

On the Use of Low Terahertz Band for Wireless Communications

by

Türker YILMAZ

A Dissertation Submitted to the
Graduate School of Sciences and Engineering
in Partial Fulfillment of the Requirements for
the Degree of

Doctor of Philosophy

in

Electrical and Electronics Engineering



September 14, 2018

On the Use of Low Terahertz Band for Wireless Communications

Koç University

Graduate School of Sciences and Engineering

This is to certify that I have examined this copy of a doctoral dissertation by

Türker YILMAZ

and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Committee Members:

Prof. Özgür Barış AKAN

Prof. Alper Tunga ERDOĞAN

Assoc. Prof. Sinem ÇÖLERİ ERGEN

Assoc. Prof. Berk CANBERK

Prof. Fatih ALAGÖZ

Date: _____



*To my kin who achieved to “put stone on top of stone”,
Sadık oğlu Hulusi, İbrahim and Fazilet Özlem YILMAZ*

ABSTRACT

The demand on the key performance indicators of wireless communication networks is constantly increasing. According to Cisco Systems' latest "Visual Networking Index" white paper, mobile data traffic rose 63% in 2016 and expected to achieve a compound annual growth rate (CAGR) of 47% until 2021. The estimation is also similar for the global average mobile network connection speed, as the expected 5-year 24% CAGR will increase that data rate to 20.4 Mb/s. These data and projections are also consistent with the industry analyses of the ITU and Ericsson.

To date, conventional sub 6 GHz bands were able to keep up with the radio interface technical performance requirements through continuous improvements in spectral efficiency. Consequently, advancing this area further became exceptionally costly. Therefore, despite the industry resistance towards changing the already established telecommunications ecosystem, carrier frequency, hence operation bandwidth, increase method is chosen as the alternative.

In this thesis, the two spectra selected for utilization in the near future, the 60 GHz ISM radio band and the low end of the THz band (260-400 GHz), are researched. The standardization activities for the mobile and nomadic networks are investigated, and both theoretical and experimental studies on the physical layer subjects of the higher frequency bands, such as channel and human blockage modeling, channel capacity, modulation and material characteristics, are conducted.

As the initial wireless personal area network standard of the low THz band, IEEE 802.15.3d, is ratified in 2017 and millimeter wave bands are being explored within the Release 16 of the 3GPP 5G specifications, which is to be completed by the end of 2019, both spectra are going to be fundamental parts of the next generation of mass market wireless communication systems.

ÖZETÇE

Kablosuz haberleşme ağlarının anahtar başarımlarının üzerindeki talep devamlı yükseliyor. Cisco Systems'ın en son beyaz kitabına göre, mobil veri trafiği 2016'da %63 yükseldi ve 2021'e kadar %47 bileşik yıllık büyüme hızına (BYBH) ulaşması bekleniyor. Küresel ortalama mobil ağ bağlantı hızı için de tahmin benzer, ve beklenen 5-yıl %24'lük BYBH bu veri hızını 20.4 Mb/s'ye artıracak. Bu veri ve kestirimler aynı zamanda Uluslararası Telekomünikasyon Birliği ve Ericsson'un endüstri çözümleri ile de tutarlı.

Bugüne kadar, geleneksel 6 GHz altı bantları, radyo arayüzü teknik başarımların gerekliliklerine sürekli tayfsal verimlilik geliştirmeleri sayesinde ayak uydurabiliyordu. Bunun sonucunda, bu alanı daha da ilerletmek fevkalade pahalı hale geldi. Bu sebeple, hâlihazırda kurulu telekomünikasyon ekosistemini değiştirmeye karşı olan endüstri direncine rağmen, taşıyıcı frekans, ve dolayısıyla çalışma bant genişliği, artırım yöntemi seçenek olarak yeğlendi.

Bu tezde, yakın gelecekte kullanım için seçilen iki tayf, 60 GHz EBT radyo bandı ve THz bandının düşük tarafı (260-400 GHz), araştırıldı. Mobil ve gezici ağlar için standardizasyon faaliyetleri incelendi, ve bu yüksek frekans bantlarının fiziksel katman konuları üzerinde kuramsal ve deneysel tetkikler, örneğin kanal ve insan blokajı modellenmesi, kanal kapasitesi, kipleme ve malzeme özellikleri, ifa edildi.

Düşük THz bandı için ilk kablosuz kişisel alan ağları standardının, IEEE 802.15.3d, 2017'de onaylanması ve milimetre dalga bantlarının 2019 sonuna kadar tamamlanacak olan 3GPP 5G spesifikasyonlarının 16. sürümü bünyesinde incelenmeleri doğrultusunda, her iki tayf da gelecek nesil kablosuz haberleşme sistemleri kitle pazarının ana unsurlarından olacaktır.

ACKNOWLEDGMENTS

I would like to express my gratitude and sincere thanks to my supervisor, Prof. Özgür Barış AKAN, who led me into this exciting novel area of terahertz communications. I am indebted to Prof. AKAN for his continued support, guidance and understanding.

I would also like to express my sincere thanks to Assoc. Prof. Berk CANBERK and Prof. Alper Tunga ERDOĞAN for accepting to supervise this thesis and to drive it further with their valuable comments throughout the whole process.

My cordial thanks similarly extend to Prof. Fatih ALAGÖZ and Assoc. Prof. Sinem ÇÖLERİ ERGEN for taking part in my thesis committee, for critical reading of this thesis and for their valuable suggestions and comments.

I would like to express my appreciation to the members of the “Terahertz Femtocell for 5G Mobile Communication Networks” project and Next-generation and Wireless Communications Laboratory for their support during my doctoral research. My special thankfulness are due to Asst. Prof. Özgür ERGÜL and Özgür YILMAZ, who have been more of a good friend than a colleague.

I also gratefully acknowledge the support of The Scientific and Technological Research Council of Turkey (TÜBİTAK) under its programmes #2211 and #2224-A.

I would like to recognize Süleyman Rıza SEBA, Rıza ÇALIMBAY and Mehmet ÖZDİLEK’s influences on my morality, and thank Metin TEKİN, Ali Kurtuluş GÜLTİKEN, Feyyaz UÇAR, İlhan MANSIZ, Pascal Olivier NOUMA, Ricardo Andrade QUARESMA BERNARDO, and, Daniel Owefin AMOKACHI, for all the wonderful childhood and adolescence memories.

And, last but foremost, I am eternally grateful to my brother, parents and grandparents for all their support, love and patience.

TABLE OF CONTENTS

List of Tables	xiii
List of Figures	xv
Nomenclature	xx
Chapter 1: Introduction	1
1.1 Low Terahertz Band Communications	1
1.2 Fundamental Contributions and Thesis Outline	3
Chapter 2: State-of-the-Art and Research Challenges for Consumer Wireless Communications at 60 GHz	8
2.1 Introduction	8
2.2 60 GHz Standardization Activities	10
2.2.1 WirelessHD	12
2.2.2 Wireless Gigabit Alliance	14
2.2.3 ECMA-387	15
2.2.4 IEEE 802.15.3c	19
2.2.5 IEEE 802.11ad	20
2.3 60 GHz Channel Characteristics	21
2.4 60 GHz Devices	27
2.5 60 GHz Applications	30
2.6 Conclusion	31
Chapter 3: Employing 60 GHz ISM Band for 5G Wireless Commu-	

Communications	33
3.1 Introduction	33
3.2 Millimeter Wave IEEE 802.11 Standardization Activities	35
3.3 The 60 Gigahertz Band	39
3.4 Indoor Simulations	43
3.5 Performance Evaluation	45
3.5.1 Received Power	46
3.5.2 Signal-to-Noise Ratio	48
3.6 Conclusion	49
Chapter 4: Millimeter Wave Communication for 5G IoT Applications	51
4.1 Introduction	51
4.2 Millimetre Wave Channel	53
4.3 Millimetre Wave Modulation	54
4.3.1 OFDM	55
4.3.2 FBMC	55
4.3.3 UFMC	56
4.3.4 SC	56
4.3.5 Evaluation	57
4.4 Millimeter Wave Channel Coding	57
4.4.1 Requirements for 5G	59
4.5 Millimetre Wave MIMO	60
4.5.1 Spatial Multiplexing	62
4.5.2 Beam Forming	63
4.5.3 Evaluation	64
4.6 Conclusions	65
4.7 Future Research Directions	66

Chapter 5:	On the Use of the Millimeter Wave and Low Terahertz Bands for Internet of Things	67
5.1	Introduction	67
5.2	Channel Capacity and Bit Rate Simulations	68
5.3	Results and Discussion	70
5.3.1	Channel Capacity	70
5.3.2	Bit Rate	71
5.4	Conclusion	74
Chapter 6:	Utilizing THz Band for Local and Personal Area Wireless Communication Systems	75
6.1	Introduction	75
6.2	Indoor Simulations	76
6.3	Results and Discussion	78
6.3.1	100 GHz	78
6.3.2	350 GHz	81
6.3.3	500 GHz and 700 GHz	83
6.4	Conclusion	84
Chapter 7:	On the Use of Low Terahertz Band for 5G Indoor Mobile Networks	85
7.1	Introduction	85
7.2	The Low Terahertz Band	87
7.3	Indoor Simulations	91
7.4	Results and Discussion	95
7.4.1	4G	96
7.4.2	5G	97
7.4.3	5G _{room}	98
7.4.4	5G _{ideal}	98

7.4.5	60 GHz	100
7.5	Conclusion	101
Chapter 8: On the 5G Wireless Communications at the Low Tera-		
hertz Band		102
8.1	Introduction	102
8.2	Standardization Activities	104
8.3	THz Band Channel Property and Models	105
8.4	Open Research Issues	112
8.5	Conclusion	114
Chapter 9: Attenuation Constant Measurements of Clear and Frosted		
Glass Samples at the Low Terahertz Band		115
9.1	Introduction	115
9.2	Attenuation Constant	117
9.2.1	Electromagnetic Wave Transmission Through Lossy Media . .	117
9.2.2	Attenuation Constant Calculation Using the S_{21} Parameter . .	118
9.3	Channel Measurements	119
9.4	Results and Discussion	122
9.4.1	Clear Glass	122
9.4.2	Frosted Glass	124
9.5	Conclusion	125
Chapter 10: Energy-efficient Modulation and Physical Layer Design		
for Low Terahertz Band Communication Channel		126
10.1	Introduction	126
10.2	THz Band Device Technologies	128
10.2.1	Signal Sources	130
10.2.2	Transmitters	132

10.2.3	Transceivers	133
10.3	THz Band Communication System Model	134
10.4	Energy Consumption Analyses of MQAM and MFSK Modulations . .	137
10.4.1	MQAM	137
10.4.2	MFSK	138
10.5	Modulation Parameters Optimization	141
10.6	PHY Parameters Optimization	144
10.7	Open Research Issues	149
10.8	Conclusion	150
 Chapter 11: A Hexagonal Grid Based Human Blockage Model for the		
	Low Terahertz Band Communications	151
11.1	Introduction	151
11.2	The Model	152
11.2.1	Motion Description	152
11.2.2	Coordinate System	154
11.2.3	Half-Sextant	156
11.3	Performance Evaluation	156
11.3.1	Results and Discussion	158
11.4	Conclusion	160
 Chapter 12: Conclusion		161
12.1	State-of-the-Art and Research Challenges for Consumer Wireless Com- munications at 60 GHz	161
12.2	Employing 60 GHz ISM Band for 5G Wireless Communications . . .	161
12.3	Millimeter Wave Communication for 5G IoT Applications	162
12.4	On the Use of the Millimeter Wave and Low Terahertz Bands for In- ternet of Things	162

12.5 Utilizing THz Band for Local and Personal Area Wireless Communi- cation Systems	162
12.6 On the Use of Low Terahertz Band for 5G Indoor Mobile Networks .	163
12.7 On the 5G Wireless Communications at the Low Terahertz Band . .	163
12.8 Attenuation Constant Measurements of Clear and Frosted Glass Sam- ples at the Low Terahertz Band	164
12.9 Energy-efficient Modulation and Physical Layer Design for Low Tera- hertz Band Communication Channel	164
12.10A Hexagonal Grid Based Human Blockage Model for the Low Terahertz Band Communications	165
Bibliography	166

LIST OF TABLES

2.1	ITU-R designated ISM bands	12
2.2	WirelessHD members	13
2.3	General parameters of WirelessHD physical layers	14
2.4	Wireless Gigabit Alliance members	16
2.5	Frequency plan and specific attenuations of 60 GHz channels	17
2.6	Timing-related parameters for IEEE 802.15.3c and 802.11ad OFDM PHYs	22
2.7	Local extrema of atmospheric attenuation	23
2.8	Technical features of the state-of-the-art 60 GHz CMOS transceivers .	29
3.1	Incorporated baselines of IEEE P802.11-2012	35
3.2	In-process and published but unincorporated IEEE 802.11 amendments	39
3.3	Simulation parameters	46
4.1	Comparison of Millimeter Wave Modulation Techniques	57
5.1	Maximum bit rate transmission distance limits	73
6.1	Simulation parameters	79
6.2	Simulation results	80
7.1	Rain attenuation results	87
7.2	Probable transmission windows	90
7.3	Simulation parameters	92
7.4	Simulation results	95

9.1	VNA measurement parameters	120
9.2	Descriptive statistics of the samples' thicknesses	122
10.1	System parameters	139
10.2	Optimized parameters for the MQAM and MFSK systems at various distances	142
10.3	Normalized system parameters	144
10.4	Optimized PHY parameters for the MQAM and MFSK systems for 1 and 3 dB back-off points	148
11.1	Coordinate change of point $\langle x, y \rangle$ after moving in direction $\mathbf{D}_i$	156
11.2	Direction change transition matrix of the points on the x-axis	157
11.3	Direction change transition matrix of the points on divider	157

LIST OF FIGURES

2.1	Specific attenuation due to atmospheric gases, calculated under standard ground-level atmospheric conditions and between 57 GHz and 66 GHz at 1 MHz intervals, with 60 GHz channels indicated.	18
2.2	Specific attenuation due to atmospheric gases and rain, calculated under standard ground-level atmospheric conditions, for rain rates of 1, 4, 8, 16, 25 and 50 mm/h and up to 275 GHz at 1 MHz intervals. . .	23
2.3	Specific attenuation due to atmospheric gases, calculated up to 275 GHz and for (a) water vapour densities of 0, 2.5, 7.5, 12.5, 20 and 30 g/m ³ , (b) temperatures of 248, 268, 288, 298, 308 and 328°K, and (c) total air pressures 973, 1013 and 1037 hPa.	24
2.4	Channel capacities of IMT-Advanced, IEEE 802.11ac and IEEE 802.11ad, calculated from -30 to 50 dB SNR.	26
3.1	Attenuation due to atmospheric gases and rain, calculated up to 500 GHz and for rain rates of 4 and 16 mm/h, as per ITU-R P.676-9 and P.838-3.	40
3.2	Absolute and squared errors, absolute error percentage and the mean squared error between the two atmospheric attenuation calculation methods provided in the ITU-R P.676-9.	41
3.3	Specific attenuation due to atmospheric gases and rain, calculated up to 78.002 GHz and for rain rates of 4, 16 and 25 mm/h.	42
3.4	Received power outcomes of 4G indoor hotspot deployment simulation, displayed for two different heights.	47

3.5	Received power outcomes of 5G mm-wave simulation, displayed for two different heights.	48
3.6	SNR outcomes at $h = 0.75$ m, displayed for both simulations.	50
3.7	SNR outcomes at $h = 1.75$ m, displayed for both simulations.	50
4.1	FSPL, calculated between 1 and 1000 m at 1 m intervals and for carrier frequencies of 5, 30, 60 and 300 GHz.	54
4.2	(a) SU-MIMO and (b) MU-MIMO structures.	61
4.3	Outline of spatial multiplexing method.	62
5.1	Channel capacity, calculated up to 100 m distance at 1 mm intervals.	71
5.2	Channel capacity of (a) IEEE 802.11ac and 802.11ad, and (b) IMT-Advanced and low-THz band, calculated from 0 to 24 dBm transmit power at 0.001 dBm intervals and for path lengths of 0.1, 1, 10 and 100 m.	72
5.3	Data rates of IEEE 802.11ad connections, calculated for QPSK, 16-QAM and 64-QAM modulation techniques and SERs of 10^{-3} , 10^{-4} , 10^{-5} and 10^{-6}	72
5.4	Data rates of low-THz band links, calculated for BPSK, QPSK, 16-QAM and 64-QAM modulation techniques and SERs of 10^{-3} , 10^{-4} , 10^{-5} and 10^{-6}	74
6.1	Attenuation due to atmospheric gases, calculated between 59.755 and 752.048 GHz, and for water vapour densities of 0, 7.5 and 15 g/m ³	79
6.2	(a) Received power and (b) SNR performance of 100 GHz at indoor simulation for $h = 1$ m.	80
6.3	(a) Received power and (b) SNR performance of 350 GHz at indoor simulation for $h = 1$ m.	82

6.4	SNR performance of (a) 500 GHz and (b) 700 GHz at indoor simulation for $h = 1$ m.	82
7.1	Specific attenuation due to atmospheric gases and rain, calculated up to 1 THz at 1 MHz intervals under standard ground-level atmospheric conditions and for rain rates of 4, 16 and 50 mm/h.	88
7.2	Specific attenuation due to atmospheric gases, calculated between 1 GHz and 380.225 GHz and for (a) temperatures of 248, 288, and 328°K and (b) pressures of 973, 1013 and 1037 hPa.	89
7.3	Specific attenuation due to atmospheric gases, calculated under ground-level atmospheric conditions and between 275 GHz and 448.013 GHz at 1 MHz intervals, with 3 dB transmission windows around local minima indicated.	90
7.4	Sketch of the simulation environment with dimensions displayed. . . .	93
7.5	(a) Received power and (b) SNR performance of 4G indoor hotspot deployment simulation, displayed for $h = 1$ m.	95
7.6	(a) Received power and (b) SNR performance of 5G mm-wave simulation for the indoor hotspot deployment setting, displayed for $h = 1$ m.	97
7.7	(a) Received power and (b) SNR outcomes of 5G _{room} mm-wave simulation setting, displayed for $h = 1$ m.	99
7.8	(a) Received power and (b) SNR outcomes of 5G _{ideal} mm-wave simulation setting, displayed for $h = 1$ m.	99
7.9	(a) SNR performance of 60 GHz simulation and (b) SNR outcome difference between 5G _{ideal} and 60 GHz simulations, displayed for $h = 1$ m.	100
8.1	Oblique uniform plane electromagnetic wave incidence on an interface.	106

8.2	Rayleigh roughness parameter, calculated for a uniform plane EM wave propagating in air at 293.089 GHz and for incident rough surfaces with standard deviations of 0.09 and 0.225 mm, where red lines demonstrate the cases of specular reflection.	111
9.1	Normal incidence of a uniform plane electromagnetic wave with parallel polarization on smooth interfaces and its transmission through media.	118
9.2	The measurement setup.	121
9.3	(a) Clear glass samples, and (b) Frosted glass samples with hexagon, blur and dot patterned irregularities, respectively.	121
9.4	Clear glass α estimate and the calculated clear glass α data set, which is color- and marker-coded according to the originating S_{21} parameter pairs.	123
9.5	Frosted glass α estimates and the calculated frosted glass α data sets.	125
10.1	Architecture of the THz band transceiver.	135
10.2	Energy consumption per information bit at various distances vs. normalized T_{act} for the MQAM system.	140
10.3	Energy consumption per information bit at various distances vs. bits per symbol (b) for the MFSK system.	141
10.4	Energy consumption per information bit at various distances for the optimized MQAM and MFSK systems.	143
10.5	PHY components parameter sweep on normalized scale vs. energy consumption per bit of the MQAM system for $d = 1.5$ m.	145
10.6	PHY components parameter sweep on normalized scale vs. energy consumption per bit of the MFSK system for $d = 10$ m.	146
10.7	Energy consumption per bit for MQAM and MFSK PHY parameters optimized at (a) 1 dB, and (b) 3 dB back-off points.	148

11.1	Communication system environment.	153
11.2	Motion model over hexagonal grid.	154
11.3	Hexagonal coordinate system.	155
11.4	P_L for growing (a) Total time steps, and (b) Movement probability. .	158
11.5	Distribution of user position for growing total time steps.	159
11.6	Probability of communication loss for growing (a) Distance between the user and user equipment, (b) User width, and (c) Hexagon edge length.	159

NOMENCLATURE

2D	Two Dimensional
3G	Third Generation Mobile Systems
4G	Fourth Generation Mobile Systems
5G	Fifth Generation Mobile Systems
AC	Access Category
ADC	Analog-to-Digital Converter
AES	Advanced Encryption Standard
AMSU-A	Advanced Microwave Sounding Unit-A
AP	Access Point
ATS	Antenna Training Sequence
AWGN	Additive White Gaussian Noise
A/V	Audio/Visual
B4G	Beyond 4G
BA	Buffer Amplifier
BB	Baseband
BC	Block Code
BE	Best Effort
BER	Bit Error Ratio
BPSK	Binary Phase-Shift Keying
BS	Base Station
b/S	Bits per Second
CAGR	Compound Annual Growth Rate
CB	Clay Brick
CC	Convolutional Code

CMOS	Complementary Metal-Oxide-Semiconductor
CP	Cyclic Prefix
CSI	Channel State Information
DAC	Digital-to-Analog Converter
DAR	Distributed Active Radiator
DBPSK	Differential Binary Phase-Shift Keying
DL-MU-MIMO	Downlink Multi-User Multiple Input Multiple Output
DMG	Directional Multi-Gigabit
DWF	Debye-Waller Factor
ECMA	European Computer Manufacturers Association
EDCA	Enhanced Distributed Channel Access
EIRP	Equivalent Isotropically Radiated Power
EM	Electromagnetic
FBMC	Filter Bank Multicarrier
FDMA	Frequency Division Multiple Access
FD-MIMO	Full-Dimension MIMO
FEC	Forward Error Correction
FoM	Figure of Merit
FSPL	Free-Space Path Loss
F/S	Frames per Second
GATS	Group Addressed Transmission Service
GCM	Galois/Counter Mode
GCR	Groupcast with Retries
GDB	Geolocation Database
GDD	Geolocation Database Dependent
HARQ	Hybrid Automatic Repeat Request
HD	High-Definition
HDF	High-Density Fiberboard

HPBW	Half-Power Beamwidth
HRP	High Rate Physical Layer
HSI	High Speed Interface
I	In-Phase
IBSS	Independent Basic Service Set
IC	Integrated Circuit
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IFFT	Inverse Fast Fourier Transform
IG THz	IEEE 802.15 WPAN Terahertz Interest Group
IMT	International Mobile Telecommunications
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
LDPC	Low-Density Parity-Check
LNA	Low-Noise Amplifier
LO	Local Oscillator
LRP	Low-Rate Physical Layer
LTE-A	Long Term Evolution - Advanced
M2M	Machine-to-Machine Communications
MAC	Medium Access Control
MBSS	Mesh Basic Service Set
MC	Multicarrier
MCS	Modulation and Coding Scheme
MDF	Medium-Density Fiberboard
mMTC	Massive Machine Type Communications
MRP	Medium-Rate Physical Layer
NF	Noise Figure

NLoS	Non-Line-of-Sight
OFDM	Orthogonal Frequency Division Multiplexing
PA	Power Amplifier
PAL	Protocol Adaptation Layer
PAPR	Peak-to-Average Power Ratio
PAR	Project Authorization Request
PBSS	Personal Basic Service Set
PHY	Physical Layer
PLCP	Physical Layer Convergence Protocol
PLL	Phase Locked Loop
PMP	Point-to-Multipoint
PNC	Piconet Coordinator
PPDU	Physical Layer Convergence Protocol Data Unit
PSD	Power Spectral Density
QAM	Quadrature Amplitude Modulation
QDEM	Quadrature Demodulator
QMF	Quality of Service Management Frame
QMOD	Quadrature Modulator
QoS	Quality of Service
RDS	Relay Directional Multi-Gigabit Station
REDS	Relay Endpoint Directional Multi-Gigabit Station
RF	Radio Frequency
RLSS	Registered Location Secure Server
RMSE	Root-Mean-Square Error
RS	Reed-Solomon
RX	Receiver
SCBT	Single Carrier Block Transmission
SCS	Stream Classification Service

SC-FDE	Single Carrier Frequency Domain Equalization
SER	Symbol Error Ratio
SG	Study Group
SLB	Sand-Lime Brick
SM	System Margin
SNR	Signal-to-Noise Ratio
SPC	Single Parity Check
STA	Station
SU	Single User
TDS	Time Domain Spectroscopy
TG3d	IEEE 802.15 WPAN Task Group 3d
TRX	Transceiver
TV	Television
TVWS	TV White Space
TX	Transmitter
UE	User Equipment
UEP	Unequal Error Protection
UFMC	Universal-Filtered Multicarrier
UL	Uplink
VCO	Voltage-Controlled Oscillator
VGA	Variable-Gain Amplifier
VHT	Very High Throughput
VNA	Vector Network Analyzer
WiGig	Wireless Gigabit
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WRC	World Radiocommunication Conference
WSM	White Space Map

Chapter 1

INTRODUCTION

1.1 Low Terahertz Band Communications

The necessity for greater human mobility brings the need to obtain information on the move, and thus an increase in mobile data traffic. According to the most recent networking index by Cisco Systems, global mobile data traffic grew 74% in 2015 and is expected to rise at a compound annual growth rate (CAGR) of 53% from 2015 to 2020. Another important trend is the projected increase at the global mobile network connection speeds. Whereas that average downstream speed for smartphones grew nearly 26% to 7.5 megabits per second (Mb/s) in 2015, the quantity is anticipated to reach 12.5 Mb/s by 2020, following a five year 11% CAGR [1].

Minimum technical performance requirements for the modern fourth generation (4G) mobile telecommunication systems were outlined in 2008 by the International Telecommunication Union (ITU) Radiocommunication Sector's (ITU-R) Report ITU-R M.2134. In the document, the minimum downlink (DL) peak spectral efficiency was defined as 15 b/s/Hz and operation in wider bandwidths up to 100 MHz was encouraged, thus setting the theoretical DL peak data rate at 1500 Mb/s [2]. However, spectral efficiency was defined assuming a 4×4 multiple input multiple output (MIMO) antenna configuration, whereas current 4G products operate on 2-stream MIMO and 4-stream MIMO is envisioned only for the user equipment (UE) of the fifth generation (5G) wireless communication systems, for which non-coherent detection would also be preferred.

As 4G systems, although currently represent just 14% of global mobile connec-

tions, are already being laid out by mobile network operators, research on 5G is taking pace. Many traffic forecast and market reports are getting published to guide initial specification and standardization activities. Two key common conclusions of these studies are an expectation of thousandfold increase in overall wireless communication traffic volume within a decade, and the forthcoming machine-to-machine (M2M) communication boom. Tenfold of the traffic rise is attributed to the increase in M2M connections, which is estimated to grow from 0.6 to 3.2 billion by 2020 owing to a five year 38% CAGR, and the rest caused by the rise in traffic per device [1, 3]. Based on these expectancies, 5G systems' peak data rate is required to be at least on the order of 10 gigabits per second (Gb/s).

Accommodating the anticipated traffic growth requires total throughput rise together with the data rates. The principal methods to accomplish this are evident: Increasing the operation bandwidth or spectral efficiency, or reducing the signalling overhead. Because the subject is applicable to nearly all areas of wireless communications, spectral efficiency enhancement efforts have traditionally led the research. A direct consequence of these studies are the spectrally very efficient systems in operation presently, one of which being the Long Term Evolution-Advanced with coordinated multi-point. Whereas orthogonal frequency division multiplexing (OFDM) is utilized by the majority of the broadband communication systems, filter bank multicarrier, despite its higher complexity, is investigated for future communication systems too, due to its better spectral efficiency [4].

Device densification inherent to the continuously growing number of mobile-connected devices leads to shorter propagation paths, originating a favourable situation for the employment of wider bandwidths over higher carrier frequencies. Higher power losses, together with the cost of developing and rolling-out new communication devices for an already established mass market would be endured because of the expected data rate and network capacity leaps by the use of the new and broader bands. Correspondingly, through Resolution COM6/20, World Radiocommunication Conference 2015 (WRC-15) also determined to invite ITU-R to conduct studies on the spectrum needs

of International Mobile Telecommunications in the frequency range between 24.25 and 86 GHz, and WRC-19 to consider additional primary service spectrum allocations for mobile communications. In accordance with these, increasing the operation frequency to the low end of the THz band is proposed in this thesis as a solution to the data rate and network capacity requirements of the future wireless communication systems.

1.2 Fundamental Contributions and Thesis Outline

The contributions of this thesis in the field of Low Terahertz Band Wireless Communications and its organization are as follows:

Chapter 2: The demand on performance of wireless networks is constantly increasing. To date, conventional sub 6 GHz bands were able to keep up with the requirements through continuous spectral efficiency improvements. Consequently, advancing this area further became exceptionally costly. Therefore, despite the industry resistance towards changing the already established communications spectrum and unavailability of sufficient number of suitable frequency bands for typical communication purposes, carrier frequency, hence operation bandwidth, increase method is chosen as an alternative. In this chapter, the first spectrum chosen for utilization, the 60 GHz band, is surveyed. Detailed explanations of the standards and their processes are provided, in addition to the characteristics of the channel and 60 GHz technologies, devices and consumer applications. As its initial standards are already complete and widespread communications usage expected to start in 2016, the 60 GHz band is a genuine candidate for the next generation of mass market wireless communication systems.

Chapter 3: Wireless data traffic is continuously increasing due to the steady rise in both connected device number and traffic per device. Wireless networks, traditionally confined below 6 GHz, are getting clogged and unable to satisfy the ever-increasing demands of its users. Already aware of this, telecommunications industry and academia have been working on solutions. One of the main methods for throughput increase is operation bandwidth expansion; however, sufficient spectrum

is not available within the conventional frequencies. Following various considerations, 60 GHz industrial, scientific and medical (ISM) radio band has been selected as the new spectrum to be utilized and wireless personal and local area network standards for the band are already completed. In line with the stated developments, this chapter proposes the use of 60 GHz band for the fifth generation (5G) communication systems. After very briefly setting the scene of the current wireless communication networks, the physical layer properties of the 60 GHz band are presented. A representative indoor simulation between the fourth generation and proposed 5G cases is set and performed. The results are assessed and compared before concluding the chapter.

