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MILLIMETER WAVE CHARACTERISTICS

Corresponding to the progress of multimedia technology and data storage technology, a high data rate of 10 Gbit/s is expected, driven by the increasing memory capacity in wireless/mobile devices. It seems clear that the demand for a high data rate and high-integrity services will continue to grow in the foreseeable future, especially at the V band (40–75 GHz) and W band (75–111 GHz). In this chapter we introduce the basic characteristics of millimeter wave communication and its areas of application.

In very broad terms, millimeter wave technology can be classified as occupying the electromagnetic spectrum that spans between 30 and 300 GHz, which corresponds to wavelengths from 10 to 1 mm. In this book, we will focus on the 60 GHz industrial, scientific, and medical (ISM) band (unless otherwise specified, the terms 60 GHz and millimeter wave will be used interchangeably), which has emerged as one of the most promising candidates for multi-gigabit wireless indoor communication systems.

This chapter is organized as follows: Section 1.1 describes the characteristics of millimeter waves. Section 1.2 describes the channel performance of millimeter waves. Using these characteristics and performance, one can achieve the concept of gigabit wireless communications as shown in Section 1.3. Section 1.4 presents the development of millimeter wave standards in different countries. Section 1.5 describes interoperability, convergence, and co-existence of millimeter wave standards with other wireless local area network (LAN) standards.

Millimeter Wave Communication Systems, by Kao-Cheng Huang and Zhaocheng Wang

1.1 MILLIMETER WAVE CHARACTERISTICS

Before beginning an in-depth discussion of millimeter wave communication systems, it is important to understand the characteristics of millimeter waves. Millimeter waves are usually considered to be the range of wavelengths from 10 to 1 mm. This means they are larger than infrared waves or x-rays, for example, but smaller than radio waves or microwaves. The millimeter-wave region of the electromagnetic spectrum corresponds to the radio band frequency range of 30–300 GHz and is also called the extremely high frequency (EHF) range. The high frequencies of millimeter waves, as well as their propagation characteristics (i.e., the ways they change or interact with the atmosphere as they travel), make them useful for a variety of applications, including the transmission of large amounts of data, cellular communications, and radar. This section presents the benefits of 60 GHz technology and its characteristics. It can be used for high-speed Internet, data, and voice communications, offering the following key benefits:

1. Unlicensed operation—No license from the Federal Communications Commission is required. (Note: details on the 60 GHz unlicensed band can be found in Section 1.4.)
2. Highly secure operation—Resulting from short transmission distances due to oxygen absorption, narrow antenna beamwidth, and no wall penetration.
3. High level of frequency re-use enabled—The communication needs of multiple cells within a small geographic region can be satisfied.
4. Fiber optic data transmission speeds possible—7 GHz (in the U.S.) of continuous bandwidth available compared to less than 0.3 GHz at the other unlicensed bands.
5. Mature technology—This spectrum has a long history of being used for secure communications.
6. Carrier-class communication links enabled—60 GHz links can be engineered to deliver “five nines” (99.999%) availability if desired. For outdoor applications, such as back bones or by-pass bridges, a huge rain margin should be considered.

Two aspects of the characterizations of millimeter wave can be discussed: free space propagation and loss factors.

1.1.1 Free Space Propagation

As with all propagating electromagnetic waves, for millimeter waves in free space the power falls off as the square of the range. When the range is doubled, the power reaching a receiver antenna is reduced by a factor of four. This effect is due to the spherical spreading of the radio waves as they propagate. The frequency and distance dependence of the loss between two isotropic antennas can be expressed in absolute numbers by the following equation (in dB):

$$L_{\text{free space}} = 20\log_{10}\left(4\pi\frac{R}{\lambda}\right)\ (dB) \tag{1.1}$$

where $L_{\text{free space}}$ is the free-space loss, R is the distance between the transmitting and receiving antennas, and λ is the operating wavelength. This equation describes line-of-sight (LOS) wave propagation in free space. It shows that the free space loss increases when the frequency or range increases. Also, that millimeter wave free space loss can be quite high even for short distances. It suggests that the millimeter-wave spectrum is best used for short-distance communication links.

When the distance of the link $R = 10\,m$, path loss can be calculated using $(4\pi R/\lambda)^2$. The path losses of different unlicensed bands are listed below.

Unlicensed Bands	Path Loss
2.4 GHz	60 dB
5 GHz	66 dB
60 GHz	88 dB

The loss difference between 60 GHz and other unlicensed bands already pushes system design to the limit. One way to cover this extra 22 dB (i.e., $88 - 66 = 22$) of loss is with a high gain antenna and architecture.

Another way of expressing the path loss is the Friis Equation (H.T. Friis, 1946). It gives a more complete accounting for all the factors from the transmitter to the receiver (as a ratio, linear units) [1]

$$P_{RX} = P_{TX} G_{RX} G_{TX} \frac{\lambda^2}{(4\pi R)^2 L} \tag{1.2}$$

where G_{TX} = transmitting antenna gain, G_{RX} = receiving antenna gain, λ = wavelength (in the same units as R), R is the line-of-sight distance separating the transmitting and receiving antennas, and L = system loss factor (≥ 1).

Here, the factor $G_{RX}\frac{\lambda^2}{4\pi}$ is the effective area of the receiving antenna, and so shows why there is a wavelength dependency in (1.1) and (1.2).

1.1.2 Millimeter-Wave Propagation Loss Factors

In addition to the free-space loss, which is the main source of transmission loss, there are also absorption loss factors, such as gaseous losses and losses from rain (or other micrometeors) in the transmission medium. The factors that affect millimeter wave propagation are given in Figure 1.1.

Atmospheric losses means that transmission losses occur when millimeter waves traveling through the atmosphere are absorbed by molecules of oxygen, water vapor, and other gaseous atmospheric constituents. These losses are greater at certain frequencies, coinciding with the mechanical resonant frequencies of the gas molecules.

The H_2O and O_2 resonances have been studied extensively for the purpose of predicting millimeter wave propagation characteristics. Figure 1.2 shows an expanded plot of the atmospheric absorption versus frequency at an altitude of 4 km and at sea level, for water content of 1 gm/m^3 and 7.5 gm/m^3, respectively (the former value represents relatively dry air while the latter value represents 75% relative humidity at a temperature of 10°C).

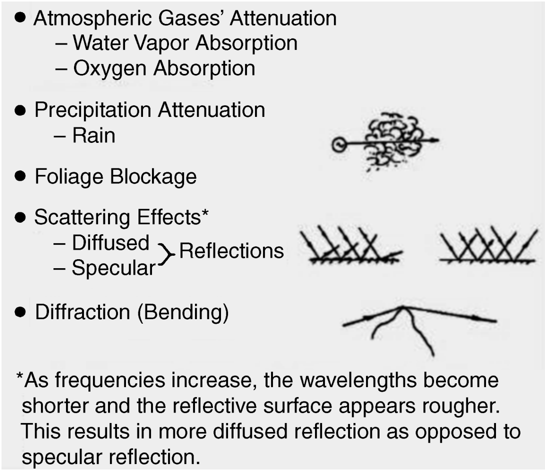

Figure 1.1. Propagation effects influencing millimeter-wave propagation [2] (© 2005 IEEE)

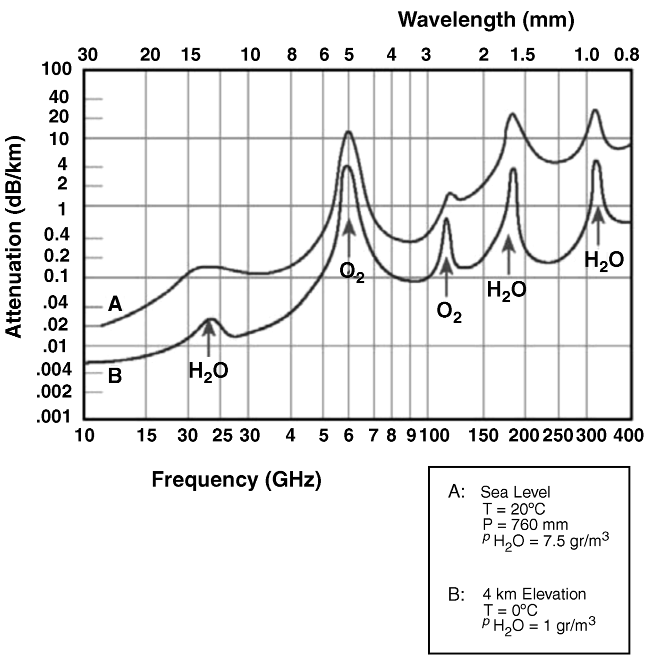

Figure 1.2. Average atmospheric absorption of millimeter waves [2] (© 2005 IEEE)

1.2 CHANNEL PERFORMANCE AT 60 GHz

Knowing the propagation characteristics and channel performance of millimeter waves is the first step to plan for a millimeter wave communication system. While signals at lower frequency bands, such as Global System for Mobile Communications (GSM) signals, can propagate for many kilometers and more easily penetrate buildings, millimeter wave signals can only travel a few kilometers, or less, and suffer from high transmission losses in the air and solid materials. However, these millimeter wave propagation characteristics can be very advantageous in some applications such as wireless personal area networks. Millimeter waves can be used to establish more densely packed communication links, thus providing very efficient spectrum utilization, by means of frequency reuse, and thus they can increase the overall capacity of communication systems. The characteristics of millimeter wave propagation are summarized in this section, including free space propagation and the effects of various physical factors on propagation.

