8.1 Frequency Band Trade-Offs

Satellite communication is a form of radio or wireless communication and therefore must compete with other existing and potential uses of the radio spectrum. During the initial 10 years of development of these applications, there appeared to be more or less ample bandwidth, limited only by what was physically or economically justified by the rather small and low powered satellites of the time. In later years, as satellites grew in capability, the allocation of spectrum has become a domestic and international battlefield as service providers fight among themselves, joined by their respective governments when the battle extends across borders. So, we must consider all of the factors when selecting a band for a particular application.

The most attractive portion of the radio spectrum for satellite communication lies between 1 and 30 GHz. The relationship of frequency, bandwidth, and application are shown in Figure 8.1. The scale along the *x*-axis is logarithmic in order to show all of the satellite bands; however, observe that the bandwidth available for

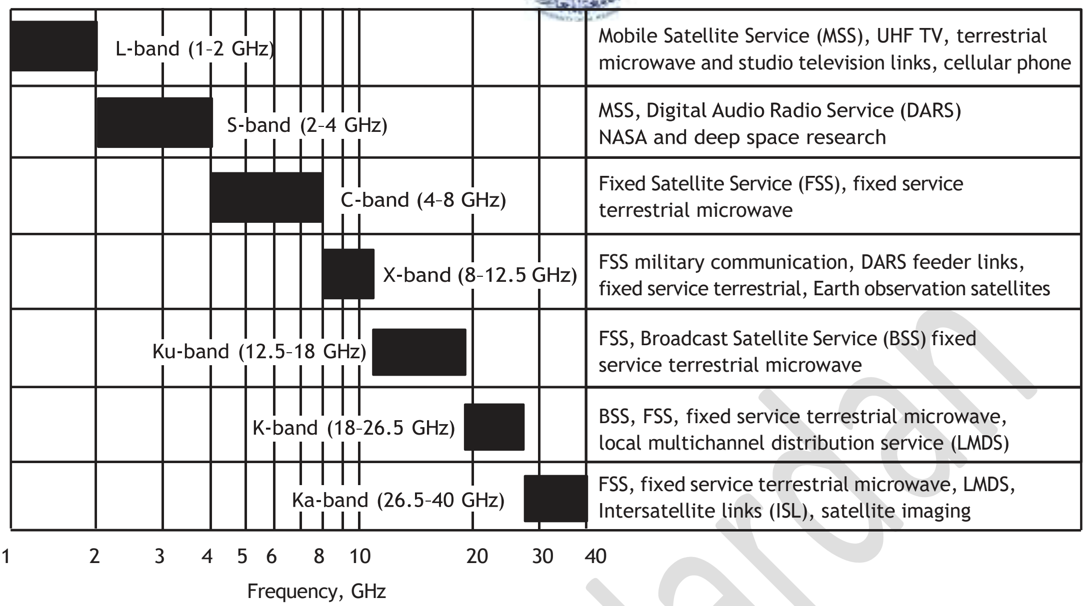

Figure 8.1 The general arrangement of the frequency spectrum that is applied to satellite communications and other radio communication services. Indicated are the short-hand letter designations along with an explanation of typical applications. Note the logarithmic scale and that frequency ranges are the general ranges and do not correspond exactly to the ITU frequency allocations and allotments.

applications increases in real terms as one moves toward the right (i.e., frequencies above 3 GHz). Also, the precise amount of spectrum that is available for services in a given region or country is usually less than indicates.

The use of letters probably dates back to World War II as a form of shorthand and simple code for developers of early microwave hardware. Two band designation systems are in use: adjectival (meaning the bands are identified by the following adjectives) and letter (which are codes to distinguish bands commonly used in space communications and radar).

Adjectival band designations, frequency in gigahertz:

Very high frequency (VHF): 0.03–0.3;
Ultra high frequency (UHF): 0.3–3;
Super high frequency (SHF): 3–30;
Extremely high frequency (EHF): 30–300.

Letter band designations, frequency in gigahertz .
L: 1.0–2.0;
S: 2.0–4.0;
C: 4.0–8.0;
X: 8–12;
Ku: 12–18;

Ka: 18–40;
Q: 40–60;
V: 60–75;
W: 75–110.

- Fixed Satellite Service (FSS): between Earth stations at given positions, when one or more satellites are used; the given position may be a specified fixed point or any fixed point within specified areas; in some cases this service includes satellite-to-satellite links, which may also be operated in the intersatellite service; the FSS may also include feeder links for other services.
- Mobile Satellite Service (MSS): between mobile Earth stations and one or more space stations (including multiple satellites using intersatellite links). This service may also include feeder links necessary for its operation.
- Broadcasting Satellite Service (BSS): A service in which signals transmitted or retransmitted by space stations are intended for direct reception by the general public. In the BSS, the term "direct reception" shall encompass both individual reception and community reception.
- Intersatellite Link (ISL): A service providing links between artificial satellites.