Chapter 4: Mobile communications industry is going through an era of very rapid advancement as multiple major innovations are about to take place. 5G of mobile communication systems is developed to become an all-encompassing solution to fundamentally every broadband wireless communication need of the next decade. Since both the communication and electronic technologies are matured enough, machine-to-machine communication is also about to take off, placing a completely new set of demands on the wireless networks. As the spectrum is already limited in the conventional sub 6 GHz bands, in order to generate efficient applications for the Internet of Things (IoT) within the 5G systems, utilization of new frequency bands are needed. Comprising, both licensed and unlicensed, ample bandwidth, millimeter wave (mm-wave) band is the primary candidate for adoption. In line with these, in this chapter mm-wave band is analyzed for use in 5G IoT implementations. Subsequent to introduction, a brief description of mm-wave band channel characteristics is provided. Then, enabling physical layer techniques of modulation, error control coding and multiple input multiple output are reviewed from the 5G mm-wave point of view. Following conclusions, the chapter ends with open research issues and future research directions.

Chapter 5: Two major wireless communication evolutions, the fifth generation mobile systems and machine-to-machine (M2M) communication boom, are imminent.

A major 5G challenge is supplying the higher than ever data rate and traffic demands using the already crunched conventional spectrum, where the expected addition of billions of new M2M connections will worsen the situation. Mm-wave band offers one substantial solution, through the utilization of parts of its vast frequency range. Following a general overview and the theoretical background, this chapter provides the first realistic channel capacity and bit rate analyses in the literature for the 60 GHz and low-terahertz bands, and compares those with the sub 6 GHz band links from the perspective of IoT application deployments. It is found that, considering the network densification intrinsic to the M2M communications, the use of the mm-wave band is a viable method to form stable and high performance links which are capable of supporting advanced IoT services.

Chapter 6: User demand on wireless communications is growing every day, however frequency spectrum is a scarce source that cannot infinitely supply the ever-increasing communication demand. Most of the research activities addressing this problem have traditionally been focused on spectral efficiency improvement and signaling overhead minimization efforts, therefore improvement in these domains is tougher than ever. The other main method for throughput enhancement is increasing the operation frequency, and towards this end, the utilization of THz band for the next-generation of wireless communications systems is investigated in this chapter. Following a general overview, an indoor computer simulation is set up to reveal both the feasibility and advantages of THz band compared to the currently used frequency spectrum. The results show that, peak data rates on the order of 10 Gb/s is possible over low-THz band; however, there are hindering issues such as coverage area and low-cost device availability.

Chapter 7: Mobile data traffic is constantly rising at huge growth rates. One evolving method to counter this expansion is operation frequency, and so bandwidth, increase, as formal standardization activities on 60 GHz ISM radio band began in 2005. In line with this, this chapter proposes the utilization of low THz band for the next-generation of mobile and wireless communications systems. Following the intro-

duction and an overview of the low-THz band propagation properties, representative indoor simulations comparing the current fourth generation (4G) and proposed high frequency 5G networks are presented. The results show that, while it is possible to form and maintain stable communication links at low-THz band, techniques to reduce signal attenuation should be researched within all related subjects.

Chapter 8: Initiation of 4G mobile telecommunication system rollouts fires the starting pistol for beyond 4G research activities. Whereas technologies enhancing spectral efficiency have traditionally been the solution to data rate and network capacity increase demands, due to the already advanced techniques, returns of the even more complicated algorithms hardly worth the complexity increase any longer. In addition, surging number of connected devices now enables operative use of short-range communication methods. Also considering the recently approved standards for the 60 GHz ISM radio band, in this section the transmission windows around 300 GHz is proposed to be utilized for the 5G wireless communication systems. Motivations for the low end of the THz band are provided in accordance with market trends, and standardization activities in higher frequencies are listed. Unified mathematical expressions of the electromagnetic wave propagation mechanisms in the low-THz band are presented. Future research directions are specified before the conclusion of the chapter.

Chapter 9: The technical performance requirements from wireless communication networks are continuously rising. One method to satisfy the demands is increasing the carrier frequency to the mm-wave or low THz band spectrum to utilize wider operation bandwidth. In order to facilitate the studies in this frequency range, the corresponding electromagnetic (EM) wave properties, channel attributes and material characteristics need to be analytically formulated. In line with these, this chapter initially presents the theoretical expressions governing the EM wave transmission across a conducting medium. Then, by using relative S_{21} parameter quantities, the results of the attenuation constant measurements performed between 260 and 350 GHz for the clear and frosted glass samples of different thicknesses are given. The chapter

concludes with the evaluation of the outcomes.

Chapter 10: Users continuously demand higher connection speeds and data traffic from wireless communication networks. The newly required network capacity should be provided by higher frequency bands, because legacy sub-6 GHz bands are already operating using advanced communication techniques that provide very high spectral efficiencies. Consequently, mm-wave communication standards are either complete or ongoing, and general submm-wave applications are next in line. Accordingly, this chapter proposes a motion model in hexagonal grid of a person carrying a user equipment. EM wave blockage analyses by utilizing channel characteristics of the low-THz band are presented. Lastly, the communication and blockage probabilities of an exemplary system are both theoretically examined and numerically simulated.

Chapter 11: High throughput capability of the terahertz band (0.3-10 THz) wireless communications is expected to be utilized by the 5G mobile telecommunication systems and enable a plethora of new applications. Supporting devices will transfer large amounts of data in both directions, causing high energy consumption by the electronic circuitries of the equipment in use. Therefore, physical layer for these systems must be designed carefully in order to reduce energy consumption per bit. In this chapter, the best performing modulation scheme and hardware parameters that minimize the energy consumption without affecting the system throughput are determined. THz band device technologies are outlined and a complete survey of the state-of-the-art low-THz band circuit blocks which are suitable for mass market production is given. It is shown that for short-range communications, M-ary quadrature amplitude modulation is the most energy-efficient technique that can lead up to 90% reduction in consumed energy. Moreover, optimal transceiver parameters which can be used to further minimize the energy consumption of the THz band system are examined.

Chapter 2

STATE-OF-THE-ART AND RESEARCH CHALLENGES FOR CONSUMER WIRELESS COMMUNICATIONS AT 60 GHZ

2.1 *Introduction*

Since Marconi's first wireless transmission at the end of 19th century, wireless communication technology has advanced to peak data rates on the order of 1 gigabits per second (Gb/s) with ever-increasing adoption. According to International Telecommunication Union (ITU), since 2009 internet users have increased from 25.6% of the world's population to 43.4% in 2015, corresponding to a nearly 1.4 billion rise from 1.75 billion. Subscriptions of mobile cellular, which is the quickest adopted technology in human history, also rose from 4.64 to 7.09 billion within the same period, and the latter value represents a 96.8% global penetration rate [5, 6].

Internet usage continues to steadily increase. However, mobile cellular market reaches towards saturation, as its latest growth rates are 1.88% for the world, and 2.17% and 0.88% for developing and developed countries, respectively. In view of the current states of the two main telecommunications services, another major technology was needed to continue the expansion of the sector, and that emerged to be mobile broadband. Since 2007, the number of mobile broadband subscriptions nearly thirteenfolded to 3.46 billion [6].

Network convergence has been a central theme in telecommunications industry for more than a decade. In 1997, ITU Radiocommunication Sector (ITU-R) classified six service information types, i.e. audio, data, image, speech, text and video, with different design constraints for the third generation of mobile telecommunications

technology. Whereas, 11 years later a single set of technical performance criteria was identified for the radio interface of the fourth generation (4G) mobile systems [2]. As all types of communication narrow down to a mere exchange of data streams, the competition between wireless standards concentrates on the transmission properties such as peak data rate, spectral efficiency, total throughput, coverage area, mobility and energy efficiency.

With the ever increasing human mobility and mobile broadband usage, the performance expectations from wireless communication networks are rising towards the upper limits of their wired counterparts. Average mobile network connection speed for smartphones was 0.614 megabits per second (Mb/s) in 2009, and 1.038 Mb/s in 2010 [7]. The most recent forecast presents the global average mobile downstream speeds of tablets and smartphones as 11.6 and 7.5 Mb/s in 2015, and predicts compound annual growth rates of 7% and 11% until 2020, respectively, rising the rates to 16.2 and 12.5 Mb/s [1].

Users constantly demand higher data rates, and continuous rise in subscriber numbers inherently necessitates greater network capacity, which causes growth in corresponding research efforts. The methods to improve peak data rate are commonly known: Increasing the operation bandwidth or spectral efficiency or decreasing the signalling overhead. Spectral efficiency, arguably, is the most investigated area of telecommunications. Therefore, any new improvements, albeit minor, come with major investigation costs. Signalling overhead, on the other hand, has a secondary effect on the data rate, and thus cannot originate significant enhancements. Consequently, the most practical approach reduces to increasing the operation bandwidth. However, accommodating any new service requests within the conventional frequency bands that are already overcrowded is problematic [8].

Currently, the vast majority of wireless data traffic is conveyed over the customary sub 6 GHz bands. Both the telecommunications industry and academia are aware of the anticipated spectrum crunch and started taking actions. One possible solution is increasing the carrier frequency to and around the industrial, scientific and

medical (ISM) radio band centered at 61.25 GHz, not just for small cell networks [9], but also for beyond 4G (B4G) mobile systems [10, 11]. Accordingly, through Resolution COM6/20, World Radiocommunication Conference 2015 (WRC-15) also determined to invite ITU-R to conduct studies on the spectrum needs of International Mobile Telecommunications (IMT) in the frequency range between 24.25 and 86 GHz, and WRC-19 to consider additional primary service spectrum allocations for mobile communications.

In line with these, this chapter investigates the forthcoming utilization of the 60 GHz ISM band for the next-generation of consumer wireless communications products. This is the first work comprising both the industrial and institutional 60 GHz standards in time for the expected launch of 60 GHz mass market communication systems in 2016, and complete with channel characteristics and device technologies. First, 60 GHz standardization efforts are discussed, before focusing on the electromagnetic (EM) wave propagation properties of these new transmission channels in Section 2.3. Following a description of the 60 GHz device technologies, state-of-the-art transceivers (TRXs) enabling mm-wave communications are introduced, and subsequently the chapter concludes with summarizing remarks.

2.2 60 GHz Standardization Activities

The higher data rate objective requires higher spectral efficiency, bandwidth, or preferably both. Since the legacy bands are already crowded, wider bandwidth is not an option for those spectra. The 2.4 GHz ISM band cannot even accommodate one 80 MHz channel of the IEEE 802.11ac, whereas at most three 160 MHz channels can be supported within the 5 GHz band, which number is lower than the user limit of downlink multi-user multiple input multiple output defined in the standard [12].

Spectral efficiency increase is another option, but because the techniques used are already advanced, the yields of the more complex and costly modulations are becoming insignificant. Furthermore, modulation rates cannot be infinitely improved. Receiver (RX) minimum input sensitivity increases with higher modulation rates: For

3/4 forward error correction (FEC) coding rate, minimum sensitivities of a 160 MHz IEEE 802.11ac channel are defined to be -61, -56 and -50 dBm, for 16-ary quadrature amplitude modulation (16-QAM), 64-QAM and 256-QAM, respectively. Taking into account the link budget equations presented by Yilmaz et al. [13], unless there is a significant margin between the received power and minimum sensitivity, the rise in the sensitivity has to be countered via either escalated transmitting power or antenna gains. However, this also cannot be done at will. Radio frequency (RF) output powers are regulated by national authorities and in the case of Europe, European Telecommunications Standards Institute restricts the mean equivalent isotropically radiated power (EIRP) to 20, 23 and 30 dBm for the 2.4-2.484, 5.15-5.35 and 5.47-5.725 GHz bands, respectively [14, 15].

Considering all of these, the need for new frequency bands becomes clear. Since wireless local area networks (WLANs) operate in the unlicensed spectrum, ISM bands at frequencies above 6 GHz were the primarily anticipated targets. Table 2.1 lists the ITU-R designated ISM bands. Frequency allocations are carried out up to 275 GHz, and there are four ISM bands in this range, with the centre frequencies (f_{centre}) of 24.125, 61.25, 122.5 and 245 GHz. The first three are very close to the local maxima of gaseous attenuation (γ). Therefore, it can be argued that ISM bands were assigned to the spectra possessing poor EM properties, and thus little financial value [16].

The first ISM band above 6 GHz, starting at 24 GHz, would be the expected choice. However, it lacks sufficient bandwidth, which is the primary requirement. Only the 100 MHz between 24.15 and 24.25 GHz is assigned for non-specific short-range devices, with an EIRP limit of 20 dBm [17]. On the other hand, as per the same Decision, 9 GHz of continuous spectrum between 57 and 66 GHz is assigned for wideband data transmission systems with 40 dBm EIRP constraint. Similar broader allocations around the stated ISM band are also true for the rest of the world [18]. Taking into account this vast amount of open spectrum, the ISM band centred at 61.25 GHz, which is mainly referred to as the 60 GHz band, is selected for wireless personal area network (WPAN) and WLAN expansions. 60 GHz standards and standardization

Table 2.1: ITU-R designated ISM bands

Frequency Range			f_{centre}	Bandwidth	
6.765	6.795	MHz	6.78	30	kHz
13.553	13.567		13.56	14	
26.957	27.283		27.12	326	
40.66	40.70		40.68	40	
433.05	434.79		433.92	1.74	MHz
902	928		915	26	
2.4	2.5	GHz	2.45	100	
5.725	5.875		5.8	150	
24	24.25		24.125	250	
61	61.5		61.25	500	
122	123		122.5	1	GHz
244	246		245	2	

efforts are explained in the remainder of this section.

2.2.1 WirelessHD

WirelessHD special interest group was formed in late 2006 to originate a specification targeting data rates over 1 Gb/s in the 60 GHz ISM band for point-to-point audio/visual (A/V) networks. Group members are listed in Table 2.2. The first version of the specification was published a year later than expected, in April 2008, and the final issued version, 1.1, was completed in May 2010 [19].

From an application point of view, data rates on the order of 1 Gb/s are needed only for high-quality video streams [20]. An uncompressed 1080p video, typically advertised as full high-definition (HD), displaying 60 frames per second (f/s) and using 3 bytes of information to represent the color of each pixel requires a data rate of 2.781 Gb/s. If the graphic resolution is increased to the subsequent common

Table 2.2: WirelessHD members

Promoters	Adopters
LG Electronics Inc.	AboCom Systems, Inc.
Panasonic Corporation	AzureWave Tech., Inc.
Samsung Electr. Co., Ltd.	Dell Global B.V.
Silicon Image, Inc.	Olympus Corporation
Sony Corporation	Seiko Epson Corp.
Toshiba Corporation	Sharp Corporation
TP Vision B.V.	Underwriters Labs Inc.

frames of 2560-to-1440 or 3840-to-2160, which are marketed as quad HD and ultra HD, respectively, the data rate requirements, keeping the f/s and color depth the same, increase to 4.944 and 11.124 Gb/s.

The WirelessHD specification is composed with the video requirements prioritized. The term “wireless video area network” is coined and used throughout the specification. This arrangement can also be directly observed from the coordinator handover priority order table, within which device types are listed in terms of suitability for the coordinator role. Coordinator resembles access points within the IEEE 802.11 architecture, and the list, which also illustrates the targeted user equipment (UE), is ordered as follows: digital TV, set-top box, DVD/BD player, DVD/BD recorder, A/V RX, personal computer, video projector, game console, digital video camera, digital still camera, personal digital assistant, portable media player, MP3 player, cell phones and other.

There are 3 physical layers (PHYs) defined in the specification: Low rate PHY (LRP), for discovery and control tasks, medium rate PHY (MRP), intended for low power applications and universal bidirectional data transmission, and high rate PHY (HRP), for top quality video streaming. Some of the important parameters of the PHYs are detailed in Table 2.3. Only for HRP an optional spatial multiplication

Table 2.3: General parameters of WirelessHD physical layers

Quantity	LRP	MRP	HRP
<i>Bandwidth</i> (MHz)	92	890	1760
<i>Sampling rate</i> (Ms./s)	317.25	1269	2538
<i>Number of subcarriers</i>	128	256	512
<i># of data subcarriers</i>	30	168	336
<i>FFT period</i> (ns)	403.47	201.73	201.73
<i>Guard interval</i> (ns)	88.26	25.22	25.22
<i>Symbol duration</i> (ns)	491.73	226.95	226.95
<i>Highest modulation</i>	BPSK	16-QAM	64-QAM
<i>Code rate</i>	2/3	2/3	5/6
<i>Peak data rate</i> (Mb/s)	40.673	1904	7138

mode is identified, which enables 4 concurrent streams, and thus the opportunity to quadruple the HRP data rate.

Starting with the 2009 Consumer Electronics Show, products including WirelessHD TRXs were started to be introduced, such as TVs, home cinema projector and personal 3-D viewer. However, WirelessHD specification could not gain the momentum necessary for vast adoption. The specification was not comprehensive enough and compatible with the other main WLAN standards, and at the time there was not an actual demand for the devised technology. A new specification is not released since May 2010 and any kind of activity related to the technology has not occurred since the beginning of 2013, making the WirelessHD effectively obsolete.

2.2.2 Wireless Gigabit Alliance

Wireless Gigabit (WiGig) Alliance is the second and final industrial organization established to contribute to the 60 GHz standardization processes. Founded on 7 May 2009 with 13 companies in the board of directors and 4 contributor members,

unlike WirelessHD, the support to the WiGig Alliance continually grew over time. This can be due to the comparative power of the members, the complete list of which is presented in Table 2.4, including all the participations throughout the years, or the inclusive approach the consortium has taken. From the start, industry leaders such as Dell, Intel and Microsoft were among the board of directors of the WiGig Alliance, in addition to the LG Electronics, Panasonic and Samsung, which were also promoter members of the WirelessHD. The initial specification was completed by the end of 2009 and in May 2010, both the cooperation with the Wi-Fi Alliance and contribution of the specification to the IEEE 802.11ad task group were announced.

In 2011, in addition to the release of version 1.1 of the standard, three protocol adaptation layer (PAL) specifications, namely WiGig Bus, Display and Serial Extensions, were published. Though, the technical details of the specifications were not made available to the public. Following nearly 2.5 years of partnership, at the beginning of 2013 the Wi-Fi and WiGig Alliances agreed for unification of activities under the former consortium, and this procedure was completed on 5 March 2013. As of 2015, WiGig interoperability certification programme is still not unveiled. However, unlike the WirelessHD's activity period, industry is now united on the need for 60 GHz communications. Consequently, mass market WiGig hardware is expected to be available for purchase in 2016.

2.2.3 ECMA-387

Originally named European Computer Manufacturers Association (ECMA), and since 1994 termed Ecma International - European association for standardizing information and communication systems, the association is historically involved with formation of standards for modern technologies. Technical Committee 48 of Ecma International, titled "High Rate Wireless Communications", was assigned to work in three fields, i.e. TV white spaces, ultra wideband and the 60 GHz band, and the ECMA-387: "High Rate 60 GHz PHY, MAC and HDMI PALs" is the first issued standard for WPAN operation in the 60 GHz ISM band. Its first edition was finalized in October

Table 2.4: Wireless Gigabit Alliance members

	Board of Directors		Contributors	
05/2009	Atheros Comm.	Dell Inc.	NXP Semiconductors	
	Broadcom Corp.	Intel Corp.	Realtek Semiconductor Corp.	
	LG Electronics	Marvell Int.	STMicroelectronics	
	MediaTek Inc.	NEC Corp.	Tensorcom, Inc.	
	Microsoft Corp.	Nokia Corp.		
	Panasonic Corp.	Wilocity		
	Samsung Electronics			
09/2009	Toshiba Corporation		Agilent Tech.	Beam Networks
			Texas Instruments	Ralink Tech.
12/2009	Nvidia Corporation		Advanced Micro Devices (AMD)	
			SK Telecom Co.	TMC Reinland
05/2010	Cisco Systems, Inc.		Samsung Electro-Mechanics	
			Harman Int. Ind.	Peraso Tech.
11/2010	AMD (raised from Contributors)		CSR PLC	Nitero, Inc.
06/2011			Hittite Microwave	Aeroflex Inc.
			Rohde & Schwarz	FTDI Ltd.
			Underwriters Labs	MET Labs, Inc.
			Institute for Infocomm Research	
			State Radio Monitoring Testing Ctr.	
02/2012	Huawei Technologies Co. Ltd.		Allegro DVT	LGE
			Silicon Image, Inc.	ZTE Corp.

2008 and approved two months later, and the initial draft of the second and current version of the standard was completed in June 2010, with the publication taking place in December 2010 [21].

Albeit not formally defined, 10 m can be considered as a conventional range limit for WPANs, and ECMA-387 was structured for high data rate requiring applications

Table 2.5: Frequency plan and specific attenuations of 60 GHz channels

	Frequency (GHz)			Attenuation (dB/m)		
	f_{start}	f_{centre}	f_{end}	$\gamma_{f_{\text{start}}}$	$\gamma_{f_{\text{centre}}}$	$\gamma_{f_{\text{end}}}$
1	57.24	58.32	59.4	0.011	0.0132	0.0144
2	59.4	60.48	61.56	0.0144	0.0154	0.0151
3	61.56	62.64	63.72	0.0151	0.0125	0.008
4	63.72	64.8	65.88	0.008	0.0044	0.0022

operating within that limit, such as wireless uncompressed or lightly compressed video, wireless docking station and short-range sync-n-go file transfer. For these purposes two device types are defined: Types A and B. Type A is positioned as the high-tech device, with antenna training and non-line-of-sight (NLoS) operation capabilities, whereas Type B is planned to cover low-cost equipment and only supports LoS links over shorter distances. Both types support coexistence and interoperability.

Channelization of all the 60 GHz ISM band specifications and standards are the same, and explained as follows: There are 4 channels defined between 57 and 66 GHz, each covering a bandwidth of 2160 MHz and having starting, center and stopping frequencies as listed in Table 2.5. The atmospheric attenuation for this 9 GHz spectrum, calculated for the standard ground-level atmospheric conditions of 15.15°C temperature, 1013.25 hPa pressure and 7.5 g/m³ water vapour density, and according to the Recommendation ITU-R P.676-9 [22] is given in Fig. 2.1, with specific values of the frequency plan provided, again, in Table 2.5. Although the losses are much greater than the surrounding spectrum, the degrading effect over a typical WPAN link is negligible.

There are 22 and 4 transmission modes defined for Type A and B devices, respectively. The mandatory mode of Type B employs differential binary phase-shift keying (DBPSK) with Reed-Solomon (RS) and differential encodings, and without the optional channel bonding, 0.794 Gb/s data rate is achievable. Other described

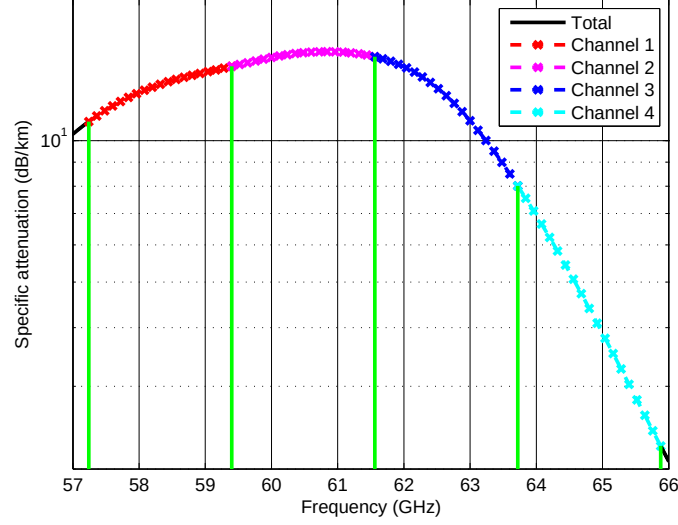


Figure 2.1: Specific attenuation due to atmospheric gases, calculated under standard ground-level atmospheric conditions and between 57 GHz and 66 GHz at 1 MHz intervals, with 60 GHz channels indicated.

modulation types are differential quadrature PSK (QPSK) and unequal error protection (UEP)-QPSK, both allowing communications at the peak rate of 3.175 Gb/s. Besides the possibility of supporting Type B modes, options specific to the Type A devices are split into two categories: 14 single carrier block transmission (SCBT) and 8 orthogonal frequency division modulation (OFDM) modes. The constellations for these range from BPSK to 16-QAM, and the encoding is either only RS or RS and one of the convolutional code (CC), trellis coded modulation and UEP-CC. This way, data rates of 6.350 and 4.032 Gb/s are possible with SCBT and OFDM, respectively.

Prior to communication link formation, devices need to detect each other, and this is performed using the discovery mode, for which channel 3 is allocated. Interoperability configuration and antenna training follows this step. A common physical layer convergence protocol (PLCP) protocol data unit (PPDU) frame is formed of 4 main sections, which are PLCP preamble, PLCP header, PPDU payload and antenna training sequence (ATS). The last two are optional, and the antenna training symbols are sent within the ATS field. A device trains its RX antenna by including training

symbols in the ATS field of a single frame, whereas its transmitter (TX) antenna can use the same antenna weights of the RX, or calculate according to the feedback from the receiving device. These TX modes are termed as open- and closed-loop, respectively.

As amendments to the IEEE 802.11 are executed over the core standard, ECMA-387's medium access control (MAC) specification is obtained through necessary revisions made to the ECMA-368: "High Rate Ultra Wideband PHY and MAC Standard". There are 3 acknowledgment policies defined for different application requirements: No, immediate and block. Active and hibernation modes are described for power management. Security is also offered through the use of Advanced Encryption Standard-128 Galois/counter mode.

2.2.4 IEEE 802.15.3c

Being IEEE standards, 802.15.3c and 802.11ad, which were ratified in October 2009 and December 2012, respectively, are widely covered in the literature [23, 24, 25]. Since it is a WPAN standard, anticipated use cases of 802.15.3c are mostly for distances shorter than 30 m [26]. One group of applications aim to replace short-range cabled communication links such as the IEEE 1394 serial bus and 802.3 Ethernet links with mm-wave. Another group tries to accomplish 60 GHz vertical wireless connections, and one other set focuses on the multimedia potentials and explores data distribution methods.

IEEE 802.15.3c mm-wave PHY defines 3 PHYs: Single carrier (SC PHY), high speed interface (HSI PHY) and A/V (AV PHY) modes [27]. 3 modulation and coding scheme (MCS) classes are stated for SC PHY, targeting inexpensive user equipment with operation data rates up to 1.5 Gb/s, top-quality products offering communications at 3 Gb/s and above, and the rest of the devices in between. Timing-related parameters are common for all the classes, and chip rate and subblock length are set at 1760 Mchip/s and 512 chips, respectively. HSI PHY is dedicated to bidirectional data transfer and all its MCSs exclusively use OFDM and low-density parity-check

(LDPC) code for FEC. Finally, AV PHY makes use of the asymmetric data transfer nature of the commonplace A/V applications and implements 2 modes: HRP and LRP. The highest attainable data rates for SC PHY's classes 1, 2 and 3 are 1650 Mb/s using the MCS 3 of $\pi/2$ BPSK and RS(255,239), 3300 Mb/s with the MCS 11's $\pi/2$ QPSK and RS(255,239) and 5280 Mb/s applying the MCS 13 of $\pi/2$ 16-QAM and LDPC(672,504), respectively. Moreover, Table 2.6 presents the MCS and timing-related parameters comparatively between HSI PHY, AV PHY and the directional multi-gigabit (DMG) PHY, which is the general term for the PHYs of the IEEE 802.11ad [28].

There are 5 types of acknowledgment: No, delayed, implied, immediate and block. No particular security mechanism, apart from the ones already existent in the core 802.15 standard, is specified. UEP is supported as well as equal error protection, primarily for the tasks where the most significant bits are more important than least significant bits, like video transmission.

A beam forming procedure, albeit optional, is also provided in the standard, supporting many antenna types, including switched antennas and antenna arrays. Of the two defined protocols, pro-active beam forming is used when a piconet coordinator (PNC) is transmitting data to any number of devices, and on-demand beam forming is used between two devices or a device and a PNC. After the two stages of beam forming, which are the coarse sector and fine beam level trainings, high resolution tracking step is, again, optional.

2.2.5 IEEE 802.11ad

802.11ad is the only WLAN standard for the 60 GHz band. Taking advantage of the wider coverage of WLANs, specified usage models include some of the WPAN services, such as short-range video streaming, in addition to the newly possible ones like outdoor campus, auditorium and manufacturing floor functions and point-to-multipoint (PMP) backhaul links [29].

There are 32 MCSs identified, divided into four categories: MCS 0 for control

PHY, MCSs 1-12 for SC PHY, MCSs 13-24 for OFDM PHY and MCSs 25-31 for low-power SC PHY. Compulsory control PHY PDDU communication is performed with DBPSK modulation at 1/2 coding rate, resulting in a data rate of 27.5 Mb/s. SC and OFDM PHYs solely use LDPC encoder, whereas an RS(244,208) outer code and a shorter inner code, which is either block code or single parity check, are employed in the case of low-power SC PHY. The highest stated data rate for SC PHY is 4620 Mb/s, using the MCS 12 consisting of $\pi/2$ 16-QAM and LDPC(672,504).

The basic service set (BSS) particularly designed for the standard is named personal BSS (PBSS). This is comparable to the independent BSS (IBSS), which is the simplest type and labelled ad hoc network, since devices communicate directly with each other. The main difference between IBSS and PBSS is, in IBSS all stations (STAs) transmit beacons, whereas in PBSS one STA undertakes the duties of PBSS control point.

Many new MAC functions are also defined in the standard. Beam forming is again described; however, unlike 802.15.3c, there is a single mechanism. It begins with a sector-level sweep where sectors, or antenna patterns, are limited to 64 per antenna and 128 per STA. Two kinds of relay operation are identified: Link switching and link cooperating. The first type includes the relay DMG STA (RDS) forwarding data from source relay endpoint DMG STA (REDS) to destination REDS in case of a link disruption, whereas in the second type data is transmitted both directly and over the RDS to the destination REDS. Finally, DMG Block Ack is the additionally defined acknowledgment policy [28].

