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Gigabit Wireless Communications

The demand for high data rate and high integrity services seems set to grow for the foreseeable future. In this chapter the basic ideas and application areas for gigabit Ethernet are introduced, and the requirements for high-performance networks are described. The role of the antenna in these systems is addressed, and consideration of the performance parameters outlined.

This chapter is organised as follows. Section 1.1 describes a number of application scenarios and highlights the requirements for a specific application, namely uncompressed high-definition video streaming. Section 1.2 describes the worldwide regulatory efforts and standardisation activities. Section 1.3 presents the characteristics of millimetre waves. Section 1.4 presents measured propagation results and channel performance. Section 1.5 describes system design and performance. Section 1.6 discusses the role of the antenna within the system and the technical challenges that need to be resolved for the full deployment of 60 GHz radio networks. Section 1.7 describes the link budget, which is pivotal in determining the performance of the system. In this section noise is also examined, and its impact on link behaviour. Section 1.8 summarises the main points of the chapter.

1.1 Gigabit Wireless Communications

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 that of the old. As the cost of 100 Mbps Ethernet decreased and approached the previous cost of 10 Mbps Ethernet, users rapidly moved to the higher performance standard. In January 2007, 10 gigabit Ethernet over copper wiring was announced by the industry [1]. Additionally, gigabit Ethernet became economic (e.g. below $200) for server connections, and desktop gigabit connections have come within $10 or less of the cost of 100 Mbps technology. 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, as well as for applications that only become practical at gigabit speeds.

Millimetre Wave Antennas for Gigabit Wireless Communications Kao-Cheng Huang and David J. Edwards

In terms of a business model, wireless communications have pointed towards an approaching need for gigabit speeds and longer-range connectivity as the applications emerge for home audio/visual (A/V) networks, high-quality multimedia, voice and data services. Current wireless local area networks (WLANs) offer peak rates of 54 Mb/s, with 200–540 Mb/s, such as IEEE 802.11n, becoming available soon. 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 a Gb/s data rate to support multiple high-speed, high-definition A/V streams (e.g. carrying an uncompressed high-definition video at resolutions of up to 1920 × 1080 progressive scans, with latencies ranging from 5 to 15 ms) [2].

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

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

Some approaches, such as IEEE 802.11n, are improving data rates by evolving the existing WLANs standards to increase the data rate; to up to 10 times faster than IEEE 802.11a or 802.11g. Others, such as the 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-honoured strategy of moving to higher, unused and unregulated millimetre wave frequencies.

Despite millimetre wave technology having been established for many decades, the millimetre wave systems 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 standardisation bodies. In very broad terms, millimetre 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, the main focus will be on the 60 GHz industrial, scientific and medical (ISM) band (unless otherwise specified, the terms “60 GHz” and “millimetre wave” will be used interchangeably), which has emerged as one of the most promising candidates for multigigabit wireless indoor communication systems.

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 Gb/s. Importantly, 60 GHz technology offers various advantages over currently proposed or existing communications systems. One of the deciding factors that makes 60 GHz technology attractive and has prompted significant interest recently, is the establishment of (relatively) huge unlicensed bandwidths (up to 7 GHz) that are available worldwide. The spectrum allocations are mainly regulated by the International Telecommunication Union. The details for band allocation around the world can be found in Section 1.2.

While this is comparable to the unlicensed bandwidth allocated for ultra-wideband purposes (∼2–10 GHz), the 60 GHz band is continuous and less restricted in terms of power limits (also there are less 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 allocated in history. This huge bandwidth offers potential in terms of capacity and flexibility and makes 60 GHz technology particularly attractive for gigabit wireless applications. Although 60 GHz regulations allow much higher transmit power compared to other existing wireless local area networks (e.g. maximum 100 mW for IEEE 802.11 a/b/g) and wireless personal area network (WPAN) systems, the higher transmit power is necessary to overcome the higher path loss at 60 GHz (see Table 1.1).

Table 1.1 Path loss and transmit power comparison for different wireless standards

	10 m path loss (dB)	Maximum transmit power (mW)
802.11a	66	40
802.11b/g	60	100
802.15.3c	88	500

In addition, the typical 480 Mbps bandwidth of UWB cannot fully support broadcast video and therefore the data packets need to be recompressed. This forces manufacturers to utilise expensive encoders and more memory into 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 UWB.

Taking into consideration the development of consumer electronics, currently the IEEE 802.15.3c standard [3] provides 1–3 Gb/s wireless personal area network solutions, projected for introduction in the years 2008 to 2009. Also, WiMedia 2.0 [4], which can be used for large file transfer applications, is to be developed, so the target is to have a data rate of 5 Gb/s or higher raw bit rates and with more than a 10 m range for indoor applications.

Figure 1.1 shows the development and the trend of wireless standards. Advanced wireless technology should always adopt timelines/milestones to increase data rates by $\sim$5 to 10 times every 3 to 4 years to keep up with the pace of projected demand.

While the high path loss seems to be a disadvantage at 60 GHz, it does however confine the 60 GHz power and system operation in an indoor environment. Hence, the effective interference levels for 60 GHz are less severe than those systems located in the congested 2–2.5 GHz and 5–5.8 GHz regions. In addition, higher frequency re-use can also be achieved over a very short distance in an indoor environment, thus allowing a very high throughput network. The compact size of the 60 GHz radio also permits multiple antenna solutions at the user terminal that are otherwise difficult, if not impossible, at lower frequencies. Compared to a 5 GHz system, the form factor of millimetre wave systems is approximately 140 times smaller and can be conveniently integrated into consumer electronic products, but 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 presents a significant research and engineering challenge. Ignoring fading for the moment, in theory, the 1 Gb/s data rate requirement can be met, if the product of bandwidth

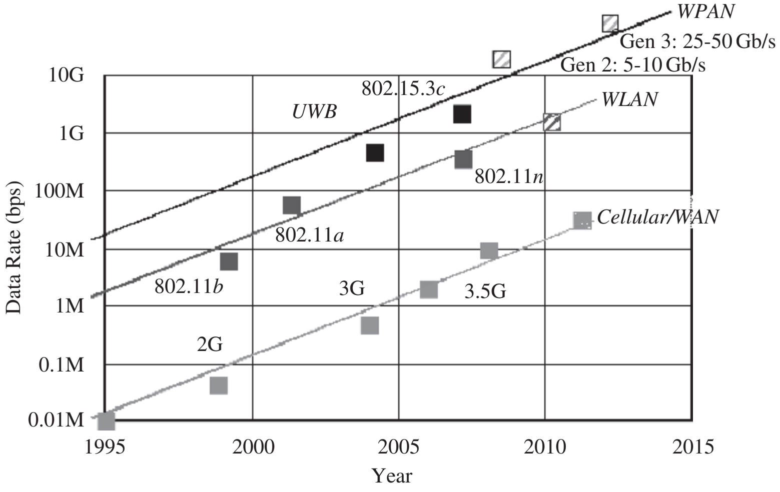


Figure 1.1 Data rate projections over time [5]

(in units of Hz) and spectral efficiency (in b/s per Hz units) equals 10^9. As shall be described in the following sections, a variety of cost, technology and regulatory constraints make such a solution very challenging.

Despite the various advantages offered, millimetre wave based communications suffer a number of critical problems that must be resolved. Figure 1.2 shows the data rates and range requirements for a number of WLAN and WPAN systems. Since there is a need to distinguish between different standards for broader market exploitation, the IEEE 802.15.3c standard is positioned to provide gigabit rates and a longer operating range. At these rates and ranges, it will be a difficult task for millimetre 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 spread values can easily increase the complexity of the system beyond the practical limit for equalisation [6].

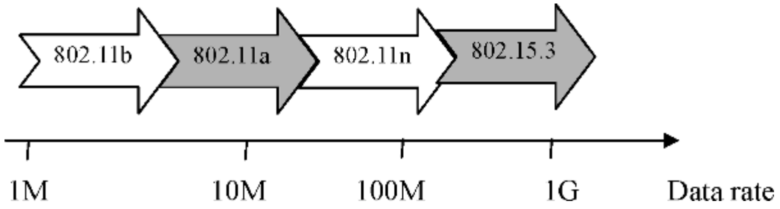


Figure 1.2 Data rates and range requirements for WLAN and WPAN standards and applications. Millimetre wave technology, i.e. IEEE 802.15.3c, is aiming for very high data rates [6]

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

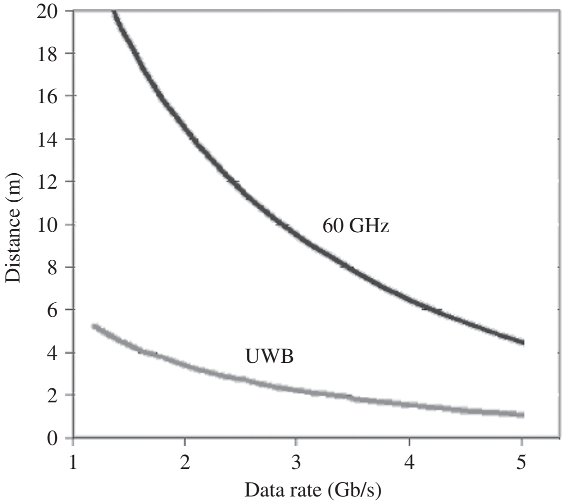


Figure 1.3 Shannon's capacity curve in a 1 GHz occupied bandwidth for 60 GHz versus UWB (noise figure is set at 8 dB) [5]

In the search for the provision of higher data rates, radio systems have tended to look at higher frequencies where an unregulated spectrum is available. As an alternative, a (free space) wireless optical LAN also competes as one of the communication technologies that are able to offer a significant unregulated spectrum. Diffuse optical networks use wide- angle sources and scatter from surfaces in the room to provide optical 'ether' similar to that which would be obtained using a local radio transmitter [7]. 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. Additionally optical transmitters launch extremely high power, and dynamic equalisation is required for high bandwidth operation.

Optical networks have the potential to offer significant advantages over radio approaches, within buildings or in spaces with limited coverage. Many current systems use directed line-of-sight paths between transmitter and receiver [8]. These can provide data rates of hundreds of megabits per second and above, depending on particular parameters. However, the coverage area provided by a single channel can be quite small, so that providing area coverage, and the ability to roam, presents a major challenge. Line-of-sight channels can also be blocked, as there is no alternative scattered path between the transmitter and receiver, and this presents a major challenge in network design [7]. Multiple-base stations within a room would provide coverage in this case, and optical or fixed connections could be used between the stations. A commercial line-of-sight system is currently offered by Victor Company of Japan, Limited (JVC), giving 10 Mb/s Ethernet connections [9].

