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Millimetre Wave Antennas for Gigabit Wireless Communications

A Practical Guide to Design and Analysis in a System Context

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Preface

This book presents antenna design and analysis at the level to produce an understanding of the interaction between a wireless system and its antenna, so that the overall performance can be predicted. Gigabit wireless communications require a considerable amount of bandwidth, which can be supported by millimetre waves. Millimetre wave technology has now come of age, and at the time of writing the standards of IEEE 802.15.3c, *WirelessHD*™ and *ECMA* are on schedule to be finalised. The technology has attracted new commercial wireless applications and new markets, such as the capacity for high-speed downloading and wireless high-definition TVs. This book summarises and reports the extensive research over recent years and emphasises the importance and requirements of antennas for gigabit wireless communications, with an emphasis on wireless communications in the 60 GHz ISM band and in the E-band. This book I reviews the particular requirements for this application and addresses the design and feasibility of millimetre wave antennas; such as planar antennas, rod antennas and antenna arrays. Examples of designs are included, along with a detailed analysis of their performance. In addition, this book includes a bibliography of current research literature and patents in this subject area. Finally, the applications of these antennas are discussed in the light of different forthcoming wireless standards.

Millimetre Wave Antennas for Gigabit Wireless Communications endeavours to offer a comprehensive treatment of antennas based on electronic consumer applications, providing a link to applications of computer-aided design tools and advanced materials and technologies. The major features of this book include a discussion of the many novel millimetre wave antenna configurations available with newly reported design techniques and methods.

Although it contains some introductory material, this book is intended to provide a collection of millimetre wave antenna design considerations for communication system designers and antenna designers. The book should also act as a reference for postgraduate students, researchers and engineers in millimetre wave engineering and an introduction to the various design considerations. It can also be used for millimetre wave teaching. A summary of each chapter is given below.

Chapter 1 introduces the near-term developments in millimetre wave communications. The importance and requirements of millimetre wave antennas are discussed based on channel performance, link budget, and applications in line-of-sight and non-line-of-sight scenarios. Sections addressing system-level considerations include references to subsequent chapters that contain a more detailed treatment of antenna design.

Chapters 2 to 8 address conventional configurations of millimetre wave antennas.

Chapter 2 considers several critical factors that limit the performance of millimetre wave antennas. As the antenna design has become critical in wireless communications, the limitations of antenna design are also discussed in this chapter.

Chapter 3 describes the variety of millimetre wave planar antennas, and lists basic feeding methods and useful references on a wide variety of techniques for producing low-profile antennas.

Chapter 4 deals with millimetre wave integrated horn antennas. The chapter includes a discussion of circular polarisation optimisation techniques, such as those for array antennas. With circular waveguide modes that can be used for mode tracking described in Chapter 8.

Chapter 5 addresses low cost and high directivity of millimetre wave rod antennas. Different feeding methods, maximum gain, and beam tilting are discussed in detail. With multiple-rod antennas that can be used as beam-switching antennas discussed in Chapter 7.

Chapter 6 describes the variety of millimetre wave lens antennas, relevant feeding methods and novel architectures. Lens antennas, with the advantages of light weight and small height, are identified as designs that can be used for new applications.

Chapter 7 discusses millimetre wave multibeam antennas and their construction. Novel antennas with advanced radiation characteristics have been demonstrated. Some of the effects of mutual coupling of signals and noises between array elements are covered. This interaction modifies the active array element patterns and can cause impedance changes during scanning.

Chapter 8 focuses on smart antennas and their usage in wireless communications. Wide-ranging technologies such as beam switching, beam steering, MIMO and mode tracking, that satisfy special needs are considered. These technologies could produce low-profile high-gain electronic scanning systems in conjunction with the antenna elements described in Chapters 3 to 7.

Chapter 9 explores millimetre wave antenna materials and manufacturing techniques. Materials technologies are discussed such as LTCC, LCP, CMOS, high-temperature super-conductors, carbon nanotubes, etc. New materials offer new design concepts and promise future exciting antenna technology trends.

Finally, chapter 10, extrapolates the wireless applications of millimetre wave antennas in a envisaged future market. This book only briefly addresses the details of electromagnetic analysis, with the fundamentals of the subject requiring a more detailed study than can be given in this system design-oriented book.

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The authors are indebted to many researchers for their published works, which were rich sources of reference upon which this book reports and summarises. Their sincere gratitude extends to the Editor, Sarah Hinton, and the reviewers for their support in the writing of this book. The help provided by Tiina Ruonamaa and other members of the staff at John Wiley & Sons, Ltd is most appreciated. The authors also wish to thank their colleagues at the University of Oxford, and University of Greenwich.

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List of Abbreviations

A/V	audio/visual
ADC	analogue-to-digital conversion
AP	access points
AR	axial ratio
ARIB	Association of Radio Industries and Business
ASP	aperture stacked patch
BER	bit error rate
CB-FGC	conductor-backed finite ground coplanar
CBCPW	conductor-backed coplanar waveguide
CCS	complementary conducting strip
CEPT	European Conference of Postal and Telecommunications Administrations
CPS	coplanar stripline
CTE	coefficient of thermal expansion
DAS	distributed antenna systems
DBF	digital beamforming
DLA	discrete lens array
DoA	direction of arrival
DRA	dielectric resonator antenna
EBGs	electromagnetic bandgaps
ECC	Electronic Communications Committee
ECMA	European Computer Manufacture Association
EIRP	equivalent isotropic radiated power
ERC	European Radiocommunications Committee
ESPRIT	Estimation of Signal Parameters via Rotational Invariance Techniques
ETSI	European Telecommunications Standards Institute
FCC	Federal Communication Commissions
FDA	Food and Drug Administration
FDTD	finite-difference time-domain
FLA	filter–lens array
FPC	Fabry–Perot cavity
FT	Fourier transform
GO	geometric optics
GSM	Global System for Mobile Communications
HDMI	high-definition multimedia interface