2.3 60 GHz Channel Characteristics

9 GHz wide unlicensed spectrum comes at a price. The gaseous attenuation up to 275 GHz, which is the upper limit of the ITU allocated spectrum [30], is calculated for the standard ground-level atmospheric conditions using ITU-R P.676-9 [22] and given in Fig. 2.2. Two separate components, water vapor and dry air, make up the total. Oxygen, nitrogen and Debye-Waller factor cause the dry air attenuation and

Table 2.6: Timing-related parameters for IEEE 802.15.3c and 802.11ad OFDM PHYs

Quantity	HSI PHY	AV HRP PHY	AV LRP PHY	DMG PHY
<i>Reference sampling rate</i> (MHz)	2640	2538	317.25	2640
<i>Fourier transform size</i>	512	512	128	512
<i>Number of data subcarriers</i>	336	336	30	336
<i>Number of pilot subcarriers</i>	16			16
<i>Number of DC subcarriers</i>	3			3
<i>Subcarrier frequency spacing</i> (MHz)	5.15625	4.957	2.4785	5.15625
<i>Fourier transform period</i> (ns)	193.94	201.73	403.47	193.94
<i>Guard interval duration</i> (ns)	24.24	25.22	88.26	48.48
<i>Symbol duration</i> (ns)	218.18	226.95	491.73	242.42
<i>Modulation</i>	64-QAM	16-QAM	BPSK	64-QAM
<i>Code rate</i>	5/8	2/3	2/3	13/16
<i>Maximum data rate</i> (Mb/s)	5775	3807	10.2	6756.75

the frequencies and values of the local extrema of the atmospheric attenuation are also explicitly denoted in the figure. Table 2.7 additionally presents the frequencies and values of the local extrema of the gaseous attenuation.

60 GHz WLANs are furthermore not constrained to indoor operation, as outdoor purposes were listed in detail during the IEEE 802.11ad standardization process [29]. Therefore, meteorological phenomena can generate additional losses on top of the gaseous attenuation. Fig. 2.2 also demonstrates the specific attenuation due to rain, calculated for rain rates of 1, 4, 8, 16, 25 and 50 mm/h assuming horizontal polarization and according to the Recommendation ITU-R P.838-3 [31].

Rain attenuation curves all exhibit a similar form, which escalates with a decreasing rate and stays approximately constant following its maximum as frequency increases. Attenuation due to rain also increases in line with the rain rate and can be severer than atmospheric attenuation. To present an example, for 50 mm/h rain

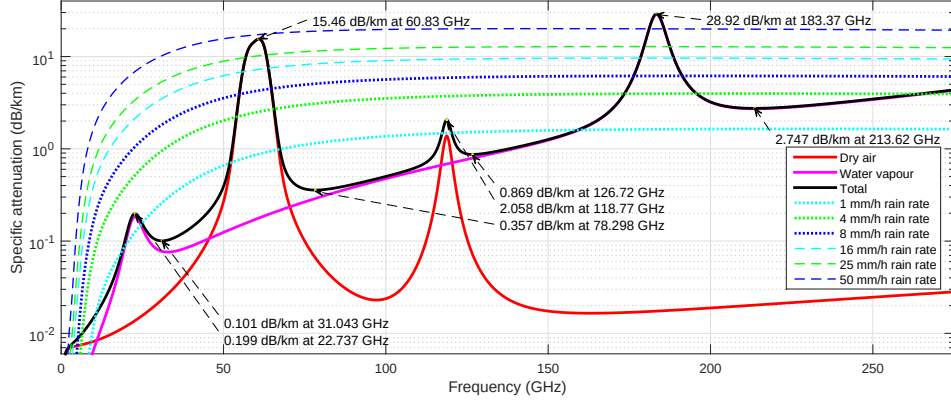


Figure 2.2: Specific attenuation due to atmospheric gases and rain, calculated under standard ground-level atmospheric conditions, for rain rates of 1, 4, 8, 16, 25 and 50 mm/h and up to 275 GHz at 1 MHz intervals.

Table 2.7: Local extrema of atmospheric attenuation

Extremum		Frequency		Attenuation	
1	Max	22.74	GHz	0.199	dB/km
	Min	31.04		0.101	
2	Max	60.83		15.47	
	Min	78.297		0.3577	
3	Max	118.77		2.0606	
	Min	126.72		0.87	
4	Max	183.37		28.943	
	Min	213.61		2.751	

rate, which is the lowest limit of the violent rain shower category, at 60.829 GHz where gaseous attenuation reaches its local maximum with 15.474 dB/km, the rain attenuations are 0.876, 2.522, 4.278, 7.258, 10.201 and 17.308 dB/km, respectively, for increasing rain rates.

Three principal parameters affect the atmospheric attenuation: Water vapor density, temperature and air pressure. Fig. 2.3 illustrates the effect of each factor as the

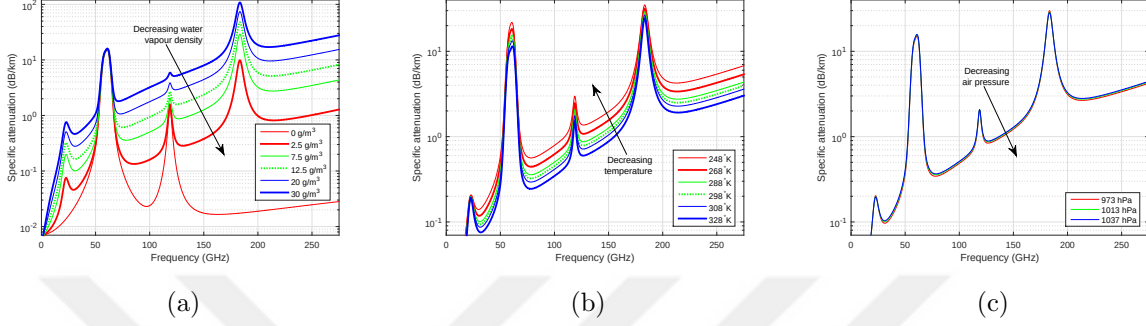


Figure 2.3: Specific attenuation due to atmospheric gases, calculated up to 275 GHz and for (a) water vapour densities of 0, 2.5, 7.5, 12.5, 20 and 30 g/m³, (b) temperatures of 248, 268, 288, 298, 308 and 328°K, and (c) total air pressures 973, 1013 and 1037 hPa.

other two are kept constant at the standard ground-level values.

In Fig. 2.3a, water vapor density is given the values 0, 2.5, 7.5, 12.5, 20 and 30 g/m³, where 0 and 7.5 g/m³ correspond to the “dry air” and “total” cases in Fig. 2.2, respectively. Attenuation increases in relation to the ρ , and as an example, the maximum attenuation is reached by the 30 g/m³ instance at 183.394 GHz with 108.111 dB/km. The local maxima in the 60 GHz band are also 15.451, 15.453, 15.474, 15.532, 15.683 and 16.007 dB/km, in the ascending ρ order, respectively. Because many of the oxygen absorption lines emerge around 60 GHz, that particular local maximum is originated by oxygen. Therefore, water vapor density has restrained impact on the outcome, causing the comparatively close attenuation values around the 60 GHz band.

Fig. 2.3b illustrates the effect of temperature, and the values of 248, 268, 288, 298, 308 and 328°K are evaluated. Contrary to the ρ , increasing the temperature reduces attenuation. The local maxima of the gaseous attenuation in the 60 GHz band are 21.791, 18.269, 15.474, 14.293, 13.233 and 11.423 dB/km, in the ascending temperature order, respectively.

The results for air pressure are available in Fig. 2.3c. Only three quantities, 973, 1013 and 1037 hPa, are computed, since even a substantial pressure change of 40 hPa

does not translate into a significant attenuation shift. The local attenuation maxima within the 60 and 122 GHz ISM bands are 14.951, 15.474 and 15.784 dB/km, and 2.038, 2.061 and 2.074 dB/km, respectively, for increasing air pressure values.

The main differences of EM wave propagation mechanisms between the legacy spectrum and the proposed 60 GHz band are:

- Free-space path loss increases by 28 and 21 dB for the 60 GHz band compared to the 2.4 and 5 GHz bands, respectively.
- Atmospheric attenuation is higher but not preventative within the range of small cell communications.
- Refractive indices of a diverse range of materials remain practically constant with frequency [32]; however, due to the general Kirchhoff solution for scattering from rough surfaces, reflection coefficient reduces as frequency increases.
- Absorption coefficients of materials rapidly grow with escalating frequency [33].
- Diffraction is almost universally negligible at and upwards of 60 GHz [34].

The combination of these form a different channel compared to typical bands where multipath propagation is evident and high-gain antenna techniques [35] or high output power TXs are required for stable communication links. In fact, the channel models developed for the IEEE 802.11ad take into account second order reflections at most. Since many of the signal attenuation sources intensify with rising frequency, upper limit for reflections can be set at 2 for the entire mm-wave band. This significantly reduces the complexity of a complete, deterministic solution, which should be the chosen modeling method [36, 37].

Higher power losses, together with the cost of developing and rolling-out new communication devices for an already established mass market are endured because of the expected data rate and network capacity leaps by the use of the 60 GHz band. To better demonstrate the possible improvements, comparative capacities of the 40

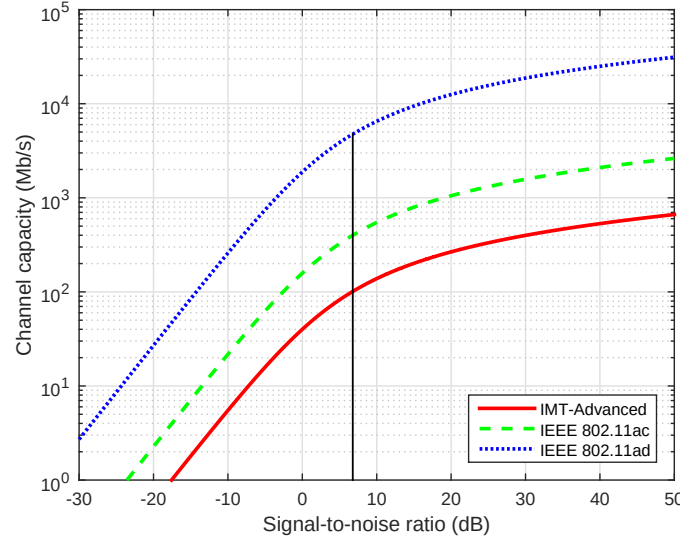


Figure 2.4: Channel capacities of IMT-Advanced, IEEE 802.11ac and IEEE 802.11ad, calculated from -30 to 50 dB SNR.

MHz IMT-Advanced, 160 MHz IEEE 802.11ac and 2.16 GHz IEEE 802.11ad channels with respect to the signal-to-noise ratio (SNR) are presented in Fig. 2.4. The channel parameters are selected as per the authors' previous work [38]. Even though an SNR of 6.79 dB is required for BPSK transmission with 10^{-3} symbol error ratio (SER) [39], which is indicated in the figure and can be reasoned to be one of the options for the lowermost limit for practical wireless communications, the SNR range is chosen to be between -30 and 50 dB. These bounds are in line with the results of the realistic 4G and 60 GHz indoor simulations existing in the literature, where the SNR values are shown to change between 30 to 50 dB in the 4G case, and between 8 to 19 dB for the 60 GHz LoS simulations. Higher material absorption at the 60 GHz band also drove corresponding NLoS SNR values below -22 dB [16].

Coverage areas of indoor mm-wave networks are restricted to a single room for the currently used building materials and access network architectures. If this predicament is accepted and performance comparisons are conducted over one room, the lowest practical SNR limit of 6.79 dB, which is below the calculated achievable quantity range for the 60 GHz band, generates a channel capacity of 4.756 Gb/s for the

802.11ad, which is nearly double and one order higher of 2.624 and 0.664 Gb/s, the capacities of the 802.11ac and IMT-Advanced for the maximum SNR outcome of 50 dB, respectively. However, bit rate analysis is more informative for the real-world use cases. 27.2 dB SNR is needed for 64-QAM with an SER of 10^{-6} . Therefore, if stable point-to-point communication links employing BPSK for the 802.11ad and 64-QAM for the 802.11ac and IMT-Advanced channels are assumed, the peak data rates become 1.88, 0.948 and 0.24 Gb/s, respectively, still clearly displaying the minimum anticipated return from the carrier frequency switch.

2.4 60 GHz Devices

60 GHz is an unoccupied territory for telecommunications. However, like most sections of the mm-wave band, it is already in use by other fields. For example, 57 to 59.3 GHz spectrum is also assigned for passive Earth exploration-satellite services [30], and actively utilized for atmospheric monitoring. One specific device operating in this band is the advanced microwave sounding unit-A (AMSU-A), which is a total-power microwave radiometer currently functioning in multiple NASA and National Oceanic and Atmospheric Administration satellites. AMSU-A monitors 15 channels, 6 of which are within the 57-59.3 GHz band [40].

At 100 kg and working with a DC power of 100.5 W, AMSU-A from the early 1990s possesses no use for present communication instruments. The mm-wave band is defined to be between 30 GHz, corresponding to a wavelength of approximately 10 mm, and 300 GHz, and this spectrum is situated between the conventional microwave and optical bands. The main methods to develop mm-wave devices thus have been increasing the operation frequency of microwave electronic circuitry, and the inverse for optical devices. Owing to the proximity to the already industrialized sub 6 GHz electronics market and the ease of integration to other components of the same type, semiconductors are the definitive choice for the 60 GHz devices.

Escalated losses within the 60 GHz band forces the use of amplifiers, hence transistors. The two foremost semiconductor transistor technologies are silicon (Si) and

III-V compounds. The latter, in theory, comprises all binary compounds made up of one group III and one group V elements, and their ternary and quarternary alloys. However, the prominent elements are aluminium, gallium and indium from group III, and nitrogen, phosphorus, arsenic and antimony from group V[41].

The performance criteria of the newest semiconductors are so diverse that the structural properties of semiconductors separately contain only partial information [42]. Large band gap is what differs an insulator from a conductor, though to enable high-temperature functioning without complete impact ionization, even higher band gap is preferred in semiconductors. Greater thermal conductivity enables high-power device applications, since it is inversely proportional to self-heating. The boundary before avalanche breakdown, that is the critical breakdown field, is also useful for high-voltage duties. Carrier mobility, which can be defined as the easiness of motion within the semiconductor and specified for both electrons and holes, is pursued for high-frequency tasks.

III-V compounds, in general, perform better at the fundamental material properties and figures of merit [43]. However, the most important parameter for a technology targeting billions of end-user wireless communication equipment is cost. The immensely abundant Si and complementary metal-oxide-semiconductor (CMOS) is unrivalled in terms of manufacturing expenses as a result of its current market dominance, and thus is the main 60 GHz band semiconductor technology [44].

To the best of authors' knowledge, the most recent entirely integrated 60 GHz CMOS TRX publication that digitally executes at least the PHY tasks is the work of Saito et al. [45]. The RF integrated circuit (IC) is able to communicate in all 4 of the defined channels, and the baseband (BB) IC is proclaimed to implement both the PHY and MAC layer of the IEEE 802.11ad. RF IC has separate antennas for TX and RX, which are made of four patch elements and supply 6.5 dBi gain over 50° beamwidth. The reference temperature compensated crystal oscillator clock can vary between 26 and 40 MHz and is connected to the fractional-N phase locked loop (PLL), which drives the quadrature modulator (QMOD) of the TX and quadrature demodulator

Table 2.8: Technical features of the state-of-the-art 60 GHz CMOS transceivers

Quantity	Saito et al. [45]		Mitomo et al. [46]		Okada et al. [47]	
	RF IC	BB IC	RF IC	BB IC	RF IC	BB IC
Process (nm)	90	40	65	65	65	40
Chip size (mm ²)	3.6×3.75	6.3×7.4	2.2×1.3	3.4×3.9	4.2×4.2	3×3
TX power (mW)	347	441	160	432	319	196
RX power (mW)	274	710	233	523	223	427

(QDEM) of the RX. Signal is generated in 110 MHz steps within the digital BB IC domain, and then passes through a digital-to-analog converter, variable-gain amplifier (VGA), QMOD and four-stage power amplifier (PA), before getting transmitted over the antenna. RX circuitry, on the other hand, starts with a four-stage low-noise amplifier (LNA) and followed by the QDEM and VGA.

Main technical features of the TRXs that are reviewed in this section are presented in Table 2.8. The first TRX realizes the MCSs 0-9 of the IEEE 802.11ad, which constitute the control PHY and SC PHY operating with BPSK or QPSK modulations, omitting 16-QAM. Using the MCS 9 and emitting a TX EIRP of 8.5 dBm, MAC layer throughputs of 1.8 Gb/s up to 0.4 m and 1.5 Gb/s up to 1 m are measured, whereas the PHY data rate is 2502.5 Mb/s [45].

Another recent associated TRX chipset is published by Mitomo et al. [46]. It also provides the PHY and MAC layer functionalities for all of the 60 GHz channels, whereas these do not mirror any of the 60 GHz standards. For the PHY, an OFDM-QPSK modulation with RS(240,224) outer and 3/4 CC inner codes for FEC is implemented. MAC is based on carrier sense multiple access with collision avoidance and retransmission using acknowledgment procedures.

There is a single, 0 dBi gain antenna connected to a TX/RX switch to reduce the size. The TX path consists of QMOD, up-conversion mixer and PA, and the RX contains LNA, down-conversion mixer, QDEM and VGA. QMOD and QDEM use the

20 GHz local oscillator PLL output, which is based on a voltage-controlled oscillator. However, the TX and RX mixers require a frequency doubler prior to usage. The TRX reaches data rates of 2.62 and 2.07 Gb/s at the PHY and MAC layers, respectively, though up to a maximum distance of 0.04 m [46].

The final complete 60 GHz CMOS TRX available in the literature is implemented by Okada et al. [47]. This TRX also operates in all 4 of the channels, but only PHY tasks are realized. Modulation choices are QPSK and 16-QAM, whereas just LDPC(1440,1344) is available for FEC. Maximum output powers of the RF IC are 5.6 and -4 dBm, for normal and low-power modes, respectively, and the independent TX and RX antennas each have gains of 6 dBi.

Architectures of the TX and RX circuitries are similar to the corresponding blocks of the previously explained TRXs: Mixer, differential preamplifier and PA for the TX, and LNA, differential amplifier and mixer for the RX. The local synthesizer is based on a 20 GHz integer-N PLL working with a 36 MHz reference clock. This part is directly connected to an injection-locked oscillator, which triples the frequency. With the technical attributes illustrated in Table 2.8, the RF IC and BB IC achieve data rates of 3.1 Gb/s up to 1.8 m and 6.3 Gb/s over 0.05 m using QPSK and 16-QAM, respectively [47].

2.5 60 GHz Applications

Wireless communication is the enabler of numerous novel user activities. Hence, the 60 GHz ISM band that offers exalted data rate and network capacity is valuable for many applications. A number of these are associated to network architecture enhancements such as single or multi-hop backhauling, mobile fronthauling and data offloading, whereas some have specific use cases like inter-rack communication at data centers. Consumer electronics related applications can be grouped under the following usage model categories:

- **Rapid file transfer:** The exceptionally wide bandwidths of the 60 GHz band channels can be very effectively utilized in ultra short range communication

settings. The 6756.75 Mb/s peak data rate identified in the IEEE 802.11ad transfers 591 MB data every second at 70% MAC layer efficiency, thus enabling the download of a 1.5 GB standard definition movie in less than 3 seconds at a kiosk or toll-gate. This solution can also lead to cordless computing in home or office scenarios [29].

- **Wireless display:** An essential high throughput requiring application is video or mass data distribution over PP or PMP network topologies. Performance requirements are lower than the sync-n-go case: 1 Gb/s data rate over a single link is sufficient for uncompressed video, and a fraction of this quantity is needed for the compressed file. However, connection can be LoS or NLoS, RX can be moving and the range covers the room for projection to TV or projector and augmented and virtual realities, and the entire occupied area for the PMP environments such as classroom, airplane and exhibition [48, 49].
- **UHD video streaming:** Similar to data rate, consumers continuously demand higher image resolution from their video monitors. 8K UHD display devices, having a graphic resolution of 7680 to 4320 pixels, are next in succession. Using 4:2:0 chroma subsampling, 8K UHD video at 60 f/s and 3 B color depth requires a data rate of 28.51 Gb/s, which is significantly higher than even the maximum total throughput of the up to date HDMI 2.0a specification. This data transfer would also require the latency and jitter to be less than 5 ms. Therefore, by channel bonding, higher order modulation and MIMO, 60 GHz band is the main technology to provide UHD video stream between a TV and an STB [50, 51].

2.6 Conclusion

This chapter is focused to the efforts on the utilization of the 60 GHz ISM band for consumer wireless communications. Standardization activities that began in 2006 are completed by the end of 2012 for both WPAN and WLANs. During these actions, EM wave transmission properties and channel models of the 60 GHz band are developed.

Low-cost 60 GHz devices are also produced, as commercial products are expected to go on sale in 2016. Overall, the 60 GHz ISM band is ready for both widespread adoption and further use in B4G systems.



Chapter 3

EMPLOYING 60 GHZ ISM BAND FOR 5G WIRELESS COMMUNICATIONS

3.1 Introduction

The increase in requirement of information and data within our daily lives and routines has been a major driver for connectivity growth for more than a decade now. Up until the end of the third generation (3G) mobile telecommunication systems, it can be argued that telecommunication and data services have been treated as separate features. However, with the introduction of fourth generation (4G), network convergence took over and all services essentially became a form of data communications.

Conventional mobile and data communications have always been conducted within the frequency bands below 6 GHz. The simple reasons are the favourable electromagnetic (EM) wave propagation conditions and hardware capabilities. However, as the demand for communications exponentially increased the available spectrum became insufficient. Wireless local area networks (WLANs) operate within the industrial, scientific and medical (ISM) radio bands centered at 2.45 and 5.8 GHz [30], the latter being extended through 5150 - 5350 MHz and 5470 - 5725 MHz with further restrictions[52]. However, because IEEE 802.11 initially designed for best service support through contention-based access and due to the open nature of the spectrum, despite the quality of service (QoS) amendments like IEEE 802.11e[53], service guarantee is not possible. To offer reliable and satisfactory communications, exclusive spectrum is needed, and therefore the high-priced mobile spectrum auctions occur. To get an idea of the worth of bandwidth, the July 2012 dated technical report commissioned by the United Kingdom (UK)'s Office of Communications can be consulted[54].

One part of the report presents benchmark valuation results which are compiled using similar recent auctions held across the Europe. For larger incumbent operators the value of the spectrum in the 800 MHz band is found to be between £0.460 and £0.714 per MHz per capita. This amount decreases to the £0.087 - £0.121 range for the 2.6 GHz band. 800 MHz is important for widespread coverage, whereas 2.6 GHz is necessary to support high data rates, and the nearly 6 times valuation difference between the bands therefore stems from the respective economic importance of the stated channel properties. The monetary quantities given in the report further validated by the results of UK's 4G mobile auction, which was held in February 2013[55].

Providing data communications without facing the hefty upfront licence costs requires resorting to the ISM bands. The corresponding designations according to the International Telecommunication Union (ITU) Radiocommunication Sector (ITU-R)'s Radio Regulations, Edition of 2012[30], are provided in Table 2.1. Since the 2.4 and 5 GHz ISM bands are already being utilized by WLANs, in order to satisfy the data rate requirements of the next-generation of wireless communication systems, ISM bands in the higher frequencies should be put into use. 24 and 61 GHz bands are the next ones in line. While 24 GHz have better EM wave propagation characteristics due to lower atmospheric and free-space losses, it is confined within a bandwidth of 250 MHz. On the contrary, although the 500 MHz wide 61 GHz ISM band is not large by itself, because the whole or continuous parts of the 57 - 66 GHz frequency band surrounding it has been allocated for unlicensed operations in all of the major regulatory domains, the 60 GHz presents a unique realizable opportunity for worldwide very high data rate supporting WLANs.

In consideration of the stated arguments, this chapter proposes the utilization of the 60 GHz ISM band for 5G communication systems and presents an indoor coverage simulation to compare transmission properties between a channel standardized within the 60 GHz band and the highest allocated frequency band for 4G systems, which is 3.5 GHz. With this aim Section 3.2 describes the steps taken in WLAN standardization activities towards the initiation of mm-wave for 5G wireless communications, and

Table 3.1: Incorporated baselines of IEEE P802.11-2012

Project	Title	Final Approval
<i>802.11s-2011</i>	Mesh Networking	1 August 2011
<i>802.11u-2011</i>	InterWorking with External Networks	25 February 2011
<i>802.11v-2011</i>	Wireless Network Management	9 February 2011
<i>802.11z-2010</i>	Extensions to Direct Link Setup	1 October 2010
<i>802.11p-2010</i>	Wireless Access for the Vehicular Environment	15 July 2010
<i>802.11w-2009</i>	Protected Management Frames	11 September 2009
<i>802.11n-2009</i>	High Throughput	11 September 2009
<i>802.11y-2008</i>	3650-3700 MHz Operation in USA	6 November 2008
<i>802.11r-2008</i>	Fast Roaming	9 May 2008
<i>802.11k-2008</i>	Radio Resource Measurement	9 May 2008

Section 3.3 provides an overview on the EM propagation characteristics of the 60 GHz ISM band. The performed simulations are explained in detail in Section 3.4 whereas the results together with their explanations are available in Section 3.5, which is then followed by the conclusion.

3.2 Millimeter Wave IEEE 802.11 Standardization Activities

Functioning to develop WLAN physical layer and medium access control (MAC) specifications since 1991, IEEE 802.11 has published 5 standards, 29 amendments, 2 recommended practices and 1 corrigendum in 27 years' time, with 5 amendments and 1 standard currently under development. Since the second standard, P802.11-1999, standard issuing practice turned into a periodic process of accumulated maintenance, where amendments published following the last standard are included in the current version. The penultimate standard, P802.11-2012, features the 10 amendments published since the previous release in 2007, whose details are available in Table 3.1.

There are 5 amendments merged to develop the current standard, P802.11-2016.

The oldest one is 802.11ae-2012, titled “Prioritization of Management Frames”. QoS mechanisms are defined for the IEEE 802.11 since the 2005 amendment 802.11e-2005. 802.11ae extends this capability towards management frames. As the 802.11 continued to expand through the years, so did the number of management frame categories. Currently 14 of the 16 possible management subtypes are allocated for various functions, whereas additional actions are set via the 1 byte long action field [56]. This rise in the variation of management frames made those a rational candidate for a QoS-type mechanism implementation. In fact, the introduction of QoS management frame (QMF) service with 802.11ae exactly endeavors this target. QMF determines enhanced distributed channel access (EDCA) access category (AC). Default QMF policy sets ACs for 32 of the management tasks to best effort (BE), video and voice, with BE also being the default category for the rest. QMF policy is also dynamic, can be changed between a station (STA) and a non-access point (non-AP) STA or an STA and an AP; but only within infrastructure basic service sets (BSSs) or mesh BSSs.

The second oldest incorporated amendment is 802.11aa-2012. It obtained the final approval on 1 June 2012 with the full title “MAC enhancements for robust audio video streaming”. Global data traffic is growing unendingly, and video streaming is no exception. Even though it is the largest global mobile traffic generator, holding a share of 60% as of 2016, video is still expected to outgrow audio, data and file sharing categories for the period between 2016 and 2021. The prediction is video will achieve a CAGR of 54% until 2021, more than the overall average mobile traffic CAGR at 47%; thus, rising its share to 78% of the total mobile traffic [57].

Apart from a mere categorization [58], which appears rather coarse a decade after its introduction, no specific attention has been given to video streaming, and 802.11aa rectifies this error for WLANs. With the standard many new policies are defined, one of them being stream classification service (SCS). SCS allows finer classification of unicast MAC service data units, such that voice and video streams can be buffered in primary or alternate transmit queues before being transmitted to the standard

EDCA function. Another new mechanism is group addressed transmission service (GATS). The aim is improved delivery of multicast transmissions and retransmission policy of GATS can be set to groupcast with retries (GCR) unsolicited retry or GCR Block Ack, in addition to the directed multicast service, which was first identified in 802.11v.

802.11af-2013, “TV White Spaces Operation”, was approved on 11 December 2013. Low frequency bands are valuable for many reasons, the foremost being the preferable transmission characteristics: Material absorption is lower [59], atmospheric attenuation is nearly non-existent and power disperses less in free space [60, 61, 62]. Legacy bands are also coveted more since necessary communications infrastructure are already deployed and operational. The economic result of these facts is spectrum being nearly 5 times more valuable in 800 MHz compared to 2.6 GHz [54].

The main aim of 802.11af is better utilization of lower frequency bands which are primarily licensed for broadcast TV. Historically, analogue TV broadcasting is performed on sub 1 GHz frequency bands. In Europe, 470 to 790 MHz was reserved for this purpose, whereas in the US a total of sixty 6 MHz channels are placed intermittently from 54 to 758 MHz. Digital TV switchover frees part of this spectrum, and the remainder is generally under-used. To better utilize the spectrum which is allocated for broadcast TV but not assigned at a specific location, formally termed as TV white space (TVWS), 802.11af is devised.

The core component of the standard’s new architecture is geolocation database (GDB). To ensure the protection of licensed usage of TVWS, it is directed by regulatory domains and stores and distributes the white space maps (WSMs) of geographic locations. WSM is a list that contains available channels and corresponding operation parameters, such as validity duration, maximum power level or channel bandwidth. Depending on the particular system design, which is not within the scope of the standard, GDB can either directly communicate with a geolocation database dependent (GDD) enabling STA, which is the complement of an AP within 802.11af, or through a registered location secure server (RLSS). Again, depending on the specific

architecture, RLSS can convey the current channel usage states of all the BSSs it communicates with to GDBs, communicate with the controllers of other TVWS networks to coordinate their operations or can be queried by GDD STAs, which are the complement of regular STAs within 802.11af, about channel usage and WSMs.