The general properties of these bands are reviewed in [3]. Suffice it to say, the lower the band in frequency, the better the propagation characteristics. This is countered by the second general principle, which is that the higher the band, the more bandwidth that is available. The MSS is allocated to the L- and S-bands, where propagation is most forgiving. Yet, the bandwidth available between 1 and 2.5 GHz, where MSS applications are authorized, must be shared not only among GEO and non-GEO applications, but with all kinds of mobile radio, fixed wireless, broadcast, and point-to-point services as well. The competition is keen for this spectrum due to its excellent space and terrestrial propagation characteristics. The rollout of wireless services like cellular radiotelephone, PCS, wireless LANs, and 3G may conflict with advancing GEO and non-GEO MSS systems. Generally, government users in North America and Europe, particularly in the military services, have employed selected bands such as S, X, and Ka to isolate themselves from commercial applications. However, this segregation has disappeared as government users discover the features and attractive prices that commercial systems may offer.

On the other hand, wideband services like DTH and broadband data services can be accommodated at frequencies above 3 GHz, where there is more than 10 times the bandwidth available. Add to this the benefit of using directional ground antennas that effectively multiply the unusable number of orbit positions. Some wideband services have begun their migration from the well-established world of C-band to Ku- and Ka-bands. In the following sections we provide some additional comments about the relative merits of these bands. These should be considered as starting points for evaluating the proper frequency band and are not substitutes for a detailed evaluation of the relative cost and complexity of different approaches. Higher satellite EIRP used at Ku-band allows the use of relatively small Earth station antennas. On the other hand, C-band should maintain its strength for video distribution to cable systems and TV stations, particularly because of the favorable propagation environment, extensive global coverage, and legacy investment in C-band antennas and electronic equipment.

8.2 Ultra High Frequency

While the standard definition of UHF is the range of 300 to 3,000 MHz (0.3 to 3 GHz), the custom is to relate this band to any effective satellite communication below about 1 GHz. Frequencies above 1 GHz are considered in the next sections. The fact that the ionosphere provides a high degree of attenuation below about 100 MHz makes this the certain low end of acceptability (the blockage by the ionosphere at 10 MHz goes along with its ability to reflect radio waves, a benefit for ground-to-ground and air-to-ground communications using what is termed sky wave or "skip"). UHF satellites employ circular polarization (CP) to avoid Faraday effect, wherein the ionosphere rotates any linear-polarized wave. The UHF spectrum between 300 MHz and 1 GHz is exceedingly crowded on the ground and in the air because of numerous commercial, government, and other civil applications. Principal among them is television broadcasting in the VHF and UHF bands, FM radio, and cellular radio telephone. However, we cannot forget less obvious uses like vehicular and handheld radios used by police officers, firefighters, amateurs, the military, taxis and other commercial users, and a variety of unlicensed applications in the home.

From a space perspective, the dominant space users are military and space research (e.g., NASA in the United States and ESA in Europe). These are all narrow bandwidth services for voice and low-speed data transfer in the range of a few thousand hertz or, equivalently, a few kilobytes per second. From a military perspective, the first satellite to provide narrowband voice services was Tacsat. This experimental bird proved that a GEO satellite provides an effective tactical communications service to a mobile radio set that could be transported on a person's back, installed in a vehicle, or operated from an aircraft. Subsequently, the U.S. Navy procured the Fleetsat series of satellites from TRW, a very successful program in operational terms. This was followed by Lea sat from Hughes, and currently the UHF Follow-On Satellites from the same maker (now Boeing Satellite Systems).

From a commercial perspective, the only VHF project that one can identify is OrbComm, a low data rate LEO satellite constellation developed by Orbital Sciences Corporation. OrbComm provides a near-real-time messaging service to inexpensive handheld devices about the size of a small transistor radio. On the other hand, its more successful use is to provide occasional data transmissions to and from moving vehicles and aircraft. Due to the limited power of the OrbComm satellites (done to minimize complexity and investment cost), voice service is not supported. Like other LEO systems, OrbComm as a business went into bankruptcy; it may continue in another form as the satellites are expected to keep operating for some time.