The main challenges in utilizing a 60 GHz channel can be described as follows:

- High loss, as calculated from Friis equation (1.2)
- Human shadowing
- Non-line-of-sight propagation, which induces random fluctuations in signal level, known as multipath fading, as shown in Figure 1.3
- Doppler shift is non-negligible at pedestrian velocities
- Noise

The Federal Communications Commission (FCC) limits the equivalent isotropically radiated power (EIRP) of a 60 GHz communication link to $+40\,\text{dBm}$. The

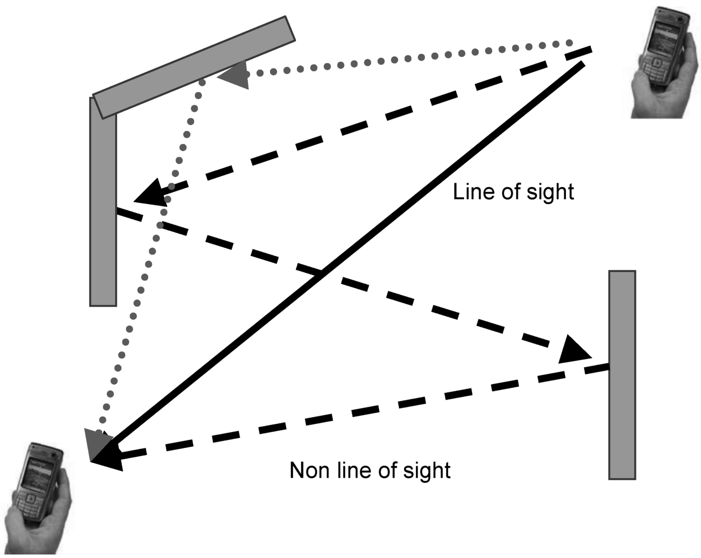

Figure 1.3. Multipath effect of indoor wireless communications

transmitter's power and path loss can be limiting factors for a high-speed wireless link. However, antenna directivity can be used to increase the power gain in the desired direction.

Assuming a simple line-of-sight free-space communication link, where both the received power P_{RX} and noise figure for the receiving system are 10 dBm and 10 dB, respectively, three different lengths are used for the distance R between the transmitter and receiver: *10, 15*, and *20 m*. Also, if we assume single omnidirectional antennas at the transmitter and receiver, the received power P_{RX} at a distance R decreases with an increase in frequency, and a 10-dB human shadowing loss is assumed for a system operating at 60 GHz.

Even when the bandwidth is unlimited, the received power $\mathrm{P_{RX}}$ is still limited by the Shannon Additive White Gaussian Noise (AWGN) capacity, as given by

$$C = BW \cdot \log_2\left(1 + \frac{P_{RX}}{BW \cdot N_0}\right) \approx 1.44\frac{P_{RX}}{N_0} \quad \text{when} \quad BW \to \infty \tag{1.3}$$

The result is shown in Figure 1.4. As we can see, it is very unlikely that we could use an omnidirectional antenna to achieve Gbps data rate when human shadowing exists.

When the transceiver has $P_T = 10$ dBm, the noise figure $NF_{RX} = 6$ dB, and the environment has a human shadowing loss of 18 dB, we need the antenna gain of α to be in the range of 10–15 dB for 1 Gbps at 60 GHz. The results for other values of α can be found in [3, 4]. This means the total antenna gain has to be approximately 30 dB at least.

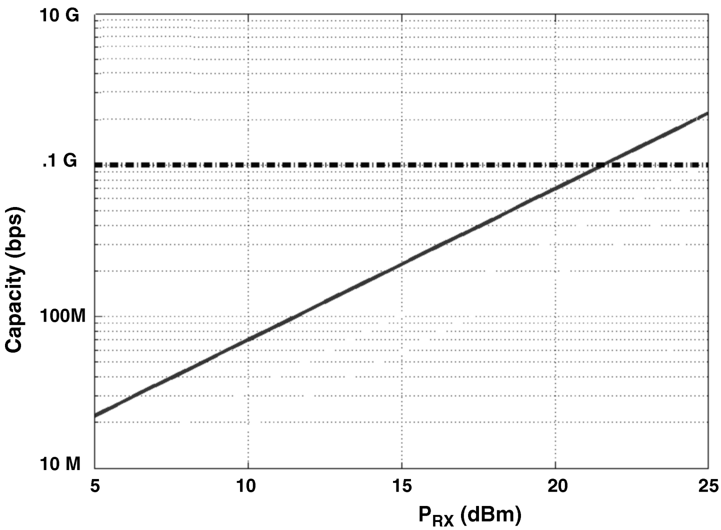

Figure 1.4. Shannon limit with distance $d = 10$ m between a transmitting omnidirectional antenna and a receiving omnidirectional antenna [3]

If we ignore the human shadowing loss, a clear path exists between the transmitter and receiver. When a 60 GHz system with the following parameters is defined,

Tx Power, P_T	10 dBm
Noise figure, NF	6 dB
Implementation loss, IL	6 dB
Thermal noise, N_0	174 dBm/MHz
Bandwidth, BW	1.5 GHz
Distance, R	20 m
Path loss at 1 m, PL_0	57.5 dB

we can calculate the ratio of the signal power to noise power at the Rx (in dB), by

$$\mathrm{SNR} = P_T + G_{Tx} + G_{Rx} - PL_0 - PL(R) - IL - (KT + 10\log_{10}(BW) - NF) \tag{1.4}$$

where G_{Tx} and G_{Rx} denote the transmitting and receiving antenna gains, respectively, and P_{Tx} denotes the transmitter power. Inserting Equation (1.4) into the Shannon capacity formula of Equation (1.3), the maximum achievable capacity in AWGN can be computed. Figure 1.5 shows the Shannon capacity limit of an indoor office for LOS and non-LOS (NLOS) cases, using an omni-omni antenna setup [12]. It was found that for the LOS condition, data rate can go up to 5 Gbps. On the other hand, the operating distance for an NLOS condition is limited to below 3 m, although the NLOS capacity decreases more drastically as a function of distance.

To improve the capacity for a given operating distance, one can either increase the bandwidth or signal-to-noise ratio (SNR) or both. It can also be seen from Figure 1.5 that increasing the bandwidth used by more than 4 times only significantly improves the capacity for distances below 5 m. Beyond this distance, the capacity for the 7-GHz

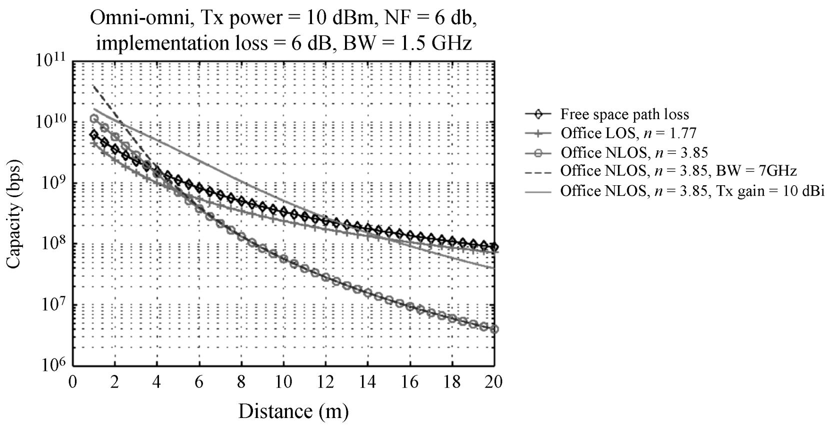

Figure 1.5. Shannon capacity limits for the case of indoor office using omni-omni antenna setup (Reproduced by permission of ©2007 S. K. Yong and C.-C. Chong [12])

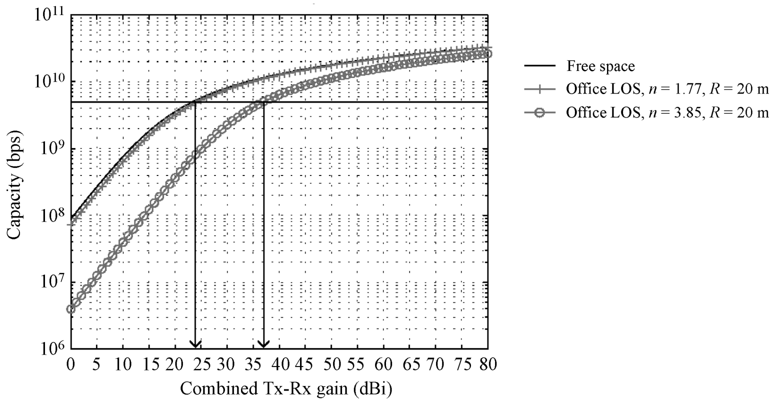

Figure 1.6. The required combined Tx-Rx antenna gain to achieve a target capacity (Reproduced by permission of ©2007 S. K. Yong and C.-C. Chong [12])

bandwidth is only slightly above the case of 1.5-GHz bandwidth, since the SNR at the Rx is reduced considerably at longer distance due to higher path loss. On the other hand, the overall capacity over the considered distance increases notably if a 10-dBi transmit antenna gain is employed as compared to the omnidirectional antenna for both 1.5-GHz and 7-GHz bandwidths. This clearly shows the importance of antenna gain in providing a very high data application at 60 GHz, which is not possible to be provided with omni-omni antenna configuration. But the question remains, how much gain is required?

To answer this question, the capacity as a function of combined Tx and Rx gain for operating distance at 20 m is plotted as depicted in Figure 1.6. In order to achieve 5 Gbps data rate at 20 m, combined gains of 25 dBi and 37 dBi were required for LOS and NLOS, respectively [12], when there was no human shadowing. These seem to be practical values, since they combine the Tx and Rx gains. However, to achieve the same data rates in a noisy channel, a higher gain is needed to overcome the interference.

Thus, directional antennas are required for Gigabit wireless communications. We can have different configurations for the access points (AP) and the mobile terminal (MT) based on different applications, as shown in Figure 1.7.