The amendment with the closest ties to the 802.11ad is the 802.11ac-2013: “Enhancements for Very High Throughput for Operation in Bands below 6 GHz”. It was approved nearly a year later than 802.11ad, on 11 December 2013; however, both were originated from the same 802.11 Very High Throughput (VHT) Study Group (SG). VHT SG was originated in May 2007 to further develop the throughput advancements achieved by 802.11n-2009: “Enhancements for Higher Throughput”. Operation in 40 MHz channels was introduced in 802.11n. The next step would be 80 MHz channels, but, because there is not enough bandwidth within the whole 2.4 GHz band, as it includes thirteen 5 MHz channels whose center frequencies uniformly increase from 2412 MHz to 2472 MHz, 802.11ac focused solely on the 5 GHz band. This spectrum search of the SG also led to another standard: 802.11ad.

Setting the aim as even higher throughput, 802.11ac instituted many new features. Highest modulation is increased from 64-ary quadrature amplitude modulation (64-QAM) to 256-QAM. According to the new channelization, 80 MHz and 160 MHz contiguous and 80+80 MHz non-contiguous channels are defined. DL multi-user multiple input, multiple output (DL-MU-MIMO) technique is introduced, which allows an AP with multiple antennas to transmit to multiple STAs over the same spectrum. In the standard, maximum number of users and spatial streams per user are limited to 4, whereas maximum total number of spectral streams is limited to 8 for the DL-MU-MIMO. Putting together all the mechanisms, the VHT MCS of 256-QAM, 5/6 forward error correction coding rate, 8 spatial streams and 400 ns guard interval over a 160 MHz contiguous or 80+80 MHz non-contiguous channel results in the maximum theoretical data rate of 6933.3 Mb/s.

To conclude, the currently in-process and published but unincorporated amendments are given in Table 3.2.

Table 3.2: In-process and published but unincorporated IEEE 802.11 amendments

Project	Title	Final Approval
802.11bb	Light Communications	<i>predicted</i> July 2021
802.11ba	Wake Up Radio	<i>predicted</i> September 2020
802.11az	Next Generation Positioning	<i>predicted</i> March 2021
802.11ay	Next Generation 60GHz	<i>predicted</i> December 2019
802.11ax	High Efficiency WLAN	<i>predicted</i> December 2019
802.11aq	Pre-Association Discovery	14 June 2018
802.11ak	General Link	8 March 2018
802.11aj	China Millimeter Wave	24 January 2018
802.11ah	Sub 1 GHz	7 December 2016
802.11ai	Fast Initial Link Setup	7 December 2016

3.3 The 60 Gigahertz Band

The unmatched 9 GHz of unlicensed spectrum makes many data-intensive applications viable, however this comes at the cost of very poor EM wave propagation properties. While intensive signal degradation is useful for some specific attributes like frequency reuse, it primarily reduces the signal-to-noise ratio (SNR), thus decreasing the coverage and link quality. In Fig. 2.2 the specific attenuation up to 275 GHz due to dry air and water vapor under standard atmospheric conditions of 15 °C, 1013 hPa and 7.5 g/m³ water vapor density, and calculated according to the Recommendation ITU-R P.676-9[22], is illustrated. When the figure is examined the four local maxima are seen to be occurring at 22.748 GHz with 0.196 dB/km, 59.755 GHz with 15.225 dB/km, 118.788 GHz with 2.065 dB/km and 183.376 GHz with 28.7 dB/km. Comparing these frequencies with the assigned ISM bands in Table 2.1, it can be concluded that actually the bands with the locally worst transmission characteristics, thus having little or no economic value, are released for open use.

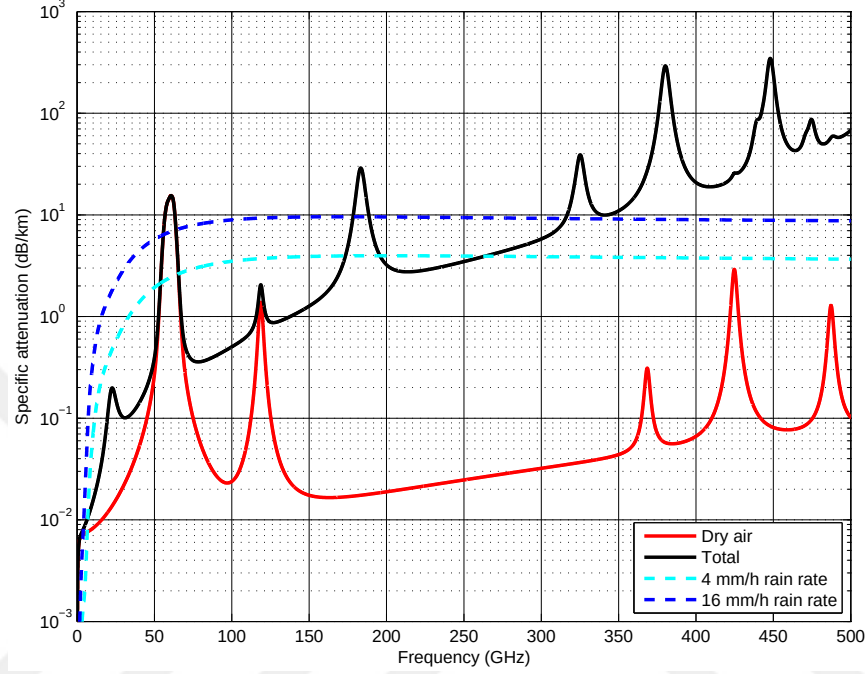


Figure 3.1: Attenuation due to atmospheric gases and rain, calculated up to 500 GHz and for rain rates of 4 and 16 mm/h, as per ITU-R P.676-9 and P.838-3.

Recommendation ITU-R P.676-9 offers two calculation methods for the atmospheric attenuation. The first and the exact one is a summation of the main factors, which are the resonance lines of oxygen and water vapor, and secondary factors. The resulting attenuations are shown in Fig. 3.1 up until 500 GHz. The other technique possesses less calculation complexity and provides an approximation of the correct results calculable by the first method within the 1-350 GHz range.

Accepting the outcomes from the first method as true values and the second method as estimations, Fig. 3.2 provides the absolute and squared errors at each 1 MHz apart points up to 350 GHz, together with the absolute error percentage and mean squared error, which is computed to be 0.007035 dB/km, again, throughout the range.

The maximum difference between the two methods occur at 59.16 GHz as 0.7685 dB/km. As expected, local maxima of the errors and gaseous attenuation overlap. Absolute error percentage, which is calculated by dividing the absolute error to the

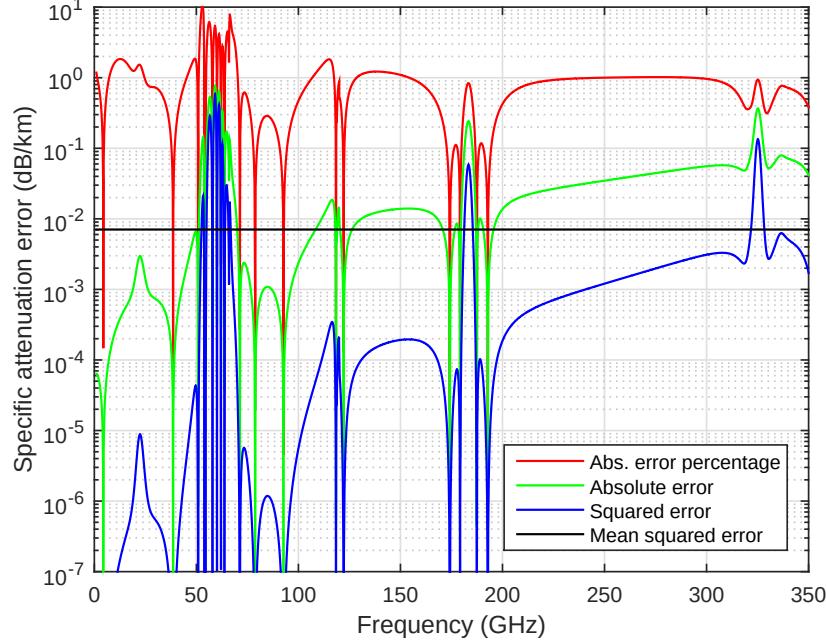


Figure 3.2: Absolute and squared errors, absolute error percentage and the mean squared error between the two atmospheric attenuation calculation methods provided in the ITU-R P.676-9.

true attenuation value at each point, is at most 10.7454% at 53.007 GHz and generally around or below 1%. Therefore, the second and computationally less intensive method can be preferred to the first one everywhere within the 350 GHz range, except for the 60 GHz band, where the absolute error peaks and the error percentage average over the 9 GHz spectrum escalates to 2.7712%.

In Fig. 3.3 emphasis is given on the specific attenuation until the local minimum of 78.002 GHz. Additionally included in the figure are the attenuations due to rain for rates of 4, 16 and 25 mm/h, representing moderate, heavy and very heavy rain categories, respectively. Recommendation ITU-R P.838-3[31] provides the procedure to calculate the specific attenuation due to rain for frequencies up to 1 THz and in the figure vertical polarization is assumed. According to the recommendation, general behaviour of rain attenuation between 1 and 1000 GHz can be described as a decelerating curve that almost flatlines around and after 100 GHz.

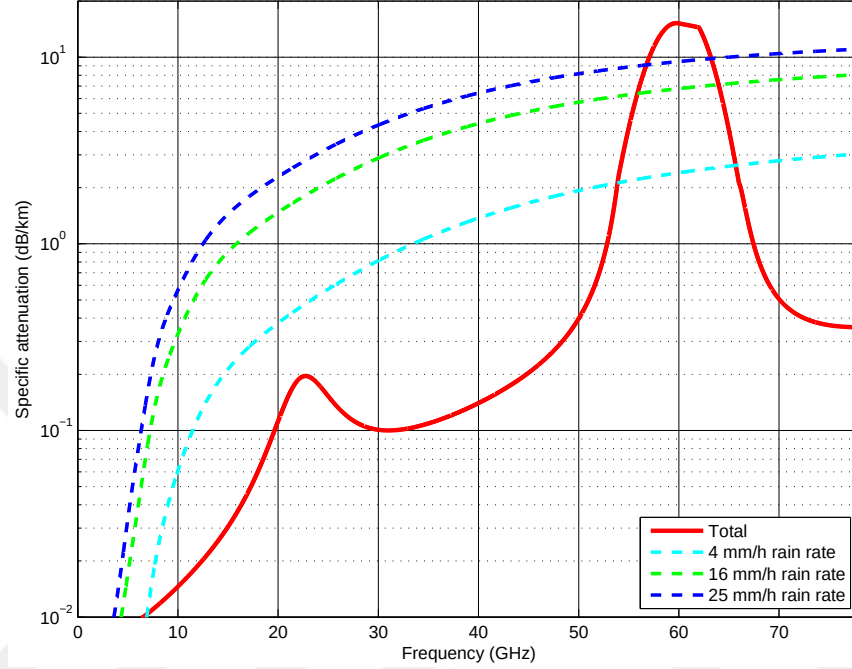


Figure 3.3: Specific attenuation due to atmospheric gases and rain, calculated up to 78.002 GHz and for rain rates of 4, 16 and 25 mm/h.

When the properties of EM wave propagation in 60 GHz is compared with the 2.4 and 5 GHz bands, the main difference is seen to be the additional free-space losses of 27.96 and 21.58 dB, respectively, for the same transmission distances. At 60 GHz attenuation by atmospheric gases is nearly 15.17 dB/km whereas this is virtually non-existent for the 2.4 and 5 GHz bands. In-building material absorption is also larger at 60 GHz[33, 63, 64]. When all these greater losses for 60 GHz are combined it can be inferred that multipath contributions would be limited and highly directive antennas are necessary to maintain reliable communication links.

One of the main steps towards standardization of a new frequency band is channel modelling, and as two 60 GHz wireless personal area network (WPAN) standards, ECMA-387[21] and IEEE 802.15.3c[27], are available since December 2008 and October 2009, respectively, together with the only WLAN standard for 60 GHz, IEEE 802.11ad[28], which is ratified in December 2012, propagation studies are comparatively advanced. Presently the IEEE 802.11ad channel model[65] is commonly used

as the benchmark for comparison by newly proposed models. The model adopts ray clustering and defines two sets of parameters for intercluster and intracluster characteristics, together with extension for polarization impact support. The intercluster parameters consist of amplitude, time of arrival and azimuth and elevation angles of arrival and departure, whereas intracluster parameters model a central ray with fixed amplitude surrounded by precursor and postcursor rays, and therefore contains the number of rays and rays' K-factors, power decay times, arrival rates and amplitude distributions.

3.4 Indoor Simulations

Low-cost mm-wave device technologies based on silicon and complementary metal-oxide-semiconductor are recently surging with output powers of different implementations are yet to reach adequate levels. Moreover, since the primarily envisioned benefit of 60 GHz utilization is expected to be extremely high peak data rates that are comparable to the current wired communication standards, it is appropriate to compare current 4G systems with proposed mm-wave 5G system in a deployment scenario where data rate maximization is intended. Correspondingly, out of the four test environments defined in report ITU-R M.2135-1[66], indoor test environment with indoor hotspot deployment scenario matches the assessment purposes.

The scenario, as described in the said report and based essentially on [67], contains one floor of a building with 16 rooms, which are divided equally between each side of the corridor that is $120\text{ m} \times 20\text{ m}$. The rooms are $15\text{ m} \times 15\text{ m}$ apiece and the height of the floor is 6 m. Two base stations (BSs) are planned for the scenario, placed in the middle of the corridor and 30 metres away from the ends of the floor. In line with this plan, for the simulation, authors' laboratory and the part of the hall directly in front of the room is selected as a real world example. Only one room is selected because at 60 GHz in-building material absorptions together with attenuation due to atmospheric gases are high enough to severely limit the coverage of a mm-wave band BS, thus also constraining the access network architecture accordingly. Furthermore,

the choice of the limited part of the hall included in simulations is due to the room-corridor measurement results provided in [67]: Additional walls to be propagated beyond the front of the room cause a leap in path loss (PL).

The authors' laboratory has dimensions of 12.12 m $\times$ 11.64 m $\times$ 3.26 m. It is separated from the hall with a 0.2 m thick wall that is constructed of sand-lime brick having a 1.82 m wide high-density fibreboard (HDF) door and the hall is 2.8 metres across. For the simulations one BS, located exactly on the centre point of the ceiling, is presumed. 4G simulation is shaped according to the baseline configuration parameters provided in [66] for the indoor hotspot scenario: Total transmit power of the BS is assumed to be 24 dBm with no antenna gains anticipated at either BS or user equipment (UE), and noise figures for the BS and UE are taken to be 5 and 7 dB, respectively. Bandwidth is taken on the large side with 100 MHz and carrier frequency is selected as 3.5 GHz, which is the midpoint of the highest allocated frequency band for mobile services, 3400 - 3600 MHz, by ITU's Radio Regulations, Edition of 2012. Temperature is assumed to be 15 °C for the noise power spectral density calculations and system margin is accepted to be 10 dB. Signal-to-noise ratio (SNR) is calculated for comparison in both simulations and for the 4G case respective line-of-sight (LOS) and non-line-of-sight (NLOS) PL models from [66] are employed, which, with d being distance in meters and f_c being carrier frequency in GHz, are:

$$PL_{LOS} = 16.9 \log(d) + 32.8 + 20 \log(f_c), \quad (3.1)$$

$$PL_{NLOS} = 43.3 \log(d) + 11.5 + 20 \log(f_c). \quad (3.2)$$

5G mm-wave simulation parameters, on the other hand, are constrained by the available literature on the subject. One useful document is the channel models that are developed for the IEEE 802.11ad standardization process[68] and the LOS PL model of the conference room STA-AP sub-scenario, which is provided below, is used for the simulations:

$$PL_{LOS} = 20 \log(d) + 32.5 + 20 \log(f_c). \quad (3.3)$$

In line with the operating classes defined in IEEE 802.11ad, the first channel set which

starts at 57.24 GHz is selected for the 5G simulations, together with the common bandwidth of 2160 MHz. Unlike 4G case, since official guidelines are not available for mm-wave simulations, for the sake of accuracy power parameters are selected from the mm-wave transmitters (TXs) which are currently available for purchase. One such TX is Hittite Microwave Corporation's model HMC6000LP711E[69], which has 16 dBm transmit power and 7.5 dBi antenna gain, and these values are used in simulations with antenna gain assumed at both TX and receiver ends. For comparison objectivity noise figures are not changed, however system margin is assumed to be 5 dB since antenna directivity reduces the likelihood of unanticipated events. To detect the hall power levels, ray tracing approach is appended to (3.3). According to Lambert-Beer's attenuation law, the intensity of a beam propagating through an absorbing medium can be expressed with

$$I_2 = I_1 \exp \left(- \int_{P_1}^{P_2} \alpha(\mathbf{r}) dl \right), \quad (3.4)$$

where the absorption coefficient α varies along the position vector $\mathbf{r}$, which is extended over a distance of l between the points P_1 and P_2 . For the simulations the absorption coefficient is assumed to be constant, reducing (3.4) to

$$I_2 = I_1 e^{-\alpha l}. \quad (3.5)$$

Since comprehensive mm-wave characterization of building materials are not currently available in literature and considering the fact that absorption coefficients of brick and wood does not tend to alter much below 100 GHz[63], the absorption coefficients available for 100 GHz, which are 171 and 185 m^{-1} for sand-lime brick and HDF[64], respectively, are used for the simulations. A summary of the simulation parameters is provided in Table 3.3.

3.5 Performance Evaluation

The simulations are run for each 1 cm^3 volume within the defined laboratory and hall area, and results are provided for two different heights: 0.75 m, representing the

Table 3.3: Simulation parameters

Quantity	4G		5G
Transmitting power	24	dBm	16
TX antenna gain	0	dBi	7.5
RX antenna gain	0		7.5
Carrier frequency	3.5	GHz	58.32
Noise bandwidth	0.1		2.16
BS noise figure	5	dB	5
UE noise figure	7		7
System margin	10		5

average height of a desk within an office room and covering fixed communications, and 1.75 m, representing the ear level of a standing person and covering mobile communications.

3.5.1 Received Power

In Fig. 3.4 received power outcomes of 4G simulation are provided for both heights, using the same colour scale. For visualization purposes received power inside the wall and door is matched to the lowest power level within the respective planes for all the figures in this section, thus the wall and door indent are clearly visible in Fig. 3.4. As expected, the power levels gradually decrease as the distance to the BS increases, and since Fig. 3.4b is closer to the BS, the power levels are higher for the $h = 1.75$ m case.

5G simulation results for power outcomes are presented in Fig. 3.5. For better illustration different colour scales are used between the figures. When Fig. 3.5a is reviewed in detail, firstly a power difference of nearly 20 dB can be noticed for the laboratory area between the 4G and 5G cases. The maximum received power is -44.81

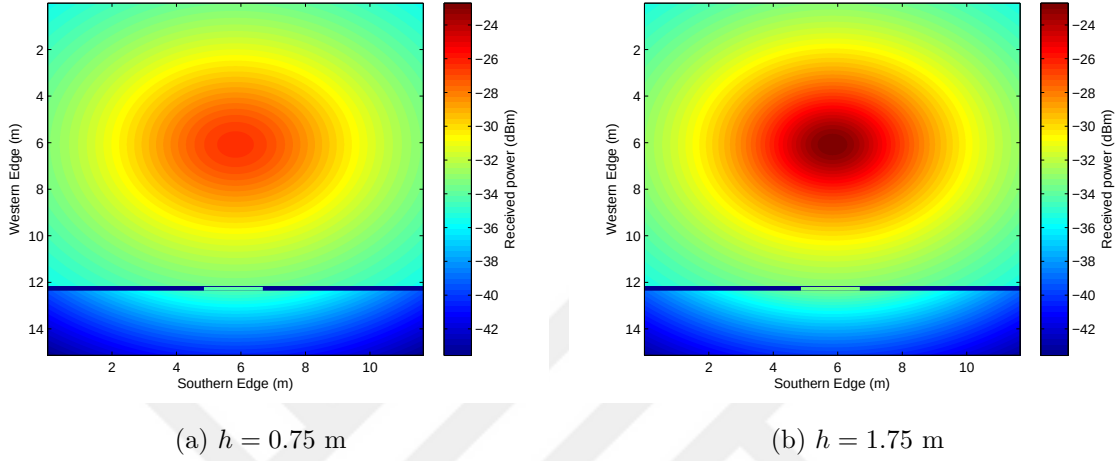


Figure 3.4: Received power outcomes of 4G indoor hotspot deployment simulation, displayed for two different heights.

dBm for 5G simulation and the power drop is in line with the additional free-space loss for 60 GHz which is explained in Section 3.3. The second consideration is the very high power difference between the extremes of the result. The minimum received power stands at -269.22 dBm, setting the power difference on the order of the immensely high 220 dB, and the absorption through the wall is the main reason for this. Although exact ray tracing with true refraction angles is conducted for simulations, to provide a general idea on the effect of material absorption, according to (3.5), propagation through 20 cm of sand-lime brick causes a loss of 148.53 dB, whereas 4 cm thick HDF door reduces the power by 32.14 dB. These facts clearly demonstrate the coverage boundaries for the 60 GHz communication systems: Unless the rooms are parted with thin materials having low absorption coefficients, the coverage is confined within one room and a different BS or access point is required for each room which is to be included in the network. Third aspect to contemplate is the trapezoid shape occurring behind the door. The reason is, rays passing through the top of the door form a much wider horizontal angle compared to the ones directly hitting the door on the $h = 0.75$ m plane, and so spread over a longer line.

To demonstrate power distribution better, in Fig. 3.5b wall propagated hall area

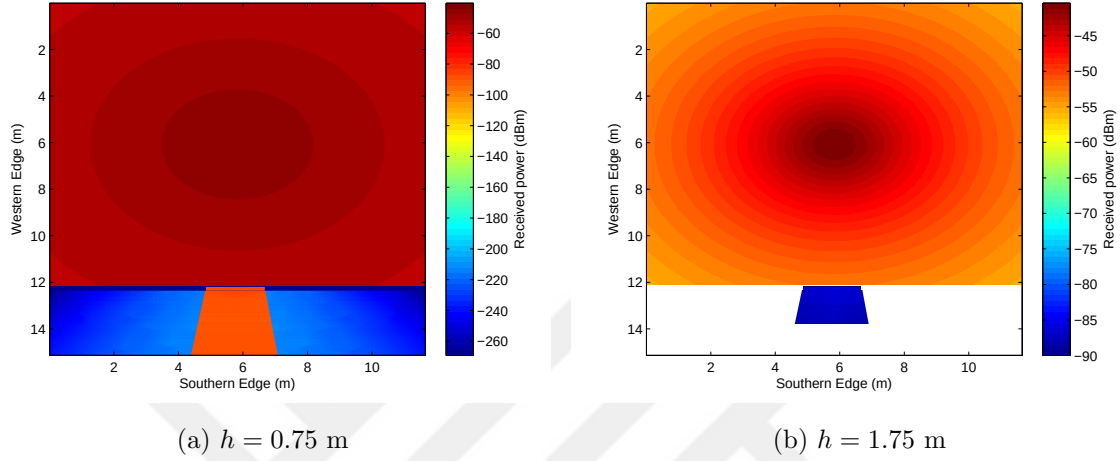


Figure 3.5: Received power outcomes of 5G mm-wave simulation, displayed for two different heights.

is left out, and the colour scale is set between the maximum received power of -40.4 dBm and -90 dBm, where the minimum of the remaining of the 1.75 m plane is nearly -89 dBm. Tighter colour scale makes the nearly 35 dB loss caused due to absorption by the door easier to notice. One other difference between the received power results of 5G simulations is the smaller trapezoid area on the $h = 1.75$ m plane. Although the hall is 2.8 m across, since the door is only 2.09 m long, rays originated from the BS that is 6.06 m away on horizontal axis and passing through the 0.36 m segment of the door are unable to cover the entire hall.

3.5.2 Signal-to-Noise Ratio

Remaining figures compare the SNR values between the 4G and 5G simulations. Fig. 3.6a shows the calculated SNR values for the $h = 0.75$ m plane of the 4G case. As can be seen from the plot, values range from 30 to 50 dB, which are much higher than the 14.9 dB required for successful transmission with 16-ary quadrature amplitude modulation (16-QAM) and bit error ratio (BER) of 10^{-6} . Here 16-QAM is chosen as the performance parameter since it is the highest defined modulation technique in the latest completed 3GPP specification, Release 11. The outcome for

4G is as expected since it is an accomplished technology with known end results. Fig. 3.6b, on the other hand, presents the SNR values of 5G simulation. Maximum SNR achieved is 18.85 dB, which is safely higher than the successful quadrature phase-shift keying (QPSK) modulated transmission with 10^{-6} BER limit of 10.78 dB. Although modulation techniques as high as 64-QAM are defined within the IEEE 802.11ad standard, since at 60 GHz QPSK is capable of providing a maximum data rate of 2079 Mb/s, for initial 60 GHz deployments QPSK performance can be accepted as satisfactory. However, SNR on the furthest point of the room within the 0.75 m plane drops to 8 dB. This clearly shows the necessity of high gain antennas and output power transmitters, even for in-room communications. With the wall propagated hall area again left out, SNR in the corridor ranges between -22.7 and -29.5 dB, the latter of which also is the end of the colour scale. As reliable communication is not possible at these rates, for practical use of 60 GHz band, alternative solutions, such as dual frequency operation with a lower band or constructing new buildings with wireless communications infrastructure just like water or energy infrastructures, should be employed.

Finally, Fig. 3.7 illustrates the SNR values for the $h = 1.75$ m plane. Apart from slightly higher values due to being closer to the BS, there is not any observable difference between Fig. 3.6 and Fig. 3.7.

3.6 Conclusion

In this chapter utilization of 60 GHz ISM band for the forthcoming 5G wireless communication systems is explored. Following a broad assessment on the current wireless and mobile communication networks, physical layer properties of 60 GHz band is explained. A realistic indoor simulation along the lines of ITU-R guidelines and commercial off-the-shelf circuitry is set for comparing present 4G and proposed 60 GHz 5G systems. From the results the suitability of 60 GHz for in-room communications can be deduced. However, the need for a novel indoor access network architecture to establish an uninterrupted communications link in 60 GHz band is also apparent.

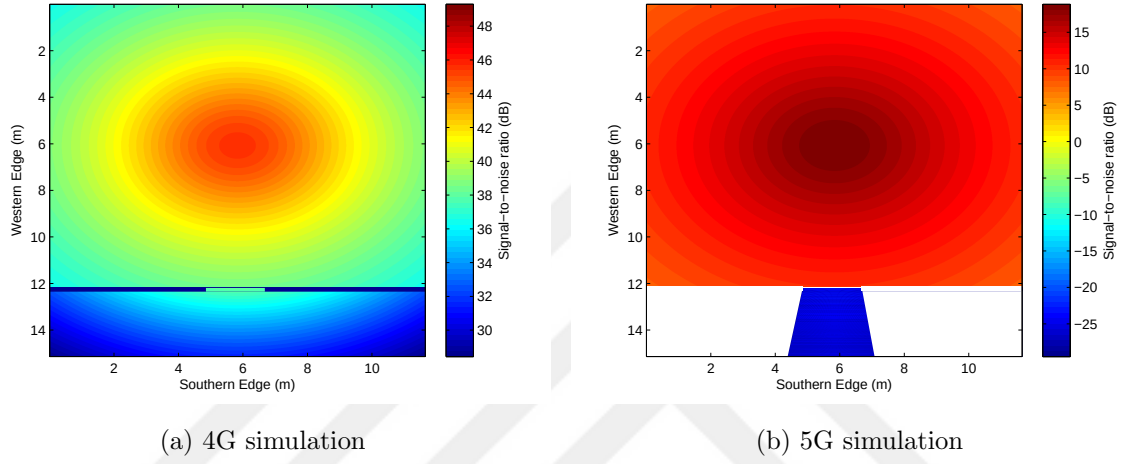


Figure 3.6: SNR outcomes at $h = 0.75$ m, displayed for both simulations.

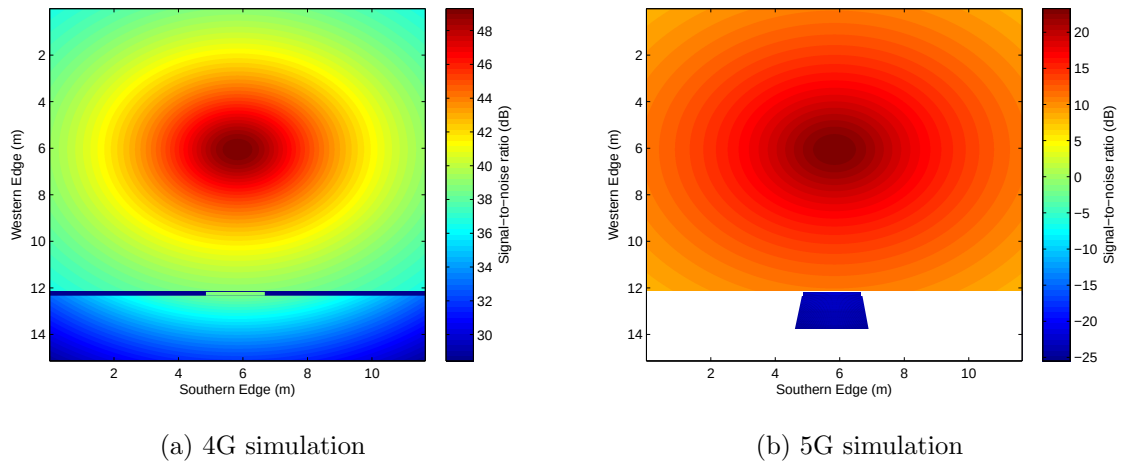


Figure 3.7: SNR outcomes at $h = 1.75$ m, displayed for both simulations.

Chapter 4

MILLIMETER WAVE COMMUNICATION FOR 5G IOT APPLICATIONS

4.1 Introduction

On our way to a connected world with smart devices, the ever increasing mobile data usage signals high data traffic amount for the near future. According to a recent white paper by Cisco Systems, global mobile data traffic increased 69% in 2014 and is expected to rise at a compound annual growth rate of 57% from 2014 to 2019 [70]. Hence, for fifth generation (5G) mobile communication systems, peak data rates on the order of 10 gigabits per second (Gb/s) are envisioned [16].

