within the loop. Electric field lines that do not form closed loops begin and end on charge, as seen from the first equation. Magnetic field lines \( \mathbf{n} \mathbf{H} \) form loops that encircle both conduction current density \( \mathbf{J} \) and also “displacement current density” \( (\delta /\delta t)\mathbf{D} \), which is generated by time-varying electric fields. Maxwell’s achievement was to realize that the term in \( (\delta /\delta t)\mathbf{D} \) was necessary; if one considers a capacitor with plates very close together, then, if the displacement current term did not generate magnetic field loops, there would be a discontinuity in the magnetic fields around the capacitor plates as one passed alternating current through the capacitor. The current density \( \mathbf{n} \mathbf{J} \) flowing out of a region (“diverging”) must result in a decrease of charge within the region.

Currents and charges give rise to the fields and are called sources. More directly, the potentials can be calculated from the source charge and current distributions, and the fields are then derived from the potentials. In an electrostatics situation, the electric field \( \mathbf{E} \) is given by \( \mathbf{E} = -\operatorname{grad}(\phi) \), which begins and ends on charges.

However, if there are changing magnetic fields, there is an additional contribution to the electric field forming the closed loops that circulate around the changing magnetic field lines. The magnetic vector potential \( \mathbf{A} \) may be used to find the magnetic field \( \mathbf{B} \) by the relation

\( \mathbf{B} = \mathbf{\operatorname{curl}}(\mathbf{A}) \)

(which is a definition of \( \mathbf{A} \)).
To define $A$ completely, one has to specify its divergence as well as its curl, and possibly an additive constant also. If one does this according to what is known as the “Lorentz Gauge,” then the electric field may be calculated from
\[ E = -(\frac{\partial}{\partial t})A - \nabla(\phi) \]
Part of the source of the electric field is from the magnetic vector potential $A$, and part from the scalar potential $\phi$. If one knows the potentials $A$ and $\phi$ completely for all time and space, one can calculate the fields $E$ and $B$. A little more detailed mathematics shows that the conduction currents $J$ give rise to the magnetic vector potential $A$, and the source charges $\rho$ give rise to the scalar potential $\phi$. Because there is a maximum velocity of propagation $c = 3 \times 10^8$ m/s, the potentials $A$ and $\phi$ at a distance $r$ meters from the source cannot follow changes in the source distributions until a time $r/c$ seconds later.

Considering the equation $E = -\nabla(\phi) - (\frac{\partial}{\partial t})A$

one observes that, in the far field, the potentials $A$ and $\phi$ fall off as $1/r$, where $r$ is the distance from the sources. However, applying the gradient operator to $\phi$ puts in a further dependence of $1/r$ on the contribution $-\nabla(\phi)$. Thus, the electric field $E$, due to the charges in the source, falls off as $1/(r^2)$ and can be neglected at large $r$ compared to the electric field contribution $-(\frac{\partial}{\partial t})A$, which falls off as $1/r$. Hence, for far-field calculations, it is true to say that only the source currents on the antenna structure need be considered. For time-harmonic currents, because the charge continuity equation links the current density $J$ to the source charge density $\rho$, the potential $\phi$ may be
expressed in terms of the vector potential $A$, and therefore, there is no loss of generality in considering the far fields as being entirely due to source currents plus any preexisting electromagnetic propagating waves. For near-field scenarios, the conduction currents on the source structures are not sufficient to use as a basis for field calculations. Consider an open-ended waveguide. Assume that the wave guide is very large in transverse dimensions compared to the wavelength. Now consider a point on the axis of the waveguide, beyond the plane at which the waveguide stops, along the z-direction. Assume that this point is closer to the point $z = 0$, which defines the exit plane, than it is to any of the current elements on the waveguide walls. If only conduction currents starting at time zero contribute to the field strength at this point, there can be no field at this observation point at a time less than the retardation time from the guide walls. Now, as one lets the guide dimensions get larger (without limit), one can show that, for any specific point on the axis of the waveguide beyond the waveguide end plane, the fields due to the currents in the walls are zero for finite time. If one takes the view that the waveguide is the only structure generating electromagnetic fields and that there are no preexisting propagating waves along the axis of the guide, then this result appears contradictory and nonphysical, and so the accepted theory, and nearly all the antenna calculations and simulation codes based on fields being set up only by the source currents, may be in error.