In general, optical channels are subject to eye safety regulation, which is difficult to meet, particularly for line-of-sight channels [7]. 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. 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 [10].

As previously mentioned, the other major problem for optical channels is that of blocking. Line-of-sight channels in particular 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 [10, 11].

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

Table 1.2 Comparison of three new technologies for gigabit wireless communications [12–14]

	Millimetre wave	UWB radio	Optical wireless
Advantage	1. High data rates (up to Gb/s) 2. Compatible with fibre 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. Low cost 2. Low power	1. Matched filter problem 2. Antenna parameter trade-off	1. Atmospheric loss ranging from 10 dB/km(sunny) to 350 dB/km(foggy) 2. Multi-user application 3. No protection for the link
Peer-to-peer	Indoor/outdoor	Indoor/outdoor	Indoor/outdoor
Multiple-access	Indoor/outdoor	Indoor	Indoor
Data rate	>1.25 Gb/s at 60 GHz ~10 Gb/s at 122.5 GHz	500 Mbps within 10 m (FCC)	~1.25 Gb/s (peer-to-peer)
Indoor maximum range	Room area	76 m (station in commercial building)	7 m (mobile) 10 m (station)
DC power consumption	High	Low	DC 5 V, 500 mA (mobile)
Maximum TX power	500 mW (FCC 15.255)	Maximum output power of 1 W 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

1.2 Regulatory Issues

1.2.1 Europe

The European Telecommunications Standards Institute (ETSI) and 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 [15]. In general, the 59–66 GHz band has been allocated for mobile services without specific decision on the regulations, as shown in Figure 1.4. The CEPT Recommendation T/R 22–03 has provisionally recommended the use of the 54.25–66 GHz band for terrestrial and fixed mobile systems [16]. However, this provisional allocation has been recently withdrawn [6].

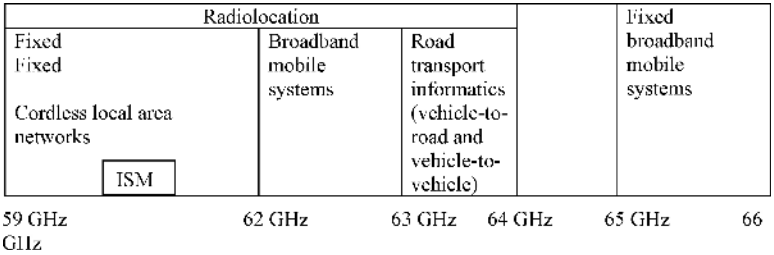


Figure 1.4 The 60 GHz frequency spectrum in Europe (ISM: industry, science and medicine) [17]

In 2003, the European Radiocommunications Committee (ERC) within the European Conference of Postal and Telecommunications Administrations revised the European Table of Frequency Allocations and Utilisations [17]. The ERC also considered the use of the 57–59 GHz band for fixed services without requiring frequency planning [18]. Later, the Electronic Communications Committee (ECC) within the CEPT recommended the use of point-to-point fixed services in the 64–66 GHz band [19]. In the most recent development, the ETSI proposed 60 GHz regulations to be considered by the Electronic Communications Committee of the European Conference of Post and Telecommunications Administrations for WPAN applications [20]. Under this proposal, 9 GHz of unlicensed spectrum has been allocated for 60 GHz operation. This band represents the union of the bands currently approved and under consideration in the first quarter of 2007.

The frequency band being considered is 57–66 GHz. The spectrum allocation is shown in Figure 1.5 and Table 1.3. This is the amalgamation of the bands currently approved for

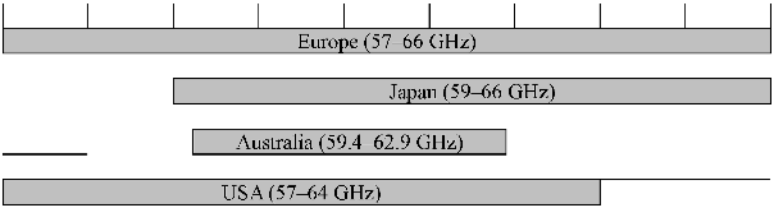


Figure 1.5 Geographically available 60 GHz spectrum and power

Table 1.3 International frequency allocation at 60 GHz [25]

Region	Unlicensed bandwidth (GHz)	Tx power	Maximum antenna gain	Reference
Europe	9 GHz (57–66) min 500 MHz	20 mW (max)	37 dBi	[20]
Japan	7 GHz (59–66) max 2.5 GHz	10 mW(max)	47 dBi	[22]
Korea	7 GHz (57–64)	10 mW(max)	To be decided	[23]
Germany	1 GHz (57.1–57.8) (58.6–58.9)	50 mW (max)	Not specified	[21]
USA	7 GHz (57–64)	500 mW (max)	Not specified	[24]

license-exempt use in Japan and the United States, and under proposed allocation in the Republic of China and the Republic of Korea. The existing etiquette rules, spectrum sharing studies and other analyses in these countries could be a model for considering the needs of commercial, military and scientific uses of these frequencies worldwide.

The proposed European Regulations were based on ETSI DTR/ERM-RM-049 [20]. It was proposed that the ECC considers the proposed regulation in Clause 6, and identifies the final frequency band for 60 GHz license-exempt operation. The proposed power level is shown in Table 1.4.

Table 1.4 Proposed power regulation [20, 26]

Minimum bandwidth	Maximum transmit power	Channel spacing	Notes
A minimum spectrum of 500 MHz is requested for the transmitted signal, which should, in theory and under the right circumstances, be able to share a spectrum with other users	+57 dBm EIRP (+20 dBm nominal with up to +37 dBi antenna gain or +10 dBm nominal with up to +47 dBi antenna gain)	No restriction	The transmit power is necessary to offset oxygen and material attenuation at this band, and is typical for gigabit commercial products in this band

In Germany, the regulatory requirements are that the frequency band of 57.1–57.8 and 58.6–58.9 GHz are used for a time-domain duplex (TDD) point-to-point connection. Its maximum EIRP (equivalent isotropic radiated power) is 15 dBW. The frequency band of 61–61.5 GHz is for location service and general use. The maximum EIRP is 10 W for the location service and 100 mW for general use [21].

1.2.2 United States

In 2001, the United States Federal Communication Commissions (FCC) allocated 7 GHz in the 54–66 GHz band for unlicensed use [24]. In terms of the power limits, FCC rules allow emission with an average power density of 9μ W/cm^2 at 3 m and maximum power density of 18μ W/cm^2 at a range of 3 m from the radiating source. These data translate to average equivalent isotropic radiated power (EIRP) and maximum EIRP of 40 and 43 dBm, respectively. The FCC also specified the total maximum transmit 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 Reference [24], Sections 1.307(b), 2.1091 and 2.1093. After taking the RF safety issues into account, the maximum transmit power is limited to 10 dBm. Furthermore, each transmitter must transmit at least one transmitter identification signal within a 1 s interval of the signal transmission. It is important to note that the 60 GHz regulations in Canada, which is regulated by Industry Canada Spectrum Management and Telecommunications (IC-SMT) [27], are harmonized with the US.

In October 2003, the FCC announced that the frequency bands from 71 to 76 GHz, 81 to 86 GHz and 92 to 95 GHz were available for wireless applications [28]. The FCC chairman heralded the ruling as opening a "new frontier" in commercial services and products [29]. The allocation provides the opportunity for a broad range of new products and services, including high-speed, point-to-point wireless local area networks and broadband Internet access at gigabit data rates and beyond.

The 70, 80 and 90 GHz allocations are significant. Collectively referred to as E-band, these three allocations are the highest frequencies ever licensed by the FCC. The nearly 13 GHz of allocated spectrum represents more bandwidth than all other previously existing commercial wireless spectrum combined. The ruling also permitted a novel licensing scheme, allowing cheap and fast frequency allocations to prospective users. All this was achieved at an unprecedented speed, from the initial petition to the formal release of the rules in scarcely more than two years.

1.2.3 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 in the 59–66 GHz band [22]. The 54.25–59 GHz band is, however, allocated for licensed use. The maximum transmit power for the 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 is no specification for RF radiation exposure and transmitter identification requirements [22].

1.2.4 Industrial Standardisation

The first international industry standard that covered the 60 GHz band was the IEEE 802.16 standard for local and metropolitan area networks [30]. However, this is a licensed band and is used for line-of-sight (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), i.e. the ARIB-STD T69 and ARIB-STD T74 [31, 32]. The former is the standard for millimetre wave video transmission equipment for a specified low-power radio station (point-to-point system), while the latter is the standard for a millimetre 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 (see Table 1.5).

Interest in the 60 GHz radio continued to grow with the formation of a Millimetre Wave Interest Group and Study Group within the IEEE 802.15 Working Group for WPAN. In March 2005, the IEEE 802.15.3c Task Group (TG3c) was formed to develop a millimetre wave-based alternative physical layer (PHY) for the existing IEEE 802.15.3 WPAN Standard 802.15.3-2003 [33]. The developed PHY is aimed to support a minimum data rate of 2 Gb/s over a few

Table 1.5 The 60 GHz standards in Japan

Code	Standard name	Note
ARIB STD-T69 (July2004)	Millimetre-Wave Video Transmission Equipment for Specified Low Power Radio Station	Bandwidth: 1208 MHz Tx power: 10 dBm Rx antenna gain: 0 dBi
ARIB STD-T69 Revision (November 2005)	Millimetre-Wave Video Transmission Equipment for Specified Low Power Radio Station (only the part of the revision from Version 2.0 to 2.1)	
ARIB STD-T74 (May 2001)	Millimetre-Wave Data Transmission Equipment for Specified Low Power Radio Station (Ultra High Speed Wireless LAN System)	Bandwidth: 200 MHz Tx power: 10 dBm Rx antenna gain: 0 dBi
ARIB STD-T74 Revision (November 2005)	Millimetre-Wave Data Transmission Equipment for Specified Low Power Radio Station (Ultra High Speed Wireless LAN System) (only the part of the revision from Version 1.0 to 1.1)	

metres with optional data rates in excess of 3 Gb/s. This is the first standard that addresses multigigabit wireless systems and will form the key solution to many data rates serving applications, especially those related to wireless multimedia distribution. In other developments, WiMedia Alliance has recently announced the formation of the WiMedia 60 GHz Study Group with the aim of providing recommendations to the WiMedia Board of Directors on the feasibility issues related to 60 GHz technology. A decision will be taken in the near future about WiMedia's direction and involvement in the 60 GHz market.