Furthermore, wireless communications are also currently on the verge of the next major evolution, the Internet of Things (IoT). IoT essentially introduces different number and types of devices, such as RFID tags, mobile phones and all kinds of sensors, to wireless networks, all of which are uniquely identified and capable of object-to-object communication. These equipments are able to communicate and cooperate with each other to achieve a given task without the need for human-to-computer interaction. As a result, the network and data traffic become things oriented, leaving the traffic generated by human interaction at a small percentage of the total [71].

Millimetre wave (mm-wave) band, covering 30 to 300 GHz which corresponds to wavelengths between 1 and 10 mm, offers large available bandwidths providing a way to achieve the required high data traffic and rates [38]. However, the characteristics of electromagnetic (EM) waves in this band introduce a number of challenges. If these are to be categorized under generic subjects such as latency, robustness or interference, it would mislead the mm-wave studies towards classical communication

problems. However, with 5G not only the vision of communication but also the definition of the problems gain a new dimension due to the higher frequencies, which are proposed to be used, have significantly different channel properties. These challenges do not have major effects on the conventional 2.4 GHz and 5 GHz wireless local area network (WLAN) channels. However, it is not the case for the 60 GHz industrial, scientific and medical (ISM) band, whose initial wireless personal area network and WLAN standards are already completed via the Institute of Electrical and Electronics Engineers (IEEE) 802.15.3c [27] and 802.11ad [28] standards, respectively, or the forthcoming low THz band communication bands such as 300 GHz [13].

For instance, free-space loss [72] faced in the mm-wave range is seen as one of the challenges that questions the practicality of mm-wave communication. This is, together with the effects of atmospheric absorption, why the mm-wave communication focuses on short distance communications. Hence, there is more emphasis on line-of-sight (LoS) path. Moreover, multipath propagation analysis differs from the previous generations and considers these challenges [73, 74], which are addressed in [75, 25, 76] introducing key mm-wave technologies, such as mm-wave multiple input multiple output (MIMO), beam forming, advanced antenna techniques including phased array antennas and femtocell structures.

Channel properties of both the lower [77] and higher [60] parts of the mm-wave spectrum are already extensively covered and available in the literature. Therefore, only an outline of the main properties of the mm-wave band is presented in the first section. Moving forward, when logical communication requests reach the physical layer (PHY), which is the first layer in the seven layer Open Systems Interconnection model, services describing the electrical, optical, mechanical, and functional interfaces to the physical medium are provided. Being responsible for transmission of the message over a physical link connecting network nodes, PHY design is directly affected by the nature of transmission medium and frequency. Operating in such high frequencies whose propagation characteristics are unlike sub 6 GHz bands, mm-wave PHY is an original and extensive research area. Continuing with the chapter, mm-wave PHY is

discussed under the three main topics: Modulation, error control coding and MIMO. After discussing the existing literature, conclusion part summarizes the major points. The chapter ends with the future research directions and open research issues.

4.2 Millimetre Wave Channel

The two main loss mechanisms of a LoS communication link are free-space path loss (FSPL) and atmospheric attenuation. The latter is quantified using the Recommendation International Telecommunication Union Radiocommunication Sector (ITU-R) P.676-9 [22], and the changes in the components of and total gaseous attenuations up to 275 GHz are illustrated in Fig. 2.2 for the standard ground-level atmospheric conditions [78]. The maximum total gaseous attenuation value is 2.89×10^{-2} dB/m at 183.374 GHz. This is 1.55×10^{-2} dB/m for the 60 GHz ISM band arising at 60.829 GHz, whereas, the peak attenuation value for sub 6 GHz bands is 9.57×10^{-6} dB/m. Therefore, while atmospheric attenuation is significantly greater in the mm-wave band, it is not high enough to have a meaningful effect in the link budgets of connections up to a few hundred meters. Furthermore, maximum rain attenuation quantities are 3.96×10^{-3} dB/m at 200.231 GHz, 9.58×10^{-3} dB/m at 171.611 GHz, and 1.99×10^{-2} dB/m at 146.389 GHz, for 4, 16 and 50 mm/h rain rates, respectively.

FSPL is computed using Friis' equation [79]. In Fig. 4.1, FSPL plots of exemplary carrier frequencies of 5, 30, 60 and 300 GHz are presented for transmission distances between 1 m and 1 km. As stated by the equation, a tenfold increase in the frequency causes a 20 dB rise in FSPL for the same node separation. This rise becomes 27.96 and 21.58 dB when the operation frequency is increased to 60 GHz from 2.4 and 5 GHz, respectively. Hence, mm-wave communication leads to a substantial amount of additional FSPL, which has to be countered in order to maintain consistent links.

Effects of non-line-of-sight (NLoS) propagation mechanisms are also different in the mm-wave band, compared to the legacy bands. While absorption coefficients of a number of materials are reported to increase with frequency [64], refractive indices essentially stay the same regardless of the changes in the frequency [32]. However,

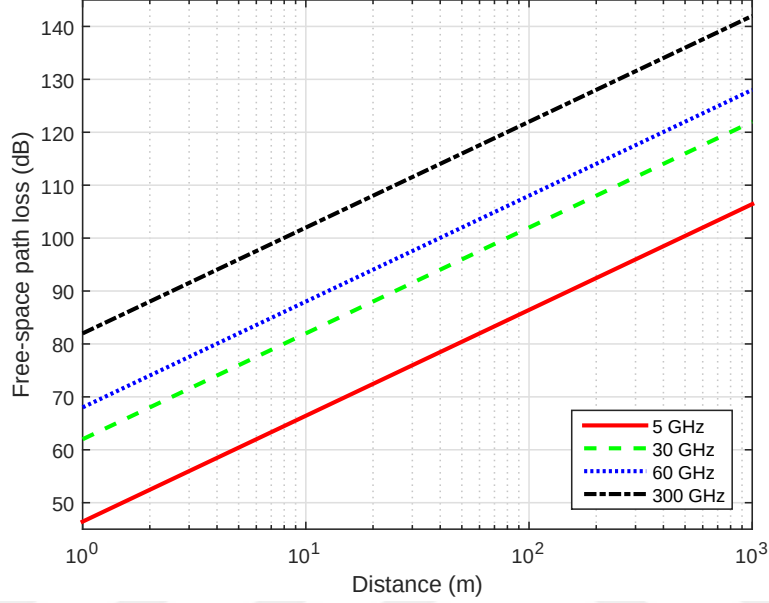


Figure 4.1: FSPL, calculated between 1 and 1000 m at 1 m intervals and for carrier frequencies of 5, 30, 60 and 300 GHz.

because the sizes of mm-wave wavelengths are comparable to the roughness of ordinary surfaces, power of reflected and scattered rays are reduced [80]. Diffraction is also demonstrated to be practically nonexistent in 60 and 300 GHz [34]. Overall, effective use of PHY techniques are necessary to overcome the decreased received power due to the weakened NLoS propagation.

4.3 Millimetre Wave Modulation

When high data rates are needed, orthogonal frequency division multiplexing (OFDM) is usually the first modulation scheme to be considered, owing to being well-known and already used for the LTE (Long Term Evolution). OFDM provides a way to lessen the multipath effects, achieve high data rates, and allows multiple users on a single channel. However, OFDM also suffers from shortcomings, about which many methods have been proposed. For instance, in [81] cognitive radio is considered together with OFDM. Performance evaluation of LTE access network is discussed in [82] where

single carrier frequency division multiple access (SC-FDMA) is used for uplink (UL) to overcome OFDM being asynchronous to the network. Moreover, with LTE-Advanced (LTE-A), OFDM is used together with MIMO techniques to further increase the data rates [83]. Hence, it can be argued that OFDM is also a strong candidate for the 5G systems. Though, it is not the only one. In this section, OFDM, filter bank multicarrier (FBMC), universal-filtered multicarrier (UFMC) and SC methods are examined. First three methods belong to multicarrier (MC) systems, where many subcarriers are used as parallel narrowband carriers instead of a single wideband carrier to deliver the message.

4.3.1 OFDM

OFDM is extensively studied due to its use in LTE systems and it is an important 5G technology candidate as a result of its resistance to multipath distortion and ease of implementation with fast Fourier transform (FFT) and inverse FFT (IFFT) blocks. Moreover, orthogonality of subcarriers reduces the effects of intercell interference and its ability to adapt to phase and frequency distortions allow OFDM to work with MIMO antenna techniques. Nevertheless, there are two disadvantages that need to be tackled. Firstly, high peak-to-average power ratio (PAPR) causes problems in the amplifiers by decreasing efficiency due to linearity concerns. Also, designing an amplifier that will avoid the distortion caused by the peaks occurring is a costly process [84, 85]. Secondly, since there are multiple subcarriers allocated next to each other, OFDM is sensitive to carrier offset and drift [86]. Cyclic prefix (CP) is used to avoid from this situation. Though, while introducing CP offers advantages such as creating a guard interval, it decreases spectral efficiency.

4.3.2 FBMC

FBMC, just like OFDM, belongs to MC systems and provides a solution to spectral efficiency problem. The main difference is, side lobes which create interference and error propagation are filtered out at FBMC. This way, a bandlimited signal that

increases spectral efficiency without CP is obtained. Although FBMC increases complexity, it also provides better subcarrier separation. Moreover, its ability to achieve network synchronization is crucial for 5G systems. As a result, while still using convenient FFT and IFFT blocks, like OFDM, UL and downlink (DL) synchronization problems are now eliminated [87, 88].

One other key aspect of FBMC is its compatibility to massive MIMO. FBMC-based massive MIMO systems enable self equalization, which introduces a number of benefits considering the reduced number of subcarriers, such as decreased latency and complexity, higher bandwidth efficiency and lower PAPR. Moreover, pilot contamination problem of massive MIMO is solved by the blind channel tracking property of FBMC [89].

4.3.3 UPMC

UPMC is another subclass of MC systems. It separates from FBMC in that, while FBMC uses filtering on each of the subcarriers, UPMC applies filtering to some subset of those [90]. Hence, UPMC offers better spectral efficiency and robustness compared to OFDM [86, 91]. Also, since filter length decreases, UPMC possesses lower latency advantage over FBMC [91, 92].

4.3.4 SC

MC systems, especially OFDM, have been enjoying a huge popularity due to their many advantages and ease of implementation. On the other hand, in addition to employing just one wideband carrier, SC has another major distinction. In MC systems, equalization and decision take place in the frequency domain, whereas in SC systems decision takes place in time domain using an IFFT block subsequent to equalization, and this increases complexity [93]. Though, with the recent advancements in electronics, high performance and low complexity equalizers operating in the frequency domain became available, raising the interest in SC techniques even further [94].

SC frequency domain equalization (SC-FDE) and SC-FDMA can be considered

Table 4.1: Comparison of Millimeter Wave Modulation Techniques

Property	OFDM	FBMC	UFMC	SC
<i>PAPR</i>	High	High	High	Low
<i>Latency</i>	High	High	High	Low
<i>Ease of implementation</i>	High	Low	Low	Low
<i>Spectral efficiency</i>	Low	High	High	High
<i>Overhead</i>	High	Low	Low	Low
<i>Bit error ratio</i>	Good	Good	Very good	Depends on SNR
<i>Synchronization error robustness</i>	Low	High	High	Low
<i>Compatibility with MIMO</i>	High	High	High	High

as the linearly precoded OFDM scheme and its multiple access counterpart. The most important advantage of SC over MC is its low PAPR values. For this reason, in [82], SC-FDMA is used for UL communication to achieve reduced cost for the power amplifier and transmit power efficiency by making use of the low PAPR. Finally, SC is also able to cope with spectral nulls and provide robustness against frequency offset [95].

4.3.5 Evaluation

Authors' direct comparison of some of the important properties of the aforementioned mm-wave modulation methods are given in Table 4.1. Additional assessments are also available in the literature [84, 85, 86, 89, 4, 96, 97].

4.4 Millimeter Wave Channel Coding

Channel coding adds redundancy to the data sequence in terms of extra bits, like parity bits, in order to increase the reliability of the transmission. The encoded sequence is decoded at the receiver (RX) to extract as much correct information as possible to detect the errors and, possibly, correct the erroneous bits. This process inevitably con-

sumes bandwidth and computational power consumption may also become a serious concern if not considered beforehand.

There are many ways to add the extra bits, which are termed as the channel codes. In addition to the selection of the code to utilize, a policy is needed to determine the approach after decoding. There are two such main policies: Forward error correction (FEC) and automatic repeat request (ARQ). FEC is used to detect and, if possible, correct the errors and ARQ causes the RXs to request for retransmission upon discovery of errors. Considering the high propagation loss nature of the mm-wave channel, the properties of the codes should be arranged in a way to attain the best possible performances for both error detection and correction. Moreover, combining the characteristics of the mm-wave channel with the IoT make 5G channel coding a very interesting and promising research area.

In the literature, both the performance evaluations of the existing channel codes applied to the 60 GHz ISM band and a number of new and promising codes proposed for the 5G, together with discussions of their capabilities, are available. To begin with, performance of low-density parity-check (LDPC) and convolutional codes for 60 GHz OFDM-based wireless communication systems are compared in terms of frame error rate and decoding hardware complexity. Generally, LDPC codes, which are also utilized for third (3G) and fourth generation (4G) mobile communication systems, are acknowledged for their high error correction performance and throughput, low latency decoding and adaptive rates [98]. On the other hand, convolutional codes offer reliable data transfer and high throughput is achieved through parallelization. Simulations showed that in both LoS and NLoS cases, LDPC provides higher coding gains than convolutional coding, which indicates that LDPC is a viable option also for the mm-wave band.

Recently propositioned channel codes include convolutional (spatially coupled) LDPC code, which can be interpreted as an enhanced version of the regular LDPC. Compared to block LDPC codes, convolutional error codes have similar performance in terms of bit error ratio. However, they offer lower decoding complexity and high

capacity for a wide range of rates [99]. Another category is the non-binary LDPC codes. These provide better performance at shorter block lengths and higher spectral efficiency, in return for increased computational complexity. Alternatively, polar codes not only achieve higher channel capacity but also demonstrate advantages when it comes to multi-terminal scenarios, like relaying and MIMO, which are crucial to the success of real world 5G deployments.

For the coding scheme, one of the proposals is type II hybrid ARQ (HARQ). In this scheme, message bits are either sent together with error detecting parity bits or only FEC parity bits are transmitted. Hence, FEC bits are transmitted only if retransmission is requested upon erroneous reception of the message. Moreover, consecutively received messages can be used to correct errors. Therefore, if the channel is good, type II HARQ can function as standard ARQ and achieve higher capacity. Additionally, when the channel is in a poor state, better throughput is achieved using FEC. These properties enable 5G channel codes to use different rates, i.e. adaptability, and rate compatibility.

4.4.1 Requirements for 5G

Iteratively decodable codes, such as turbo and LDPC codes are mainly used by 3G mobile communication systems. This type of codes have many advantages, like low encoding and decoding complexities and high error correction performance. With the 4G, the employed codes were essentially kept the same as LDPC, turbo and convolutional codes. Though, one 4G policy addition has been the introduction of HARQ [100, 101]. HARQ observes the channel condition and uses FEC or ARQ accordingly. Hence, HARQ allows to obtain the benefits of FEC over ARQ in poorer channel states. As 5G deployments begin, the channel is expected to be less stable and frequently exposed to interactions from highly mobile agents. Moreover, high signal degradation of the mm-wave channel would also cause additional problems. In view of these effects, the channel coding algorithms for 5G need to consider the following [102]:

- Robust and adaptive coding schemes,
- Low latency,
- Low complexity encoder and decoders,
- Flexibility in code block size and rates,
- Multi-terminal coding and decoding, and,
- Transmission and computational power efficiencies.

4.5 Millimetre Wave MIMO

MIMO antenna system is one of the most important enabling technologies of 5G. The main idea behind MIMO is employing multiple transmit and receive antennas which communicate on the same channel. Each RX antenna then collects both the direct and indirect components arriving from the multiple antennas at the transmitter (TX) side. Moreover, combining the advanced antenna methods, such as phased array antennas, together with the higher frequencies proposed for communications, antenna dimensions have reduced. In addition to this, due to higher path losses, frequency reuse potential in the mm-wave band is also very much improved compared to the legacy bands, which enables densification of the base stations (BSs), where each BS contains a large number of antennas. These antennas are used to serve multiple co-channel users, which is labelled as massive MIMO [103].

MIMO is mainly divided into two categories: Single user (SU) and multi-user (MU) MIMO. In SU-MIMO, there are one TX and RX communicating with each other, and an exemplary 4×4 SU-MIMO antenna configuration is illustrated in Fig. 4.2a. Alternatively, for the MU-MIMO, there may be multiple RXs communicating with the same TX. An MU-MIMO example depicting two RXs is also presented in Fig. 4.2b. MU-MIMO presents some important properties, which can be listed as increased data rate, enhanced reliability, improved energy efficiency and reduced interference [104].

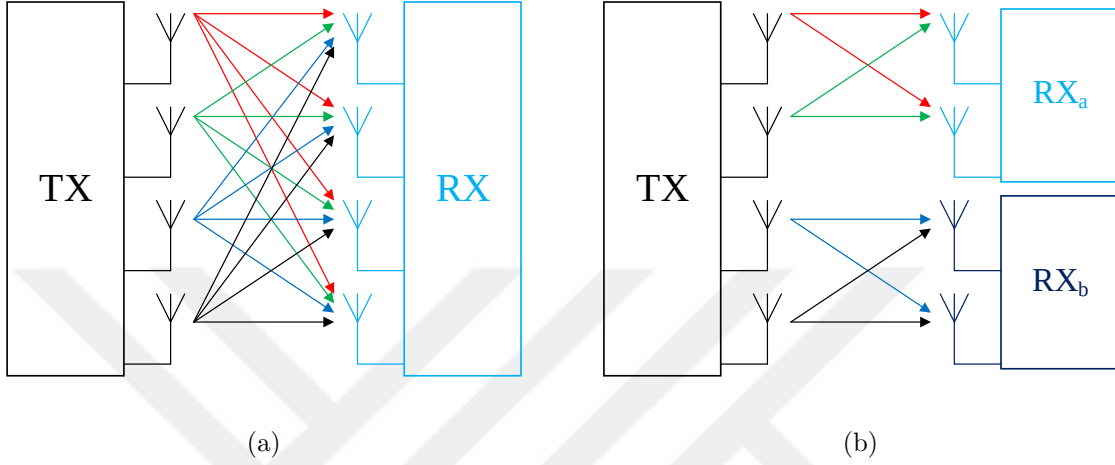


Figure 4.2: (a) SU-MIMO and (b) MU-MIMO structures.

These benefits were decisive for the inclusion of MU-MIMO into LTE-A standard [105]. However, in order to be adopted by the IoT applications of the beyond 4G (B4G) systems, further improvements are necessary.

As the carrier frequency is increased to the mm-wave range, 5G operation bandwidth gets larger too. Also, since the wavelength is reduced, antennas with smaller aperture areas are now able to provide the same amount of directivity as before, which allows decreased antenna sizes. Therefore, dense deployments of high capacity small cells can utilize the new ample bandwidths very efficiently. Moreover, as the number of antenna array elements increase, they become able to focus energy into smaller areas too. This is the general way MIMO increases throughput and lowers radiation power, leading to energy efficiency for 5G systems [104]. Massive MIMO also fits this process very well. It scales up the standard MIMO to a few hundred antenna array elements and allows simultaneous transmission to multiple terminals in the same time-frequency resource using spatial multiplexing and beam forming techniques.

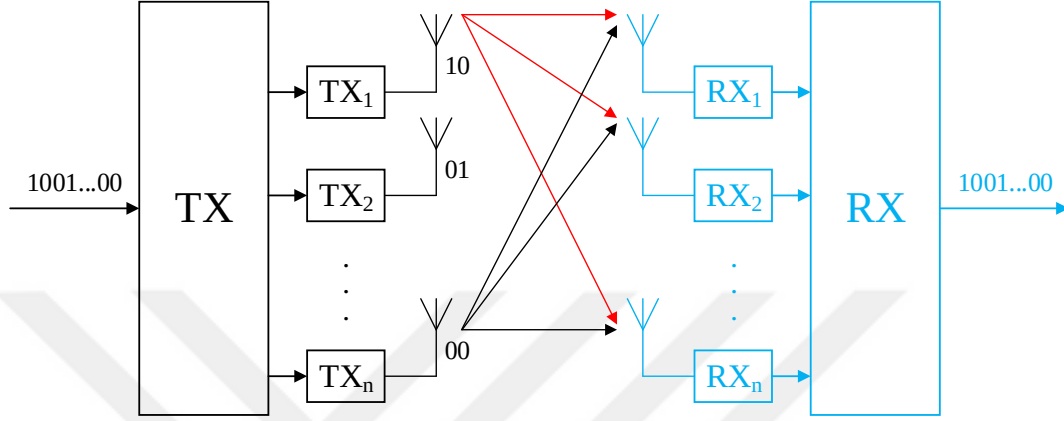


Figure 4.3: Outline of spatial multiplexing method.

4.5.1 Spatial Multiplexing

There are many ways to send data from TX to RX. To increase the quality of transmission in terms of high robustness, high capacity and low latency, one method is making use of multiplexing techniques on the data stream. However, there usually is a trade-off between these parameters and thus, cannot be realized all at once. Therefore, the correct multiplexing technique should be selected among the options such as time, frequency, space or code, in consideration of the requirements of the application.

For 5G communications, increased channel capacity is the primary system target due to the expected peak data rates. This necessitates the use of space division multiplexing, or spatial multiplexing. In spatial multiplexing, data stream is divided to be transmitted over multiple independent channels in space using different TX and RX antenna pairs. An illustration of the technique is also presented in Fig. 4.3.

Spatial multiplexing is considered to be suitable with both the MIMO and 5G due to the rich scattering environment, large signal attenuation at higher frequencies and channel-unawareness due to high mobility within the indoor channels. For instance, if there were a channel-aware structure, then introducing only diversity without multiplexing would increase the system's robustness since the signal-to-noise ratio (SNR)

values at the RX side would rise. In that case, a linear increase in the number of antennas would lead to a logarithmic grow in the capacity due to Shannon's channel capacity theorem. However, this level of capacity expansion is not enough to meet the expectations from 5G. The mm-wave channels considered for 5G networks may encounter channel estimation problems more frequently than the previous generations. Because the number of receiving antennas exceed the number of transmitting ones in spatial multiplexing, a linear increase in the channel capacity occurs [106, 107]. Therefore, spatial multiplexing assists massive MIMO in terms of capacity expansion.

There are a number of difficulties which might restrain the performance of spatial multiplexing massive MIMO. First of all, if some of the data streams experience weak channel gains, the total multiplexing gain becomes limited by the spatial correlation. Secondly, spatial multiplexing increases the amount of sources, which may lead to interference problem in cellular systems [106]. Finally, to achieve a required level of SNR, diversity is employed together with spatial multiplexing, which leads to beam forming discussion.

4.5.2 Beam Forming

Beam forming institutes diversity to the MIMO structures using phased array systems. When the same information is radiated over multiple TX antennas, some modification in amplitude or phase is necessary due to the effective radiation pattern. In phased array systems, by altering the relative phases, signals transmitted in unfavourable directions are suppressed, whereas the rest are emphasized. In addition to increasing the signal power, beam forming helps with the interference problem too, if the channel state information (CSI) is available. The latter is also one of the challenges of beam forming in 5G systems [108].

There is a trade-off between robustness and capacity in MIMO systems. Independently, diversity is not capable of attaining the required channel capacity values and spatial multiplexing is not capable of reaching the necessary SNR quantities for 5G systems. Therefore, beam forming and spatial multiplexing should be used in MIMO

together to meet the demands of B4G applications.

4.5.3 Evaluation

Using spatial multiplexing and beam forming, massive MIMO offers a number of opportunities for 5G. The main advantages, besides reduced latency, increased robustness and simplified medium access layer [104], can be listed as follows:

- **Tenfold network capacity increase:** The capacity increase is obtainable by efficient use of spatial multiplexing, as explained in Subsection 4.5.1 [104, 106].
- **Radiated energy efficiency rise:** Massive MIMO uses very large number of antennas which are small in size. This allows highly directional energy radiation into very focused regions, which decreases the energy lost into space, and thus realizing higher energy efficiency [104]. In [109], UL power savings are analyzed while keeping track of spectral efficiency. It is concluded that massive MIMO is able to increase the spectral efficiency while simultaneously achieving energy efficiency with linear processing.
- **Availability of inexpensive, low-power components:** The major increase in the number of antennas required for massive MIMO structures compared to the conventional antenna arrays allows the use of cheaper devices in the designs. To begin with, high-power amplifiers can now be replaced by many low-cost amplifiers that output lower power. Moreover, massive MIMO architecture make some costly components redundant, like coaxial cables. In essence, the performance of regular antenna arrays depend greatly on all elements of the system, making highly performing devices expensive. Massive MIMO, on the other hand, relies on the sheer number of its antennas to overcome propagation problems rather than individual components, allowing the system to be constructed at much lower costs [104].

As for challenges, one important performance limiting problem for massive MIMO systems is pilot contamination. Channel estimation at the BSs are performed in the time division duplex mode by making use of the reciprocity between UL and DL pilots. At this point, the frequency reuse opportunity of mm-wave band, which is considered for the 5G networks, becomes complicated. Reusing the same band of frequencies results in the use of same pilot sequences. Hence, without any interaction, a BS would receive other terminals' CSI that share the same pilot waveform. This will lead to inter-cellular interference, which is termed as pilot contamination [110].

The effects of pilot contamination on communication links' performances are analyzed for different scenarios in the literature [110, 111]. It is shown that attainable data rates are limited due to it. Several solution methods, such as optimization of allocation of pilot waveforms, clever channel estimation algorithms and new pre-coding techniques, are also proposed in order to utilize massive MIMO as planned [104, 112, 113].

Another difficulty is the undetermined channel response to the large arrays. Because large and small scale fading effects can be different from the few antenna case, realistic channel measurements need to be carried out [104].

4.6 Conclusions

In this chapter, the use of mm-wave band for 5G IoT applications is examined. In general, path losses of different propagation mechanisms are increased in the mm-wave band. While OFDM is extensively and reliably used in current communication systems, modulation techniques with better spectral efficiency are needed to meet the data rate and network capacity requirements of B4G systems. Mm-wave channel coding is an active research area that does not currently exhibit a commonly favored solution for 5G. Theory of MIMO systems is thoroughly researched; though, real world massive MIMO implementations are distant. To sum up, utilization of mm-wave band is necessary for efficient IoT applications within 5G mobile networks, and correspondingly, the research efforts in the area continues to steadily intensify.

4.7 Future Research Directions

PHY open research issues can be summarized as follows:

1. Modulation schemes need to be evaluated simultaneously with other 5G technologies, taking into account compatibility within the communication system.
2. Massive MIMO has several problems to be solved before being deployed in actual networks, such as:
 - (a) Pilot contamination,
 - (b) Reciprocity calibration,
 - (c) Fast, distributed and coherent signal processing,
 - (d) Hardware impairments, and,
 - (e) Low-cost hardware manufacturing.
3. Proposed channel coding techniques for 5G need to be experimented and analyzed in a realistic test scenarios.

A further research topic for mm-wave 5G is Tactile Internet. Tactile Internet makes use of the expected decrease in latency within a reliable and secure communication link, aiming round trip delay of 1 ms [114]. When the latency is below this level, human perception cannot notice the delays in the audio and visual interactions. Thus, real time wireless control of objects becomes an achievable goal. In addition to the reliable obtainment of latency at levels this low, design of electronic circuitries that can process information at the increased amount and rates is another difficulty. However, when utilized properly, there are various areas Tactile Internet will be very beneficial to, including health care, traffic and smart grid applications, to name a few.

Chapter 5

ON THE USE OF THE MILLIMETER WAVE AND LOW TERAHERTZ BANDS FOR INTERNET OF THINGS

5.1 *Introduction*

Wireless communications have been experiencing a revolution since the introductions of the second generation of mobile communication systems and Institute of Electrical and Electronics Engineers (IEEE) 802.11 wireless local area network (WLAN) standards. During this period, peak data rate, network capacity and coverage area have all steadily increased. By the end of 2014, there were 2.9 billion Internet users [6], and 7.4 billion mobile connections [70]. This amount of widespread adoption resulted in the availability of low-cost communication equipment and maturity of communication techniques. As a result, the number of machine-to-machine (M2M) connections is expected to rise to 3.2 billion by 2019, achieving a 5-year compound annual growth rate of 45% [70].

Throughput and network capacity requirements from the beyond fourth generation (B4G) mobile systems are already difficult to accomplish within the highly congested sub 6 GHz bands, as the current spectral efficiency methods are very advanced. The soon addition of billions of new M2M links is also impairing. However, the device densification gives rise to shorter transmission distances, creating a suitable environment for the utilization of higher frequency bands where the greater path losses have traditionally been preventive of general communications usage.

Internet of Things (IoT) applications would benefit greatly from the extensive unused bandwidth within the millimetre wave (mm-wave) frequencies, which extend from 30 to 300 GHz. Ratifications of initial 60 GHz industrial, scientific and medical

(ISM) band standards are complete: The IEEE 802.11ad is the WLAN [28], and the IEEE 802.15.3c and ECMA-387 are the wireless personal area network (WPAN) standards [77]. The other mm-wave spectrum considered for utilization is the low end of the THz band. WPAN standardization activities are ongoing under the IEEE 802.15 THz Interest Group since 2008, and Task Group 3d since 2014.

To support our efficacy claim of mm-wave band for IoT applications, the line-of-sight (LoS) performances of two mm-wave communication links at separate spectrum are compared with mobile and wireless communication connections at legacy bands from channel capacity and bit rate perspectives. Theory behind the simulations are described in Section 5.2, and results are presented together with discussions in Section 5.3, before the chapter concludes. To the best of authors' knowledge, this is the first study that comparatively analyses the channel capacity and bit rate of 60 GHz and low-THz band links using formally approved models and in a setting meaningful for IoT services.