Another way of looking at this problem is that the wave front progresses along the waveguide at
the group velocity, which is lower than the velocity of light in the medium. Regarded as a radiating
structure, the mouth of the waveguide sets off a propagating wave in free space that travels at the
velocity of light. There must, therefore, be a contribution to the radiated fields from the center of
the guide mouth, where the conduction currents are zero. Yet another insight may be obtained by
appealing to Huygen’s principle in wave optics, where each point on a propagating wave front is regarded as giving rise to an outgoing hemispherical wave front. Thus, if one considers radiation from a burst of microwaves propagating in free space at time zero, there are no source currents in the problem at all within the limits of the definition of the problem. Most antenna calculations are made assuming that the time-harmonic radiation has persisted/persists for all times past and future, and so the problem of what happens at the start of a radiating wave front is hidden from the analysis. Further examination of the equations shows that A, and therefore E (in the far field), lies in the preferred direction of the current sources. (The preferred direction may be taken to be an average direction over all the source currents.) The magnetic field B, on the other hand, forms loops around the current direction, and therefore B is at right angles to E and to the preferred direction of the current sources. Moving charge constitutes a current. In most wires, there is a near balance between mobile negative charge (electrons) and a background sea of positive charge (ions), which is stationary. It is therefore possible to have an “electrically neutral
current" wherein the moving charge forming
the current does not by itself provide a source of charge
density \( \rho \) and, therefore, of electrostatic
scalar potential \( \phi \). For this reason, in many antenna
analyses, near-field as well as far-field radia

tion is assumed to be entirely determined if only the
current distribution in the source is known.

This is sufficient for many antenna problems. However, where there are significant discrepancies
between the predictions of standard theory and the
measurements on a specific antenna structure,

one should look to see if there are any significant
time-varying charge accumulations within the
antenna conductor structure or on any local scattering
objects. One should also look to see if there
are any photons emitted by transitions between electron
energy levels and if there are any preexist
ing electromagnetic waves. Although the laws of
electrodynamics are defined by Maxwell, they are most readily understood
in terms of the source and vortex interpretation of
Helmholtz and the field pictures of Faraday.

Helmholtz has shown that vector fields may be regarded as
the superposition of two different basic
field types, known as source type and vortex type (see
Figure 2.A1). In the illustration of a purely
source field, one finds field lines of electric field
originating in a region of positive charge. If these
field lines terminate somewhere, it is in a region of
negative charge; these source type field lines,
however, never intersect nor close upon themselves. In the
illustration of a purely vortex field, one

Figure 2.A1 Source and Vortex Fields. Source Field Vortex Field
finds field lines of magnetic field surrounding a wire carrying a current. These vortex field lines are always in the form of closed curves, and never have a starting point or an ending point. What one learns about electric fields from Maxwell’s equations is that the electric field $E$ can be either source type or vortex type, or a mixture of both. The regions of space providing sources of $E$ can be charges on conductors, and those providing vortices of $E$ are regions where there is a time-varying magnetic flux density. What one learns about magnetic fields from Maxwell’s equations is that the magnetic field $H$ can, in the absence of magnetic media, be only the vortex type. The regions of space providing vortices of $H$ are those where there is neither an electric current nor a time-varying electric flux density. When electromagnetic fields propagate to a significant distance from their originating antenna, it is the property of time-varying electric fields to create surrounding vortices of the magnetic field and time-varying magnetic fields to create surrounding vortices of the electric field that may be regarded as providing the mechanism for the propagation phenomenon.
3 Chapter 3. Antenna Engineering Basics


[ANT200601] Antenna Introduction/Basics, ANITA (Antarctic Impulsive Transient Antenna) Department of Physics and Astronomy at the University of Hawaii and Manoa, RF Hardware Reference Library, excerpts from the Military EW Handbook.