Considering the 60 GHz measurement setup shown in Figure 1.8, the synthesizer has a maximum output power of 0 dBm at 65 GHz. The coaxial cables have a maximum transmission loss of 6.2 dB/m at 60 GHz. The conversion loss of the subharmonic mixer is assumed to be 40 dB and its noise figure is 40 dB, while voltage standing wave ratio (VSWR) is 2.6:1. The noise floor for the spectrum analyzer is assumed to be −130 dBm.

The dynamic range can be measured as a function of the total antenna gain and the distance between antennas at 60 GHz. The results are shown in Figure 1.9.

Multipath propagation occurs when waves emitted by the transmitter travel along a multiplicity of different paths and interfere with waves traveling in a direct line-of-sight path, or with other multipath waves. Fading is caused by the destructive interference of these waves [5]. This phenomenon occurs because waves traveling along different paths may be completely out of phase when they reach the antenna, thereby canceling each

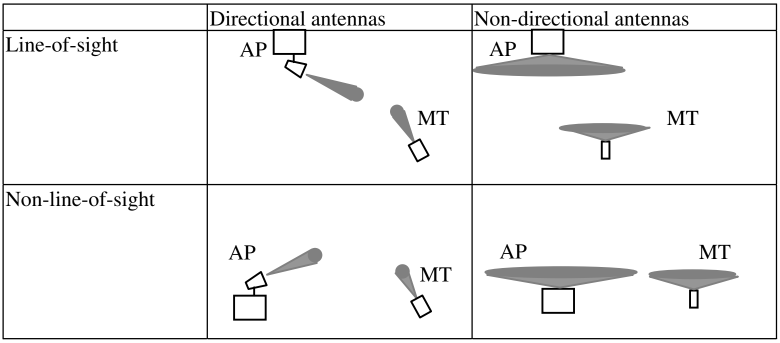

Figure 1.7. Classification of millimeter wave links according to the antenna beamwidth of the access point (AP) and mobile terminal (MT), in respect to the existence of a line-of-sight path. The radiation beamwidth is shown in gray

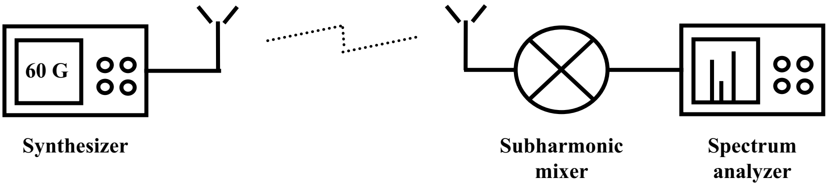

Figure 1.8. Channel measurement setup

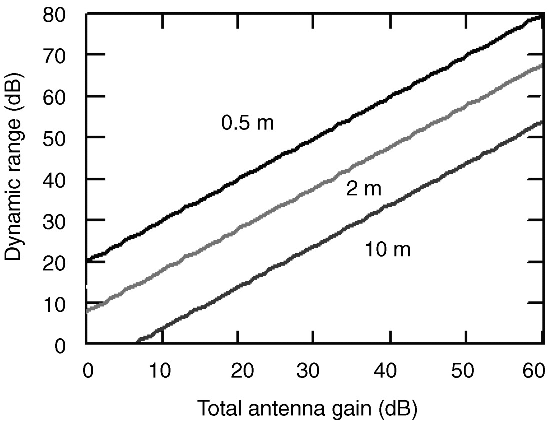

Figure 1.9. Dynamic range as a function of total antenna gain and the distance between antennas at 60 GHz

other out and forming an electric field null. One method of overcoming this problem is to transmit more power (either omnidirectionally or directionally). In an indoor environment, multipath propagation is always present and tends to be dynamic (constantly varying), due to the movement of scatterers. Severe fading due to indoor multipath propagation can result in a signal reduction of more than 30 dB. It is therefore essential to provide an adequate link margin to overcome this loss when designing a wireless system. Failure to do so will adversely affect the reliability of the link. The amount of extra radio frequency (RF) power radiated to overcome this phenomenon is referred to as a fade margin. The exact amount of fade margin required depends on the desired reliability of the link, but a good rule of thumb is 20–30 dB.

In channel measurements, as shown in Figure 1.10, we compare antennas with different beamwidths. For antennas with a narrow beamwidth, a notch appears in the frequency response of channel measurement. For antennas with a broad beamwidth, the notch in the frequency response becomes severe. In the extreme case, if an antenna beam is as sharp as a laser, this notch will not exist in the frequency response.

The notch step is affected by the delay time, while the notch depth is affected by the difference in the path gains (or losses). In addition, the notch position is affected by the difference in the lengths of the propagation paths.

Based on these observations, three solutions can be considered to minimize the notch effect. One would be to employ a narrow beam antenna to reduce reflected paths and achieve a smaller notch depth and wider notch period. However, this would involve solving the tracking resolution and the tracking speed. In addition, the selection of suitable equalizers having good performance should be investigated. Finally, we could use precise source tracking or space diversity to avoid the notch effect. A few implementation issues, such as tracking algorithm and dual antenna implementation, need to be tackled.

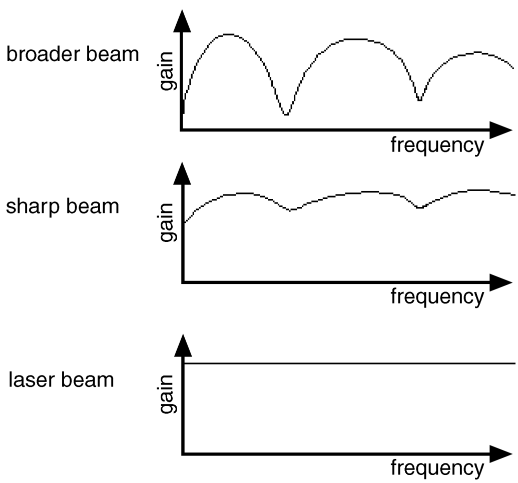

Figure 1.10. Beamwidth and channel distortion

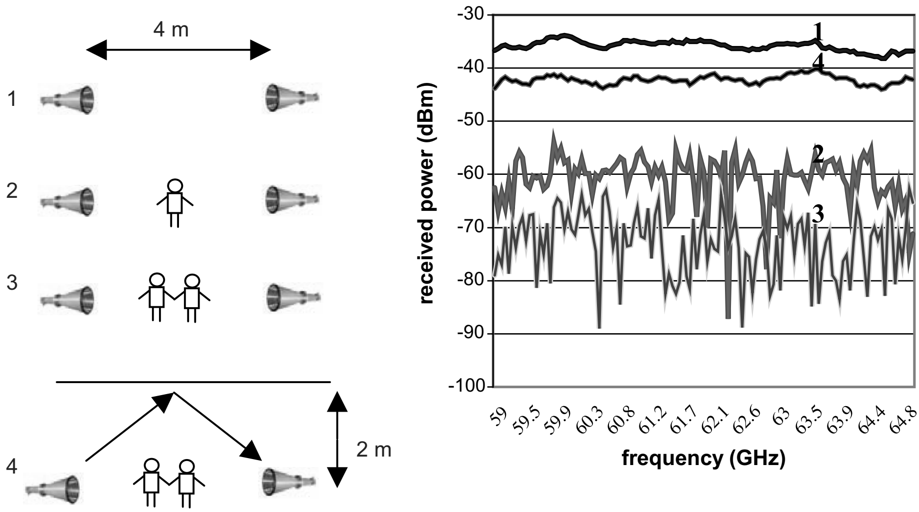

Figure 1.11. Indoor channel measurement at 60 GHz for NLOS

In an office environment, the reflection characteristics of interior structures have been studied [6]. Furthermore, the human shadowing problem has been investigated and the results are shown in Figure 1.11. When 0 dBm power at 60 GHz is transmitted via a 10 dBi gain transmitting antenna to a receiving antenna with a 10 dBi gain at a distance of 4 m, the spectrum shows that the received power is approximately −35 dBm when there is no human shadowing (Case 1). If there is a human body between the two antennas, the signal is reduced to a range of between −55 dBm and −65 dBm (Case 2). If there are two human bodies between the two antennas, the signal is reduced to a range of between −65 dBm and −80 dBm (Case 3). If we change the beam direction of the 10 dBi transmitting antenna so that the signal can bounce off the concrete ceiling, at a height of 2 m, so that it is reflected to the receiver, the received signal is increased to −42 dBm (Case 4). This shows that reflected propagation at 60 GHz can be used for NLOS wireless communications.

The transmitting and receiving antennas have a gain of 10 dBi. No. 1 shows a LOS scenario. No. 2 shows a person standing between the two antennas. No. 3 shows two people standing between the two antennas. No. 4 shows an NLOS wireless link, which improves the received signal power.

1.3 GIGABIT WIRELESS COMMUNICATIONS

After knowing the millimeter wave channel performance, we can start thinking of its application in wireless communication. In wired communication, the adoption of each successive generation of Ethernet technology has been driven by economics, performance demand, and the rate at which the price of the new generation has approached the old one. As the cost of 100 Mbps Ethernet dropped and approached the previous cost of

10 Mbps Ethernet, users rapidly moved to the higher performance standard. In 2007, the industry announced the availability of 10-Gb Ethernet over copper wiring [7]. Also, gigabit Ethernet became affordable (below $200) for server connections, and desktop gigabit connections have come within $10 or less of the cost of 100 Mbps technology. The serial 100-Gb Ethernet PHY (physical layer) based on advanced modulation techniques such as differential quadrature-phase-shifted-keying (DQPSK) have been experimentally demonstrated worldwide [8]. Consequently, gigabit Ethernet has become the standard for servers, and systems are now routinely ordered with gigabit network interface cards. Mirroring events in the wired world, as the prices of wireless gigabit links approach the prices of 100 Mbps links, users are switching to the higher-performance product, both for traditional wireless applications and for applications that only become practical at gigabit speeds.