In 2007, another group, WirelessHD^{TM} (high definition), also released a specification that uses the unlicensed 60 GHz radio to send uncompressed HD video and audio at 5 Gb/s over distances of up to 30 feet, or within one room of a house. Its core technology promotes theoretical data rates up to 20 Gb/s, permitting it to scale to higher resolutions, colour depths and ranges. Coexisting with other wireless services, the Wireless HD platform is designed to operate cooperatively with existing, wireline display technologies. The specification maintains high-quality video, ensures the interoperability of consumer electronics devices, protects from signal interference and uses existing content protection techniques. The WirelessHD^{TM} Group predicts that 60 GHz will allow the fast transmission speeds required for high-definition content.

In addition, the European Computer Manufacturers Association (ECMA International) Technical Committee Task Group (TG20) has also developed a standard for a 60 GHz physical (PHY) and medium access control (MAC) for short-range unlicensed communications. The standard provides up to 10 Gb/s wireless personal area network (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 underlines the role of the millimetre wave antenna in gigabit communications.

Table 1.6 summarises potential applications of millimetre wavelength systems as submitted in response to the IEEE Call for Applications (CFA). The submissions illustrate the support for some of the applications listed. The applications have been arranged in the numeric order of the IEEE CFA document number (last column)[34].

Table 1.6 Possible applications for millimetre wave communications. (Reproduced by permission of © 2007 IEEE [34])

No.	Description of applications	Outdoor	Indoor	IEEE CFA Doc. number
1	Gigabit Ethernet link, wireless IEEE1394 applications	–	• LOS • Data rate: $\leq$ 1 Gb/s duplex • Range: $\leq$ 17 m	04-0019
2	Ad hoc information distribution system	–	• LOS • Data rate: 622 Mb/s • Range: $\geq$ 20 m (AP-AP) $\geq$ 3 m (AP-MT)	04-0097
3	Multimedia, information distribution system	–	• LOS • Data rate: $\geq$ 1 Gb/s • Range: $\leq$ 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 Mb/s to 1.5 Gb/s • Range: 400 m to 1 km	• LOS • Data rate: 100 Mb/s to 1.6 Gb/s • Range: ~10 m	04-0118
5	Small office/meeting scenario, general office applications	–	• NLOS • OFDM • Data rate: $\leq$ 200 Mb/s • Range: 2 to 4 m	04-0141
6	Distribution links in apartments, stadium, etc.	• LOS • P2P • Bandwidth: $>$ 300 MHz • Range: $\leq$ 220 m	–	04-0153
7	Wireless home video server connected to HDTV, PC and other video devices	–	• LOS • Data rate: 300 Mb/s, 400 Mb/s and 1.5 Gb/s uncompressed HDTV data • Range: $\leq$ 10 m	04-0348

(*continued overleaf*)

Table 1.6 (*continued*)

No.	Description of applications	Outdoor	Indoor	IEEE CFA Doc. number
8	• 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 Gb/s and ≥ 622 Mb/s • Range: ≥ 20 m and ≥ 3 m	04-0352
9	PowerPoint and such applications	–	• LOS and NLOS • Data rate: ≥ 1 Gb/s • Range: ≤ 3 m • Space diversity	04-0514
10	• Replacement for 1394 FireWire • Replacement for USB • Military – future combat systems, secure communication	–	• LOS and NLOS (people) • 100 to 500 Mb/s link, 1 Gb/s in 2007 • Short range	04-0665

1.3 Millimetre Wave Characterisations

This section presents benefits of 60 GHz technology and its major characteristics. It can be used for high-speed Internet, data and voice communications, and offers the following key benefits:

1. Unlicensed operation
2. Highly secure operation: resulting from short transmission distances due to oxygen absorption, narrow antenna beamwidth and no wall penetration
3. Virtually interference-free operation: resulting from short transmission distances due to oxygen absorption, narrow antenna beam width and limited use of 60 GHz spectrum
4. High level of frequency re-use enabled: the communication needs of multiple customers within a small geographic region can be satisfied
5. Fibre optic data transmission speeds possible: 7 GHz (in the USA) of continuous bandwidth available compared to < 0.3 GHz at the other unlicensed bands (3.5 GHz internationally available)
6. Mature technology: long history of this spectrum being used for secure communications
7. Carrier-class communication links enabled: 60 GHz links can be engineered to deliver “five nines” (99.999 %) availability if desired (outdoor applications such as backbone or bypass bridges)

There is a widespread belief that the characteristics of a millimetre wave present many difficulties in terms of propagation environment for high data rate wireless communications.

While the oxygen absorption does indeed cause a 15 dB/km loss, this translates to only a 1.5 dB loss at 100 m, so for indoor applications the absorption loss from oxygen is small, if not negligible.

Another loss – proportional to the frequency squared – comes from the *Friis path loss* equation (1.2). This "loss", however, can be attributed to another factor. If omni-directional antennas, such as half-wavelength dipoles, are used, then as the frequency rises, the effective area of the antennas decreases as frequency squared. If, on the other hand, the (physical) area of the antennas is kept constant, then there is no increase in path loss because the electrical area increases as the wavelength decreases (squared).

For instance, a 60 GHz antenna, which has an effective area of 1 square inch, will have a gain of approximately 25 dBi, but this gain comes at the expense of being highly directional. This would mean that for millimetre wave radios to be used at their full potential they would need a solution for precise pointing.

1.3.1 Free Space Propagation

As with all propagating electromagnetic waves, for millimetre waves in free space the power flux density falls off as the square of range. For a doubling of range, power flux density at 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 (in dB):

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

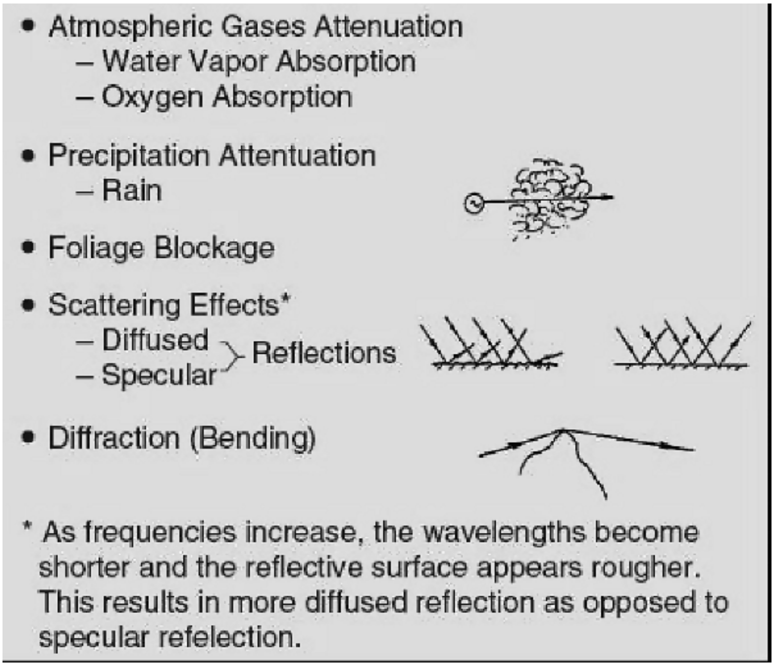
where $L_{\text{free space}}$ is the freespace loss, R is the distance between transmit and receive antennas, and λ is the operating wavelength. This equation describes line-of-sight wave propagation in free space. This equation shows that the free space loss increases when the frequency or range increases. Thus, millimetre wave free space loss can be quite high, even for short distances. This indicates that the millimetrewave spectrum is best used for short-distance communications links. The Friis equation (1946) gives a more complete expression for all the factors from the transmitter to the receiver (as a ratio, linear units) [35]:

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

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

1.3.2 Millimetre Wave Propagation Loss Factors

In microwave systems, transmission loss is accounted for principally by the free space loss. However, in the millimetrewave bands additional (absorption) loss factors come into play, such as gaseous losses and rain (or other micrometeors) in the transmission medium. Factors that affect millimetre wave propagation are given in Figure 1.6.



- Atmospheric Gases Attenuation
  - Water Vapor Absorption
  - Oxygen Absorption
- Precipitation Attentuation
  - Rain
- Foliage Blockage
- Scattering Effects*
  - Diffused
  - Specular

  Reflections
- Diffraction (Bending)

* As frequencies increase, the wavelengths become shorter and the reflective surface appears rougher. This results in more diffused reflection as opposed to specular refelection.

Figure 1.6 Propagation effects influencing millimetre wave propagations. (Reproduced by permission of © 2005 IEEE [36])

1.3.3 *Atmospheric Losses*

Transmission losses occur when millimetre waves travelling through the atmosphere are absorbed by molecules of oxygen, water vapour 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 millimetre wave propagation characteristics. Figure 1.7 shows an expanded plot of the atmospheric absorption versus frequency at altitudes of 4 km and sea level, for water content of 1 and 7.5 gm/m^3 respectively (the former value represents relatively dry air while the latter value represents 75 % humidity for a temperature of 10°C).

1.4 Channel Performance

Planning for millimetre wave spectrum use is based on the propagation characteristics and channel performance of radio signals and the noise apparent in this frequency range. While signals at lower frequency bands, such as a GSM signal, can propagate for many kilometres and penetrate more easily through buildings, millimetre wave signals can travel only a few kilometres or less, and suffer from high transmission loss in the air and solid materials. However, these characteristics of millimetre wave propagation can be very advantageous in some applications.