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[GAR200401] D. E. Gary, Radio Astronomy Lecture Notes,
Appendix 3A: Amplifier Preemphasis

The issue of amplifier power is important for proper operation of a satellite system. Sufficient power is needed to be able to close the link (as covered in
Chapter 4). Backoff is needed to avoid intermodulation problems. Preemphasis is needed to deal with group delay considerations (covered in Chapter 3). This appendix provides a quick tutorial on amplifications, based primarily on reference [SIL200201] by J. Sills. Three types of HPAs are found in satellite applications, as follows [FOC200701]:

Solid-state power amplifiers (SSPA). HPAs that use solid-state components (e.g., transistors) to amplify the RF power level at its input. Solid-state amplifiers typically have more linear characteristics than other types of amplifier, but they are limited to lower power levels (however, in recent years, they have achieved fairly high levels in the 2-3 KW range). Traveling wave tube amplifiers (TWTA). HPAs that use a complex series of magnets, cavities, and an electron beam encased in a vacuum tube to amplify the power of the input signal. TWTTAs can provide more power than SSPAs, but they are not normally operated at their full output power level because of nonlinear effects that adversely affect the transmission quality. They are usually operated at several decibels below their maximum output power level so that the device’s behavior is approximately linear. This is especially true if the TWTA is amplifying multiple carriers, which are susceptible to mutual interference caused by device nonlinearities. Klystron Power Amplifier (KPA). HPAs that use a series of interconnected resonant cavities to successively amplify the input signal. They produce similar output power levels to TWTTAs and, for equal output powers, can be the more economical choice. However, their bandwidth is limited to around 100 MHz or less, and consequently, they may not be suitable for earth stations that need to be able to transmit over a wide frequency range. Figure 3.A.1 depicts the typical power response of HPAs. Figure 3.A.2 (top) shows the input-output block diagram of a power amplifier, where $v_i(t)$ and $v_o(t)$ are the input and output signals, respectively. The output can be expressed as

$$v_o(t) = v_i(t) g(t) e^{j(\phi(t)+2\pi f_c t)}$$

where $g(t)$ and $\phi(t)$ are the amplifier’s amplitude-transfer (AM-to-AM) and phase-transfer (AM-to-PM) characteristics.
tics. The amplitude and phase values can be plotted as a function of input power; see Figure 3.A.3

for an example (the transfer characteristics can be measured by applying an input pulse to the

power amplifiers (PA) and measuring the output amplitude and phase). The amplifier’s linear characteristic is defined by $g(t) = G \cdot a(i(t)) v(t)^2$.

where $G$ corresponds to a given gain. The linear region is defined as that set of inputs for which $g_a a g g g = = and \phi$.

For the example in Figure 3.A.3, the upper limit of the linear region falls between +5 and +10 dBm.

the amplifier exhibits a 35-dB gain; beyond that, the amplifier cannot sustain this gain. The 1-dB compression point is defined as the input power at which the amplifier’s output

power is 1 dB below the linear response. In the example highlighted in Figure 3.A.3, the 1-dB

compression point occurs at +20 dBm. With the input power at +20 dBm, the output power is

+54 dBm, which is 1 dB less than the +55-dBm output power required for linear operation. The

saturation point corresponds to the input level that results in the largest output. In this case, the

saturation point is at +25 dBm.

Figure 3.A.1 HPA power response. Output Power TWTA SSPA Input Power Max Power Max Power

Figure 3.A.2 PA operation. Top: block diagram of PA’s input and output. Bottom: diagram of a
cascaded digital predistorter plus a PA. $v_i(t) v_i(t) v d(t) v d(t) v o(t) v o(t) f(\cdot) g(\cdot) g(\cdot)$ A predistortor preceding the amplifier can be used to linearize the amplifier. Figure 3.A.2

(bottom) shows the predistortion PA cascade, where $n d(t)$ is the predistortion output. Expanding the equation given at the start of this discussion gives $v t g f v t v t f v t$.
By definition, the PA is linearized when \( G f v t t f v t g \)
\( v i i a i = -g v \). For input levels in the linear range of the amplifier, the 
predistortor applies a gain of 0 dB and

has no effect on the signal. In the nonlinear range, it

applies a gain to either amplify or attenuate

the input signal. The value of the gain depends on the

input level. For example, with an input

of +20 dBm, the predistortor applies a gain of

approximately 2 dB. The amplifier input is now

+22 dBm, which results in the desired +55-dBm output. The

predistortor must also linearize the amplifier’s phase

response. Figure 3.A.3 shows that the

phase distortion is approximately 2° at the 1-dB

compression point, and nearly 6° at saturation.