8.3 L-Band

Frequencies between 1 and 2 GHz are usually referred to as L-band, a segment not applied to commercial satellite communication until the late 1970s. Within this 1 GHz of total spectrum, only about 30 MHz of uplink and downlink, each, was initially allocated by the ITU to the MSS. The first to apply L-band was COMSAT with their Marisat satellites. Constructed primarily to solve a vital need for UHF communications by the U.S. Navy, Marisat also carried an L-band transponder for early adoption by the commercial maritime industry. COMSAT took a gamble that MSS would be accepted by commercial vessels, which at that time relied on high-frequency radio and the Morse code. Over the ensuing years, Marisat and its successors from Inmarsat proved that satellite communications, in general, and MSS, in particular, are reliable and effective. By 1993, the last commercial HF station was closed down in favor of satellite links. With the reorganization and privatization of Inmarsat, the critical safety aspects of the original MSS network are being transferred to a different quasigovernmental operating group.

As is familiar to readers, early MSS Earth stations required 1-m dish antennas that had to be pointed toward the satellite. The equipment was quite large, complex, and expensive. Real demand for this spectrum began to appear as portable, land-based terminals were developed and supported by the network. Moving from rack-mounted to suitcase-sized to attaché case and finally handheld terminals, the MSS has reached consumers.

The most convenient L-band ground antennas are small and ideally do not require pointing toward the satellite. We are all familiar with the very simple cellular whip antennas used on cars and handheld mobile phones. Common L-band antennas for use with Inmarsat are not quite so simple because there is a requirement to provide some antenna gain in the direction of the satellite so a coarse pointing is needed. Additional complexity results from a dependence on circular polarization to allow the mobile antenna to be aligned along any axis (and to allow for Faraday rotation). First generation L-band rod or mast antennas are approximately 1m in length and 2 cm in diameter. This is to accommodate the long wire coil (a bifilar helix) that is contained within. The antenna for the handheld phone is more like a fat fountain pen.

While there is effectively no rain attenuation at L-band, the ionosphere does introduce a source of significant link degradation. This is in the form of rapid fading called ionospheric scintillation, which is the result of the RF signal being split into two parts: the direct path and a refracted (or bent) path. At the receiving station, the two signals combine with random phase. Then, the signals may cancel, producing a deep fade. Ionospheric scintillation is most pronounced in equatorial regions and around the equinoxes (March and September). Both ionospheric scintillation and Faraday rotation decrease in frequency increases and are nearly negligible at Ku-band and higher. Transmissions at UHF are potentially more seriously impaired and for that reason, and additional fade margin over and above that at L-band may be required.

From an overall standpoint, L-band represents a regulatory challenge but not a technical one. There are more users and uses for this spectrum than there is spectrum to use. Over time, technology will improve spectrum efficiency. Techniques like digital speech compression and bandwidth efficient modulation may improve the utilization of this very attractive piece of spectrum. The business failure of LEO systems like Iridium and Globalstar had raised some doubts that L-band spectrum could be increased. One could argue that more lucrative land-based mobile radio services (e.g., cellular and wireless data services) could end up winning over some of the L-band. This will require never-ending vigilance from the satellite community.

8.4 S-Band

S-band was adopted early for space communications by NASA and other governmental space research activities around the world. It has an inherently low background noise level and suffers less from ionospheric effects than L-band. DTH systems at S-band were operated in past years for experiments by NASA and as operational services by the Indian Space Research Organization and in Indonesia. More recently, the ITU allocated a segment of S-band for MSS and Digital Audio Radio (DAR) broadcasting. These applications hold the greatest prospect for expanded commercial use on a global basis.

As a result of a spectrum auction, two companies were granted licenses by the FCC and subsequently went into service in 2001–2002. S-band spectrum in the range of 2,320 to 2,345 MHz is shared equally between the current operators, XM Radio and Sirius Satellite Radio. A matching uplink to the operating satellites was assigned in the 7,025- to 7,075-MHz bands. Both operators installed terrestrial repeaters that fill dead spots within urban areas. With an EIRP of nominally 68 dBW, these broadcast satellites can deliver compressed digital audio to vehicular terminals with low gain antennas.

As a higher frequency band than L-band, it will suffer from somewhat greater (although still low) atmospheric loss and less ability to adapt to local terrain. LEO and MEO satellites are probably a good match to S-band since the path loss is inherently less than for GEO satellites. One can always compensate with greater power on the satellite, a technique used very effectively at Ku-band.

8.5 C-Band

Once viewed as obsolete, C-band remains the most heavily developed and used piece of the satellite spectrum. During recent World Radio communication Conferences, discussed in Chapter 12, the ITU increased the available uplink and downlink bandwidth from the original allocation of 500 to 800 MHz. This spectrum is effectively multiplied by a factor of two with dual polarization and again by 180, assuming 2° spacing between satellites. Further reuse by a factor of between two and five takes advantage of the geographic separation of land coverage areas. The total usable C-band spectrum bandwidth is therefore in the range of 568 GHz to 1.44 THz, which compares well with land-based fiber optic systems. The added benefit of this bandwidth is that it can be delivered across an entire country or ocean region.