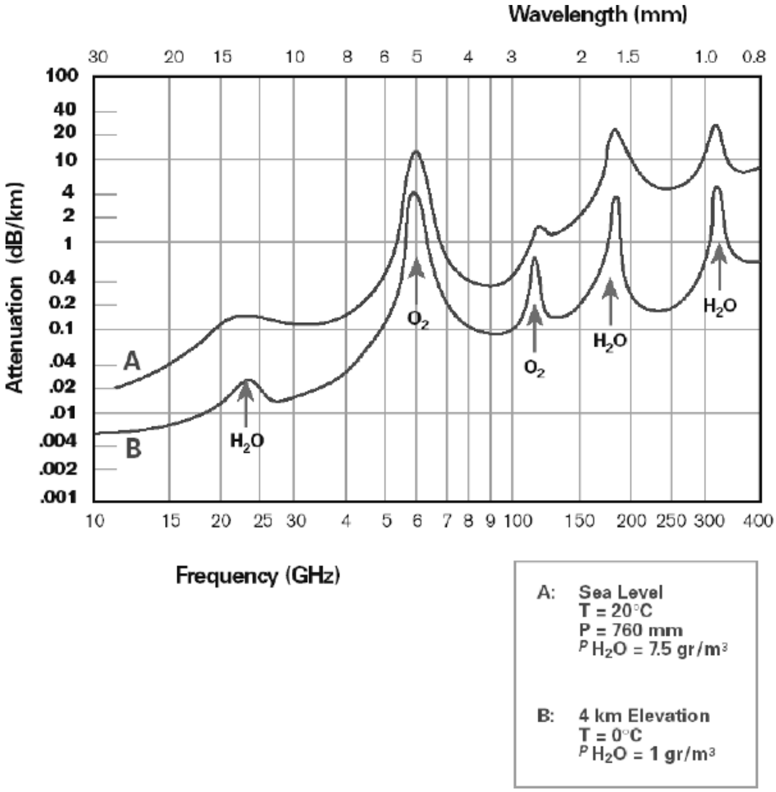


Figure 1.7 Average atmospheric absorption of millimetre waves. (Reproduced by permission of © 2005 IEEE [36])

Millimetre waves can establish more densely packed communications links, thus providing very efficient spectrum utilization; the high absorption enabling shorter range frequency re-use, and therefore increasing the overall capacity of communication systems. The characteristics of millimetre wave propagation are summarised in this section, including free space propagation and the effects of various physical factors on propagation.

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

- High loss from the Friis equation
- Doppler shift is non-negligible at pedestrian velocities
- Human shadowing
- Non-line-of-sight propagation, which induces random fluctuations in the signal level, known as multipath fading, as shown in Figure 1.8
- Noise

The transmitting power of a 60 GHz communications link is restricted to +40 dBm EIRP limit by the FCC in the USA. Transmitter power and path loss can be limiting factors

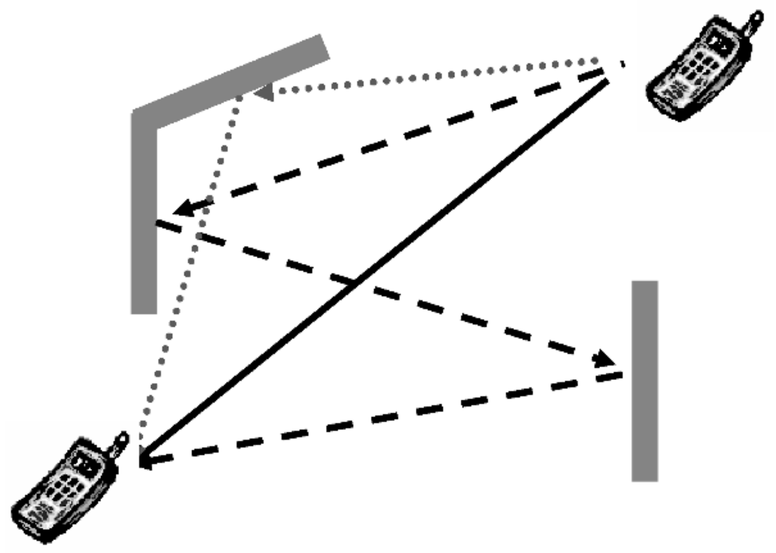


Figure 1.8 Multipath effect for indoor wireless communications

for a high-speed wireless link. However, at these frequencies antenna directivity can be used to increase power gain in the desired direction.

The capacity limits of a 60 GHz link with omnidirectional antennas at both ends should be considered. Even when the bandwidth is unlimited, the received power P_{Rx} is still limited by the Shannon AWGN capacity, as given by:

$$C = BW\ \log_2\left(1 + \frac{P_{Rx}}{BW\ N_o}\right) \approx 1.44\frac{P_{Rx}}{N_o} \quad \text{when} \quad BW \to \infty \qquad (1.3)$$

The result is shown in Figure 1.9. As can be seen, it is very unlikely that an omnidirectional antenna can be used to achieve a Gb/s data rate when human shadowing exists. When the transceiver has $P_{Tx} = 10\,\text{dBm}$, $NF_{Rx} = 10\,\text{dB}$ and the environment has a human shadowing loss of 18 dB, α needs to be in the range of 10 to 15 dB for 1 Gb/s at 60 GHz; the results for other values of α are shown in Reference [38]. This means that the total antenna gain has to be approximately at least 30 dB.

Ignoring the human shadowing loss, means that there exists a clear path between the transmitter and receiver. A 60 GHz system with the following parameters can be considered as an illustration:

Tx power, P_{Tx}	10 dBm
Noise figure, NF	6 dB
Implementation loss, IL	6dB
Thermal noise, N	174 dBm/MHz
Bandwidth, B	1.5 GHz
Distance, R	20 m
Path loss at 1 m, PL_0	57.5 dB

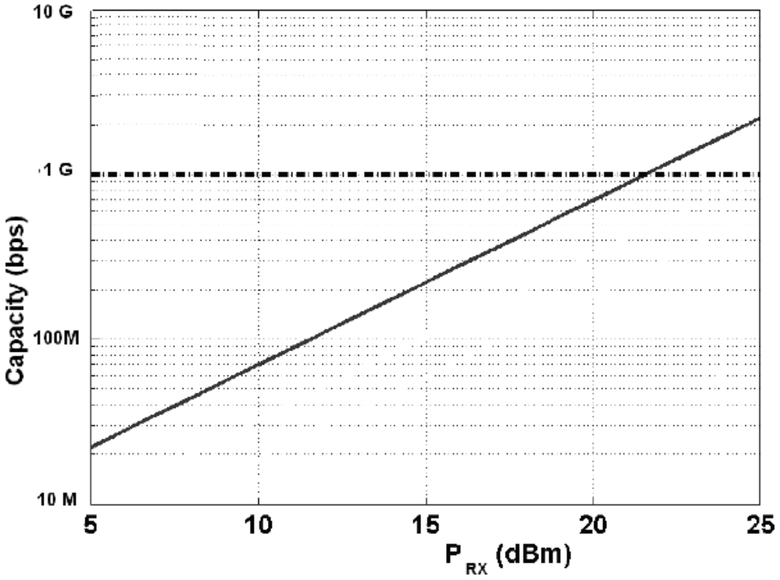


Figure 1.9 Shannon limit with distances $d = 10\,\text{m}$ between a transmitting omnidirectional antenna and a receiving omnidirectional antenna [37]

the ratio of signal power to noise power (SNR) at the receiver can be calculated, as (in dB):

$$\text{SNR} = P_{Tx} + G_{Tx} + G_{Rx} - PL_0 - PL(R) - IL - [KT + 10\log_{10}(B) - NF] \qquad (1.4)$$

where G_{Tx} and G_{Rx} denote the transmit and received antenna gain respectively. P_{Tx} denotes transmitter power, PL_0 is the path loss at 1 m and B is the bandwidth, and the link length is R. Inserting Equation (1.4) into the Shannon capacity formula of Equation (1.3), the maximum achievable capacity in an AWGN can be calculated. In non line of sight (NLOS) links the path loss due to scattering exceeds the square law for free space links. This path loss exponent can vary from 2 (LOS) to 5 in extreme NLOS links. The path loss exponent n is more fully explained in Reference [39]. Figure 1.10 shows the Shannon capacity limit for an indoor office in the LOS and non-LOS (NLOS) cases, using an omni-directional antenna configuration. It can be observed that for the LOS condition, a 5 Gb/s data rate is not possible at any distance. Whereas, the operating distance for the NLOS condition is limited to below 3 m, though the capacity for NLOS decreases more drastically as a function of distance.

To improve the capacity for a given operating distance, either the bandwidth or signal-to-noise ratio (SNR) or both should be increased. It can also be seen from Figure 1.10, 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 bandwidth is only slightly above the case of the 1.5 GHz bandwidth, since the SNR at the Rx is reduced considerably at longer distances due to higher path loss. But, 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 and 7 GHz bandwidths. This clearly shows the importance of antenna gain in providing a very high data rate application at 60 GHz, which it is not possible

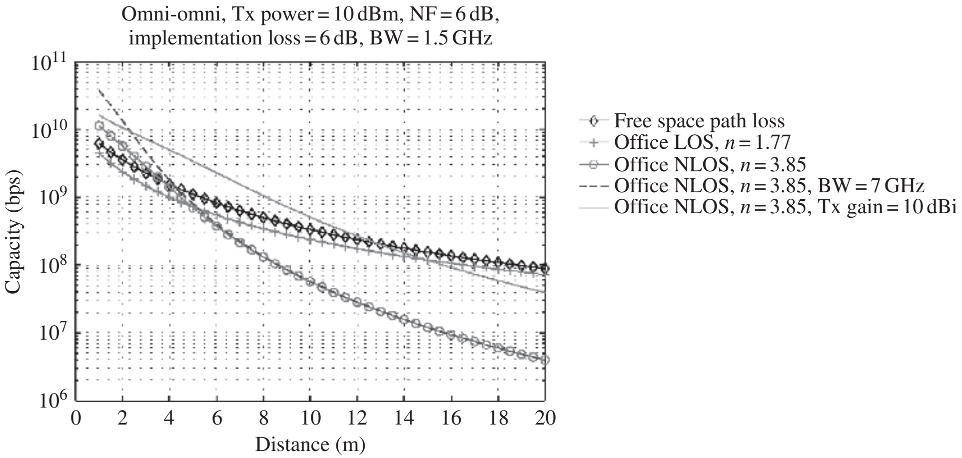


Figure 1.10 Shannon capacity limits for the case of an indoor office using the omni-omni antenna setup. (Reproduced by permission of © 2007 S. K. Yong and C.-C. Chong [6])

to provide with the omni-directional antenna configuration. However, this does indicate how much gain is required.

The capacity as a function of combined Tx and Rx gain for an operating distance of 20 m is plotted in Figure 1.11. To achieve 5 Gb/s at 20 m, a combined gain of 25 and 37 dBi are indicated for LOS and NLOS, respectively, with no shadowing. This is a practical value since it is a combined Tx and Rx gain. However, to achieve the same data rates in multipath channels, a higher gain is needed to overcome the fading margin.