It introduces a phase shift that is equal and opposite to

that of the amplifier. The two-tone analysis

that follows gives clear evidence that phase linearization

cannot be neglected. PAs can be characterized by their

response to inputs constructed from two sinusoidal tones

because that drives intermodulation. Consider the two-tone

input \( v j t j t i t ve ve( ) = + w 1 2 w \)

Here, the PA output is the product of three terms:

\( g v t e i a i t i \)

\( i j \phi \) and \( t \)

that is, \( v t g v t v t g v t e i i a i v i 0 2 2 ( ) (| ) ( | ) ( | ) ( | ) ( | ) ( | ) = jg \phi ( ) ( ) t i v t 2 \)
The spectrum of the output is equal to the spectral convolution of these three terms.

Figure 3.A.4 depicts the spectrum of the two-tone input signal, where \( w_1 = 5 \text{ MHz} \), and

\[
w_2 = 9 \text{ MHz}.
\]
The phase response can be expressed as a Taylor’s series:

\[
e^{-j \omega t} e^{-j \omega t} \cos \left( \frac{2 \pi}{\omega_1} t \right) + \cos \left( \frac{2 \pi}{\omega_2} t \right) \cos \left( \frac{2 \pi}{\omega_3} t \right) ...
\]

\[
C_{\omega_1} + C_{\omega_2} + C_{\omega_3} + ... = 0
\]

where \( C_{\omega_m} = \frac{1}{\omega_m^2} \frac{d^2}{dt^2} \sum_{\omega_m} \frac{1}{\omega_m^4} \)

and \( C_{\omega_m} = \frac{1}{\omega_m^2} \frac{d^2}{dt^2} \sum_{\omega_m} \frac{1}{\omega_m^4} \)

It is clear here that the phase response has an infinite number of spectral components, but the amplitude of these components falls off rapidly as shown in Figure 3.A.4. Say, for example, that the peak-to-average ratio (PAR) is 3 dB (the average power of the two tone signal being +17 dBm, and the peak being +20 dBm). Thus, in this example, the average power was backed off by 3 dB so that the peak power did not exceed the 1-dB compression point of the amplifier. Multicarrier communication signals can exceed 9-dB PAR and therefore require greater backoff. Unfortunately, as backoff increases, efficiency decreases. For an ideal strong nonlinear

linearity, the minimum backoff required for linear operation is equal to the PAR. In a more realistic model that includes a weak nonlinearity, the backoff needs to be increased even further.

Digital predistortion can be used to linearize the weak nonlinear behavior of the amplifier and
reduce backoff, thereby increasing efficiency. Figure 3.A.5 shows a typical PA output with and without predistortion.

Figure 3.A.5 PA with and without predistortion. (Courtesy CommsDesigns, www.commsdesigns.com)

Without applying predistortion (i.e., without linearizer) With application of predistortion (i.e., with linearizer)

Appendix 3B: FCC Rules on EIRP Density

This appendix contains four charts illustrating the FCC EIRP density limits for four combinations of analog/digital and C/Ku-band operations [RYA199901]. Ku-Band Analog E/S Antenna Gain (dBi) RF Power Density (dBW/4kHz) EIRP Density (dBW/4kHz) CFR 25.209(a)(1) CFR 25.212(c)

<table>
<thead>
<tr>
<th>Angle Off Main Axis (deg.)</th>
<th>-10</th>
<th>-5</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIRP Density (dBW/4kHz)</td>
<td>29.0</td>
<td>21.5</td>
<td>17.1</td>
<td>13.9</td>
<td>11.5</td>
<td>9.5</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>RF Power Density (dBW/4kHz)</td>
<td>-6</td>
<td>-7</td>
<td>-7</td>
<td>-7</td>
<td>-4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Ku-Band Digital E/S Antenna Gain (dBi) RF Power Density (dBW/4kHz) EIRP Density (dBW/4kHz) CFR 25.209(a)(1) CFR 25.212(c)

<table>
<thead>
<tr>
<th>Angle Off Main Axis (deg.)</th>
<th>-10</th>
<th>-5</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIRP Density (dBW/4kHz)</td>
<td>29.0</td>
<td>21.5</td>
<td>17.6</td>
<td>14.4</td>
<td>12.0</td>
<td>10.0</td>
<td>8.5</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>RF Power Density (dBW/4kHz)</td>
<td>-6</td>
<td>-7</td>
<td>-7</td>
<td>-7</td>
<td>-4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

C-Band Analog E/S Antenna Gain (dBi) RF Power Density (dBW/4kHz) EIRP Density (dBW/4kHz) CFR 25.209(a)(1) CFR 25.212(c)