5.2 Channel Capacity and Bit Rate Simulations

The mobile channel is implemented according to the indoor hotspot deployment scenario from the International Mobile Telecommunications-Advanced (IMT-Advanced) evaluation guidelines [66]. Simulation bandwidth is 40 MHz, assigned between 3410 and 3450 MHz in line with [115]. IEEE 802.11ac is chosen for wireless links. The largest defined channel is 160 MHz wide; yet, due to the respective transmit spectrum mask, 158 MHz is utilized in calculations from 5171 to 5329 MHz [116].

The first IEEE 802.11ad channel, centred at 58.32 GHz is realized for one of the mm-wave links. Again, as per the transmit spectrum mask, operation bandwidth is 1.88 GHz rather than the whole 2.16 GHz channel spacing. Finally, low-THz band is modelled as the other mm-wave communication alternative. Since finalized regulations are unavailable, the first transmission window between 275 and 311.178 GHz, which covers 36.178 GHz of bandwidth, is used, as explained in [60].

The designated bandlimited communication channels in all instances are assumed

to experience white Gaussian noise. As a result, the channel capacities C in bits per second (b/s) are calculated using Shannon's famous formula

$$C = B \log_2 \left(1 + \frac{P_r}{N_0 B} \right), \quad (5.1)$$

where B is the band of the channel in Hz, P_r is the received power in watts (W) and $N_0/2$ is the noise power spectral density (PSD) in W/Hz. In order to present an entirely capacity evaluation, all transmissions are assumed to occur in single input single output systems, without considering the multiple input multiple output device availability for the conventional bands. Moreover, calculations are performed under standard ground-level atmospheric conditions [78] and only white thermal noise is incorporated into the noise PSD.

Frequency selectivity is inherent in radio communications, and mm-wave with its ample spectrum is no exception [117]. Therefore, to compute the accurate capacities, channel bandwidths are divided into 1 MHz blocks in all cases and the channels are assumed to be time-invariant and flat fading. With equal power allocated to each subchannel, the channel capacity then becomes

$$C(d) = \sum_i B \log_2 \left(1 + \frac{P_t A(f_i, d)}{N_0 B} \right), \quad (5.2)$$

where P_t is the transmitted power in W, and $A(f_i, d)$ is the channel path loss for a distance of d m and the center frequency of the subchannel f_i in Hz [118].

Path losses are computed according to the respective recommendations of the standards, except for the low-THz band where it is calculated as the sum of the free-space path loss (FSPL) and atmospheric attenuation [22]. IEEE 802.11ac instructs only FSPL [119], and the path loss models for the realized 4G [66] and IEEE 802.11ad LoS living room [68] scenarios are as follows in decibels (dB)

$$PL_{4G} = 32.8 + 20 \log_{10}(f_i/10^9) + 16.9 \log_{10}(d), \quad (5.3)$$

$$PL_{802.11ad} = 32.5 + 20 \log_{10}(f_i/10^9) + 20 \log_{10}(d). \quad (5.4)$$

Furthermore, bit rate calculations are based on the probability of a symbol error. Consistent with the IEEE 802.11ad standard [28], binary phase-shift keying (BPSK),

quadrature PSK (QPSK), 16-ary quadrature amplitude modulation (16-QAM) and 64-QAM modulations are simulated on all wireless links. A subchannel is only utilized if the attained average signal-to-noise ratio (SNR) per symbol γ_s is greater than the necessary γ_s for a particular symbol error ratio (SER) of a modulation type. Then, the bit rate R in b/s is computed by

$$R = B \log_2 M, \quad (5.5)$$

where M is the number of signal waveforms of a modulation method [39].

5.3 Results and Discussion

5.3.1 Channel Capacity

In Fig. 5.1, the changes in channel capacity of all the communication links with respect to the transmission distance for a transmitter (TX) power of 24 dBm, which is selected according to [66], are presented. Path length is limited to 100 m considering small cell networks. Being directly proportional to the available bandwidth, as evident from (5.2), channel capacities are ordered correspondingly. However, the capacity decline rate also increases with carrier frequency. When the capacities are proportioned by the channel bandwidths, IMT-Advanced becomes the best performing communication mode. The difference between any two links also monotonically increases with path length too. For example, while the unit channel capacity of IMT-Advanced is 1.332 times of the low-THz band at the first simulation iteration of 1 mm distance, this value increases to 3.843 at 100 m. These quantities also change from 1.024 to 1.187 and 1.189 to 2.01 for IMT-Advanced compared to IEEE 802.11ac and IEEE 802.11ad, respectively.

Fig. 5.2 illustrates the effect of transmitted power on the channel capacity over all four communication channels at distances of 0.1, 1, 10 and 100 m. Axis limits are set to the same values in both subfigures for easier assessment. While the capacity of the longer distance mm-wave band connections appear to deteriorate more rapidly with decreasing output power than their legacy band counterparts, that is not the

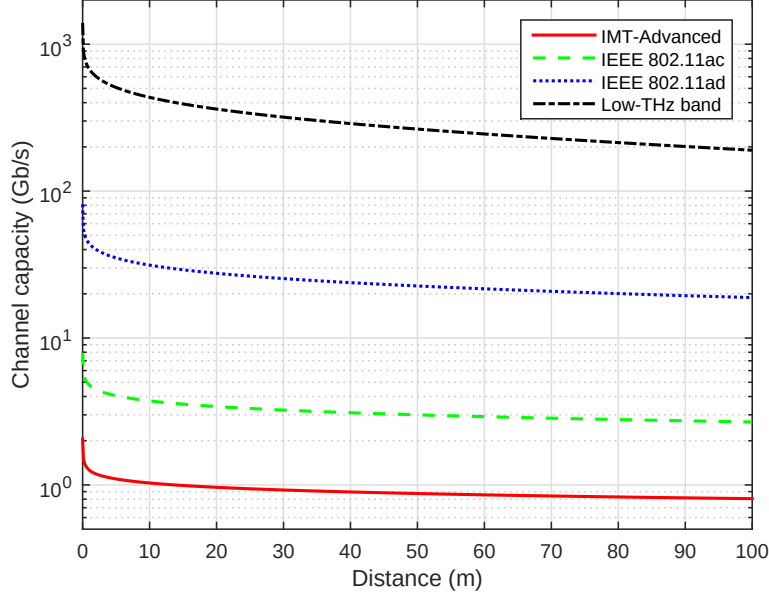


Figure 5.1: Channel capacity, calculated up to 100 m distance at 1 mm intervals.

case. In fact, the channel capacities decline linearly with the transmit power in dBm, barring the 100 m low-THz band link. Moreover, the differences between the extrema of the channel capacities are nearly constant for each band, irrespective of the path lengths. This situation also holds for the low-THz band, except for the part of the 100 m link where transmitted powers are lower than approximately 10 dBm. Taking into account the subsequent decrease in the channel capacity decline rate, that point indicates the beginning of the negative SNR values. These quantities vary between 0.31889 and 0.31891 Gb/s, 1.2592 and 1.2597 Gb/s, and 14.41 and 14.99 Gb/s, for IMT-Advanced, IEEE 802.11ac and IEEE 802.11ad connections, respectively.

5.3.2 Bit Rate

Fig. 5.3 and 5.4 demonstrate the achievable data rates in relation to the distance for the modulation techniques listed in Section 5.2 and SERs of 10^{-3} , 10^{-4} , 10^{-5} and 10^{-6} . Transmitted power is set at 12 dBm owing to the specifications of a commercially available 60 GHz band TX [120]. At all path lengths, IMT-Advanced and IEEE

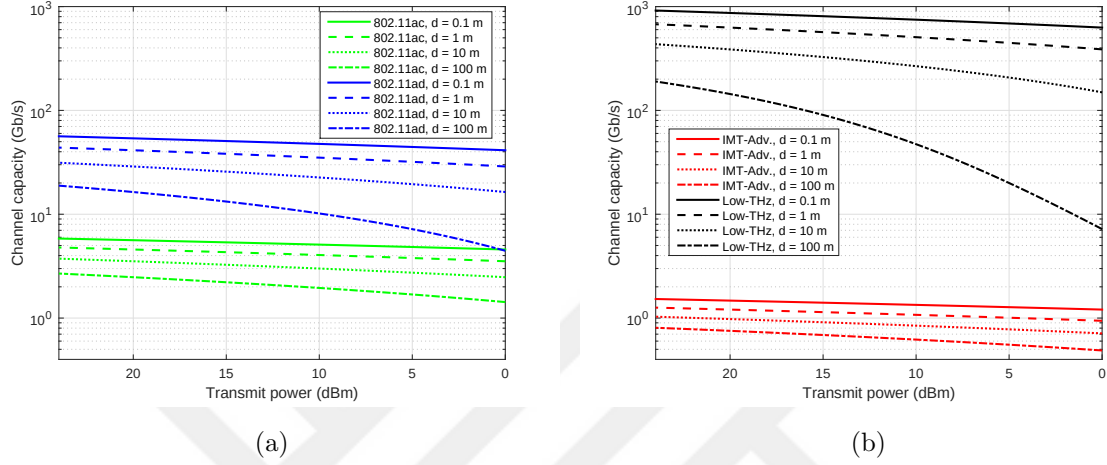


Figure 5.2: Channel capacity of (a) IEEE 802.11ac and 802.11ad, and (b) IMT-Advanced and low-THz band, calculated from 0 to 24 dBm transmit power at 0.001 dBm intervals and for path lengths of 0.1, 1, 10 and 100 m.

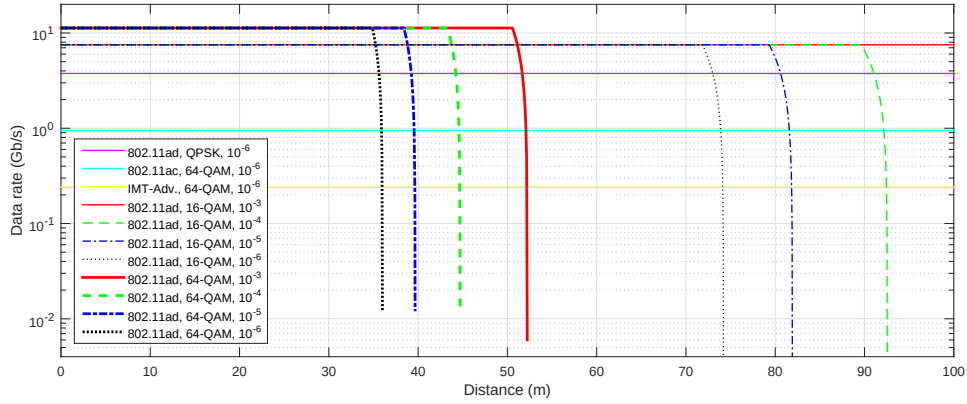


Figure 5.3: Data rates of IEEE 802.11ad connections, calculated for QPSK, 16-QAM and 64-QAM modulation techniques and SERs of 10^{-3} , 10^{-4} , 10^{-5} and 10^{-6} .

802.11ac links provide γ_s higher than the required minimum of 27.2 dB for the 10^{-6} SER transmission of 64-QAM modulation. Therefore, in the figures, conventional bands are represented only with the bit rate lines of this group, which have the values of 0.24 and 0.948 Gb/s.

Due to the number of simulations, IEEE 802.11ad and low-THz band curves are

Table 5.1: Maximum bit rate transmission distance limits

SER	IEEE 802.11ad		Low-THz Band			
	16QAM	64QAM	BPSK	QPSK	16QAM	64QAM
10^{-6}	71.844	34.865	43.865	30.482	13.606	6.642
10^{-5}	79.321	38.405	48.69	33.679	15.004	7.312
10^{-4}	89.617	43.29	55.518	38.084	16.924	8.236
10^{-3}	104.927	50.569	66.207	44.8	19.768	9.609

plotted separately in Fig. 5.3 and Fig. 5.4, respectively. Like the lower frequencies, γ_s of the 60 GHz connection is always above the QPSK modulation with 10^{-6} SER threshold of 13.79 dB for the distances spanned. However, this behavior ends with the 16-QAM. Same modulation techniques with different SERs are bundled up to the path length where the γ_s limit for the 10^{-6} SER is reached. Then, the packs branch out in ascending SER order, and shortly become unable to support the modulation-SER group. In Table 5.1, the distances where each remaining modulation-SER pair start to descend from the theoretical bit rate boundary are given.

The limiting path lengths are around 85 and 40 m for the 16- and 64-QAM IEEE 802.11ad connections, and in the region of 50, 35, 13 and 8 m for the BPSK, QPSK, 16-QAM and 64-QAM modulated low-THz band links, respectively. The corresponding peak data rates, which are 7.52, 11.28, 36.178, 72.356, 144.712 and 217.068 Gb/s, are one or two orders of magnitude greater than the sub 6 GHz bands. We showed that, device availability, transmission range and communication protocol are not problems for the 60 GHz ISM band, and the research on the low-THz band are continuing [16, 13, 35]. The excessive number of soon anticipated M2M connections will also greatly increase the LoS coverage area for the IoT applications, making the mm-wave links even more feasible.

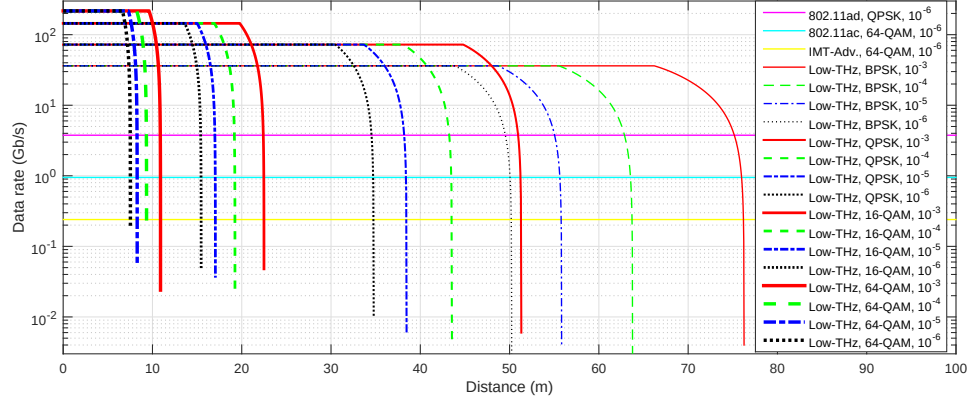


Figure 5.4: Data rates of low-THz band links, calculated for BPSK, QPSK, 16-QAM and 64-QAM modulation techniques and SERs of 10^{-3} , 10^{-4} , 10^{-5} and 10^{-6} .

5.4 Conclusion

Channel capacity and attainable data rates are examined in this chapter for 4 different legacy and mm-wave band links, using a simulation environment significant for the IoT applications. Lower frequency bands are more efficient in terms of channel capacity, which increases with transmission distance too. However, the amounts are incomparable to the effect of the vast spectrum available within the mm-wave band. Path length boundaries for maximum bit rate also decrease as the carrier frequency or modulation technique increases; though, the calculated distances are still useful for IoT services. For these reasons, mm-wave band is not just an option, but a performance improving enabling technology for the IoT.

Chapter 6

UTILIZING THZ BAND FOR LOCAL AND PERSONAL AREA WIRELESS COMMUNICATION SYSTEMS

6.1 *Introduction*

Humankind is going through the most connected era of its history due to the unending advancements in transportation and communications. Correspondingly, both the number of wireless connections and traffic volume per user is constantly increasing. The number of global mobile devices and connections grew to 7 billion in 2013 and this figure is expected to increase to 10.2 billion by the end of 2018, corresponding to a compound annual growth rate (CAGR) of 8% [121]. Global mobile data traffic also rose by 81% in 2013 and predicted to grow 11-fold within 5 years with a CAGR of 61% [121].

International Telecommunication Union (ITU) Radiocommunication Sector (ITU-R) named third generation mobile telecommunication systems as International Mobile Telecommunications-2000 (IMT-2000) and fourth generation (4G) as IMT-Advanced and the radio interface objectives of these are defined in the reports ITU-R M.1034-1[122] and ITU-R M.2134[2], respectively. Composed in 1997 to a different telecommunications environment where network integration was not existent, six service types, namely speech, audio, data, text, image and video, were defined for IMT-2000 with maximum data rate provisionally identified to be 20 Mb/s for data and video services and available for single cells. ITU-R M.2134, on the other hand, declares minimum downlink peak spectral efficiency to be 15 b/s/Hz and as bandwidths up to 100 MHz are encouraged for utilization, peak data rates of 1500 Mb/s are articulated for 4G systems.

This continuously increasing demand for wireless communications requires major throughput and capacity enhancements, the main methods for which are widely known: Increasing the spectral efficiency or operation bandwidth, or decreasing the signalling overhead. Spectral efficiency is the most explored, and thus, the most developed of the three, leading to smallest amount of return for any new research effort invested. Having an indirect effect, reduction in signalling overhead also cannot generate major improvements, leaving the operation bandwidth as the method to pursue. However, apart from the industry resistance towards changing the already established communications spectrum, there are also not many suitable frequency bands available for general communications purposes. Still, due to the unavoidable necessity, formal standardization activities on 60 GHz industrial, scientific and medical (ISM) radio band officially began in March 2005 with the formation of IEEE 802.15 Task Group 3c, and the first widespread commercial products under Wi-Fi Alliance's certification are expected to be available for purchase in 2015.

This chapter concentrates on increasing the carrier frequency, and thus, using more bandwidth to counter the higher data rate and volume demands of wireless communication networks. This work develops the analyses provided in [16] and, to the best of authors' knowledge, is the first study presenting realistic transmission simulations above 350 GHz, revealing the upper limit of realistic THz communications. With these aims, Section 6.2 sets up the simulations, Section 6.3 provides the performance evaluation and the chapter concludes with Section 6.4.

6.2 Indoor Simulations

Keeping in mind the narrow coverage submillimeter-wave (submm-wave) communication can offer, the author's laboratory and the corridor in front of the room is selected for simulation, the details of which are available in [16]. Due to the unavailability of transmission properties of many building materials in THz band, the walls are assumed to be clay brick (CB) and the door made of medium-density fibreboard (MDF).

THz simulation parameters are also further constrained by the available literature on the subject. Although research on THz band devices is on a sharp rise, for a technique to be suitable for adoption in wireless communication systems it primarily has to be inexpensive. At present only devices of silicon and complementary metal-oxide-semiconductor origin possess that requirement and this further narrows published solutions. To the best of authors' knowledge, a tunable signal source within low-THz range is able to radiate -1.19 dBm for output power at most [123]; therefore, transmit power for THz simulations is taken as 0 dBm.

Due to the additional free-space loss on the order of 40 dB occurring at low-THz band, a compensation has to be generated for viable THz communication links. Since transmitting power is decided upon, only antenna gains are left for solution. In the extreme case of lens use, leaving the half-power beamwidth consequence aside, a gain of 35.6 dBi is reported [124]; however, EM radiation power densities are regulated by respective authorities. For the case of Europe, European Telecommunications Standards Institute limit the mean equivalent isotropically radiated power (EIRP) to 20 dBm for the 2.4 GHz ISM band [14] and 20, 23, 27 and 30 dBm for different parts of the 5 GHz ISM band [15]. For the simulations, an EIRP of 23 dBm is assumed, thus setting the antenna gains on both ends at 23 dBi.

Four simulations are carried out, calculating the received power and signal-to-noise ratio (SNR). All simulations use the same parameters and environment, except for the increasing carrier frequency and the proportional noise bandwidth. Due to the available material properties data [64], simulation frequencies are set at 100, 350, 500 and 700 GHz. Taking a comparative approach to the communications standards on 60 GHz, which set channel spacing as 2160 MHz, bandwidths are selected to be 3.6, 12.6, 18 and 25.2 GHz, respectively. Noise figures and system margin are again chosen according to [16] and ground-level standard temperature and water-vapour density quantities are employed from [78].

Since there are no comprehensive channel or path loss models available for THz band, ray tracing technique is employed [125]. Received power (P_r) and SNR for

line-of-sight (LoS) situations are calculated, with d being distance in metres and f_c carrier frequency in Hz, using

$$P_r = (P_t + G_t + G_r) - \left(\frac{20 \log(4\pi d)}{(C_0/f_c)} \right) - (\gamma d 10^{-3}) \quad (6.1)$$

$$\text{SNR} = P_r - (N_0 + 10 \log(B) + \text{NF} + \text{SM}) \quad (6.2)$$

where P_t is transmitting power, G_t and G_r are transmitter (TX) and receiver (RX) antenna gains, respectively, N_0 is noise spectral density and B is the bandwidth employed. γ represents specific gaseous attenuation in dB/km, therefore, the 10^{-3} term added to convert d into km, and Fig. 6.1 illustrates the change in this attenuation with frequency for standard atmospheric conditions of 15 °C, 1013 hPa and varying water vapour densities of 0, 7.5 and 15 g/m³. The middle part of (6.1) is the Friss equation with C_0 being speed of light in free space in m/s and for non-line-of-sight (NLoS) an additional absorption loss is subtracted from (6.1), which is calculated using Lambert-Beer's attenuation law as detailed in [16]. Absorption coefficients (α) through walls and door are assumed to be constant and obtained from the respective values of CB and MDF as reported in [64]. The only coefficient that is not available, α_{CB} at 700 GHz, is interpolated to 1500 m⁻¹ using the respective graph illustrated in [64]. The simulation parameters overall are listed in Table 6.1.

6.3 Results and Discussion

The calculations are performed for each of the 1 cm³ volume within the described environment and results are provided for a representative height of 1 m. A summary of extrema of all simulations are presented in Table 6.2, where TN denotes thermal noise.

6.3.1 100 GHz

Received power and SNR results of 100 GHz simulation are provided in Fig. 6.2. Since there is a single source available, power, as expected, dissipates in a uniformly circular manner within the laboratory LoS region. The corridor, however, does not adhere to

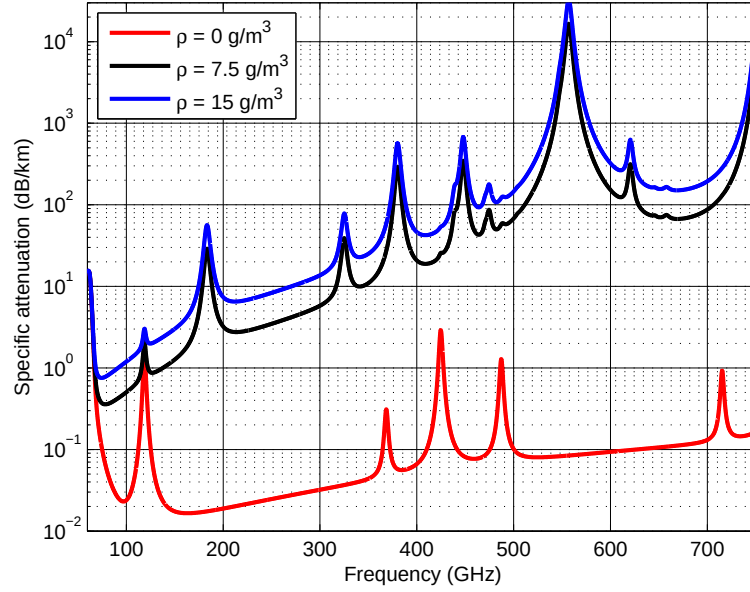


Figure 6.1: Attenuation due to atmospheric gases, calculated between 59.755 and 752.048 GHz, and for water vapour densities of 0, 7.5 and 15 g/m³.

Table 6.1: Simulation parameters

Quantity	100 G	350 G	500 G	700 G
Transmitting power		0 dBm		
TX and RX antenna gain		23 dBi		
BS noise figure		5 dB		
UE noise figure		7		
System margin		5		
Noise bandwidth (GHz)	3.6	12.6	18	25.2
α_{CB} (m ⁻¹)	86	482	916	1500
α_{MDF} (m ⁻¹)	116	461	779	1310

this explanation and requires the observation of SNR outcome which is illustrated in Fig. 6.2b.

Table 6.2: Simulation results

Quantity		Laboratory				Corridor		
		100 G	350 G	500 G	700 G	100 G	350 G	500 G
(P_r) (μ W)	min	0.0299	0.0024	0.001	0.0005	5.72×10^{-13}	1.83×10^{-63}	5.84×10^{-118}
	max	0.4435	0.036	0.0171	0.0087	0.0005	2.41×10^{-11}	2.19×10^{-17}
SNR (dB)	min	16.199	-0.214	-5.3552	-9.9078	-90.981	$\ll$ TN	$\ll$ TN
	max	27.911	11.566	6.7901	2.3624	-2.0154	-80.182	-142.14

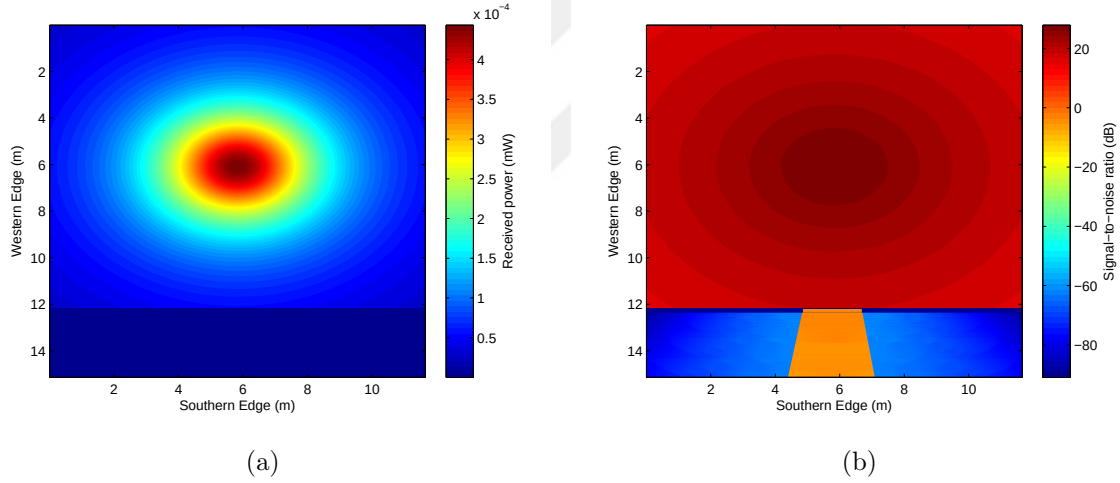


Figure 6.2: (a) Received power and (b) SNR performance of 100 GHz at indoor simulation for $h = 1$ m.

The first point to notice in Fig. 6.2b is the trapezoid shape, which is also present but unnoticeable in Fig. 6.2a due to very broad colour range. The reasons for this formation are the differences between the thicknesses and absorption coefficients of CB and MDF and the inclined electromagnetic (EM) waves that penetrate through the door to reach the $h = 1$ m plane. The SNR values within this semi-permeable region vary between -2 dB and -6 dB, whereas it is below -60 dB over the remainder of the hall.

The LoS laboratory area benefits from SNR values in the range of 16 dB to 28 dB. As successful wireless transmission with 16-ary quadrature amplitude modulation

(16-QAM) requires an SNR of 14.9 dB for a bit error ratio (BER) of 10^{-6} , within the laboratory a theoretical total throughput of 14.4 Gb/s, before signalling overhead, is possible. The requirement for an uncompressed high-definition video traffic utilizing 60 frames/s is just short of 2.8 Gb/s. Therefore, this setting is capable of supporting any wireless display applications within the range limits of wireless personal area networks (WPANs). Cables can also be replaced with this type of wireless transceivers since even the latest high-definition multimedia interface specification, version 2.0, sets maximum throughput per channel at 6 Gb/s [126]. Thus, all personal area network applications, ranging from local file transfer to docking functionalities, can theoretically be replicated via a carrier at 100 GHz frequency.

The NLoS corridor area, on the other hand, is incapable of supporting high data rate transmissions according to the performed simulation. A 100 GHz carrier traversing 1 cm thick CB loses 3.735 dB of its power, whereas this value is 5.038 dB for MDF. Considering simulated EM waves propagated through in excess of 20 cm of CB or 4 cm of MDF to reach the corridor, the proportionally increasing absorption losses emerge as the main reason for the stated inability. However, the two region outcome suggests the possibility of handover, which is critical for uninterrupted wireless communications. The SNR values within the semi-permeable region behind the MDF door are high enough to assist transfer of communication links from one access point (AP) to another. Hence, this deduction can be utilized to even realize the next-generation of mobile telecommunication systems indoors at frequencies in the neighbourhood of 100 GHz, by constructing buildings using THz-friendly materials and implementing access networks, which will address the specific challenges of submm-wave communication.

6.3.2 350 GHz

Fig. 6.3 illustrates the received power and SNR outcome of the 350 GHz simulation. The received power performance given in Fig. 6.3a directly replicates the 100 GHz result, except for the reduced levels. In fact, this is also the case for the 500 GHz and 700 GHz simulations, for which reason the power outcomes of those are not provided.

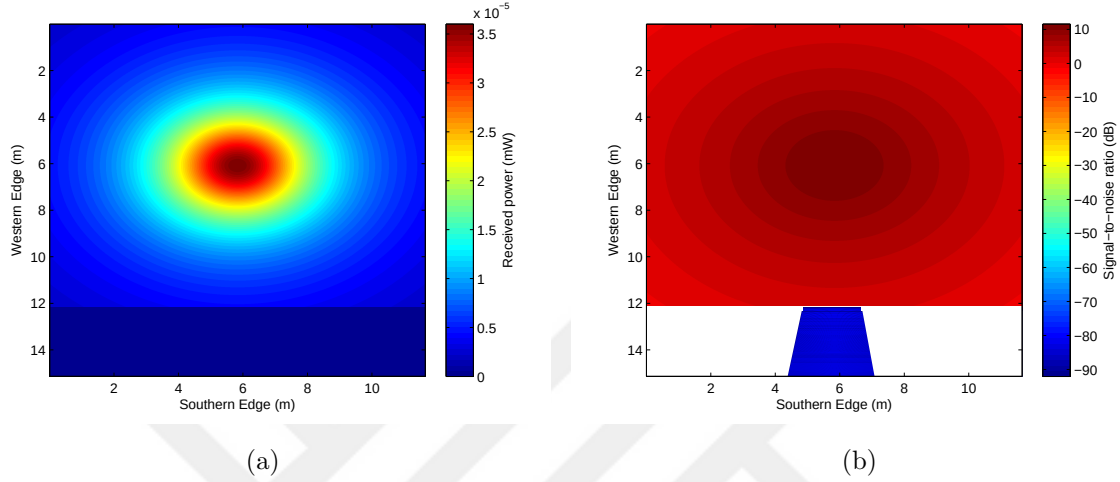


Figure 6.3: (a) Received power and (b) SNR performance of 350 GHz at indoor simulation for $h = 1$ m.