In terms of a business model, wireless communications have pointed toward the need for wireless USB (Universal Serial Bus) 2.0, gigabit speeds, and longer-range connectivity as applications emerge for home audio/video (A/V) networks, high-quality multimedia, and voice and data services. Previously wireless local area networks (WLANs) only offered peak rates of 54 Mb/s, but 150–300 Mb/s, such as IEEE 802.11n, have become available. However, even 500 Mb/s is inadequate when faced with the demand for higher access speed from rich media content and competition from 10-Gb/s wired LANs. In addition, future home A/V networks will require Gb/s data rates to support multiple high-speed high-definition A/V streams (e.g., carrying uncompressed high-definition video at resolutions of up to 1,920 $\times$ 1,080 progressive scan, with latencies ranging from 5 ms to 15 ms) [9].

Based on the technical requirements of applications for high-speed wireless systems, both the industry and the standardization bodies need to take the following issues into account:

1. Pressure to increase the data rate will persist. More specifically, there is a need for advanced domestic applications, such as high-definition wireless multimedia, which demand higher data rates.
2. Data streaming and download/memory back-up times for mobile and personal devices will also place demands on shared resources and user models point to very short dwell times for these downloads.

Some approaches, such as IEEE 802.11n, enhance data rates by evolving the standards of the existing wireless LANs to increase data rates to speeds that are up to 10 times faster than IEEE 802.11a or 802.11g. IEEE 802.16 (WiMAX) can provide broadband wireless access up to 50 km with speeds around 70 Mbps. Others, such as ultra-wideband (UWB), are pursuing much more aggressive strategies, such as sharing spectra with other users. Another approach that will no doubt be taken will be the time-honored strategy of moving to higher, unused, and unregulated millimeter wave frequencies.

Despite the fact that millimeter wave technology has been established for many decades, the millimeter wave systems that are available have mainly been deployed for military applications. With the advances in process technologies and low-cost integration solutions, this technology has started to gain a great deal of momentum from academia, industry, and standardization bodies.

Although the IEEE 802.11n standard will improve the robustness of wireless communications, only a modest increase in wireless bandwidth is provided and the data rate is still lower than 1 Gbps. Importantly, 60 GHz technology offers various advantages over the currently proposed or existing communications systems. One of the deciding factors that makes 60 GHz technology attractive is the establishment of a (relatively) huge unlicensed bandwidth (up to 7 GHz), which is available worldwide. Spectrum allocation is mainly regulated by the International Telecommunication Union (ITU). The details of band allocation around the world can be found in Section 1.4.

While this is comparable to the unlicensed bandwidth allocated for UWB purposes ($\sim$2 GHz–10 GHz), the 60 GHz band is continuous and less restricted in terms of power limits (also there are fewer existing users). This is due to the fact that the UWB system is an overlay system, and thus subject to different considerations and very strict regulation. The large band at 60 GHz is, in fact, one of the largest unlicensed spectral resources ever allocated. This huge bandwidth offers great potential in terms of capacity and flexibility and makes 60 GHz technology particularly attractive for gigabit wireless applications. Although 60 GHz regulations allow a much higher transmission power compared to other existing WLAN (e.g., maximum 100 mW for 802.11 a/b/g, as defined in Table 1.1) and wireless personal area network (WPAN) systems, the higher transmission power is necessary to overcome the higher path loss at 60 GHz.

In addition, the typical 480 Mbps bandwidth of the UWB cannot fully support broadcast video, requiring the recompression of packets. This forces manufacturers to utilize expensive encoders and install more memory in their systems, in effect losing video content and adding latency in the process. Therefore, 60 GHz technology could actually provide better resolution, with less latency and cost for television, DVD players, and other high-definition equipment, compared to the UWB.

IEEE standard 802.15.3C was published in September 2009 [10]. It allows very high data rate over 2 Gbit/s applications. Optional data rate in excess of 3 Gbit/s can be provided.

Figure 1.12 shows the development and trends for wireless standards. Advanced wireless technology should always adopt a timeline, or milestones, to increase data rates by 5 to 10 times every three or four years to keep pace with the projected demand.

TABLE 1.1. Transmission Power Comparison for Different Wireless Standards

	Maximum Transmission Power
802.11 a	40 mW
802.11 b/g	100 mW
802.15.3c	500 mW

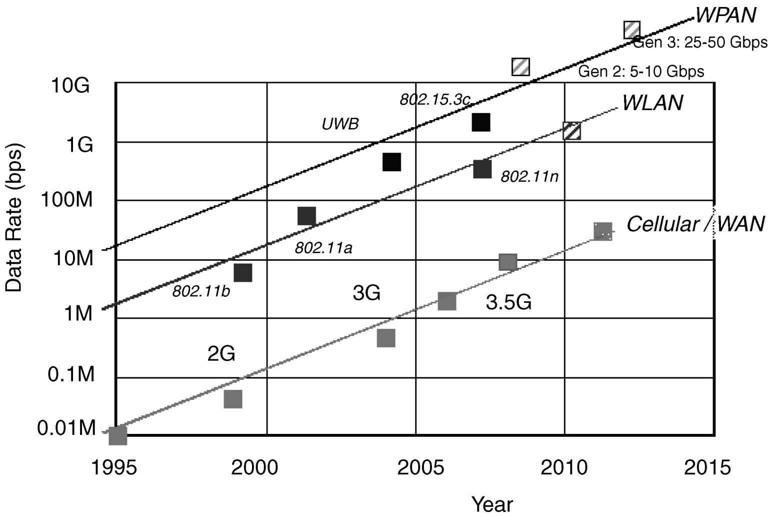

Figure 1.12. Data rate projections over time [11]

Although the high path loss at 60 GHz seems to be a disadvantage, it essentially confines the 60 GHz power and system operation to within a room in an indoor environment. Hence, the effective interference levels for 60 GHz are less severe than for those systems located in the congested 2–2.5 GHz and 5–5.8 GHz regions. In addition, higher frequency reuse can also be achieved over a very short distance in an indoor environment, thus allowing a very high throughput network. The compact size of a 60 GHz receiver also permits multiple antenna solutions at a user terminal, which are otherwise difficult, if not impossible, at lower frequencies. Compared to a 5-GHz system, the form factor of millimeter wave systems is approximately 140 times smaller and can be conveniently integrated into consumer electronic products. Thus, it will require new design methodologies to meet modern communication needs.

Designing a very-high-speed wireless link that offers good quality of service and range capability constitutes a significant research and engineering challenge. Ignoring fading for the moment, we can, in principle, meet the 1 Gbps data rate requirement if the product of the bandwidth (in units of Hz) and spectral efficiency (in b/s/Hz units) equals 10^9. As we shall describe in the following sections, a variety of cost, technology, and regulatory constraints make such a solution very challenging.

Despite the various advantages offered, millimeter wave–based communications suffer from a number of critical problems that must be resolved. Figure 1.13 shows the data rates for various WLAN and WPAN systems. Since there is a need to distinguish between different standards for broader market exploitation, IEEE 802.15.3c is positioned to provide gigabit rates and longer operating ranges. At these rates and ranges, it will be a nontrivial task for millimeter wave systems to provide a sufficient power margin to ensure a reliable communication link. Furthermore, the delay spread of the channel under consideration is another limiting factor for high-speed transmission. Large delay

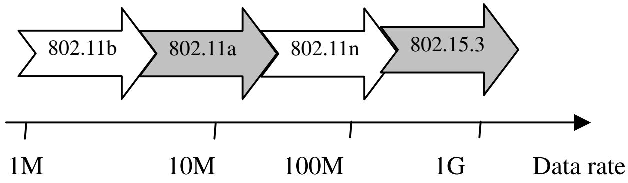

Figure 1.13. Data rates requirements for WLAN and WPAN standards and applications. Millimeter wave technology, that is, IEEE 802.15.3c, aims at very high data rates [12]

spread values can easily increase the complexity of the system beyond the practical limit for equalization [12].

Millimeter wave technology is certainly the first choice to build gigabit wireless communications. To understand its features, we can compare it with other technologies such as wireless optical LANs and UWB.

Wireless optical LANs also compete as a communication technology that is able to offer a significant unregulated spectrum. Diffuse optical networks use wide-angle sources and scatter from surfaces in the room to provide an optical "ether" similar to that obtained using a local radio transmitter [13]. This produces coverage that is robust to blocking, but the multiple paths between the source and receiver cause dispersion of the channel, thus limiting its performance. The optical transmitters require extremely high power, and dynamic equalization is needed for high-bandwidth operation.

Within buildings or in spaces with limited coverage, optical networks have the potential to offer significant advantages over radio approaches. One approach is to use direct LOS paths between the transmitter and receiver [14]. These can provide data rates of hundreds of megabits per second and above, depending on the particular parameters. However, the coverage area provided by a single channel can be quite small. Thus, providing area coverage and the ability to roam presents a major challenge. LOS channels can be blocked, as there is no alternative scattered path between the transmitter and receiver, and this presents a major challenge in network design [13]. Multiple base stations within a room would provide coverage in this case, and optical or fixed connections could be used between the stations. JVC offers a commercial LOS system with 10 Mb/s Ethernet connections [15].

In general, optical channels are subject to eye safety regulations, and these are difficult to meet, particularly for LOS channels [13]. Typically, optical LANs work in the near-infrared region (between 700 and 1000 nm), where optical sources and detectors are low cost, and regulations are particularly strict in this region. At longer wavelengths (1500 nm and above) the regulations are much less stringent, although sources at this wavelength and power output are not widely available [16].

As previously mentioned, the other major problem for optical channels is that of blocking. LOS channels are required for high-speed operation and these are by their nature subject to blocking. Within a building, networks must be designed using appropriate geometries to avoid blocking, and this is usually solved by using multiple access points to allow complete coverage [16, 17].