<table>
<thead>
<tr>
<th>Angle Off Main Axis (deg.)</th>
<th>-10</th>
<th>-5</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIRP Density (dBW/4kHz)</td>
<td>29.5</td>
<td>22.0</td>
<td>17.6</td>
<td>14.4</td>
<td>12.0</td>
<td>10.0</td>
<td>8.5</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>RF Power Density (dBW/4kHz)</td>
<td>-6</td>
<td>-7</td>
<td>-7</td>
<td>-7</td>
<td>-4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 3.B.3 Routine licensing of small antennas: C-band analog EIRP density limits. C-Band Digital E/S Antenna Gain (dBi) RF Power Density (dBW/4kHz) EIRP Density (dBW/4kHz)

<table>
<thead>
<tr>
<th>CFR 25.209(a)(1)</th>
<th>CFR 25.212(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>-1</td>
</tr>
<tr>
<td>-2</td>
<td>-3</td>
</tr>
<tr>
<td>-4</td>
<td>-5</td>
</tr>
<tr>
<td>-6</td>
<td>-7</td>
</tr>
<tr>
<td>29.0</td>
<td>21.5</td>
</tr>
<tr>
<td>17.1</td>
<td>13.9</td>
</tr>
<tr>
<td>11.5</td>
<td>9.5</td>
</tr>
<tr>
<td>8.0</td>
<td>6.8</td>
</tr>
<tr>
<td>5.3</td>
<td>4.4</td>
</tr>
<tr>
<td>11.2</td>
<td>8.0</td>
</tr>
<tr>
<td>6.8</td>
<td>5.3</td>
</tr>
<tr>
<td>4.4</td>
<td>3.3</td>
</tr>
<tr>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>-2.7</td>
<td>-2.7</td>
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<tr>
<td>-2.7</td>
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<td>-2.7</td>
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<tr>
<td>-2.7</td>
<td>-2.7</td>
</tr>
<tr>
<td>15.0</td>
<td>20.0</td>
</tr>
<tr>
<td>25.0</td>
<td>30.0</td>
</tr>
<tr>
<td>35.0</td>
<td>40.0</td>
</tr>
<tr>
<td>45.0</td>
<td>50.0</td>
</tr>
</tbody>
</table>

Figure 3.B.4 Routine licensing of small antennas: C-band digital EIRP density limits.
Chapter 4. Modulation and Multiplexing Techniques


[TOR199801] A. Torres, V. Demjanenko, Inclusion of Concatenated Convolutional Codes in the ANSI T1.413 Issue 3, Contribution to Standards Committee T1-Telecommunications, Plano, Texas T1E1.4/98-301R1, November 30-December 4, 1998, VoCAL Technologies Ltd.

Chapter 5. Error Correction Techniques


Table 5.3 Comparison of DVB-S2 and DVB-S broadcasting services

<table>
<thead>
<tr>
<th>Satellite EIRP (dBW)</th>
<th>51</th>
<th>53.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>DVB-S</td>
<td>DVB-S2</td>
</tr>
<tr>
<td>Modulation and coding</td>
<td>QPSK 2/3</td>
<td>QPSK 3/4</td>
</tr>
<tr>
<td>Symbol rate (Mbaud)</td>
<td>27.5 ($\alpha = 0.35$)</td>
<td>30.9 ($\alpha = 0.0$)</td>
</tr>
<tr>
<td>C/N (in 27.5 MHz) (dB)</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Useul bitrate (Mbit/s)</td>
<td>33.8</td>
<td>46 (gain = 36 percent)</td>
</tr>
<tr>
<td>Number of SDTV programs</td>
<td>7 MPEG-2</td>
<td>15 AVC</td>
</tr>
<tr>
<td>Number of HDTV programs</td>
<td>1-2 MPEG-2</td>
<td>3-4 AVC</td>
</tr>
</tbody>
</table>


Oslo, Department of Informatics, Oslo, Norway.