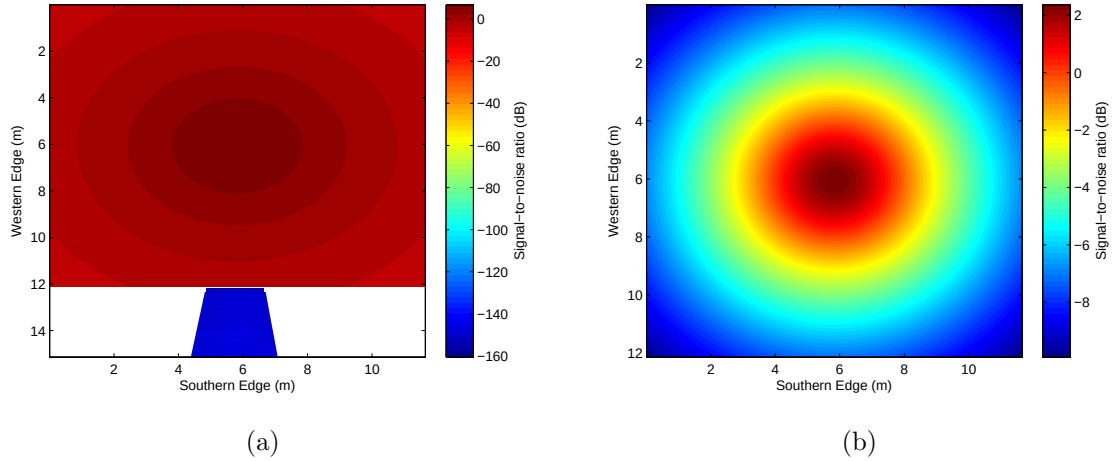


Figure 6.4: SNR performance of (a) 500 GHz and (b) 700 GHz at indoor simulation for $h = 1$ m.

The more significant SNR results are provided in Fig. 6.3b. The first difference compared to the 100 GHz case is in visualization. Because the lower end of the received power is very small - in fact practically undetectable, the corresponding SNR values are also very small. This widens the colour range to such extent that figure becomes incomprehensible. To make the result plainer, the wall and the corridor area

accessible through wall are removed from the SNR performance plots of 350 GHz and 500 GHz simulations.

The SNR results of the laboratory vary between -0.2 dB and 11.6 dB. While 0 dB does not provide a hospitable environment for high data rate communications, 10.78 dB is enough for a BER of 10^{-6} using 4-QAM. Since this only halves the spectral efficiency while the simulation bandwidth is tripled compared to the 100 GHz case, all the applications listed before are also feasible for 350 GHz carrier. The shortcoming is the reduced coverage due to the higher free space path (FSPL) and atmospheric losses. For the same distance, EM waves lose 10.88 dB more at 350 GHz because of FSPL, and the specific attenuation due to atmospheric gases are 10.941 and 0.503 dB/km for 350 and 100 GHz, respectively.

The values behind the door in the hall are between -80 dB and -92 dB. The TN is -73 dB for the 350 GHz simulation parameters, so in this case it is not possible to provide any transmission into the hall area. Absorption is again the main reason, since through 1 cm of CB and MDF the losses are 20.933 dB and 20.021 dB, respectively. Therefore, to realize indoor wireless communications at 350 GHz either materials generating lesser absorption losses should be used, or a network architecture with at least one AP per room should be adopted.

6.3.3 500 GHz and 700 GHz

For the remaining simulations only the SNR outputs are given in Fig. 6.4. While the values of the semi-permeable region behind the door are available for 500 GHz, since the highest NLoS SNR output is calculated as -241.73 dB in the 700 GHz case, just the results within the LoS limits of the laboratory are demonstrated in Fig. 6.4b.

The LoS SNR results vary between -5.4 dB and 6.8 dB in the 500 GHz simulation. The upper limit is adequate to sustain successful wireless communications using binary phase-shift keying (PSK) with a BER of 10^{-3} , or quadrature PSK or 4-QAM with a BER of 2×10^{-3} . Comparison of these results with the 350 GHz case illustrates that further carrier frequency increase causes worse maintainable BERs,

even shorter coverage range and no improvement on spectral efficiency. While higher bandwidth would assist short-range data rate intensive applications like rapid sync-n-go file transfer [29], the considerably worse BER is preventative towards wireless display implementations at 500 GHz.

LoS SNR values of 700 GHz simulation resulted between -9.9 dB and 2.4 dB. These levels clearly cannot support a communication link but rather be useful for handover. Moreover, NLoS SNR values of 500 and 700 GHz are below -142.14 dB and -241.73 dB, respectively, both which are remarkably lower than TN. Innovative developments are still required in multiple different domains of wireless communications for these test settings to be operational.

6.4 Conclusion

In this chapter, the use of THz band for wireless communication systems is investigated. Subsequent to a general introduction on the current state of wireless and mobile communication systems, the realistic simulation environment of [16] is extended across 700 GHz. According to the results, transmission windows up to 500 GHz are capable of supporting WPANs, which can theoretically provide peak data rates between 10 and 20 Gb/s. Severe material absorption on the higher frequencies is the principal reason against coverage expansion. Towards that end, indoor access network architectures featuring multiple APs that support a handover mechanism and building materials with workable absorption coefficients should be investigated.

Chapter 7

ON THE USE OF LOW TERAHERTZ BAND FOR 5G INDOOR MOBILE NETWORKS

7.1 *Introduction*

The speed of our lives, and so the demand for information, are unendingly increasing. The device that keeps us connected permanently, mobile phone, is at the forefront of this new situation, in line with the ever-increasing flash memory storage sizes [127]. As of 2014, global mobile communication subscription number is 7 billion, corresponding to a penetration rate of 96%, with developed and developing countries standing at 121% and 90%, respectively [128]. Together with user amount, usage also steadily increases, as average traffic per smartphone rose by 45% to 819 MB per month in 2014, and this figure is expected to continue growing with a compound annual growth rate (CAGR) of 60.1% for the following 5 years [70]. Furthermore, mobile connection speeds are also escalating, with global average network downstream speed for smartphones rising to 6097 Kb/s in 2014, corresponding to a yearly increase of 53% and the forecasted CAGR up to 2019 is given at 11%, rising the speed to 10.4 Mb/s by the end of the period [70].

While continuous increase in subscriber amount and average traffic per subscriber mandate for capacity improvement from the next-generation wireless communication systems, mobile connection speeds force increase in peak data rates. Furthermore, considering the global mobile data traffic forecasts and peak data rate leaps between mobile telecommunication generations, downlink peak data rate designation for fifth generation (5G) mobile technologies has to be on the order of 10 Gb/s [91]. Conventional ways of raising data rate, i.e., increasing operation bandwidth or spectral

efficiency or decreasing signalling overhead, are collectively known. Among these alternatives, spectral efficiency improvement efforts have traditionally led the research in academia, resulting in advanced technology for the area. Consistent with the excessive amount of effort that currently needs to be put in to obtain even the modest gains in spectral efficiency, industry's response has been the already finalized wireless personal area network (WPAN) and wireless local area network (WLAN) standardization activities on 60 GHz industrial, scientific and medical (ISM) radio band [21, 27, 28], with 300 GHz aimed next.

In light of the stated arguments, we propose the employment of the low end of the THz band for 5G wireless communications. International Telecommunication Union (ITU) Radiocommunication Sector (ITU-R) has allocated frequencies up to 275 GHz [30], leaving higher frequencies, including the THz band, which can be defined to be between 0.3 and 10 THz, available for any radio service. As plans to include the 60 GHz ISM band to the operation frequencies of WPAN and WLAN devices are already in motion, with first such commonplace devices expected to be on the market by 2016, mobile phones will likely follow the example. In fact, comprehensive urban propagation measurements up to 73 GHz are already complete [129]. However, while the 60 GHz band offers at most 9 GHz of continuous bandwidth, only the first two THz transmission windows that are below 400 GHz provides multiples of that spectrum. Moreover, according to the IEEE 802.11ad channel model [68], transmission characteristics of the 60 GHz band are significantly different from the legacy 2.4 and 5 GHz bands, such as the multipath contributions are limited to second order reflections, at most. If the current wireless communications trends are strong enough to cause a shift from the highly established frequencies, communication techniques, network architectures and user equipment (UE) to include 60 GHz implementation, we argue that, displaying similar electromagnetic (EM) wave propagation properties, low-THz band can also be used without causing substantial further difficulties for much improved network capacity and peak data rate benefits.

To support our claims, following a general description of the channel characteristics

Table 7.1: Rain attenuation results

Quantity	4 mm/h		16 mm/h		50 mm/h	
	Max	Mean	Max	Mean	Max	Mean
f (GHz)	207.46	1000	179.8	1000	148.67	1000
γ (dB/km)	3.968	3.348	3.611	9.626	8.126	8.679
	20.075	16.843	17.88			

of the low-THz band given in Section 7.2, indoor coverage simulations to compare one of the transmission windows from the low-THz band, namely 350 GHz, with an operation frequency (f) selected from the highest allocated frequency band for fourth generation (4G) systems, that is 3.4 GHz, and the first transmission channel of the 60 GHz ISM band are presented. The test environment, which is explained thoroughly in Section 7.3 together with the simulations, is directly replicated from the related ITU-R evaluation guideline [66], and therefore this work is the first publication in literature that presents the performance of THz band communications within a standardized environment. Section 7.4 provides results together with their analysis and subsequently section is concluded.

7.2 The Low Terahertz Band

As the frequency increases, not just signal generation but also signal propagation gets tougher. Fig. 7.1 illustrates the atmospheric attenuation (γ) up to 1 THz together with the dry air component, calculated for the standard ground-level atmospheric conditions [78] and as per the Recommendation ITU-R P.676-9 [22]. Additionally included in the figure are the attenuations due to rain for rain rates of 4, 16 and 50 mm/h, representing moderate, heavy and violent rain categories, respectively. Recommendation ITU-R P.838-3 [31] provides the procedure to compute the specific attenuation due to rain for frequencies up to 1 THz and horizontal polarization is assumed for calculations. According to the recommendation, the general behaviour of rain attenuation between 1 and 1000 GHz is an increasing function with a declining

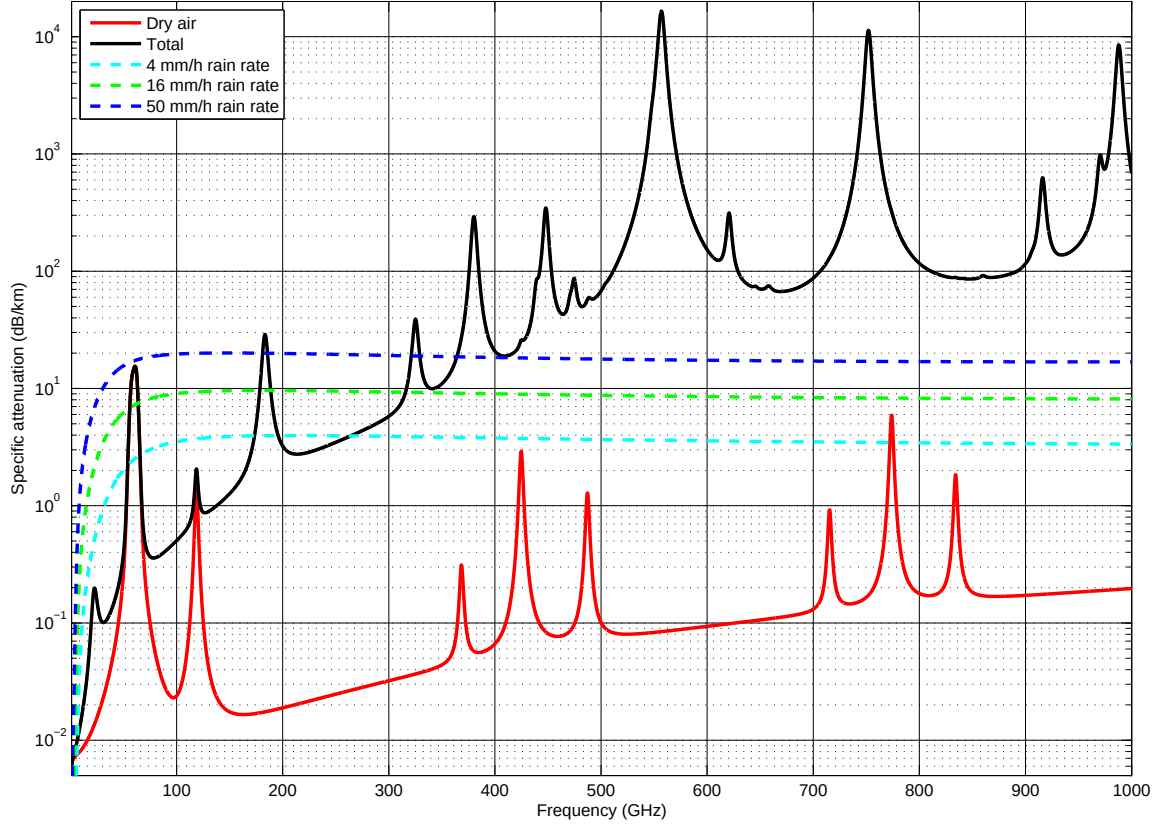


Figure 7.1: Specific attenuation due to atmospheric gases and rain, calculated up to 1 THz at 1 MHz intervals under standard ground-level atmospheric conditions and for rain rates of 4, 16 and 50 mm/h.

rate which reaches its maximum at around 100 GHz and then flatlines.

The figure shows three main local maxima in the THz band up to 500 GHz, occurring at 325.178 GHz with 39.071 dB/km, 380.225 GHz with 292.984 dB/km and 448.013 GHz with 346.816 dB/km. Some of the important points of the rain attenuation curves, which are global maximum, value at 1 THz and the mean attenuation amount in between, are illustrated in Table 7.1.

To extend the discussion further, in Fig. 7.2 the impacts of temperature and air pressure on the gaseous attenuation is investigated. The values given to temperature in Fig. 7.2a are 248, 288, and 328°K and to air pressure in Fig. 7.2b are 973, 1013 and 1037 hPa. In the computations, the remaining two parameters are kept at standard

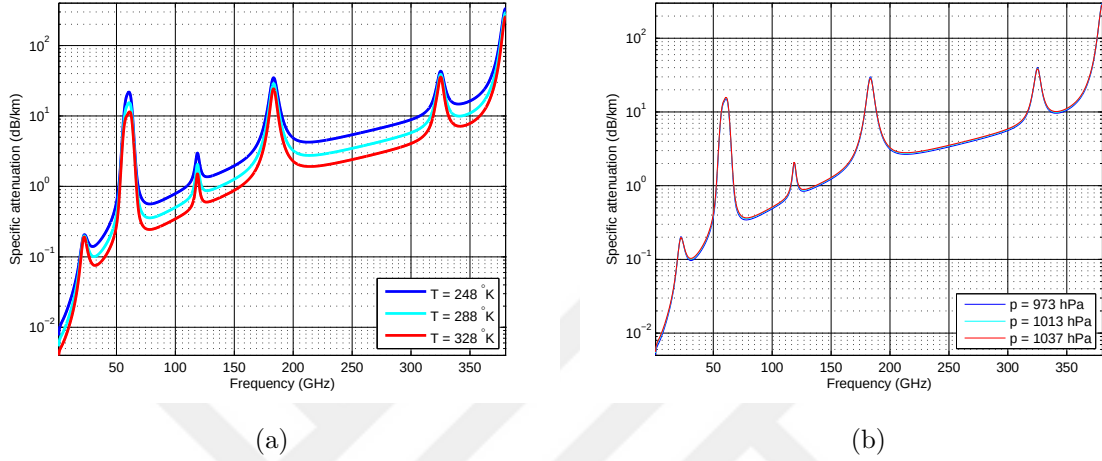


Figure 7.2: Specific attenuation due to atmospheric gases, calculated between 1 GHz and 380.225 GHz and for (a) temperatures of 248, 288, and 328°K and (b) pressures of 973, 1013 and 1037 hPa.

atmospheric conditions.

The effect of water vapour density, as demonstrated in [13] and can also be construed from Fig. 7.1, is supplementary to atmospheric attenuation; i.e. Attenuation rises with increasing water vapour density. According to Fig. 7.2a, the opposite is true for temperature, whereas, while its impact is small compared to the other two factors, increasing air pressure also enhances gaseous attenuation.

While the detailed analysis of the attenuation components below the THz band is available in [61], in Fig. 7.3 emphasis is given on the specific attenuation between 275 GHz and the third local maximum within the THz band at 448.013 GHz. The attenuation value at 275 GHz is 4.362 dB/km and the local minima among the first three THz band local maxima occur at 340.997 GHz with 9.942 dB/km, and 409.017 GHz with 18.871 dB/km. If we define transmission windows within the low-THz band as spectrum which has a maximum of 3 dB/km attenuation difference with the local minimum it surrounds, the first three such bands above 275 GHz emerge as detailed in Table 7.2 and marked within Fig. 7.3.

A comparison of properties of the EM wave propagation in 300 GHz with the

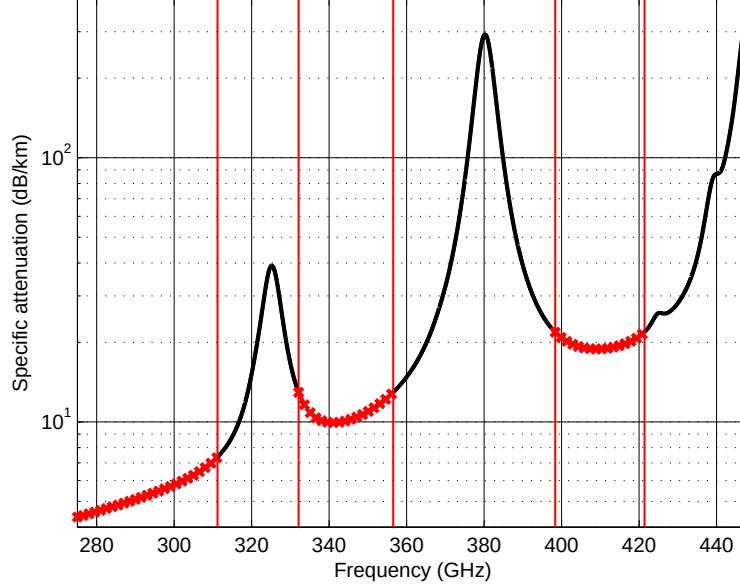


Figure 7.3: Specific attenuation due to atmospheric gases, calculated under ground-level atmospheric conditions and between 275 GHz and 448.013 GHz at 1 MHz intervals, with 3 dB transmission windows around local minima indicated.

Table 7.2: Probable transmission windows

Frequency Range				f_{centre}	Bandwidth
275	—	311.178	GHz	293.089	36.178
332.094	—	356.532		344.313	24.438
398.338	—	421.377		409.858	23.039

2.4, 5 and 60 GHz bands indicates that the main difference is the additional free-space losses of 41.938, 35.563 and 13.979 dB, respectively, for the same transmission distances [79]. At 300 GHz attenuation by atmospheric gases is nearly 5.783 dB/km, whereas this attenuation is virtually non-existent for the 2.4 and 5 GHz bands, and much higher for 60 GHz at 15.037 dB/km. In-building material absorption is also greater at 300 GHz [64]. Combining all these larger losses for 300 GHz suggests that multipath would also be limited, at most, to first and second order reflections just

like the IEEE 802.11ad's 60 GHz channel models [68] and high-gain antennas will be necessary to maintain reliable communication links.

The upper frequency boundary for next-generation of mobile networks is certainly on the rise, with extensive field measurements for 28 GHz, 38 GHz and 73 GHz are already performed [130, 129], in addition to the theoretical research outputs [131, 11]. However, to date, very little amount of study on channel measurement and propagation modelling at low-THz band has been conducted, as analogue [132] and digital [133, 134] transmission demonstrations are recently performed and, to the best of the authors' knowledge, there is only one THz indoor channel model discussed in the literature [135]. The model was developed atop the previous works of the corresponding group and provides a stochastic solution for the frequency range between 275 and 325 GHz. All parameters for a complete channel transfer function, which are amplitude, polarization, time of arrival, phase, frequency dispersion and angles of arrival and departure, are claimed to be characterized. However, the model is far from final. Model parameter sets are based on one specific office scenario and, due to time constraints, outputs of ray tracing simulations are used instead of actual channel measurements. Reflected wave phase rotations are modelled to have a uniform distribution between -180° and 180° , thus including no particular information. Distributions of arrival and departure angles are explored at length, however, those are the result of the geometry of the room and locations of the transmitters (TXs) and receivers (RXs), rather than EM wave propagation. The usage of the model is also severely hindered because of the need to adapt the model with ray tracing for each new environment to be considered. Overall, despite its limitations, the channel model is another encouraging step towards a new wireless communication paradigm.

7.3 Indoor Simulations

Primary aim of the proposed millimeter wave (mm-wave) communication systems is increased peak data rates that are comparable to wired alternatives. Therefore, test environment in simulations is selected to maximize data rate and consequently,

Table 7.3: Simulation parameters

Quantity	4G	5G
<i>Transmitting power</i>	24 dBm	0
<i>TX and RX antenna gains</i>	0 dBi	23
<i>Carrier frequency</i>	3.4 GHz	350
<i>Noise bandwidth</i>	0.04	10.8
<i>BS noise figure</i>	5 dB	5
<i>UE noise figure</i>	7	7
<i>System margin</i>	10	5

the indoor hotspot scenario of the indoor test environment from the four available scenarios identified in report ITU-R M.2135-1 [66] is chosen.

The scenario is set on one floor of a building having dimensions of 120 m $\times$ 50 m $\times$ 6 m. There are eight rooms in both sides of the hall, having lengths and widths of 15 m each, leaving 20 m for the corridor. Two base stations (BSs) are installed to the ceiling of the floor, both in the middle and located 30 m away from the borders of the hall. All simulations are conducted over this plan, the sketch of which is available in Fig. 7.4, and the missing information is supplied from the authors' laboratory building for the purpose of authenticity. The walls are therefore assumed to be 0.2 m thick and constructed of sand-lime brick (SLB).

A total of five simulations are performed, the first one for the 4G case, the next three on the 5G and the final one to compare the idealized 5G setting with the realistic 60 GHz deployment in [16]. 4G simulation parameters, except for the system margin (SM), are selected directly from the baseline evaluation configuration of the indoor hotspot scenario given in [66], and listed in Table 7.3. SM is assumed to be 10 dB. Received power and signal-to-noise ratio (SNR) are calculated for every simulation, and for the 4G case, line-of-sight and non-line-of-sight (NLoS) path loss models from

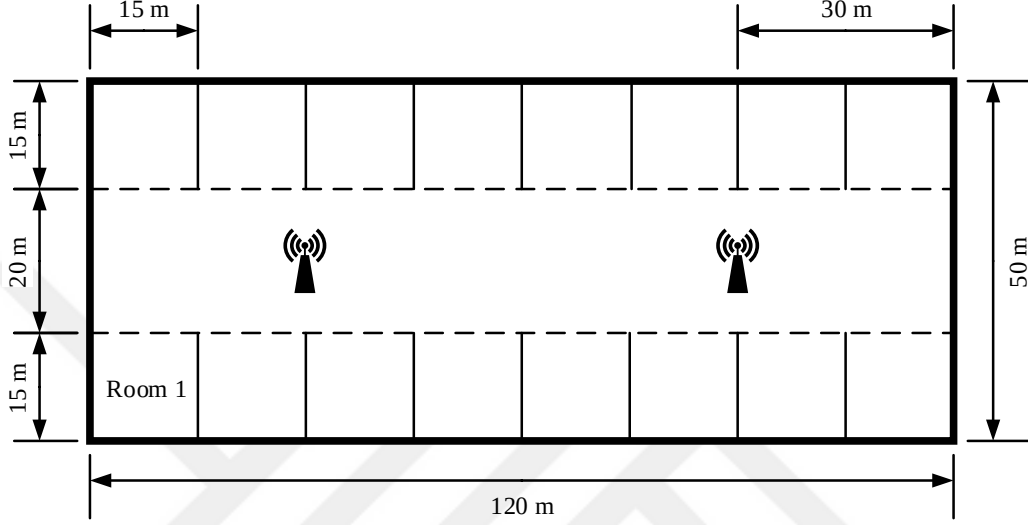


Figure 7.4: Sketch of the simulation environment with dimensions displayed.

[66] are used for these purposes, as described in depth within our previous work [16].

Three different simulations are performed for 5G to thoroughly assess the transmission characteristics of mm-wave. While all 5G simulations are conducted on the same floor plan as in the 4G case, the first simulation additionally replicates the BS locations and building properties, such as the thickness and constituent of the walls, as well. In the second simulation, a more favourable environment for low-THz band propagation is assumed, with one BS located at the centre of the ceiling of each room, and the rooms are assumed to be separated from the corridor with a 0.02 m thick clear window glass, imitating a modern office setting. Moreover, the BSs in the hall are removed to test if non-stationary users can be supported by access points (APs) within the rooms. Finally, the third 5G simulation portrays a rather ideal situation, where BSs are available in every room and the hall. Additionally, hardware used is assumed to be superior, reflected by reducing each of the noise figures (NFs) and SM by 3 dB compared to other 5G simulations. The last 60 GHz simulation is also run on this setting, using the parameter and methods of [16] for comparison purposes.

Characterization of building materials in the THz range is available only from 350 GHz and onwards in the literature [64]. Therefore, the second THz transmission window centred around 344.313 GHz is chosen for 5G simulations, and 350 GHz is considered as the corresponding centre frequency for the remaining of the chapter. Standardization activities for the 60 GHz ISM band were completed with channel spacing set at 2160 MHz. Taking a proportional approach, for the 5G simulations channel bandwidth is selected to be 10.8 GHz.

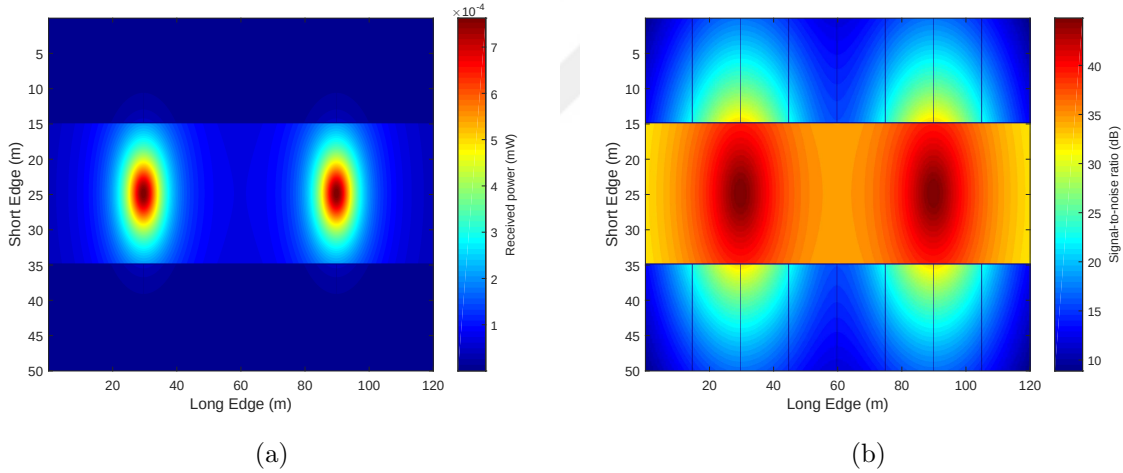
The arguments behind the choices of 0 dBm transmitted power and 23 dBi TX and RX antenna gains are presented at length in [13]. Moreover, like 4G simulation, the same NFs and ground-level atmospheric conditions are used for 5G calculations. The only difference for the SNR computation is the reduced SM of 5 dB, which is selected due to the narrow half-power beamwidth caused by high antenna directivities.

Wide-ranging channel models are not present for 5G as in the 4G instance. Therefore, ray tracing method is employed [125]. Diffraction is shown to be insignificant in almost all propagation cases above 60 GHz [34]. Therefore, it is not included in the computations. The surfaces of the simulation environment are also assumed to be perfectly smooth, consistent with [135], thus nullifying diffuse scattering and making reflection the only mechanism to contribute to the NLoS coverage. The link budget based procedure is, again, explained fully in [13].

While reflection coefficients of a variety of materials tend not to alter noticeably in the low-THz band [32], absorption coefficients increase at different rates [64]. The two materials which are selected for simulations, SLB and glass, show further similarity in their absorption behaviour towards mm-waves. While absorption coefficients of SLB and glass are measured to be 171 and 195 m^{-1} at 100 GHz, and 909 and 995 m^{-1} at 350 GHz, respectively, their absorption coefficient plots are also intertwined between 100 and approximately 400 GHz [64]. 5G simulation parameters overall are also summarized in Table 7.3.

Table 7.4: Simulation results

Quantity		Room 1			Corridor		
		5G	5G _{room}	5G _{ideal}	5G	5G _{room}	5G _{ideal}
<i>Received power</i> (μW)	min	1.42×10^{-253}	0.0013	0.0013	0.0002	5.38×10^{-15}	0.0002
	max	8.32×10^{-98}	0.0073	0.0073	0.0073	4.16×10^{-12}	0.0073
<i>SNR</i> (dB)	min	$\ll \text{TN}$	-2.1454	6.8546	-10.664	-116.02	-1.6714
	max	$\ll \text{TN}$	5.3078	14.308	5.3337	-87.138	14.334

Figure 7.5: (a) Received power and (b) SNR performance of 4G indoor hotspot deployment simulation, displayed for $h = 1$ m.

7.4 Results and Discussion

Simulation resolution is chosen as $1 \text{ cm} \times 1 \text{ cm} \times 1 \text{ cm}$ within the defined floor of a building. The results are provided for a single height of 1 m, selected to be between average heights of a desk and ear level of a standing person. Additionally, Table 7.4, within which TN denotes thermal noise, lists the received power and SNR extrema for the 4G and 5G simulations in both the corridor and room in the bottom left corner, which is indicated as Room 1 in Fig. 7.4.