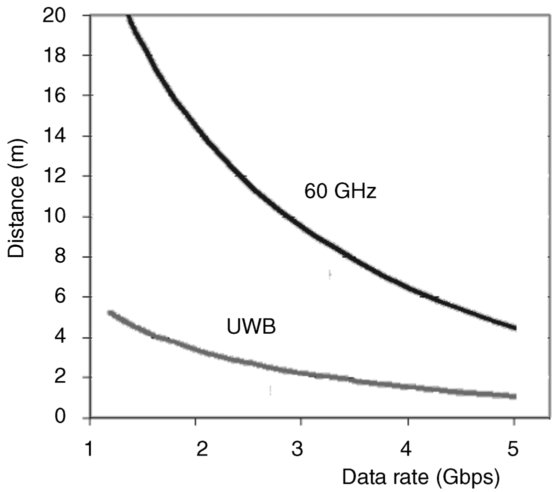

Figure 1.14. Shannon's capacity curve at an occupied bandwidth of 1 GHz for 60 GHz vs. UWB (noise figure is set at 8 dB) [11]

If we assume a 10-mW power input to the antenna, with a 10-dBi gain based on a highly integrated, low-cost design with a steerable beam at 60 GHz, we get the Shannon capacity curve shown in Figure 1.14. The formula used to derive these curves is presented in Equations (1.3) and (1.4) in Section 1.2.

Table 1.2 compares the characteristics of three technologies for gigabit communications: UWB radio, millimeter wave, and wireless optics.

1.4 DEVELOPMENT OF MILLIMETER WAVE STANDARDS

1.4.1 Europe

The European Telecommunications Standards Institute (ETSI) and the European Conference of Postal and Telecommunications Administrations (CEPT) have been working closely to establish a legal framework for the deployment of unlicensed 60 GHz devices [21]. In general, the 59–66 GHz band has been allocated for mobile services without a specific decision on the regulations, as shown in Figure 1.15. In Recommendation T/R 22–03, the CEPT provisionally recommended the use of the 54.25–66 GHz band for terrestrial and fixed mobile systems [22]. However, this provisional allocation was withdrawn in September 2005 [12].

In 2003, the European Radiocommunications Committee (ERC) of the European Conference of Postal and Telecommunications Administrations revised the European Table of Frequency Allocations and Utilizations [23].

The ERC also considered the use of the 57–59 GHz band for fixed services without requiring frequency planning [24]. Later, the Electronic Communications Committee (ECC) of CEPT recommended the use of point-to-point fixed services in the 64–66 GHz band [25]. A few years ago, ETSI proposed 60 GHz regulations to be considered by the

TABLE 1.2. Comparison of Three Technologies for Gigabit Wireless Communications [18–20]

	Millimeter Wave	UWB Radio	Optical Wireless
Advantage	1. High data rates (up to Gbps) 2. Compatible to fiber optic networks at 60 GHz	1. Low power 2. Short range 3. Low data 4. Penetration through obstacles in the transmission path	1. High data rate 2. Unlicensed and unregulated
Challenge	1. Reduce cost 2. Reduce power	1. Matched filter problem 2. Antenna parameter tradeoff	1. Atmospheric loss ranging from 10 dB/km(sunny) to 350 dB/km(foggy) 2. Multi-user application 3. No federal rights or protection for the link.
Peer to peer	Indoor/outdoor	Indoor/outdoor	Indoor/outdoor
Multiple-access	Indoor/outdoor	Indoor	Indoor
Data rate	$>$1.25 Gbps at 60 GHz $\sim$10 Gbps at 122.5 GHz	500 Mbps within 10 m (FCC)	$\sim$1.25 Gbps (peer-to-peer)
Indoor max. range	Room area	76 m (station in commercial building)	7 m(mobile) 10 m (station)
DC power consumption	High	Low	5 VDC, 500 mA (mobile)
Max TX power	500 mW(FCC 15.255)	Maximum output power of 1 Watt spread over spectrum. Maximum power density: -41.3 dBm/MHz (FCC)	Power density should be less than 1 mW/cm^2 (FDA)
Notes	Antenna design is one of the main challenges	1. Infrastructure or peer-to-peer for indoor application 2. Only peer-to-peer for hand-held application (FCC)	Eye safety should be considered.

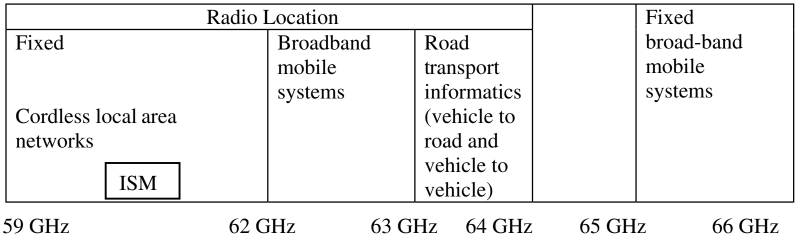

Figure 1.15. 60 GHz frequency spectrum in Europe [23]

ECC of the European Conference of Post and Telecommunications Administrations for WPAN applications [26]. Under this proposal, a 9-GHz unlicensed spectrum has been allocated for 60 GHz operation. This band that represents the union of the various previous bands was approved in 2009 [27].

The frequency band being considered is 57–66 GHz. The spectrum allocation is shown in Figure 1.16 and Table 1.3. This is an amalgamation of the bands currently approved for license-exempt use in Japan and the United States, and being proposed for allocation in the Republic of China and the Republic of Korea. The existing etiquette rules, spectrum sharing studies, and other analyses in these countries may be a model for considering the needs of the commercial, military, and scientific uses of these frequencies worldwide. In Germany, the regulatory requirements are that the frequency bands of 57.1–57.8 GHz and 58.6–58.9 GHz be used for time division duplex (TDD) point-to-point connections [28].

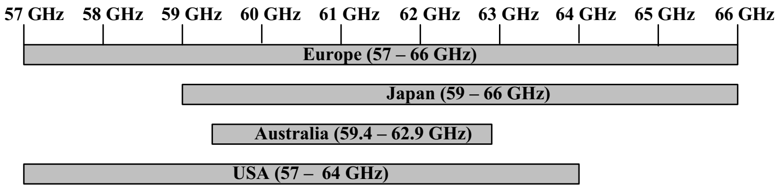

Figure 1.16. Geographically available 60 GHz spectrum and power

TABLE 1.3. International Frequency Allocation at 60 GHz [32]

Region	Unlicensed Bandwidth (GHz)	Max. Tx Power	Max. Antenna Gain	Ref.
Europe	9 GHz (57–66) min 500 MHz	20 mW	37 dBi	[26]
Japan	7 GHz (59–66) max 2.5 GHz	10 mW	47 dBi	[29]
Korea	7 GHz (57–64)	10 mW	To be decided	[30]
Germany	1 GHz (57.1–57.8) (58.6–58.9)	50 mW	Not specified	[28]
USA	7 GHz (57–64)	500 mW	Not specified	[31]

1.4.2 United States

In 2001, the U.S. FCC allocated 7 GHz in the 54–66 GHz band for unlicensed use [31]. In terms of the power limits, the FCC rules allow emissions with an average power density of 9 μW/cm^2 at 3 m and a maximum power density of 18 μW/cm^2 at a range of 3 m from the radiating source. These data translate to an average equivalent isotropic radiated power (EIRP) and a maximum EIRP of 40 dBm and 43 dBm, respectively. The FCC also specified a total maximum transmission power of 500 mW for an emission bandwidth greater than 100 MHz. The devices must also comply with the radio frequency (RF) radiation exposure requirements specified in [31]. After taking the RF safety issues into account, the maximum transmission power is limited to 10 dBm. Furthermore, each transmitter must transmit at least one transmitter identification signal within a one-second interval of the signal transmission. It is important to note that the 60 GHz regulations in Canada, which are regulated by Industry Canada Spectrum Management and Telecommunications (IC-SMT) [33], harmonize with the United States.

In 2003, the FCC announced that the frequency bands found at 71–76 GHz, 81–86 GHz, and 92–95 GHz were available for wireless applications [34]. FCC chairman Michael Powell heralded the ruling as opening a "new frontier" in commercial services and products for the U.S. users [35]. The allocation provides the opportunity for a broad range of new products and services, including high-speed, point-to-point WLANs and broadband Internet access at gigabit data rates and beyond.

The significance of the 70, 80, and 90 GHz allocations cannot be overstated. Collectively referred to as the E-band (60–90 GHz), these three allocations are the highest ever licensed by the FCC. Together, the nearly 13 GHz of allocated spectrum is greater than all of the other previously existing commercial wireless spectra combined. The FCC ruling also permits a novel licensing scheme, allowing cheap and fast allocations to prospective users. All this was achieved at unprecedented speed, with barely more than two years from the initial FCC petition to the formal release of the rules.

1.4.3 Japan

In the year 2000, the Ministry of Public Management, Home Affairs, Posts, and Telecommunications (MPHPT) of Japan issued 60 GHz radio regulations for unlicensed utilization of the 59–66 GHz band [29]. However, the 54.25–59 GHz band is allocated for licensed use. The maximum transmission power for this unlicensed use is limited to 10 dBm, with a maximum allowable antenna gain of 47 dBi. Unlike the arrangements in North America, the Japanese regulations specified that the maximum transmission bandwidth must not exceed 2.5 GHz. There was no specification for RF radiation exposure and transmitter identification requirements [29].

1.4.4 Industrial Standardization

Originally, the first international industry standard that covered the 60 GHz band was the IEEE 802.16 (WiMAX) Standard for local and metropolitan area networks [36].