Chapter 6. Link Budget Analysis


Antenna, area aperture For a circular antenna, \( A = \pi D^2 / 4 \)

Antenna, effective aperture area \( A_{\text{eff}} = \eta A \), where \( \eta \) is the efficiency of the antenna (usually between 55% and 75%)

Antenna, maximum gain Maximum in the direction of maximum radiation (the electromagnetic axis of the antenna, the boresight) \( G_{\text{max}} = (4\pi/\lambda)^2 A_{\text{eff}} = \eta (\pi D/\lambda)^2 = \eta (\pi D f/c)^2 \)

In dBi, relative to an isotropic antenna, the maximum antenna gain is \( G_{\text{max}} \), dB = \( 10 \log \eta (\pi D/\lambda)^2 \)

Carrier-to-noise ratio \( C/N = \text{EIRP} + G/T - (L_p + k + B_{\text{IF}}) \)

\( \text{EIRP} = \) effective radiated power of satellite (dBW)

\( L_p = \) path loss

\( k = \) Boltzmann’s constant \((-228.6 \text{ dBW/K/Hz})\)

\( B_{\text{IF}} = 10 \log \) (bandwidth of IF in Hz)

Decibel Defined as being equal to ten times the common (or base ten) logarithm of a ratio of power measurements, that is: \( X = 10 \times \log \frac{P_1}{P_0} \)

To recover the original ratio the equation can be inverted: \( \frac{P_1}{P_0} = 10^{X/10} \)

Figure of merit \( G/T = \) antenna gain in dB/(10 log (antenna + LNA noise)) LNA noise is in K IF bandwidth \( B_{\text{IF}} = 10 \log \) (bandwidth of IF), bandwidth is in Hz Noise power spectral density \( N_0 \) \( = kT \) (watts/Hz) where \( k \) is the Boltzman constant \((1.38 \times 10^{-23} \text{ J/K})\) and \( T \) is the absolute temperature in Kelvins (K). Total noise power, \( N \) (in the bandwidth of interest) is calculated by multiplying the noise power spectral density \( N_0 \) by the bandwidth: \( N = kT B \) (watts) where \( B \) is the bandwidth of interest (in Hz)

Path loss \( L_p = 37 + 20 \log F + 20 \log D F = \) frequency in
MHZ D = distance in miles (Continued) Appendix 6A: Formulas
Generally Used in Link Budget Analysis (Continued)

Probability of a transmission error on the AWGN
channel \( P_m \) \[
= \frac{1}{2} \erfc \left( \frac{\sigma}{\sqrt{2}} \right) \]
with \( \erfc(x) = 2 \int_{x}^{\infty} e^{-t^2} dt \)

Converting noise figure (NF) (dB) to noise
temperature (NT) (K)
\[
NF = 10 \log \left( \frac{NT}{290} + 1 \right) \]
Converting
noise temperature (NT) (K) to noise figure (NF) (dB)
\[
NT = 290 \left( 10 \left( \frac{NF}{10} \right) - 1 \right) \]

Free space loss becomes \( L \) dB =
\[
21.98 + 20 \times \log \left( \frac{d}{\lambda} \right) \]
d = distance

Satellite link budget at the receiver (summarized)
\[
\frac{\text{C/N}}{0} [\text{dB}] = \frac{\text{E}_b}{\text{N}_0} [\text{dB}] + 10 \log R \]
where \( \text{C/N} \) is carrier to
noise density ratio, \( \text{E}_b / \text{N}_0 \) is energy per information
bit to noise density ratio, and \( R \) is the information bit
rate. For a data rate \( R \) of 2 Mbps ( = 63 dB) a satellite
receiver using QPSK modulation and rate 1/2
convolutional/Reed-Solomon coding, requires \( \text{E}_b / \text{N}_0 = 5 \)
dB to achieve a target bit error rate (BER) less than \( 10^{-10} \)
over a satellite channel. Therefore, the required \( \text{C/N} \)
0 is more than 68dB [ITE200401].

Clear-air attenuation known as gaseous attenuation,
\[
A = \left[ \log \left( \frac{\text{A}_{g}(t)}{T_t} \right) \right] \left( \frac{\text{m}}{10} \right) \]
[T t m is the mean radiating temperature, and \( \text{T}_t \) \( bg \) is the
cosmic background temperature, and \( \text{T}_t \) \( cs \) \( sky \) [K] is the
sky noise temperature( ) Earth terminal to satellite slant
range The range calculation for a geostationary satellite
in terms of the satellite orbital slot, and the earth
station longitude and latitude is shown following.