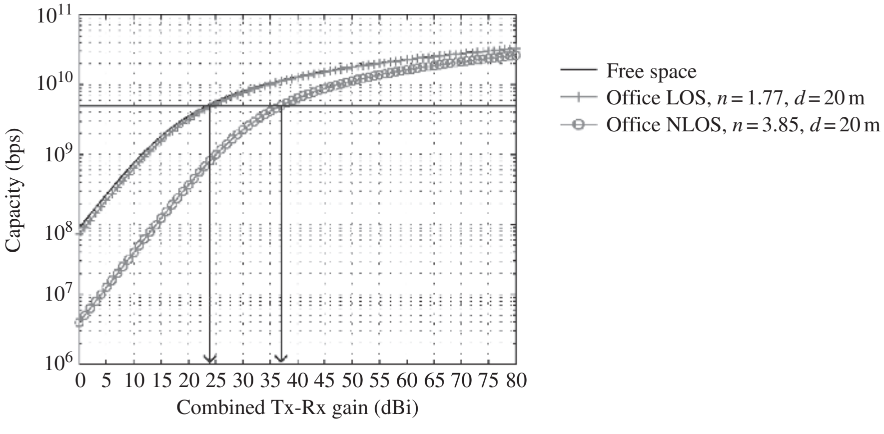


Figure 1.11 The required combined Tx–Rx antenna gain to achieve a target capacity. (Reproduced by permission of © 2007 S. K. Yong and C.-C. Chong [6])

Because directional antennas are required for gigabit wireless communications, there can be different configurations for the access point (AP) and mobile terminal (MT) depending on the application, as shown in Figure 1.12.

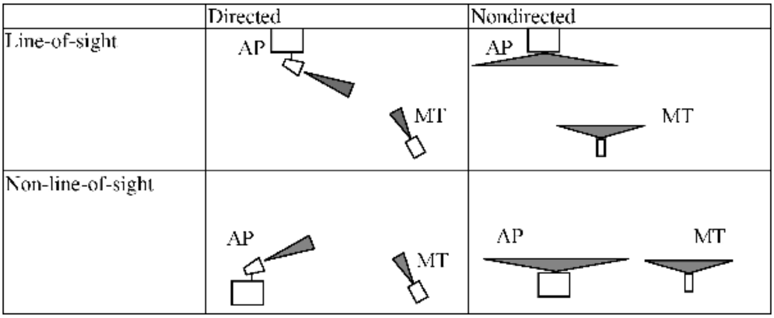


Figure 1.12 Classification of millimetre wave links according to the antenna beamwidth of the access point (AP) and mobile terminal (MT), in respect of the existence of a line-of-sight path. The radiation beamwidth is shown in grey

Consider a 60 GHz measurement as shown in Figure 1.13. The synthesiser has a maximum output power of 0 dBm (1 mW) at 65 GHz. The connecting coaxial cables have a transmission loss of a maximum 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 the voltage standing wave ratio (VSWR) is 2.6:1. The noise floor for the spectrum analyser is assumed to be −130 dBm.

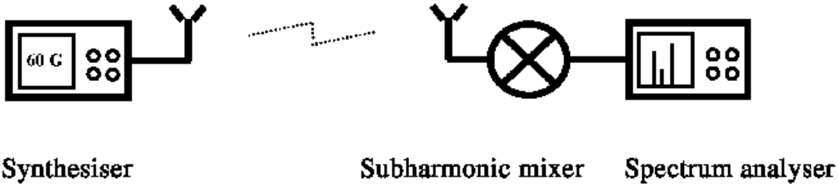


Figure 1.13 Channel measurement setup

The dynamic range for this configuration can be measured as a function of the total antenna gain and the separation of the antennas at 60 GHz. The result is shown in Figure 1.14.

Multipath propagation occurs when waves emitted by the transmitter travel along a multiplicity of different paths and interfere with waves travelling in a direct line-of-sight path. Fading is caused by the destructive interference of these waves. This phenomenon occurs because waves travelling along different paths may be out of phase when they reach the antenna, thereby cancelling each other to form an electric field null. Since signal cancellation is almost never complete, one method of overcoming this problem is to transmit more power (either omnidirectionally or directionally). In an indoor environment, multipath propagation is almost always present and tends to be dynamic (constantly varying) due to moving scatterers. Severe fading due to the multipath can result in a signal reduction of more than 30 dB. It is

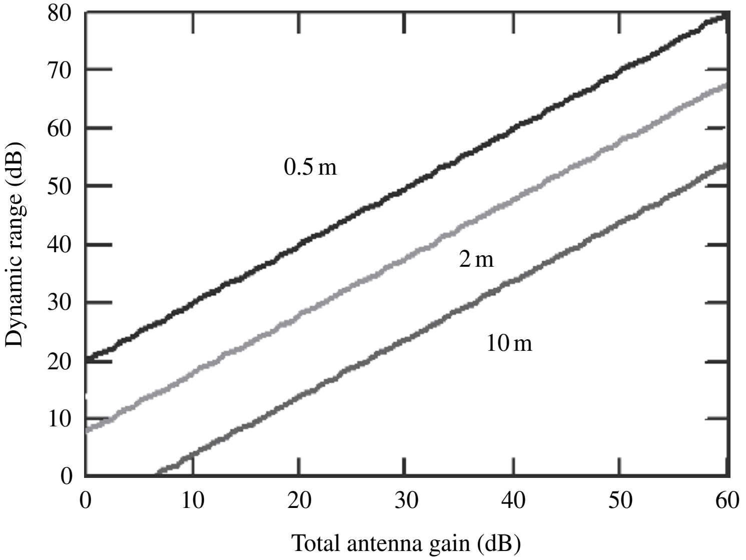


Figure 1.14 Dynamic range as a function of total antenna gain and distance between the antennas at 60 GHz

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 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 estimate is 20 to 30 dB.

In channel measurements, as shown in Figure 1.15, antennas with different beamwidths are compared. For antennas with a narrow beamwidth, a notch appears in the frequency response. For antennas with a broad beamwidth (many multipaths received), the notch in the frequency response becomes severe. In the extreme case, if the antenna beam is as narrow as a laser, this notch will not exist in the frequency response.

The notch width is affected by the range of delays (delay spread), while the notch depth is affected by the difference in path gain (or loss) for the multipath signals. In addition, the notch position in the frequency domain is affected by the length differences between the propagation paths.

To minimise the notch effect, a number of solutions can be considered. One is to employ a narrow-beam antenna to reduce reflected paths and achieve a smaller notch depth (fewer multipaths). However, the problem of tracking resolution and the speed of tracking (pointing) of the narrow beam antenna will need to be solved. Alternatively, precise source tracking or space diversity can be used to avoid the notch effect. However, there are some issues that still need to be tackled in multi-antenna implementations.

In an office environment, reflection characteristics of interior structures have been studied and reported in [40]. Human shadowing was investigated and typical results are summarised in Figure 1.16. When 0 dBm power at 60 GHz is transmitted via a 10 dBi gain transmitting antenna to a receiving antenna with 10 dBi gain at a distance of 4 m, the spectrum

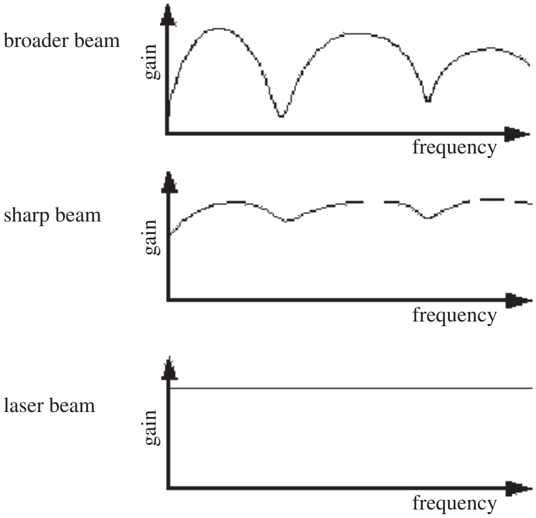


Figure 1.15 Beam width and channel distortion

shows that the received power is −35 dBm approximately when there is no human shadowing. (Case 1). If there is a human body between two antennas, the signal is reduced to the range of between −55 and −65 dBm (Case 2). If there are two human bodies between two antennas, the signal is reduced to the range of between −65 and −80 dBm (Case 3). If the beam direction of the 10 dBi transmitting antenna is changed so that the signal can bounce off a concrete ceiling at a height of 2 m and be reflected to the receiver, the received signal is

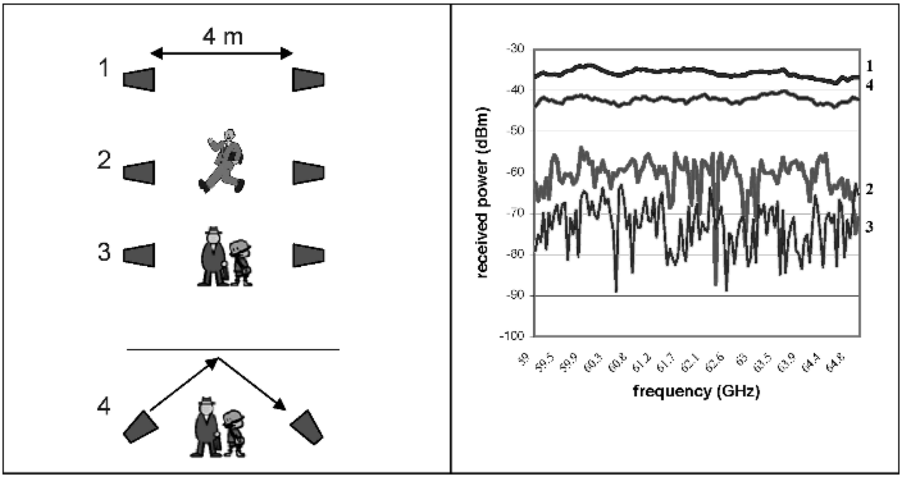


Figure 1.16 Indoor channel measurement at 60 GHz for NLOS. Transmitting antennas and receiving antennas have a 10 dBi gain. Case 1 shows a line-of-sight scenario. Case 2 shows a person standing between two antennas. Case 3 shows two people standing between two antennas. Case 4 shows a non-line-of-sight wireless link [40]

increased to −42 dBm (Case 4). This illustrates that reflected propagation at 60 GHz can be used for non-line-of-sight wireless communications.