TABLE 1.4. 60 GHz Standards in Japan

Code	Standard Name	Note
ARIB STD-T69 (Jul.2004)	Millimeter-Wave Video Transmission Equipment for Specified Low Power Radio Station	Bandwidth: 1208 MHz
ARIB STD-T69 Revision (Nov. 2005)	Millimeter-Wave Video Transmission Equipment for Specified Low Power Radio Station (Only the part of the revision from Ver.2.0 to Ver.2.1)	Tx power: 10 dBm Rx antenna gain: 0 dBi.
ARIB STD-T74 (May 2001)	Millimeter-Wave Data Transmission Equipment for Specified Low Power Radio Station (Ultra High Speed Wireless LAN System)	Bandwidth: 200 MHz
ARIB STD-T74 Revision (Nov. 2005)	Millimeter-Wave Data Transmission Equipment for Specified Low Power Radio Station (Ultra High Speed Wireless LAN System) (Only the part of the revision from Ver.1.0 to Ver.1.1)	Tx power: 10 dBm Rx antenna gain: 0 dBi.

However, this is a licensed band and is used for LOS outdoor communications for last mile connectivity. In Japan, two standards related to the 60 GHz band were issued by the Association of Radio Industries and Business (ARIB), namely, ARIB-STD T69 and ARIB-STD T74 [37, 38], as shown in Table 1.4. The former is a standard for millimeter wave video transmission equipment for a specified low-power radio station (point-to-point system), while the latter is a standard for a millimeter wave ultra high-speed WLAN for specified low-power radio stations (point-to-multipoint). Both standards cover the 59–66 GHz band defined in Japan.

The interest in 60 GHz radio continued to grow with the formation of the Millimeter Wave Interest Group and the Millimeter Wave Study Group within the IEEE 802.15 Working Group for WPAN. In 2005, the IEEE 802.15.3c Task Group (TG3c) was formed to develop a millimeter wave-based alternative physical layer (PHY) for the existing IEEE 802.15.3 WPAN Standard 802.15.3-2003 [39]. The developed PHY is aimed at supporting a minimum data rate of 2 Gbps over a few meters with optional data rates in excess of 3 Gbps. This is the first standard that addresses multi-gigabit wireless systems and will form the key data rate solution for many applications, especially those related to wireless multimedia distribution. Its channel plan is divided into two groups: full-rate channel plan and half-rate channel plan (see Figure 1.17). The full-rate plan has four full-rate channels in 9-GHz bandwidth. It supports data rates of up to 6.118 Gbps approximately in single-carrier mode or up to 7.3 Gbps in OFDM mode. The half-rate channel plan has four half-rate channels with the same center frequencies as the full-rate channels. It supports data rates of up to 1.530 Gbps using $\pi/2$ BPSK in single-carrier mode.

In 2007, another group, WirelessHD™ (high definition), also released a specification, which uses the unlicensed 60 GHz radio waves to send uncompressed HD video and audio at 5 Gbps at distances of up to 30 feet, or within one room of a house. Its core technology promotes theoretical data rates of up to 20 Gbps, permitting it to scale to

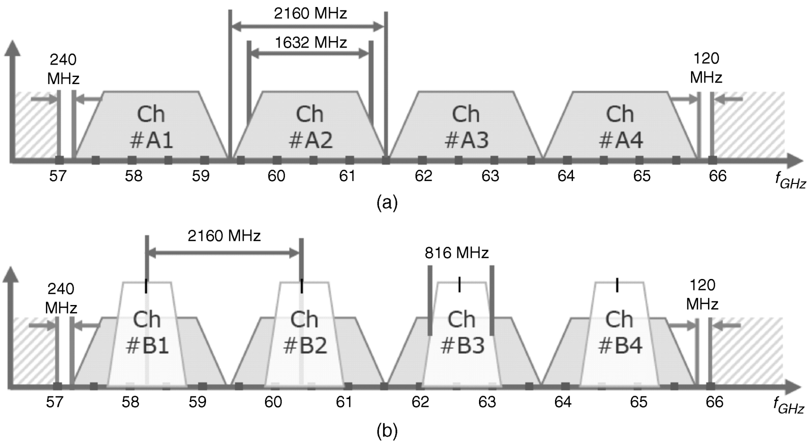

Figure 1.17. (a) Full-rate channel plan, (b) Half-rate channel plan of IEEE 802.15.3c [40] (©2007 IEEE)

higher resolutions, color depths, and ranges. Coexisting with other wireless services, the WirelessHD platform is designed to operate cooperatively with existing, wireline display technologies. The specification maintains high-quality video, ensures the interoperability of consumer electronic devices, provides signal interference protection, and uses existing content protection techniques. The WirelessHD™ group believes that 60 GHz will allow the fast transmission speeds required for high-definition content. The ideal speed for WirelessHD is 5 Gbps and a coverage range of up to 10 m. It is worth noting that IEEE 802.15.3c targets at Fast Data Download whereas wirelessHD targets at wireless entertainment and displays.

In addition, technical committee task group TG20 of the European Computer Manufacturers' Association (ECMA International) is also developing a standard for a 60 GHz PHY and Media Access Control (MAC) short-range unlicensed communications. This standard provides up to 10 Gbps WPAN (including point-to-point) transport for both bulk data transfer and multimedia streaming. TG20 is considering three device types ranging from high-end devices with steerable antennas to low-end devices for cost-effective, short-range, gigabit solutions. This confirms the role of millimeter wave antennas in gigabit communications.

Also in 2007, the National Institute of Information and Communications Technology (NICT) in Japan and 20 companies formed a organization called CoMPA (Consortium of Millimeter-wave Practical Applications). The group, together with IEEE 802.15.3c, had to discuss three key points, namely the system model, the usage model, and the channel model. In 2009, the Wireless Gigabit Alliance also completes multi-gigabit 60 GHz wireless specification to set up wireless multimedia streaming. It supports data transmission rates up to 7 Gbps and supports for beamforming, enabling robust communication at distances beyond 10 m.

Table 1.5 summarizes the potential applications of millimeter wavelength systems as submitted in response to the IEEE Call for Applications (CFA). The proposals are intended to illustrate support for some of the applications listed. The applications have been arranged in the numeric order of the CFA document number (last column) [41].

TABLE 1.5. Possible Applications for Millimeter Wave Communications [41]

No.	Description of Applications	Outdoor	Indoor	IEEE CFA Document Number
1	• Outdoor: Distribution links in apartments, stadium, etc. • Indoor: Ad hoc network	• LOS • P2P and P2MP • Bandwidth: >300 MHz • Range: ≤ 220 m	• LOS • Data rate: ≥ 1 Gbps and ≥ 622 Mbps • Range: ≥ 20 m and ≥ 3 m	04-0352
2	Gigabit Ethernet link, wireless IEEE1394 applications	–	• LOS • Data rate: ≤ 1 Gbps duplex • Range: ≤ 17 m	04-0019
3	Multimedia, information distribution system	–	• LOS • Data rate: ≥ 1 Gbps • Range: ≤ 10 m	04-0098
4	• Outdoor: Fixed wireless access, distribution in stadiums, intervehicle communication, etc. • Indoor: Connecting multimedia devices (wireless home link), ad hoc meeting, heavy content download, distribution system	• LOS • P2P, P2MP • Data Rate: 156 Mbps to 1.5 Gbps • Range: 400 m to 1 km	• LOS • Data Rate: 100 Mbps to 1.6 Gbps • Range: ~ 10 m	04-0118

5	Distribution links in apartments, stadium, etc.	• LOS • P2P • Bandwidth: >300 MHz • Range: ≤220 m	–	04-0153
6	Wireless home video server connected to HDTV, PC, and other video devices	–	• LOS • Data rate: 300 Mbps, 400 Mbps, and 1.5 Gbps uncompressed HDTV data • Range: ≤10 m	04-0348
7	• Replacement for 1394 FireWire • Replacement for USB • Military: future combat systems, secure communication	–	• LOS and NLOS (people) • 100–500 Mbps link, 1 Gbps in 2007 • Short range	04-0665

1.5 COEXISTENCE WITH WIRELESS BACKHAUL

Millimeter wave communication can operate with other wireless/mobile communication standards. For instance, the 802.16 specification applies across a wide range of the RF spectrum, and WiMAX could function on any frequency below 66 GHz [42] (higher frequencies would decrease the range of a base station to a few hundred meters in an urban environment). Although 802.16-2004 and 802.16e have reduced their operating frequencies to the 2–11 GHz range, a millimeter wave link could still work as its wireless backhaul solution. In fact, two of the best solutions are the millimeter-wave V-band and E-Band for supporting WiMAX operations in the enterprise and urban markets. The options for wireless backhaul, simply put, are 60 GHz and 80-GHz high-power radios. The short range of these products is, relative to other wireless backhaul options, the strength of the solution. Short propagation range is due to the oxygen molecules absorb electromagnetic energy at 60 GHz. This shortcoming of 60 GHz is used as an advantage to reuse the same frequency in short distance applications.

Free-space optical backhaul is another means of high-bandwidth transmission technology. It is a LOS technology using invisible beams of light to provide optical bandwidth connections using laser or LED. While both millimeter-wave and free-space optical backhauls can provide gigabit transmission rate, the requirement of high-stability mounting for free-space optics and the potential of beam obstruction have rendered free-space optics less attractive for large-scale mobile backhaul deployment [43].

1.5.1 60 GHz: V-band

The 57–64 GHz band (best known as 60 GHz) is located in the millimeter-wave portion of the electromagnetic spectrum. The advantages of using this band include interference mitigation, strong security, traffic prioritization (QoS), frequency re-use, and rain fade mitigation. In the United State, the 60 GHz band is unlicensed.