Appendix 6A: Formulas Generally Used in Link Budget
Analysis (Continued) Center of Earth C Range Nadir
Point Ground B H A Slant Range Grazing Angle Slant
range is the length of a line drawn from the antenna to
the satellite Point of Interest \( D \) \( r_s \) \( R \) \( R \) \( e \) \( e \)
\( \Theta \) FL \( \psi \) pi 2 Center of Earth Earth Station d d :

Slant Range \( r_s \) : Earth Radius \( l_e \) : West Longitude \( l_s \)
West Longitude \( \cos (\gamma) = \cos (L_e) * \cos (l_s - l_e) \)
d = \( r_s \) \( * \left[ 1 + \left( \frac{r_e}{r_s} \right) 2 - 2 * \left( \frac{r_e}{r_s} \right) \right] \)
E : North Latitude \( r_s \) : Orbital Radius \( \gamma \)
Central Angle Satellite Earth Station Location Satellite
Orbital Slot: \( r_s \) \( r_e \) The range equation is then merely
a function of the central angle, \( \gamma \), as the other values
are known. Specifically, \( r_s = 42,242 \) km for
geostationary \( r_e = 6,370 \) km for average Earth radius The
equation can then be written \( d = 42,242 \) \( * \left[ 1.02274 -
0.301596 * \cos (\gamma) \right] \) with the result in kilometers.
The result is used to calculate free space loss in the
appropriate equation.
Chapter 7. IPv6 Overview

[6NE200501] 6NET, “D2.2.4: Final IPv4 to IPv6 Transition Cookbook for Organizational/ISP (NREN) and Backbone Networks,” Version: 1.0 (4th February 2005), Project Number: IST-2001-32603, CEC Deliverable Number: 32603/UDS/DS/2.2.4/A1.


[DEE199801] S. Deering, R. Hinden, “Internet Protocol, Version 6 (IPv6) Specification,” RFC 2460, December 1998. (C) The Internet Society (1998). All Rights Reserved. This document and translations of it may be copied and furnished to others, and derivative works that comment on or otherwise explain it or assist in its implementation may be prepared, copied, published and distributed, in whole or in part, without restriction of any kind, provided that the above copyright notice and this paragraph are included on all such copies and derivative works.


[DRO200301] R. Droms, Ed., J. Bound, B. Volz, T. Lemon, C. Perkins, M. Carney, Dynamic Host Configuration Protocol for IPv6 (DHCPv6), RFC 3315, July 2003. (C) The Internet Society (2003). All Rights Reserved. This document and translations of it may be copied and furnished to others, and derivative works that comment on or otherwise explain it or assist in its implementation may be prepared, copied, published and distributed, in whole or in part, without restriction of any kind, provided that the above copyright notice and this paragraph are included on all such copies and derivative works.


Appendix 7A: Header Compression
Implementation of IPv6 raises concerns related to new packet headers because, as we have seen in this chapter, the packet header size for an IP datagram doubles from 20 bytes (IPv4) to at least 40 bytes (IPv6). Furthermore, incorporation of network-layer encryption mechanism (i.e., IPSec) nearly doubles the IP operational overhead. This predicament is undesirable for many wireless and satellite networks because they are typically bandwidth-constrained or bandwidth is (relatively) expensive. This issue also impacts delay-sensitive applications such as VoIP and IP-based video conferencing; this is the reason Header Compression (HC) was deemed critical for VoIP even in an IPv4 environment. HC is, therefore, particularly important in IPv6-over-satellite environments. This appendix, based on reference [ERT200401] and used with permission, provides a short overview of this important topic. HC methods that reduce the expanded overhead of IPv6 are able to increase user throughput and the number of users a network can support. Consider a case where two routers are connected using a line operating at 1 Mbps and where the packet payload is 20 bytes (constant). With the addition of the 40 byte IPv6 Header, 2083 packets can be sent per second transmitted across the link. Over a one second period about 666 kb transmitted is IPv6 overhead and about 333 kb transmitted is actual user data (i.e., 66 percent of data transmitted is overhead). If the header is compressed to 2 bytes, about 5680 packets sent per second; over a one second period, about 90 kb transmitted is IPv6 overhead and about 910 kb transmitted
is actual user data (i.e., 9 percent of
data transmitted is overhead). This shows that, under the
best case scenario, HC can theoretically
decrease header overhead by 95 percent. Obviously, the
shorter the packets, the more onerous is
the impact of the overhead. VoIP and video-over-IP use
relatively short packers. Furthermore,

studies show that 40 percent of packets that traverse the
Internet are 40 bytes in length. It follows