1.5 System Design and Performance

Cost-effective millimetre wave solutions for high data rate transmissions at 60 GHz still need to be determined. In this respect, some important selections have to be made which might be crucial for its commercial success:

- Selection of antennas
- Selection of the 60 GHz radio front-end architecture

1.5.1 *Antenna Arrays*

A presumed advantage of a 60 GHz radio is the small antenna area compared to a lower-frequency wireless system. Thus, it becomes possible to integrate antenna arrays into portable devices, and the antenna directivities can be improved. While it is possible to increase the antenna gain for a single antenna (e.g. using mechanical structures such as a horn antenna), it is more desirable to increase the directivity by employing an antenna array or multiple-input multiple-output system as shown in Figure 1.17. For a fixed antenna aperture size A the directivity is $D = 4\pi a/\lambda^2$, and from Equation (1.2) it can be seen that there is actually an improvement in the received power by moving to higher frequencies for a fixed antenna form factor. For example, a 60 GHz system with a 16-element antenna array has a 3 dB gain over a 5 GHz omnidirectional system while occupying only 10 % of the antenna area.

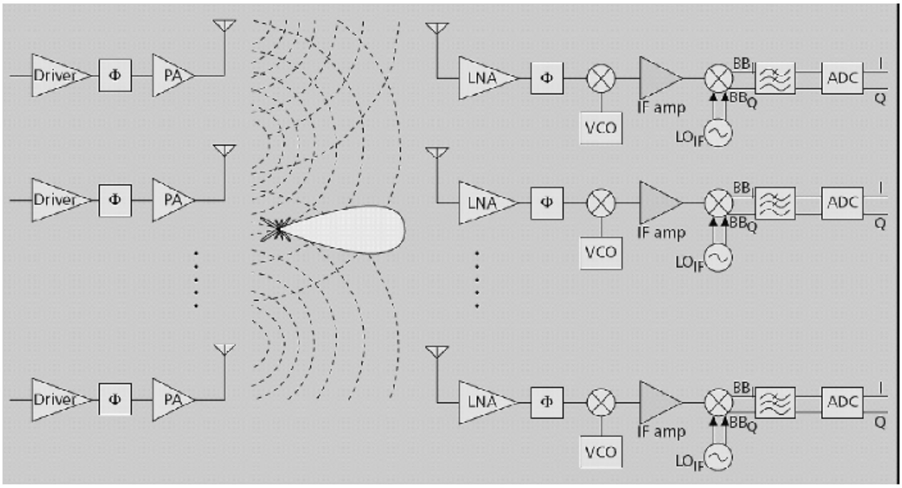


Figure 1.17 A generic multiple transceiver architecture with beam-steering antennas. (Reproduced by permission of © 2004 IEEE [41])

1.5.2 Transceiver Architecture

A generic adaptive beamforming multiple antenna radio system is shown in Figure 1.17. It is assumed that the antenna elements are small enough to be directly integrated into the package or potentially even on-chip. The main benefit of the multiantenna architecture used here is the increased gain that the directional antenna pattern can provide, which as has been seen, is needed in order to support multigigabit per second data rates at typical indoor distances. In addition to the antenna gain, the use of antenna arrays also provides spatial (or angular) diversity, automatic spatial power combining, and an electronic beam steering function. The transceiver architecture in Figure 1.17 depicts N independent transmit and receive chains. Such an approach would enable a flexible multiple-input multiple-output (MIMO) system that could fully exploit a multipath-rich environment for increased capacity and/or robustness [41].

The main disadvantage with this arrangement is the high transceiver complexity and power consumption since there is little sharing of the hardware components. Measurements of the 60 GHz channel properties indicate that most of the received energy is contained in the specular path [42], so a full MIMO solution targeting capacity may not be able to benefit fully from this channel. A more efficient implementation would be to use a phased array that takes the identical RF signal and shifts the phase for each antenna to achieve beam steering. Essentially, communication systems can select one strong path and apply an angular or spatial filter, forming a narrow beam in the direction of the chosen signal [43]. This approach significantly reduces hardware costs, as most of the transceiver can be shared with the addition of controllable phase shifters between the transceiver and antenna array.

For the choice of the architecture of the 60 GHz front-end radio there are, in principle, four options:

1. Employing superheterodyning architecture
2. Employing direct conversion architecture
3. Employing five-port technology
4. Employing software radio architecture

1.5.2.1 Superheterodyning Architecture

With regard to the superheterodyning option, a simple architecture is considered as depicted in Figure 1.18(a). This figure shows a basic 60 GHz RF front-end architecture for application at the portable station (PS) end. Ideally it should be an integrated on-chip solution consisting of a receive branch, a transmit branch and a frequency generation function. The receive branch consists of the receive antenna, a low-noise amplifier (LNA) and a mixer that downconverts to IF. The transmit branch consists of a mixer, a power amplifier (PA) and the transmit antenna. The antennas are (integrated) patch antennas. The mixers are image rejecting mixers (they do not need to be in-phase/quadrature (IQ) mixers). The IF in this example is taken as 5 GHz with the idea that, with appropriate modifications, an IEEE 802.11a RF chip set can serve as the IF here, to allow dual-mode operation and interoperability. Superheterodyning architecture requires more components and more DC power so is unsuitable for mobile devices.

1.5.2.2 Direct Conversion Architecture

The advantages of a direct conversion are that it is well suited to monolithic integration, due to the lack of image filtering and its intrinsically simple architecture [44, 45]. FSK modulated signals are especially well-suited to direct conversion, due to their low-signal energy at DC. However, the direct conversion receiver has not gained widespread acceptance to date, especially in high-performance wireless transceivers, due to its intrinsic sensitivity to DC offset problems, harmonics of the input signal and local oscillator (LO) coupling problems back in to the antenna. Offset arises from three sources [46]:

1. Transistor impedence mismatch in the signal path
2. LO signal leaking to the antenna because of poor reverse isolation through the mixer and RF amplifier, and then reflecting at the antenna terminals and ultimately self-downconverting to DC through the mixer
3. Strong adjacent or near channel signal leaking into the LO part of the mixer, which then self-downconverts to DC

Good circuit design may reduce these effects to a certain extent, but they cannot be eliminated completely, particularly so if quadrature phase shift keying (QPSK) or Gaussian minimum shift keying is used since the spectra of these schemes possess a peak at DC. However, when orthogonal frequency division multiplexing (OFDM) is used there may be a solution, which avoids the use of those subcarriers which, after conversion, correspond with, or will be close to, the DC component. There may also be other solutions that exploit the particularities of the 60 GHz physical layer.

A block diagram of an example millimetre wave direct conversion architecture is shown in Figure 1.18 (b). This example consists of transmit and receive paths which combine with a 60 GHz switch at the antenna side.

The voltage-controlled oscillator (VCO) operates in the 3–4 GHz range. This VCO is modulated with the data stream (>1 Gb/s), which does not affect the low bandwidth phase-locked loop (PLL) circuitry. The modulated signal is multiplied (16 times for the transmit side and 8 times for the receive paths) and filtered, before being transmitted or used to drive the subharmonic receiver mixer.

To support output power requirements, two amplifier monolithic microwave integrated circuits (MMICs) are cascaded in series. A low-noise amplifier (LNA) in the receive chain guarantees low-noise figure values. The most important issues for the functionality of the architecture are the filters placed after each multiplier stage. Each filter must be designed to avoid unwanted emissions in the transmit and receive bands.

The voltage-controlled oscillator (VCO) can be driven by an (off-chip) frequency synthesizer. In conventional designs the VCO is usually implemented off-chip because it occupies too much area on the chip without providing sufficient performance. At frequencies as high as 60 GHz it may become, however, feasible to implement the VCO directly on the chip because the minimum dimensions to achieve the required performance become much smaller. The advantage of this approach is the reduction in components that have to be mounted on an external circuit board and the avoiding of on-chip frequency multiplier circuits, thus saving space on the chip and reducing any VCO performance degradation that could arise. It is important to note that an on-chip VCO, that directly generates a reference frequency close to 60 GHz,

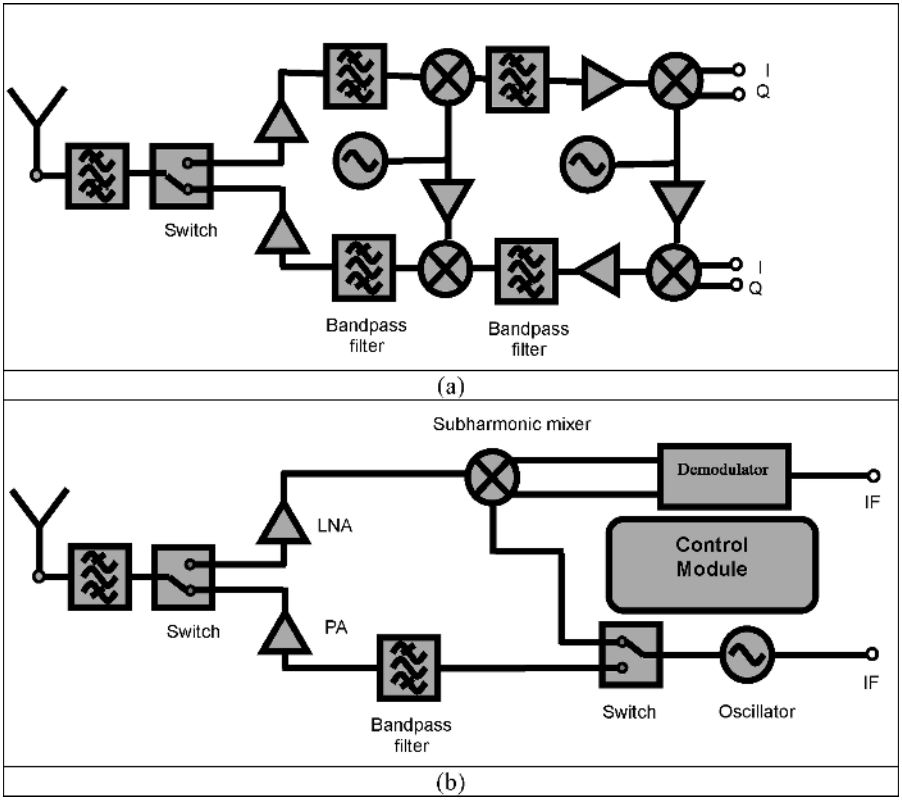


Figure 1.18 (a) Block diagram for millimetre wave/microwave circuits. (b) Block diagram for a 60 GHz direct conversion architecture

may have a relatively lower performance when compared with the requirements of a VCO that operates on a much lower frequency in combination with a couple of frequency multipliers.

1.5.2.3 Five-Port Radio

The five-port technology (or six-port technology), described in [47] is a passive linear device, composed of two input ports and three outputs (see Figure 1.19). A phase shifter is used to adjust the phase between RF and LO. On the ports of P1, P2 and P3, diode detectors are used in each port, instead of mixers, as the frequency converter. Five-port technology has been extended to direct digital transmitters and can be used for software-defined radio applications, as it can accommodate different wireless modulation standards without requiring hardware modification.