1.5.2 80 GHz: E-Band

The E-Band refers to 10 GHz of licensed-band spectrum allocated by the U.S. FCC, split between 71–76 GHz and 81–86 GHz. With more spectrally efficient modulations, full duplex data rates of 10 Gbps (OC-192 or 10GigE) can be reached. Diffraction in the 80-GHz band is not as severe as it is at 60 GHz, thus allowing greater range at 80 GHz compared to 60 GHz. E-Band products are similar to millimeter-wave products, except that in the United States, for example, E-Band frequencies are licensed by the FCC in a streamlined licensing process. Licensed spectrum products are allowed more power than unlicensed spectrum products, further enhancing the range and throughput of 80-GHz products.

1.5.3 Very Narrow Beamwidth

One advantage of the 60- and 80-GHz bands is that they overcome the fallibilities of lower-frequency backhaul options. Antenna directivity (beamwidth) is limited by the physical principle of diffraction, wherein the beamwidth is inversely proportional to the operating frequency. So, at 60 GHz, for example, the beamwidth is far narrower than at lower frequencies (such as 5.8 GHz). This very narrow beam gives a backhaul solution the following advantages:

1. It avoids interference from other emitters in the same band, since the beam is so sharp that the potential for interfering with another such beam on the same frequency is very remote.
2. It offers superior security: the beam is so narrow, it is difficult to intercept or otherwise exploit.
3. It offers a high rate of frequency reuse in a backhaul network.
4. It has the power to overcome rain fading.

When engineering a backhaul network to support a millimeter wave/WiMAX network, the service provider should consider the following elements in backhaul planning:

1. Range and throughput demands of the market
2. Security
3. Quality of service (QoS)
4. Interference mitigation
5. Frequency reuse
6. Rain fade
7. Ease of licensing: E-Band in the United States

The selection of backhaul solutions, like the WiMAX platforms they support, should be driven by the business plan. That is, the appropriate platform should be selected for the market. More specifically, we consider an enterprise/urban market.

1.5.4 Range and Throughput

At first look, a backhaul solution offering a range of a couple of kilometers, as seen in Table 1.6, would not seem to fit the notion of backhaul. There are wireless backhaul solutions on the market that offer ranges of up to 160 km. For enterprise or dense urban

TABLE 1.6. Range and Throughput Parameters for 60- and 80-GHz Backhaul Solutions

Technology	V-Band	E-Band
Range	3 km	5 km
Throughput	1 Gbps	10 Gbps
Frequency	57–64 GHz	71–84 GHz
Licensed	No	Yes

markets, a long-range backhaul is not required in most cases. Millimeter wave and E-Band backhaul solutions are best suited to the enterprise and urban markets.

A well-known saying in the telecom world goes, "Bandwidth is the answer now, what was the question?" The 60- and 80-GHz products are also known as gigabit radios, indicating their high throughput. A WiMAX service provider in an enterprise/urban market must plan for gigabit speeds through their base stations. These speeds are not available through other wireless backhaul solutions.

1.5.5 Security

Given that a backhaul solution will need to support a base station that might have dozens of WiMAX radios servicing thousands of enterprise subscribers, the security of the wireless backhaul solution should be of paramount concern to the WiMAX service provider. In the service provider market, casual hackers are less of a concern than the wholesale theft of services via rogue base stations. Figure 1.18 illustrates the narrow beamwidths of 60- and 80-GHz solutions and demonstrates the difficulty of intercepting a point-to-point backhaul signal.

A very narrow beamwidth is not enough to ensure good security on any wireless networks. Most backhaul solutions can be engineered for rigorous authentication processes, followed by equally demanding encryption programs for the data stream. Figure 1.19 shows a possible 60 GHz/WiMAX OFDM mapping solution.

1.5.6 Quality of Service

When millimeter wave radio works with a WiMAX system, one of the major selling points of WiMAX is its ability to prioritize traffic to deliver the best possible quality of service (QoS) relative to the traffic (for example; VoIP and video can be assigned top priority). Most 60 and 80 GHz products offer traffic prioritization schemes to ensure VoIP and video over the backhaul link. In addition, most of these products also offer

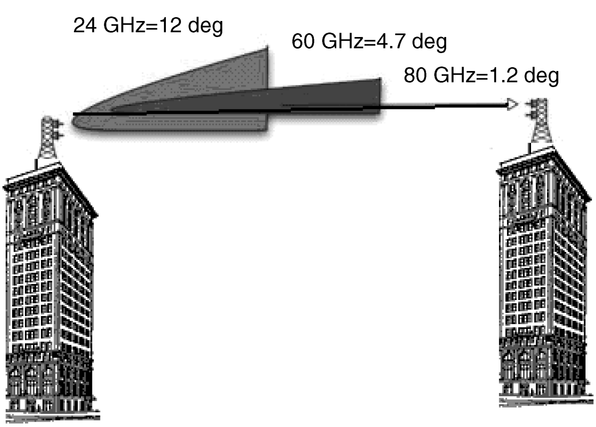

Figure 1.18. Beamwidth comparisons for wireless backhaul solutions

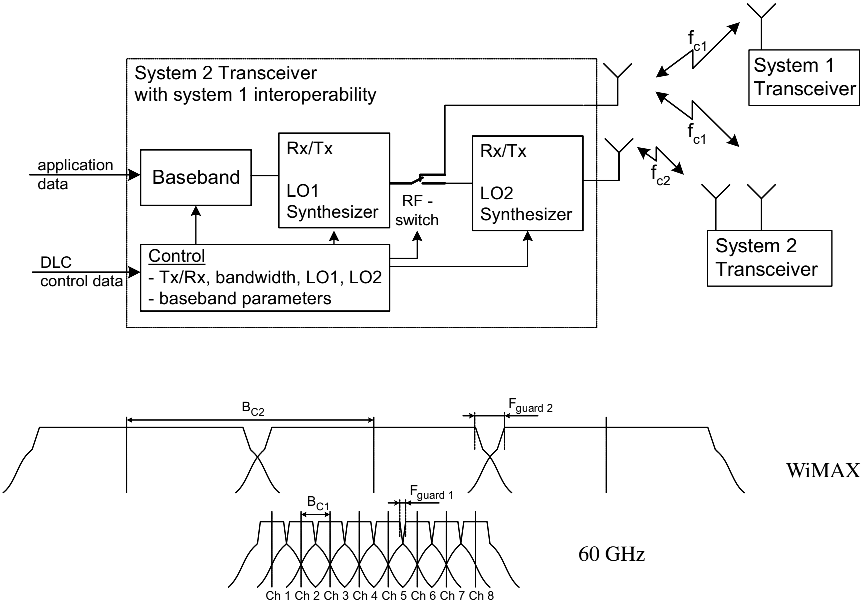

Figure 1.19. Possible 60 GHz/WiMAX OFDM mapping solution

sophisticated modulation schemes to ensure good QoS with up to 99.999% availability. forward error correction (FEC) and frequency division duplexing are features offered on some products to ensure QoS.

Potentially, the number one detractor to QoS in wireless links is latency. Millimeter wave V-band and E-Band products keep latency over their respective wireless links at single digit milliseconds (<10 ms). This ensures good QoS for time-sensitive applications, such as VoIP and video.

1.5.7 Interference Mitigation

Excessive interference can take down a backhaul link. It is imperative that the backhaul solution be engineered to mitigate interference as much as possible.

As illustrated in Figure 1.20, not only does the narrow beamwidths of 60 and 80 GHz products alleviate the possibilities of interference, they also focus the power of the beam, making for a strong link budget over its short transmission range, which further mitigates interference.

1.5.8 Frequency Reuse

One advantage of using the 60- and 80-GHz bands is that, owing to their short range propagation, the backhaul frequencies across the backhaul network can be reused. Figure 1.21 shows an example of frequency reuse in a 60 GHz communication network.

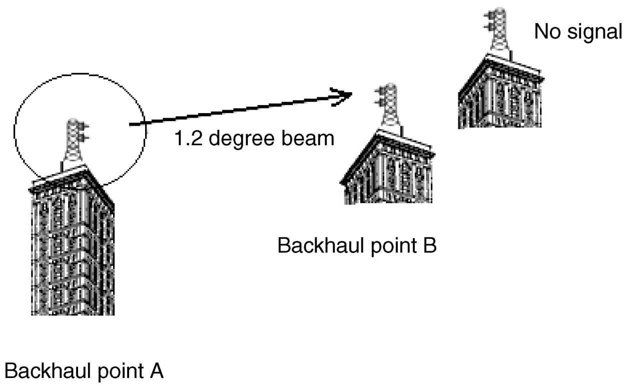

Figure 1.20. The narrow beamwidths of 60- and 80-GHz solutions mitigate interference while enhancing security

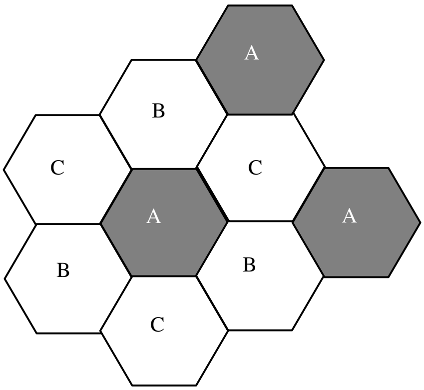

Figure 1.21. The 60- and 80-GHz bands offer dense frequency reuse

In the figure, frequencies A, B, and C are used three times to cover the communication area.

1.5.9 Rain Fade

Just as with excessive interference, service providers must engineer their backhaul solutions to deal with local meteorological conditions that can degrade the performance of their networks. Especially a sufficient rain margin will be needed. Data shows that the currently available commercial equipment can achieve gigabit speeds at 99.999% availability (uptime) with links of approximately one mile, regardless of rain. For a lower 99.9% availability, distances approaching three miles are routine.

1.5.10 Ease of Licensing: E-Band in the United States

An advantage to E-Band solutions is the relative ease of obtaining a license for the spectrum in the United States. Given its short range and narrow beamwidth, and its minimal propensity to interfere with other broadcasters, the FCC provides a streamlined licensing process for the E-Band spectrum. The price for a nationwide, nonexclusive, one-time license is about $1,500. Additional links thereafter are about $250.