that in IPv6 the 40 byte header on a datagram carrying a
40-byte payload results in a situation

where 50 percent of the bandwidth is consumed for overhead.
The same studies show that the
average packet length is around 355 bytes (Header and
Payload). Assuming that no header compression is applied,
IP header overhead is calculated as follows: Percentage
Overhead = IP Header Bytes/Total Bytes Transmitted = 40
Bytes/375 Bytes = 10.67% overhead Assuming that a header
compression algorithm is applied to the ESP/IP header,
overhead cal

culations can be made as follows (assuming header size is
reduced to 2 bytes per packet): Percentage Overhead =
Compressed Header Bytes/Total Bytes Transmitted = 2
Bytes/337 Bytes = 0.59% overhead Recognizing the need to
reduce the size of IP headers, the IETF has led the
development of HC

algorithms. In these algorithms, compression is applied to
Layer 3 (IP) and several Layer 4 protocol

headers. HC solutions can reduce the additional overhead
introduced by network-layer encryption

mechanisms (e.g., IPSec). Compression algorithms
instantiated on encryption/decryption devices

have the ability to (a) compress inner headers before
encryption; and (b) compress outer ESP/IP

headers after encryption. See Figure 7A. HC algorithms
exploit protocol inter-packet header field
redundancies to improve overall efficiency. Compression is applied over a link between a source node (i.e., compressor) and a destination node (i.e., decompressor). Both compressor and decompressor store header fields of each packet stream and associate each stream with a context identifier (CID). Upon receipt of a packet with an associated context, the compressor removes the IPv6 header fields from the packet header and appends a CID. Upon receipt of a packet with a CID, the decompressor inserts IPv6 header fields back into the packet header and transmits the packet. The reduction in the number of full headers transmitted can result in an overall decrease in overhead. See Figure 7B. Two compression protocols have emerged from the IETF: (1) Internet Protocol Header Compression (IPHC), and (2) ROHC Working Group: Robust Header Compression (ROHC).

Figure 7A Goal of compression algorithms in an IPv6 environment. 60 Byte RTP/UDP/IPv6 Header 2 to 4 Byte Compressed Header Payload Figure 7B Compression process. 7. Packets header in packet streams are “compressed” based on the context array. Compressor 1. Initial packets in packet streams arrive TCP/IPv6 Header TCP/IPv6 Header CID = 90 TCP/IPv6 Header CID = 100 TCP/IPv6 Header Data TCP/IPv6 Header Data TCP/IPv6 Header Data TCP/IPv6 Header Data TCP/IPv6 Header Data Data Data Data Data Data 3. Context initialization headers (CID embedded in the length field of IPv6 header) 6. Subsequent packets in packet streams arrive 2. Context information for both packet streams stored on compressor 8. Packets with compressed headers are transmitted CID 100 CID 90 CID 90 100 Source ABC0:0:0:2::1 ABC0:0:0:2::2 Destination CEF0:0:0:2::1 CEF0:0:0:2
IPHC mechanisms facilitate compression of dynamic header fields (e.g., TCP sequence numbers.)

Delta-based differential encoding mechanisms provide compression of incremental header fields,

as depicted in Figure 7C. However, if sequential packets are lost, compressor--decompressor contexts will desynchronize; resynchronization depends on how quickly the compressor notices desynchronization; the compressor reestablishes context by transmitting a full header. IPHC algorithm performs poorly over high BER, long-RTT links. ROHC
provides improved header compression over IPHC in high BER and high RTT wire

less links. These benefits, however, come at a cost, because ROHC implementation is significantly

more complex than IPHC. The operation of ROHC is shown in Figure 7D (for details of state

machines, see RFC 3095.) ROHC incorporates enhanced mechanisms compared to IPHC; for

example, implementation flexibility (capability to compress headers with or without a feedback

mechanism), and improved compression ratios (specifically, the ability to compress, e.g., TCP

SYN and FIN messages and timestamps). In summary, it provides greater compression compared

to IPHC at the cost of greater implementation complexity. Note: Cisco Systems OS provides IPHC implementation; furthermore, both IPHC and ROHC

are specified in Release 4 and Release 5 of the 3rd Generation Partnership Project (3GPP).
Chapter 8. Carrying IPv4, IPv6, and TCP over Satellite Links


Chapter 9. Satellite Communication in IPv6 Environments