1.5.2.4 Software Defined Radio

Employing analogue-to-digital conversion (ADC) and digital-to-analogue conversion (DAC) directly at the antennas would appear to make the complete RF and IF part of the transceiver

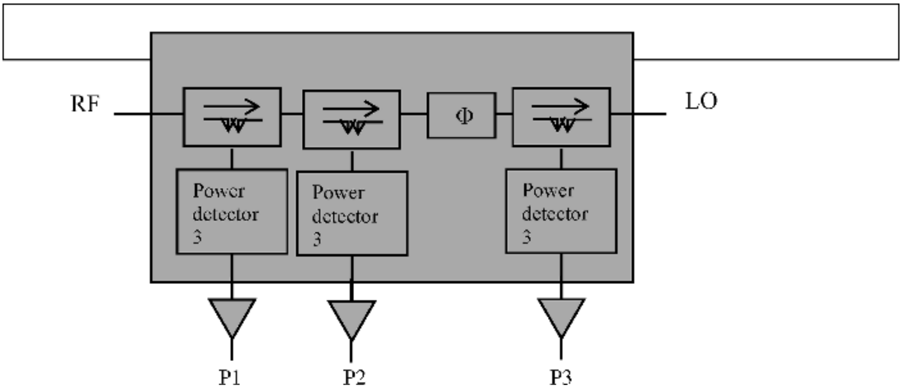


Figure 1.19 Block diagram for the five-port technology

chain obsolete. However, this option for the current purpose can be ruled out immediately because this would require ADC and DAC devices operating at a 60 GHz or more. A low-cost implementation of this in the medium term is not considered feasible. An alternative approach, the subsampling receiver, is claimed to represent the "ultimate" solution for simple low-power downconversion. This essentially consists of a sampling switch, clocked at a much lower frequency, and an analogue-to-digital (A/D) converter. The limitations of the subsampling approach, however, illustrate the inherent problems in low-power receiver implementations. In a subsampling receiver, image frequencies exist at integral multiples of the sampling rate and can alias (map) onto the band of interest. As a result, careful filtering prior to the downconversion is required. For example, downconversion of an RF signal having a bandwidth of 500 MHz would require a sampling rate of at least 1 GHz, assuming a "brick wall filter" (a filter with infinite cut off outside the working band). In practice, the sampling rate would have to be much higher – at least 2 GHz – in order to minimise the effects of the filter. It is questionable whether a 2 GHz ADC with a 10 bit quantisation, will become available in the medium term. In addition, the signal-to-noise ratio (SNR) of the downsampled signal will inevitably be poorer than that of an equivalent system employing a mixer for downconversion. This is due to the noise aliased from the bands between DC and the passband [48].

1.6 Antenna Requirements

In this book, an overview is presented, of an approach within the application area that utilises millimetre wave antenna technology and offers significant promise in making these Gb/s wireless links a reality. Throughout the book, topics will be revisited and approached from different angles in order to present alternative ways of analysing the various components and parameters that make up millimetre wave systems.

For a single antenna element with an antenna gain of more than 30 dBi with a half-power beamwidth (HPBW) of approximately 6.5°, a reliable communication link is difficult to establish even in a LOS condition at 60 GHz. This, as has been seen, can be due to human movement which can easily block and attenuate such a narrow beam signal. To overcome this problem, a switched beam antenna array or adaptive antenna array can be implemented to search and beamform, in order to capture the available signal. The array is required to track the signal path either continuously or periodically, depending on the stability of the link. One major parameter of the performance of the link is how many antenna elements are required to achieve the intended antenna gain. This is a separate consideration from the array gain, which refers to the performance improvement in terms of the SNR over a single antenna element. Also of interest is the angular resolution or beamwidth of such antennas, since this defines the number of multipaths that the antenna sees in a scattering environment. The directivity of the linear array is given by [49]:

$$D = \frac{4\pi}{\iint |F_n(\phi, \theta)|^2 \sin\theta \, d\theta \, d\phi} \tag{1.5}$$

where $F_n(\varphi, \theta)$ is the normalized field pattern, which can be expressed as a product of the normalized element pattern and the normalized array factor. The variables φ and θ represent the azimuth and elevation angle, respectively. For a uniform linear array, the normalized array factor can be expressed as:

$$\mathrm{f}_n(\varphi, \theta) = \frac{\sin[(N/2)(kd\cos\theta + \beta)]}{N\sin[(1/2)(kd\cos\theta + \beta)]} \tag{1.6}$$

where N, d and β are the number of antenna elements, the antenna spacing between adjacent elements and the phase shift between elements, respectively. For an omnidirectional antenna, it can be shown that up to 100 omni-element arrays are required to achieve a gain of only 23 dBi, which is far from the requirement discussed previously. Hence a more directive/higher gain element is required to improve the overall gain of the array.

Many types of antenna structures are considered not suitable for 60 GHz WPAN/WLAN applications due to the requirements for low cost, small size, light weight and high gain. In addition, 60 GHz antennas are also required to be operated with approximately constant gain and high efficiency over the broad frequency range (57–66 GHz). The importance of beamforming at 60 GHz has been introduced in Section 1.4, and can be achieved by either switched beam arrays or phased arrays. Switched beam arrays have multiple fixed beams that can be selected to cover a given service area. They can be implemented more easily compared to phased arrays, which require the capability of continuously varying a progressive phase shift between the elements.

The complexity of phase arrays at 60 GHz typically limits the number of elements. In Reference [50], a 2 × 2 beam-steering antenna with circular polarization at 61 GHz was developed. The gain is approximately 14 dBi with 20° half power beamwidth (HPBW). Similarly, in Reference [51], another 60 GHz integrated four-element planar array was developed. Each antenna is integrated with a subharmonic I/Q mixer for the convenience of high-speed signal processing, such as adaptive beamforming. The implementation of a larger phased array, however, presents technical challenges, such as the requirement for a higher feed network loss, a more complex phase control network, stronger coupling between antennas as well as feedlines, etc. These challenges make the design and fabrication of larger phase arrays more complex and expensive. Hence, research is required to develop a low-cost, small-size, light-weight and high-gain steerable antenna array that can be integrated into the RF front-end electronics.

To achieve this, the design approach can be focused on either:

(a) accepting the presence of multipath (with delays corresponding to the room size) and mitigating it with equalisation techniques or
(b) using line-of-sight links with narrow-beam antennas to eliminate virtually all multipaths, and thus use simple unequalised modulation schemes, such as FSK and PSK.

In the first case, the design effort would concentrate on narrow beam antenna design techniques, whereas in the second approach, the work would concentrate on antenna/beam-steering techniques. These must be used because multipath delay in the typical indoor environment is on the order of the target bit period (tens of nanoseconds) and causes intersymbol interference. The multipath delays for indoor systems depend on the size of a room and the density and placing of scatterers within the illuminated space.

It is assumed for the moment that for high speed data transmission a simple two- or four-level FSK or PSK system is used, because complex modulation schemes such as equalisation, diversity or multicarrier techniques are deemed to be impractical or too expensive for 60 GHz. For such a simple system to work reliably the channel impulse response should not contain significant multipath components, so that the data rate is not limited by multipath effects. Also an initial assumption is made, that high-speed and high-capacity WLANs can use a femtocellular architecture, with a single cell for each room and multiple cells for a large open area office.

For the “LOS with narrow beam antennas” approach, the amount of multipath power will depend on the number of paths between the transmitter and receiver, which in turn will depend on the directivity of the antennas at the transmitter and receiver, as well as specific environmental factors. It will also depend on the ability of the antenna to resolve the multipaths’ angular space. If omnidirectional antennas are used at both the transmitter and receiver, then there will be many possible paths, whereas if highly directional antennas are used, there may be only a single LOS path. Once the beamwidth is sufficiently narrow, there is no significant multipath in most practical circumstances. (Of course, if the transmit and receive LOS is perpendicular to a pair of parallel reflectors an infinite number of multipaths will occur.)

To explore the consequences of this approach, three different antenna designs are now considered.

1. Phased Array

Considering an 8 × 8 phased array antenna with beam steering, this arrangement requires complex phase shifters (or hybrid Tees and attenuators applied to the I and Q channels), and therefore is subject to high loss at 60 GHz. These losses reduce the effective gain of the antenna array. In addition, currently there is no phase shifter MMIC available at 60 GHz on the market so a hybrid Tee and real weights (attenuators) would be needed to build phase- shifting functions. In addition, the beam shape becomes asymmetric when the beam direction moves away from the z axis (this is generally called aberration). This means that the sidelobes of the radiation pattern will grow when the beam is away from broadside. Also, circular polarisation at wide angles with a phase-shifted array is almost impossible to achieve. The performance of circular polarisation is unlikely to be achieved as the phased array becomes increasingly complex. The main challenge of this design is to have a complex phase shifter and to have low loss. Lastly, it is also difficult to achieve good circular polarisation in all directions.

2. A 2 × 2 Horn Array Plus Beam Switching

The gain of this design is limited by the size and the separation distance of horns. Each unit consisting of a 2 × 2 element array acts as an independent source [52]. This design requires a multibit phase shifter but generates good circular polarisation. By adding several tilted horns, this design can have ±100° coverage. The feeding network needs to have the correct amplitude and phase in the two orthogonal linear polarisations in order to generate good circular polarisation. The main challenge of this design is to reduce the sidelobe level caused by using 2 × 2 elements.

3. Beam Switching Array

This design uses a minimum number of elements (4 × 4) to achieve ±100° coverage [53]. No phase shifter is required. Each element generates an independent beam. The configuration operates in a different manner to that of the phased array, and there is no size limit for each element. Each element can be optimised individually to meet the specifications for the individual links. Sidelobe levels can therefore be controlled by a single horn design. The gain of each element can be improved by adding a superstrate together with a horn, or using stacked patches. More details about gain enhancement can be found in Chapter 2. The feed network needs to have the correct amplitude excitation for each element, but not the phase. Circular polarisation can be improved by a tilted waveguide or helical element. More details of this configuration will be discussed in Chapter 4. The main defining parameters for these designs are compared in Table 1.7.