HDTV	high-definition television
HEM	hybrid electromagnetic
HPBW	half-power beamwidth
HTS	high-temperature superconductors
IC-SMT	Industry Canada Spectrum Management and Telecommunications
ISM	industrial, scientific and medical
ISPs	Internet Service Providers
IVC	Inter-Vehicle Communications
LA	lens array
LCP	liquid crystal polymer
LHCP	left-hand circular polarisation
LHM	left-handed materials
LNA	low-noise amplifier
LOS	line-of-sight
LPD	low probability of detect
LPI	low probability of intercept
LTCC	low-temperature co-fired ceramic
MANETs	mobile ad hoc networks
MCM	multichip modules
MEMS	microelectromechanical system
MIMO	multi-input multi-output
MMIC	monolithic-microwave integrated circuit
MPHPT	Ministry of Public Management, Home Affairs, Posts, and Telecommunications
MSK	minimum shift keying
MT	mobile terminal
NLOS	non-line-of-sight
OFDM	orthogonal frequency division multiplexing
OMT	orthomode transducer
OOK	on/off keying
PA	1. power amplifier 2. phased array
PAPR	peak-to-average power ratio
PCB	printed circuit board
PDA	personal data assistant
PHY	physical layer
PMP	portable media player
PRS	partially reflective surface
PS	portable station
PTHs	plated through holes
QPSK	quadrature phase-shift keying
RAUs	radio access units
RF	radio frequency
RHCP	right-hand circular polarisation
RRH	remote radio heads
SC	single carrier
SCBT	single-carrier block transmission

SIR	signal-to-interference
SNR	signal-to-noise ratio
SoC	system-on-chip
SoP	system-on-package
SP3T	single-pole triple-throw
SSFIP	strip slot foam inverted patch antenna
ULA	uniform linear arrays
UWB	ultra-wideband
VCC	voltage-controlled oscillator
WLANs	wireless local area networks
WMN	wireless mesh network
WPANs	wireless personal area networks

Contents

1

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.

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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 ($\sim$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 ~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

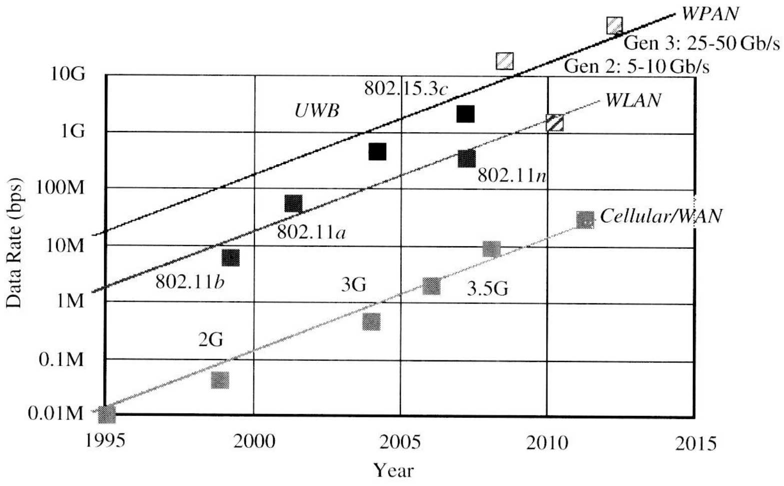

Figure 1.1 Data rate projections over time [5]

(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].

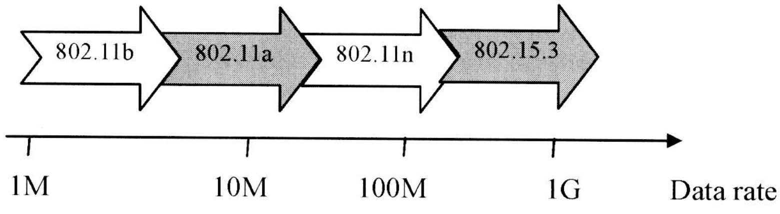

Figure 1.2 Data rates and range requirements for WLAN and WPAN standards and applications. Millimetre wave technology, i.e. IEEE 802.15.3c, is aiming for very high data rates [6]

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.

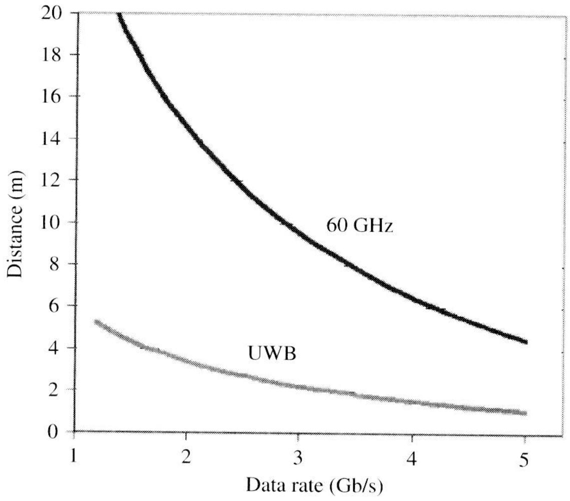

Figure 1.3 Shannon's capacity curve in a 1 GHz occupied bandwidth for 60 GHz versus UWB (noise figure is set at 8 dB) [5]

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].