Even though this represents a lot of capacity, there are situations in certain regions where additional satellites are not easily accommodated. In North America, there are more than 35 C-band satellites in operation across a 70° orbital arc. This is the environment that led the FCC in 1985 to adopt the then radical (but necessary) policy of 2° spacing. The GEO orbit segments in Western Europe and east Asia are becoming just as crowded as more countries launch satellites. European governments mandated the use of Ku-band for domestic satellite communications, delaying somewhat the day of reckoning. Asian and African countries favor C-band because of reduced rain attenuation as compared to Ku- and Ka-bands, making C-band slots a vital issue in that region.

C-band is a good compromise between radio propagation characteristics and available bandwidth. Service characteristics are excellent because of the modest amount of fading from rain and ionospheric scintillation. The one drawback is the somewhat large size of Earth station antenna that must be employed. The 2° spacing environment demands antenna diameters greater than 1m, and in fact 2.4m is more the norm. This size is also driven by the relatively low power of the satellite, itself the result of sharing with terrestrial microwave. High-power video carriers must generally be uplinked through antennas of between 7m and 13m; this assures an adequate signal and reduces the radiation into adjacent satellites and terrestrial receivers.

The prospects for C-band are good because of the rapid introduction of digital compression for video transmission. New C-band satellites with higher EIRP, more transponders, and better coverage are giving C-band new life in the wide expanse of developing regions such as Africa, Asia, and the Pacific.

8.6 X-Band

Government and military users of satellite communication established their fixed applications at X-band. This is more by practice than international rule, as the ITU frequency allocations only indicate that the 8-GHz portion of the spectrum is designated for the FSS regardless of who operates the satellite. From a practical standpoint, X-band can provide service quality on par with C-band; however, commercial users will find equipment costs to be substantially higher due to the thinner market. Also, military-type Earth stations are inherently expensive due to need for rugged design and secure operation. Some countries have filed for X-band as an expansion band, hoping to exploit it for commercial applications like VSAT networks and DTH services. As discussed previously, S-DARS in the United States employs X-band feeder uplinks. On the other hand, military usage still dominates for many fixed and mobile applications. This segregation helps maintain a degree of security for military users for whom availability of a larger consumer market would not necessarily be considered advantageous. X-band is likewise shared with terrestrial microwave systems, somewhat complicating frequency coordination.

8.7 Ku-Band

Ku-band spectrum allocations are somewhat more plentiful than C-band, comprising 750 MHz for FSS and another 800 MHz for the BSS. Again, we can use dual polarization and satellites positions 2° apart. Closer spacings are not feasible because users prefer to install yet smaller antennas, which have the same or wider beamwidth than the correspondingly larger antennas for C-band service. Typically implemented by different satellites covering different regions, Ku regional shaped spot beams with geographic separation allow up to approximately 10X frequency reuse. This has the added benefit of elevating EIRP using modest transmit power;

G/T likewise increases due to the use of spot beams. The maximum available Ku-band spectrum could therefore amount to more than 4 THz.

Exploiting the lack of frequency sharing and the application of higher power in space, digital DTH services from DIRECTV and EchoStar in North America ushered in the age of low-cost and user-friendly home satellite TV. The United Kingdom, continental Western Europe, Japan, and a variety of other Asian countries likewise enjoy the benefits of satellite DTH. As a result of these developments, Ku-band has become a household fixture (if not a household word).

The more progressive regulations at Ku-band also favor its use for two-way interactive services like voice and data communication. Low-cost VSAT networks typify this exploitation of the band and the regulations. Being above C-band, the Ku-band VSATs and DTH receivers must anticipate more rain attenuation. A decrease in capacity can be countered by increasing satellite EIRP. Also, improvements on modulation and forward error correction are making terminals smaller and more affordable for a wider range of uses. Thin route applications for telephony and data, discussed in Chapters 8, 9, and 10, benefit from the lack of terrestrial microwave radios, allowing VSATs to be placed in urban and suburban sites.