Table 1.7 Comparison of three 60 GHz antenna designs

	8 × 8 phased array	2 × 2 array plus beam switching	16 beam switching array
High gain	Yes (but the loss of phase shifters is also high)	Yes	Yes
HPBW 20°	Yes	Yes	Yes
Sidelobe −10 to −20 dB	Not at the 100° beam direction	Not easy	Yes
Circular polarisation	Medium	Possible	Possible
Beam steering range	Beam direction is controlled by phase shifting. Sidelobe level increases when the beam is away from broadside.	Beam direction is controlled by the height of horns and phase shifters.	Beam direction is controlled by switches.
Feeding point design	Amplitude, phase	Amplitude, phase	Amplitude
Phase shifters	Complex	2 bits	No
Challenge	Complex phase shifter, low-loss phase shifter	Sidelobe reduction	High gain with small size

1.7 Link Budget

The link budget is used to determine system capabilities under a range of operating conditions for the specified data rates, ranges and bit error rate. The expressions below identify the necessary parameters, which can be used to calculate the final link margin:

Path loss at 1 m ($PL_0 = 20\ \log_{10}(4\pi f_c/c)) = 68.00$ dB
where f_c (centre frequency) $= 60$ GHz, $c = 3 \times 10^8$ m/s
Average noise power per bit (dB) $= N = -174 + 10 \times \log_{10}(R_b)$
where R_b (Gb/s) is the bit rate
Average noise power per bit (dBm) $P_N = N +$ Rx noise figure (referred to the antenna terminal) (dB)
Total path loss (dB) $= PL = P_T + G_T + G_R - P_N - S - M_{\text{shadowing}} - I - PL_0$

where P_T is average Tx power (dBm)
G_T is Tx antenna gain (dBi)
G_R is Rx antenna gain (dBi)
S is minimum E_b/N_0 for the AWGN channel (dB)
$M_{\text{shadowing}}$ is shadowing link margin (dB)
I is implementation loss (dB), including filter distortion, phase noise, frequency errors
Maximum operating range $d = 10^{PL/10n}$ (m)

where n is path loss exponent, subject to the scenario.

The following path loss parameters are considered by the IEEE 802.15.3c standard [54]:
For LOS scenarios:

• Path loss at 1 m:	$PL_0 = 68$ dB
• Path loss exponent:	$n = 2$
• Shadowing link margin:	$M_{\text{shadowing}} = 1$ dB

For NLOS scenarios:

• Path loss at 1 m:	$PL_0 = 68$ dB
• Path loss exponent:	$n = 2.5$
• Shadowing link margin:	$M_{\text{shadowing}} = 5$ dB

A simple millimetre wave link can be represented as in Figure 1.20.

From this perspective the signal-to-noise ratio for the system can be calculated. In Table 1.8, an example such as the configuration in Figure 1.16 (Case 4) is used to calculate the signal and noise of a millimetre wave system with two 15 dBi directional antennas in a 5 m wireless link. Both free space loss, and reflection loss are taken into account.

When the transmitted signal level is set to 15 dBm, a 5 dB loss can be expected due to the feeding network of transmitting antennas. The power delivered to the antenna is therefore 10 dBm. The EIRP is then effectively increased to 25 dBm when the transmitting antenna has a

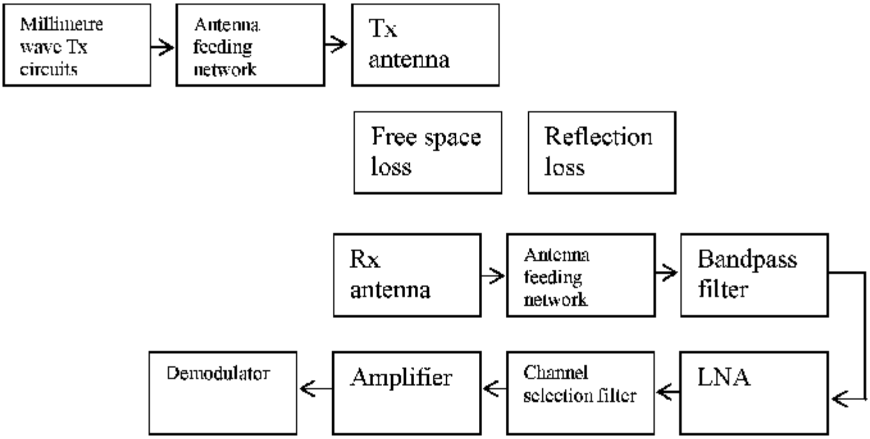


Figure 1.20 The 60 GHz transmitter, receiver and wireless link

Table 1.8 An example of a millimetre wave scenario

Transmit power (dBm)	10
Bandwidth (GHz)	2
Distance (m)	5
Free space loss (dB)	81.98419713
Tx antenna gain (dBi)	15
Rx antenna gain (dBi)	15
Reflection loss (dB)	15
Input level (dBm)	−56.98419713
Input noise level (dBm)	−81

15 dBi gain. In a 5 m link, the 60 GHz signal suffers a free space loss of approximately 81.98 dB. The signal is therefore attenuated by 81.98 dB due to this free space loss, and a further 15 dB due to reflection loss. The final EIRP at the receiving antenna is therefore −72 dBm.

The input noise of the converter is the theoretical thermal noise floor limit, *KTB*. *KTB* is calculated as follows:

$$KTB = 4.002 \times 10^{-21} \text{ watts (or in log form} = -174\,\text{dBm)}$$

where

K = Boltzmann's constant = 1.381×10^{-23} W/Hz K
T = 290 K at room temperature
B = normalized bandwidth of 1 Hz

When the bandwidth is taken into account, the input noise level is calculated by:

$$\begin{aligned}\text{Input noise level} &= 10\ \log(KTB)\\ &= 10\ \log_{10}(B) - 174 \quad \text{(dBm)}\end{aligned}$$

where B = bandwidth (Hz). For a 2 GHz bandwidth, from the above, there is −81 dBm noise at the receiver.

Table 1.8 is an example of a millimetre wave communication system link budget. Based on this table, the signal-to-noise ratio of the system can be calculated.

Table 1.9 is an example of a cascaded millimetre wave receiver, which includes a feeding network, a bandpass filter, a low-noise amplifier, a switch and channel selection filter, and an amplifier. The gain and noise figures for each component are provided, and the cumulative gain and noise figures are calculated.

Table 1.9 Components and their gain / noise figures

	Feeding network	Bandpass filter	LNA	Switch and channel selection filter	Amplifier
Gain (dB)	−5	−1	20	−5	30
Cumulative gain (dB)	−5	−6	14	9	39
Cumulative gain (real)	0.31	0.25	25	7.94	7943
Noise figure (dB)	5	1	3	5	10
Noise figure (linear)	3.16	1.26	2.00	3.16	10.00
Cumulative noise figure (linear)	3.16	3.98	7.94	8.03	9.16
Cumulative noise figure (dB)	5	6	9	9.04	9.62

A typical cascaded millimetre wave system is illustrated in Table 1.10. The transmit power is assumed to be 10 dBm, and the loss for the feeding network for the transmitting antenna is assumed to be 5 dB. 15 dBm of power should be achieved before the signal enters the feeding network. The transmitting antenna has a gain of 12 dBi, so the effective isotropic radiated power (e.i.r.p) increases to 22 dBm. During propagation, the signal undergoes free space loss and reflection loss, and so is reduced to −75 dBm. After the 12 dBi gain of the receiving antenna and the 5 dB loss of its feeding network, the signal increases to −68 dBm. Then the signal then passes through a filter with a −1 dB loss, a low-noise amplifier with a 20 dB gain (−43 dBm), a selection filter with a −5 dB loss (−48 dBm) and an amplifier with a 30 dB gain. Finally, the signal power is −18 dBm.

The input noise level in Table 1.10 is stated as −81 dBm, as the bandwidth is assumed to be 2 GHz. The noise then increases to −58 dBm due to a low-noise amplifier with a 3 dB noise figure, which is then reduced to −63 dBm due to the selection filter with a 5 dB loss. Therefore, the signal-to-noise ratio at the output of the selection filter is $(-54) - (-63) = 9$ dB. The power level is plotted in Figure 1.21.

Table 1.10 Spreadsheet for a cascade of millimetre wave circuits

	Feeding network (Tx)	Tx antenna	Free space loss	Reflection loss	Rx antenna	Feeding network (Rx)	RF bandpass filter	LNA	Channel selection filter	Amplifier		
Input signal level (dBm)	15	10	22	−59.9842	−74.9842	−62.9842	−61.9842	−62.9842	−42.9842	−47.9842	−17.984	Output signal level (dBm)
Input noise level (dBm)						−80.9897	−80.9897	−80.9897	−57.9897	−62.9429	−32.37	Output noise level (dBm)
Input SNR (dB)						18.0055	19.0055	18.0055	15.005503	14.95869	14.385	
Gain (dB)	−5	12	−81.9842	−15	12							

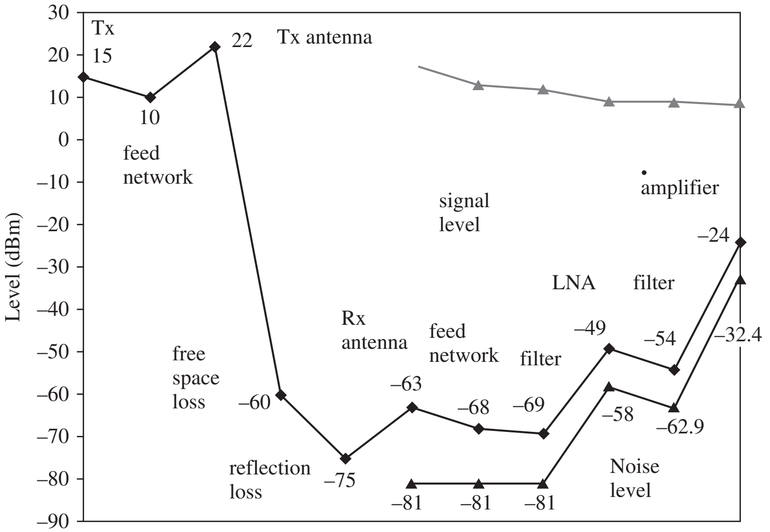


Figure 1.21 The 60 GHz link budget from Tx to Rx

1.8 Summary

This chapter explained the overall ideas and the importance of a gigabit wireless communication system using millimetre wave technology. A number of application scenarios are discussed. The international standards and regulations are compared, and the communication system concept is analysed. The role of antennas in the gigabit communication system is discussed. The characteristics of millimetre waves are addressed and a measured propagation result and channel performance are presented. The technical challenges for different antennas are investigated. Finally, an example of the link budget was provided, to show the performance of the system. Noise and its impact on link behaviour are also considered.

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