E-Band link registration is normally completed using an automated online registration database system. The system checks for possible interference between a proposed E-Band installation and all the existing registered E-Band links based on the GPS coordinates of the E-Band radio locations and the operating parameters of the proposed radio. Registrants have 12 months to complete construction of the link, and the license is valid for 10 years, at which time it can be renewed.

Researchers believe that the advanced architectures used by 3G and 4G cell systems will drive network design and implementation so that cell site connectivity will demand 1-Gbps data rates and the aggregated cell site backbone cores will see data rate demands growing to 2.5 Gbps and even 10 Gbps [44]. Where fiber optic connections prove impractical, the millimeter wave radio community will stand ready to provide a cost-effective solution. There is a trend and new challenge in operating millimeter-wave technology with other mobile/wireless standards. The study of interoperability and convergence among these wireless standards is continuing.

Despite its large potential, development and applications of millimeter wave technology at 60 GHz band have not yet been promoted as expected. Short wavelength allows use of compact, low-profile devices. However, it suffers from high costs of hardware and high-speed signal processing compared with low-frequency bands below microwave.

REFERENCES

[1] H. T. Friis, "A note on a simple transmission formula." *Proc. IRE*, Vol. 34, No. 5, pp. 254–256, May 1946.

[2] M. Marcus, B. Pattan, "Millimeter wave propagation: spectrum management implications." *IEEE Micro. Mag.*, Vol. 6, No. 2, pp. 54–62, Jun. 2005.

[3] D. Sobel, "60 GHz wireless system design: towards a 1 Gbps wireless link." Berkeley Wireless Research Centre, Jun. 2003.

[4] D. Sobel, R. W. Brodersen, "60GHz CMOS system design: challenges, opportunities, and next steps." Research Retreat at Berkeley Wireless Research Centre, Jan. 2003.

[5] M. K. Simon and M. S. Alouini, *Digital Communication over Fading Channels*, 2nd edition, New York; Wiley-IEEE Press, 2004.

[6] K. Sato, T. Manabe, T. Ihara, H. Saito, S. Ito, T. Tanaka, K. Sugai, N. Ohmi, Y. Murakami, M. Shibayama, Y. Konishi, and T. Kimura, "Measurements of reflection and transmission characteristics of interior structures of office building in the 60GHz band." *IEEE Trans. Antennas Propag.*, Vol. 45, No. 12, pp. 1783–1792, 1997.

[7] J. Caruso, "Copper 10 gigabit ethernet NICs unveiled." *Network World*, Jan. 2007.

[8] W.I. Way, "Spectrally efficient parallel PHY for 100GbE MAN and WAN." *IEEE Commun. Mag.*, Vol. 45, No. 12, pp. 20–23, 2007.

[9] R. Merritt,"New tech breaks into network specs war." *EE Times,* Dec. 2006.

[10] IEEE 802.15 WPAN Task Group 3c (TG3c) Millimeter Wave Alternative PHY, available at http://www.ieee802.org/15/pub/TG3c.html

[11] K. Kimyacioglu, "WiMedia next gen UWB and 60 GHz considerations." *WiMedia Conference*, Mar. 2006.

[12] S. K. Yong and C. C. Chong, "An overview of multigigabit wireless through millimeter wave technology: potentials and technical challenges." *EURASIP Journal on Wireless Communications and Networking*, Vol. 2007 (2007), Article ID 78907, 10 pages doi:10.1155/2007/78907 .

[13] D. C. O'Brien, G. E. Faulkner, K. Jim, and D. J. Edwards, "Experimental characterization of integrated optical wireless components." *IEEE Photon. Technol. Lett.*, Vol. 18, No. 8, pp. 977–979, 2006.

[14] D. C. O'Brien, G. E. Faulkner, K. Jim, E. B. Zyambo, and D. J. Edwards, "High-speed integrated transceivers for optical wireless." *IEEE Commun. Mag.*, Vol. 41, No. 3, pp. 58–62, 2003.

[15] A. Tsukioka,"JVC develops base technologies for next-generation optical wireless access system." *JCN Network*, Oct. 2005.

[16] A. M. Street, P. N. Stavrinou, D. C. O'Brien, and D. J. Edwards, "Indoor optical wireless systems: a review." *Optical and Quantum Electronics*, Vol. 29, No. 3, pp. 349–378, 1997.

[17] D. C. O'Brien, E. B. Zyambo, G. Faulkner, D. J. Edwards, D. M. Holburn, R. J. Mears, R. J. Samsudin, V. M. Joyner, V. A. Lalithambika, M. Whitehead, P. Stavrinou, G. Parry, J. Bellon, and M. J. Sibley, "High-speed optical wireless transceivers for in-building optical local area networks (LANs)." *Optical Wireless Communications III*, 4124, paper 4124-16, SPIE, Boston 2000.

[18] K. C. Huang and Z. C. Wang, "Millimeter-wave circular polarized beam-steering antenna array for gigabit wireless communications." *IEEE Trans. Antennas Propag.*, Vol. 54, No. 2, Part 2, pp. 743–746, 2006.

[19] R. C. Qiu, H. Liu, and X. Shen, "Ultra-wideband for multiple access communications." *IEEE Commun. Mag.*, Vol. 43, No. 2, pp. 80–87, 2005.

[20] JVC Products, VIPSLAN OA-301, JVC Corporation Japan. Available at http://www.jvc.co.jp/

[21] A. Medeisis,"SE19 drafting group meeting on MGWS at 60 GHz, ERO, Copenhagen, 26 March 2007." ERO SE19 Broadband Applications in Fixed Service, Available at http://www.ero.dk/

[22] European Radiocommunications Committee (ERC), T/R 22-03E, "Provisional Recommended Use of the Frequency Range GHz by Terrestrial Fixed and Mobile Systems." pp. 3, 1990.

[23] CEPT, ERO, "The European table of frequency allocations and utilizations covering the frequency range 9 kHz to 275 GHz." Lisboa January 2002, Dublin 2003, Turkey 2004, Copenhagen 2004.

[24] ERC Recommendation 12-09, "Radio frequency channel arrangement for fixed service systems operating in the band 57.0–59.0 GHz which do not require frequency planning, the Hague 1998 revised Stockholm." Oct. 2004.

[25] ECC Recommendation (05)02, "Use of the 64–66 GHz frequency band for fixed services." Jun. 2005.

[26] ETSI DTR/ERM-RM-049, "Electromagnetic compatibility and radio spectrum matters (ERM); system reference document; technical characteristics of multiple gigabit wireless systems in the 60 GHz range." Mar. 2006.

[27] ECC Recommendation (05)02, "Use of the 64–66 GHz frequency band for fixed service." Revised ECC/REC/(05)02 Edition, Feb. 2009.

[28] IEEE 802.15-15-06-0044-00-003c document, "60 GHz regulation in Germany." Jan. 2006.

[29] Japan Regulations for enforcement of the radio law 6-4-2 specified low power radio station (11) 59–66 GHz band, Ministry of Public Management, Home Affairs, Posts, and Telecommunications, Japan, 2000.

[30] Ministry of Information Communication of Korea, "Frequency allocation comment of 60 GHz band." Apr. 2006.

[31] FCC, "Code of Federal Regulation, Title 47 Telecommunication, Chapter 1, Part 15.255." Oct. 2004.

[32] S. K. Yong and C. C. Chong, "An overview of multigigabit wireless through millimeter wave technology: potentials and technical challenges." *EURASIP Journal on Wireless Communications and Networking*, Volume 2007, Article ID 78907, 10 pages doi: 10.1155/2007/78907 (2007).

[33] Spectrum Management Telecommunications, "Radio Standard Specification-210, Issue 6, Low-Power Licensed-Exempt Radio Communication Devices (All Frequency Bands): Category 1 Equipment." Sep. 2005.

[34] FCC document, OMB 3060-1070, "Allocations and Service Rules for the 71–76 GHz, 81–86 GHz, and 92–95 GHz Bands."

[35] J. Wells,"Multigigabit wireless connectivity at 70, 80 and 90 GHz." RF Design, pp. 50–54, May 2006.

[36] ERC Recommendation 12-09, "Radio Frequency Channel Arrangement for Fixed Service Systems Operating in the Band 57.0–59.0 GHz Which Do Not Require Frequency Planning." The Hague, 1998; revised Stockholm, Oct. 2004.

[37] ARIB STD-T69, "Millimeter-Wave Video Transmission Equipment for Specified Low Power Radio Station." Jul. 2004.

[38] ARIB STD-T74, "Millimeter-Wave Data Transmission Equipment for Specified Low Power Radio Station (Ultra High Speed Wireless LAN System)." May 2001.

[39] IEEE 802.15 WPAN Task Group 3C (TG3c) Millimeter Wave Alternative PHY, available at http://www.ieee802.org/15/pub/TG3c.html

[40] IEEE 802.15-07-0761-15-003c, "Unified and flexible millimeter wave WPAN systems supported by common mode." Nov. 2007.

[41] IEEE 802.15-05-0353-07-003c, "Working group for wireless personal area networks (WPANs), TG3c System Requirements." Jan. 2007.

[42] "IEEE Standard for Local and Metropolitan Area Networks. Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1." IEEE Std 802.16e-2005 and IEEE Std 802.16-2004/Cor 1-2005 (Amendment and Corrigendum to IEEE Std 802.16-2004), p. 3, 2006.

[43] S. Chia, M. Gasparroni, and P. Brick, "The next challenge for cellular network backhaul." *IEEE Microw. Mag.*, Vol. 10, No. 5, pp. 55–66, 2009.

[44] D. Lockie and D. Peck, "High-data-rate millimeter-wave radios." *IEEE Microw. Mag.*, Vol. 10, No. 5, pp. 75–83, 2009.