8.8 Ka-Band

Ka-band spectrum is relatively abundant and therefore attractive for services that cannot find room at the lower frequencies. There is 2 GHz of uplink and downlink spectrum available on a worldwide basis (500 MHz of this spectrum has been allocated to non-GEO satellites, particularly Teledesic, and another 500 MHz for fixed wireless access). In addition, the fact that ground antenna beamwidths are between one-half to one-quarter the values that correspond at Ku- and C-bands means that more satellites could conceivably be accommodated. Conversely, with enough downlink EIRP, smaller antennas will still be compatible with 2° spacing. Another facet of Ka-band is that small spot beams can be generated onboard the satellite with achievable antenna apertures. (Practical implementations need multiple reflectors to allow feed spacing and avoid scan loss.) The design of the satellite repeater is somewhat more complex in this band because of the need for cross connection and routing of information between beams. Consequently, there is considerable interest in the use of onboard processing to provide a degree of flexibility in matching satellite resources to network demands.

The Ka-band region of the spectrum is perhaps the last to be exploited for commercial satellite communications. Research organizations in the United States, Western Europe, and Japan have spent significant sums of money on experimental satellites and network application tests.

From a technical standpoint, Ka-band has many challenges, the biggest being the much greater attenuation for a given amount of rainfall (nominally by a factor of three to four, in decibel terms, for the same availability). This can, of course, be overcome by increasing the transmitted power or receiver sensitivity (e.g., antenna diameter) to gain link margin. Some other techniques that could be applied in addition to or in place of these include (1) dynamic power control on the uplink and downlink, (2) reducing the data rate during rainfall, (3) transferring the transmission to a lower frequency such as Ku- or C-bands, and (4) using multiple-site diversity to sidestep heavy rain-cells. Consideration of Ka-band for an application will involve finding the most optimum combination of these techniques.

The popularity of broadband access to the Internet through DSL and cable modems has encouraged several organizations to consider Ka-band as an effective means to reach the individual subscriber. Ultra-small aperture terminals (USATs) capable of providing two-way high-speed data, in the range of 384 Kbps to 20 Mbps, are entirely feasible at Ka-band. Hughes Electronics filed with the FCC in 1993 for a two-satellite system called Spaceway that would support such low-cost terminals. In 1994, they extended this application to include up to an additional 15 satellites to extend the service worldwide. The timetable for Spaceway has been delayed several times since its intended introduction in 1999. Almost at the same time, several strong backers introduced another proposal called Teledesic, which would employ the same Ka band from LEO satellites—up to 840 in number (later reduced to 288, then again to 30). While this sounds amazing, strong support from Craig McCaw, founder of McCaw Cellular (now part of AT&T Wireless), and Bill Gates (cofounder of Microsoft) lent apparent credibility to Teledesic. In 2001, Teledesic purchased an interest in ICO and delayed introduction of the Ka-band LEO system. A further development occurred in 2003 when Craig McCaw bought a controlling interest in L/S-band non-GEO Globalstar system.

While the commercial segment has taken a breather on Ka-band, the same cannot be said of military users. The U.S. Navy installed a Ka-band repeater on some of their UHF Follow-On Satellites to provide a digital broadcast akin to the commercial DTH services at Ku-band. It is known as the Global Broadcast Service (GBS) and provides a broadband delivery system for video and other content to ships and land-based terminals. In 2001, the U.S. Air Force purchased three X- and Ka-band satellites from Boeing Satellite Systems. These will expand the Ka-band capacity by about three on a global basis, in time to support a growth in the quantity and quality of Ka-band military terminals. The armed services, therefore, are providing the proving grounds for extensive use of this piece of the satellite spectrum.

8.9 Q- and V-Bands

Frequencies above 30 GHz are still considered to be experimental in nature, and as yet no organization has seen fit to exploit this region. This is because of the yet more intense rain attenuation and even atmospheric absorption that can be experienced on space-ground paths. Q- and V-bands are also a challenge in terms of the active and passive electronics onboard the satellite and within Earth stations. Dimensions are extremely small, amplifier efficiencies are low, and everything is more expensive to build and test. For these reasons, few have ventured into the regime, which is likely to be the story for some time. Perhaps one promising application is for ISLs, also called cross links, to connect GEO and possibly non-GEO satellites to each other. To date, the only commercial application of ISLs is for the Iridium system, and these employ Ka-band.

8.10 Laser Communications

Optical wavelengths are useful on the ground for fiber optic systems and for limited use in line-of-sight transmission. Satellite developers have considered and experimented with lasers for ISL applications, since the size of aperture is considerably smaller than what would be required at microwave. On the other hand, laser links are more complex to use because of the small beam widths involved. Control of pointing is extremely critical and the laser often must be mounted on its own control platform. In 2002, the European Space Agency demonstrated a laser ISL called SILEX, which was carried by the Artemis spacecraft. The developers of this equipment achieved everything that they intended in this government-funded program.