7.4.1 4G

In Fig. 7.5 received power and SNR outcomes of the 4G simulation are presented. In all of the figures, the values within the walls and glass are set to the lowest outcome of the respective plane; therefore they are visible. The received power ranges from $0.763 \mu\text{W}$, which points are directly below the BSs, to 0.195 nW , occurring at the corners of the floor, both as expected. Due to the proof of concept nature of the work, in all five simulations, total power at each modelled 1 cm^3 volume is found by directly adding power received from all of the BSs. Consequently, $0.751 \mu\text{W}$ of the maximum values is received from the BSs directly above the points, and $0.011 \mu\text{W}$, or 1.47%, is received from the distant BSs.

For practical purposes, SNR is more informative than the received power. Accordingly, the SNR outcome of the 4G simulation is available in Fig. 7.5b. Since the BSs are located in the hall, values, which range from 31.81 dB to 44.81 dB, are higher compared to the rooms. Maximum SNR received within the rooms is 32.31 dB, which reduces down to the minimum of 8.89 dB. For a bit error ratio (BER) of 10^{-6} , successful transmission with 4-ary quadrature amplitude modulation (4-QAM), 16-QAM and 64-QAM require SNRs of 10.78, 14.9 and 19.42 dB, respectively. While all these quantities are well below the results in the hall and most parts of the rooms, the lowest outcome of 8.89 dB forces BER of 4-QAM reduce to 10^{-4} and 16-QAM to 2×10^{-2} .

As the final statement of the subsection, for the points directly below the BSs, the total power of $0.763 \mu\text{W}$ those receive corresponds to -31.18 dBm, whereas $0.751 \mu\text{W}$ obtained solely from the closer BS is equal to -31.24 dBm. The same values for the outermost points in the corridor are -44.17 dBm and -44.86 dBm, respectively. These show that, at lengths over 60 m, which is the distance between the two BSs positioned in hall, the assistance of the distant BS towards the SNR, and so to coverage, is notably negligible.

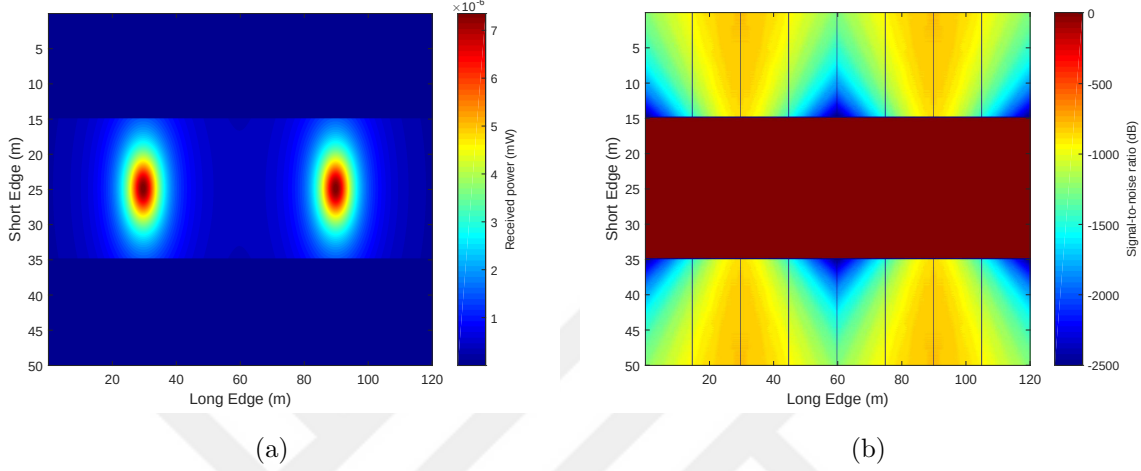


Figure 7.6: (a) Received power and (b) SNR performance of 5G mm-wave simulation for the indoor hotspot deployment setting, displayed for $h = 1$ m.

7.4.2 5G

The first 5G simulation has the same deployment setting as in the 4G case, and the results are available in Fig. 7.6. Firstly, when the scales of Fig. 7.5a and Fig. 7.6a are compared, a reduction on the order of 10^2 is observed for the 5G case, which translates into 20 dB of reduced signal power. Values in the corridor ranges from 7.35 nW to 0.1847 nW, whereas the corresponding values for the rooms are found to be between 1.27×10^{-87} mW and 1.42×10^{-256} mW. While theoretically calculable, practically the latter values are unmeasurable. Thus, we can conclude that no signal penetration occurs through the 0.2 m thick SLB wall. In fact, according to Lambert-Beer's law, EM wave propagating through the stated barrier is attenuated by 789.54 dB, therefore practically gets diminished. Furthermore, in reality, and thus reproduced exactly in our simulations, EM wave propagates through an even longer distance due to its angled incidence, and so the resulting oblique refraction path [136].

Fig. 7.6b illustrates the SNR results of the first 5G simulation. The corridor values change between 5.33 dB and -10.66 dB, and range for the rooms is between -812.3 dB and -2501.79 dB. Because the SNR values are below the noise floor, those values are

not measurable in actuality. However, the colour scale of Fig. 7.6b is still selected to cover all the values. This is both because for a scale between 5.33 dB and -10.66 dB, the resulting image looks very much like Fig. 7.5a and Fig. 7.6a, and the current scale clearly demonstrates the true theoretical SNR achieved within the rooms, therefore confirming the correctness of the simulations run. The highest SNR value of 5.33 dB dictates a BER of 5×10^{-3} and 10^{-2} for successful binary phase-shift keying (BPSK) and quadrature PSK modulated transmissions, respectively.

7.4.3 $5G_{room}$

One of the main conclusions from the comparison of the 4G and 5G simulations performed over the indoor hotspot scenario is, for an operational communication system working at higher frequency bands, a new indoor access network architecture concept has to be structured. It can be proposed that users who are within their offices need both higher throughput and peak data rates compared to the ones walking through the hall. The setting of the second 5G simulation stems from this idea, where BSs are placed at the centres of the ceiling of each room and 2 cm thick glass dividers replace the walls between the rooms and corridor. The outcomes are available in Fig. 7.7. Received power within the rooms change from $0.0073 \mu\text{W}$ to $0.0013 \mu\text{W}$, whereas the range for the corridor is $4.16 \times 10^{-15} \text{ mW}$ to $5.38 \times 10^{-18} \text{ mW}$. When the SNR results are examined from the Fig. 7.7b, it is seen that SNR values change from 5.31 dB to -2.14 dB within the rooms, and -87.14 dB to -116.02 dB within the corridor. The outcome is still poor within the rooms, and the loss of 86.42 dB through 2 cm thick glass prevents any possibility of sustaining a communication link between the hall and BSs at 350 GHz.

7.4.4 $5G_{ideal}$

Third and final 5G simulation represents an ideal situation with hardware having lower NFs and SM, and BSs placed both in the rooms and the corridor without regard to cost, which normally is the key at general commercial deployments. The

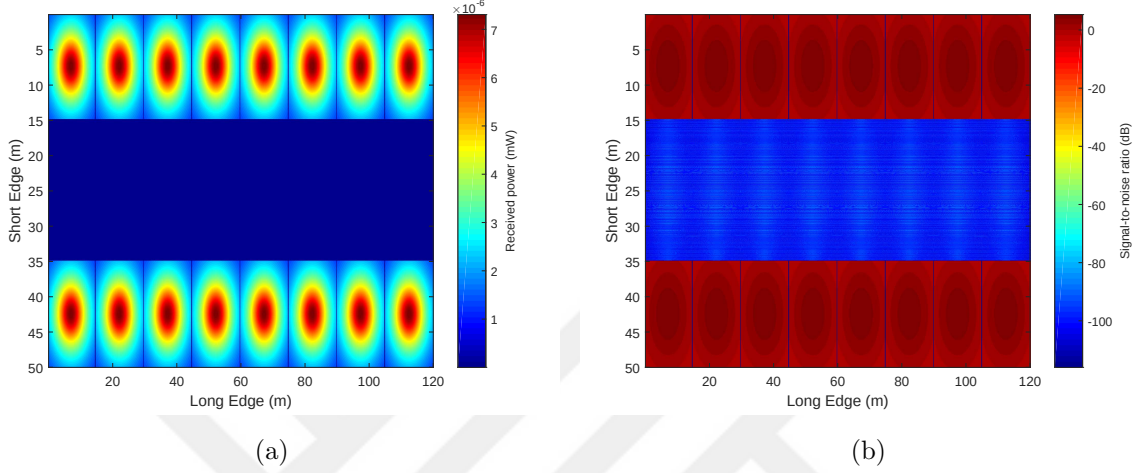


Figure 7.7: (a) Received power and (b) SNR outcomes of 5G_{room} mm-wave simulation setting, displayed for $h = 1$ m.

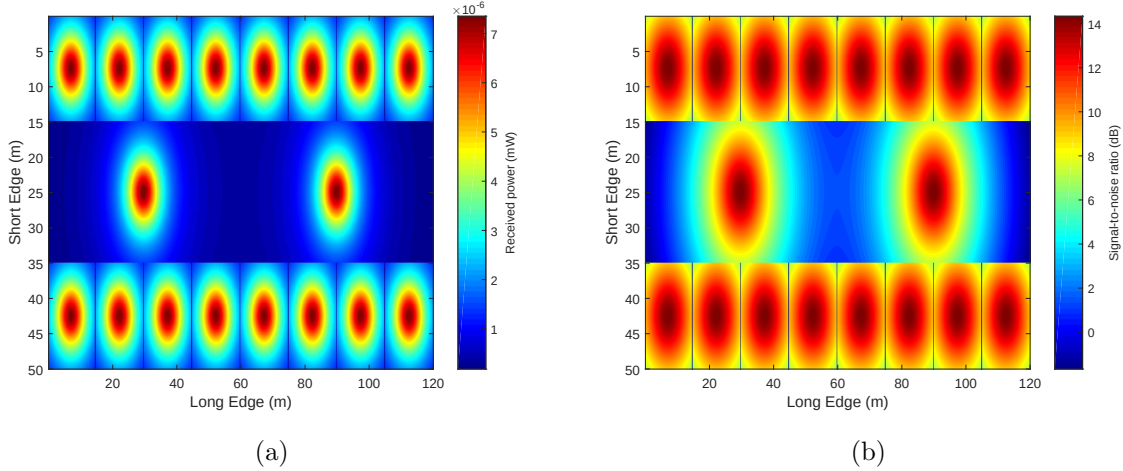


Figure 7.8: (a) Received power and (b) SNR outcomes of 5G_{ideal} mm-wave simulation setting, displayed for $h = 1$ m.

results are available in Fig. 7.8. While received power ranges from 7.35×10^{-6} mW to 1.84×10^{-7} mW and 7.31×10^{-6} mW to 1.31×10^{-6} mW within the hall and rooms, respectively, SNRs for the same spaces change from 14.33 dB to -1.67 dB and 14.31 dB to 6.85 dB. Successful transmission with 16-QAM requires an SNR of 14.9 dB for 10^{-6} BER and 5.2 dB is sufficient for BPSK transmission with 5×10^{-3} BER. Therefore,

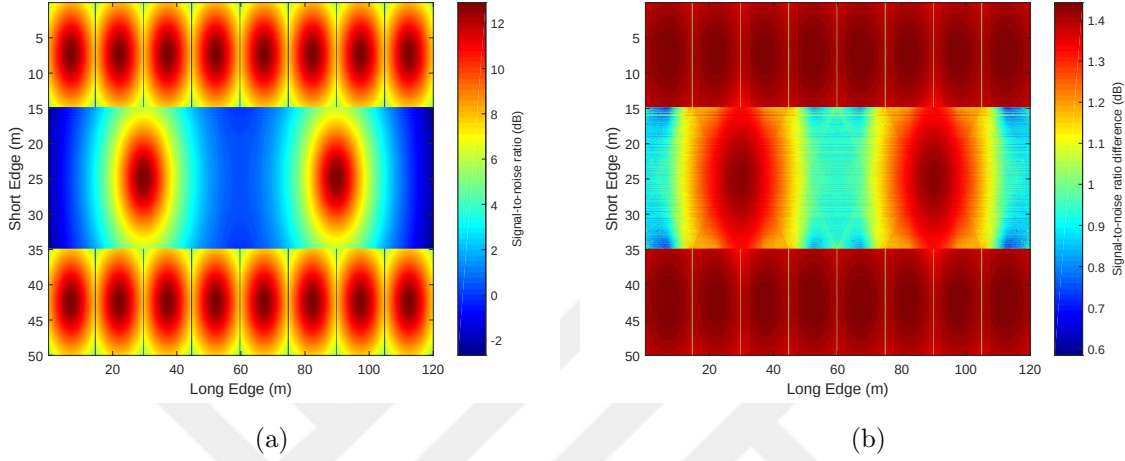


Figure 7.9: (a) SNR performance of 60 GHz simulation and (b) SNR outcome difference between 5G_{ideal} and 60 GHz simulations, displayed for $h = 1$ m.

the current setting is capable of supporting high data rate wireless communication at 350 GHz.

7.4.5 60 GHz

Since the core focus of this work is low-THz band, received power outcome of the 60 GHz simulation is omitted, whereas the SNR results are available in Fig. 7.9a. The values change between 12.91 dB and -2.67 dB within the hall, and from 12.87 dB to 5.49 dB in the rooms. This indicates a performance drop of 1.44 dB to 0.58 dB across the floor compared to the idealized 5G setting. Point-to-point SNR differences between the final two simulations are illustrated in Fig. 7.9b.

Even though 60 GHz simulation is resulted in lower SNR values, two important points need to be taken into consideration before any further analyses. Firstly, the total of NFs and SM, which has a direct effect on the consequent SNR, is 9 dB lower in the 5G_{ideal} case. Secondly, although the final 5G simulation is set using attainable targets, 60 GHz parameters are selected from readily available hardware. Overall, while the 60 GHz ISM band certainly performs better under even conditions, low-THz band is not afar, and the additional benefits justify the research efforts.

7.5 Conclusion

The suitability of the low-THz band for 5G mobile communication systems is examined in this chapter using both theoretical analyses and numerical simulations. Free-space path loss, atmospheric attenuation and absorption and reflection losses are all higher for the THz band compared to the sub 6 GHz bands, limiting the coverage area of BSs. However, this can be offset by the network densification expected from the 5G. Simulation results clearly show that it is possible to achieve peak data rates on the order of 10 Gb/s using the low-THz band, though THz band signals are confined within the room containing the AP. There are still several important challenges that need to be solved during the standardization processes before actual deployments. High-performance and low-cost devices are needed to be able to implement the communication systems. Novel access network architecture solutions should be devised to overcome the greater losses in the THz band. A practical channel model is also compulsory for the continuation of the theoretical research efforts.

Chapter 8

ON THE 5G WIRELESS COMMUNICATIONS AT THE LOW TERAHERTZ BAND

8.1 *Introduction*

The regulatory activities for the fifth generation (5G) mobile systems within the International Telecommunication Union (ITU) Radiocommunication Sector (ITU-R) began in 2012, principally under the Working Party 5D. The 3 key usage scenarios of International Mobile Telecommunications (IMT) for 2020 and beyond were determined as enhanced mobile broadband, ultra-reliable and low latency communications and massive machine type communications (mMTC). mMTC use case mainly covers the very high number of connected devices which are required to be inexpensive with very long battery life, resulting in low volume of non-delay sensitive data transmission [137]. Also, the minimum requirement for connection density was set to be 1M devices/km² [138], or 1 device/m² on average.

Several 5G-related articles in the literature mention an expectation of a thousandfold growth in global mobile data traffic between 2010 and 2020, some of which referring to a 2011 white paper by Nokia Networks [3]. However, that document does not contain any scientific analysis. UMTS Forum's market study, which was also published in 2011, assessed 33 times growth for the same decade [139]. To assist future spectrum allocations, ITU has also estimated 2020 traffic volumes, using different forecasts of external sources, which are available in ITU-R M.2243. The lowest and highest approximations were taken into account and extrapolated to 2020, which yielded growths of approximately 25 and 100 times, respectively, and this span was accepted as the estimated range. 44- and 80-fold, corresponding to 25 and 75% of the

range, then used to specify the exact 2020 market attributes for lower and higher user density settings, respectively [140]. The accuracies of these forecasts can be checked using Cisco Systems' annual "Visual Networking Index" white papers. Cisco reported the total mobile data traffic as 0.237 EB/month in 2010 [7] and 7.241 EB/month in 2016 with the projection of 34.59 EB/month for 2020 [57]. These values result in 30.59 and 146.1 times growths in periods of 6 and 10 years, respectively.

The constant increase in the number of connected user equipment (UE) already has a substantial congesting effect on the sub 6 GHz legacy bands. Achieving either of the IMT-2020's 20 Gb/s downlink (DL) or 10 Gb/s uplink peak data rate minimum requirements is challenging enough under ideal conditions, let alone realistic test environments. The most researched and utilized technique to increase the data rate and network capacity have been spectral efficiency enhancement. However, since modulation and coding schemes (MCSs) are already vastly advanced, the returns of additional development efforts are diminishing. To illustrate, keeping the coding parameters the same, an ascent from binary phase-shift keying (BPSK) to quadrature PSK (QPSK) results in doubling the bit rate. However, the jump from 64-ary quadrature amplitude modulation (64-QAM) to 256-QAM leads to an increase of only 33%. A further hypothetical leap to 1024-QAM would result in an even lesser increase of 25% [35].

Another possible method to attain the target rates is increasing the operation bandwidth via transmitting in higher bands. This approach was not preferred exhaustively so far, largely due to the higher free space and atmospheric attenuations, in addition to the difficulties in generating signals with high enough output power in the mm-wave band (30-300 GHz). However, the forthcoming device densification and subsequent decrease in mean link distances offer novel opportunities to wireless networks. Consequently, investigation of new frequency spectra for wireless communications have already started for 5G mobile communications concurrently with the respective standardization activities [77, 141, 142], and this chapter describes the first steps toward a resolution of this predicament. The remainder of this chapter

is organized as follows. Section 8.2 presents a brief overview of the standardization activities on the low-THz band, namely the 300 GHz spectrum, and Section 8.3 outlines its channel characteristics and available models. Key open research issues are identified in Section 8.4 and the chapter concludes with recapitulating remarks.

8.2 Standardization Activities

The need for new spectral resources has been addressed by choosing the 60 GHz as the new industrial, scientific and medical (ISM) radio band to be used for unlicensed wireless communications. In addition to the two wireless personal area network (WPAN) standards, ECMA-387[21] and IEEE 802.15.3c[27], which have been available since December 2008 and October 2009, respectively, the only wireless local area network (WLAN) standard for the 60 GHz, IEEE 802.11ad, was ratified in December 2012. To provide an initial sense of the potential gains obtainable by the increase in operation frequency, 802.11ad standard makes use of the 9 GHz of unlicensed bandwidth available in most parts of the world between 57 and 66 GHz, by defining channel bandwidths to be 2160 MHz. This ample channel lets single carrier waveforms to reach a maximum data rate of 4620 Mb/s with $\pi/2$ 16-ary quadrature amplitude modulation (16-QAM), and OFDM waveforms to reach 6756.75 Mb/s using 64-QAM[28]. Detailed explanations of all three 60 GHz standards are available in the literature[61, 77].

According to ITU's latest Radio Regulations, Edition of 2015, frequencies up to 275 GHz are completely allocated to various services and stations, whereas frequency bands in the range of 275-1000 GHz are identified only for the passive service applications of radio astronomy, Earth exploration-satellite and space research. Therefore, the spectrum beyond 275 GHz is nearly uninhabited and at present obtainable by any valuable service, including wireless and mobile communications. In fact, relevant standardization activities began in 2008 with the formation of IEEE 802.15 WPAN Terahertz Interest Group (IG THz) whose focus was on the THz frequency bands between 275 and 3000 GHz. By July 2013, the efforts both within the group and industry reached to the adequate level to transform IG THz into a study group, SG

100G, with the aim of developing project authorization request (PAR) and five criteria documents addressing 40/100 Gb/s over beam switchable wireless point-to-point links. The PAR, which identifies data centers for the beam switched point-to-point applications and adds kiosk and fronthaul and backhaul intra-device communications to the usage models, was approved in March 2014, resulting in the formation of the Task Group 3d (TG3d). IG THz is also retained for applications outside the scope of the TG3d.

8.3 THz Band Channel Property and Models

The answer to electromagnetic (EM) wave propagation is available since 1865 through Maxwell's equations. However, by making use of the general properties of typical wireless communication scenarios, the complexity of solving four differential equations for a point in space and time can be greatly reduced via specific channel models which provide satisfactory approximations.

The non-line-of-sight (NLoS) EM wave propagation mechanisms are transmission, reflection, scattering and diffraction. When a uniform plane EM wave propagating in a near-perfect dielectric medium, such as air whose relative permittivity, ε_r , which is also termed as the dielectric constant in the literature, equals 1.0006, is incident upon a lossy medium, as shown in Fig. 8.1, part of its wave intensity is transmitted into this medium, and the rest is reflected back. The ratios of the transmitted and reflected electric field components, $\mathbf{E}^t$ and $\mathbf{E}^r$, to the incident electric field component, $\mathbf{E}^i$, are labelled as the transmission and reflection coefficients at the interface, T^b and Γ^b , respectively. The equations for T^b and Γ^b depend on the polarization of the incident wave and expressed as

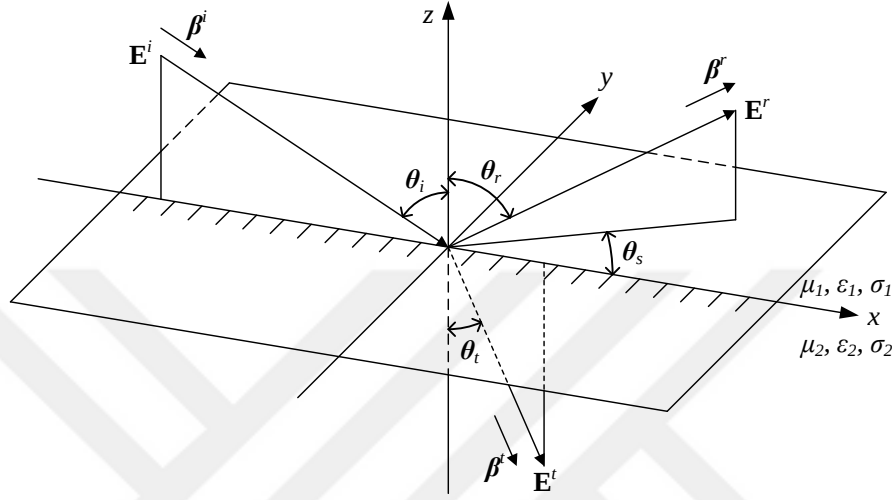


Figure 8.1: Oblique uniform plane electromagnetic wave incidence on an interface.

$$T_{\perp}^b = \frac{2\eta_2 \cos \theta_i}{\eta_2 \cos \theta_i + \eta_1 \cos \theta_t} \quad (8.1)$$

$$\Gamma_{\perp}^b = \frac{\eta_2 \cos \theta_i - \eta_1 \cos \theta_t}{\eta_2 \cos \theta_i + \eta_1 \cos \theta_t} \quad (8.2)$$

$$T_{\parallel}^b = \frac{2\eta_2 \cos \theta_i}{\eta_2 \cos \theta_t + \eta_1 \cos \theta_i} \quad (8.3)$$

$$\Gamma_{\parallel}^b = \frac{\eta_2 \cos \theta_t - \eta_1 \cos \theta_i}{\eta_2 \cos \theta_t + \eta_1 \cos \theta_i} \quad (8.4)$$

for perpendicular ($\perp$), or horizontal, and parallel ($\parallel$), or vertical, polarizations, respectively, where θ_i and θ_t are the incident and transmission, or refracted, angles, and η_1 and η_2 are the intrinsic impedances of the dielectric and conductor media in ohms, respectively.

EM waves can have any general polarization and one method to attain the resulting $\mathbf{E}^t$ and $\mathbf{E}^r$ is separating the $\mathbf{E}^i$ into its $\perp$ and $\parallel$ components, calculating the $\mathbf{E}_{\perp}^t$, $\mathbf{E}_{\perp}^r$ and $\mathbf{E}_{\parallel}^t$, $\mathbf{E}_{\parallel}^r$ independently and vector summing the parted components.

For any polarization category, $\mathbf{E}^t$ in V/m can be written as

$$\begin{aligned}\mathbf{E}^t &= \mathbf{E}_2 e^{-\gamma^t \cdot \mathbf{r}} \\ &= \mathbf{E}_2 \exp[-\gamma_2(x \sin \theta_t + z \cos \theta_t)] \\ &= \mathbf{E}_2 \exp[-(\alpha_2 + j\beta_2)(x \sin \theta_t + z \cos \theta_t)]\end{aligned}\tag{8.5}$$

where

$$E_2 = T^b E^i \tag{8.6}$$

$$E^i = \hat{\mathbf{e}}_i \cdot \mathbf{E}^i \tag{8.7}$$

$$\mathbf{r} = \hat{\mathbf{a}}_x x + \hat{\mathbf{a}}_y y + \hat{\mathbf{a}}_z z \tag{8.8}$$

γ^t is the propagation constant of the wave, $\hat{\mathbf{e}}_i$ is the unit vector in the direction of $\mathbf{E}^i$ and $\mathbf{r}$ is the position vector in rectangular coordinates [136]. EM waves attenuate in all media except for the perfect dielectrics, and this effect is represented by the only real exponential in (8.5), which includes the attenuation constant α in Np/m that is defined as

$$\alpha = w\sqrt{\mu\varepsilon} \left\{ \frac{1}{2} \left[\sqrt{1 + \left(\frac{\sigma}{w\varepsilon} \right)^2} - 1 \right] \right\}^{1/2} \tag{8.9}$$

where w is the angular frequency in rad/s, μ is the permeability in H/m, ε is the permittivity in F/m and σ is the conductivity in S/m. A medium whose constitutive parameters, which are μ , ε and σ , depend on the frequency of the applied field is termed as dispersive. Whereas all materials possess different levels of dispersion, the variation is typically insignificant, except for the permeabilities of ferromagnetic and ferrimagnetic, and permittivity and conductivities of dielectric materials. Therefore, for the ordinary lossy media, it can be assumed that only w in (8.9) increases with rising operation frequency, and so the α . Consequently, transmission losses are greater for the low-THz band compared to the conventional spectra, which is also evidenced by respective measurements [64].

Similarly, $\mathbf{E}^r$ can be expressed as

$$\begin{aligned}\mathbf{E}^r &= \mathbf{E}_1^r e^{-j\beta^r \cdot \mathbf{r}} \\ &= \mathbf{E}_1^r \exp[-j\beta_1(x \sin \theta_r - z \cos \theta_r)]\end{aligned}\quad (8.10)$$

where

$$E_1^r = \Gamma^b E^i \quad (8.11)$$

$$\beta = w\sqrt{\mu\varepsilon} \left\{ \frac{1}{2} \left[\sqrt{1 + \left(\frac{\sigma}{w\varepsilon} \right)^2} + 1 \right] \right\}^{1/2} \quad (8.12)$$

β is the phase constant in rad/m, which is also known as the wave number and represented with k in the literature, and θ_r is the reflected angle. Hence, the amplitude of $\mathbf{E}^r$ varies with Γ^b , which depends on η and θ_t , that are calculated using

$$\eta = \sqrt{\frac{jw\mu}{\sigma + jw\varepsilon}} \quad (8.13)$$

$$\gamma_1 \sin \theta_i = \gamma_2 \sin \theta_t \quad (8.14)$$

(8.14) is Snell's law of refraction and it generates a complex θ_t for incidences comprising a lossy medium. Therefore, the true refracted angle, ψ_t , and the direction of wave travel, $\hat{\mathbf{n}}_t$, are written as [143]

$$\psi_t = \tan^{-1} \left(\frac{\beta_1 \sin \theta_i}{\alpha_2 \operatorname{Im}(\cos \theta_t) + \beta_2 \operatorname{Re}(\cos \theta_t)} \right) \quad (8.15)$$

$$\hat{\mathbf{n}}_t = \hat{\mathbf{a}}_x \sin \psi_t + \hat{\mathbf{a}}_z \cos \psi_t \quad (8.16)$$

Unlike the α , there are many frequency dependent parameters contained within the non-linear equation of Γ^b . Thus, determining the precise effects of ascending carrier frequency on Γ^b , and so $|\mathbf{E}^r|$, via broad theoretic observations for different material classes is unachievable. Although very limited in the number of materials covered, there are existing studies which are based on actual EM wave measurements that report the Γ^b of the evaluated specimens. One of these illustrate the $\Gamma_{\perp}^b$ and $\Gamma_{\parallel}^b$ of one sample of paperboard with ingrain wallpaper pasted on front and two concrete plaster examples, up to 1 THz and for two different θ_i . Whereas the exact values

are not released, the available graphs of $\Gamma_{\perp}^b$ and $\Gamma_{\parallel}^b$ show that even though there is fluctuation present in the curves, it is negligible for the computed frequency range and both θ_i [144].

This result is actually expected for customary materials which are poorly dispersive. However, it cannot be concluded that the increasing operation frequency does not affect $|\mathbf{E}^r|$, since this also invalidates the smoothness assumption for the planar interface between the media under which (8.10) is derived. Therefore, a more comprehensive analysis incorporating rough surfaces into reflection and scattering formulations is needed.

An irregular, or rough, boundary, or interface, is described to have periodic or random variations of height from a pre-set mean plane, or smooth, boundary. The scattering coefficient, ρ , is defined as

$$\rho = \frac{E^s}{E^r} \quad (8.17)$$

where $\mathbf{E}^s$ is the scattered electric field component, and E^r is assumed to be the reflection created by an $\mathbf{E}_{\perp}^i$ upon a smooth and perfectly conducting interface in the specular direction, whose conditions are

$$\theta_r = \theta_i \quad (8.18)$$

$$\theta_s = 0 \quad (8.19)$$

(8.18) is Snell's law of reflection. The mean scattered power density, $\langle S^s \rangle$, in W/m² is then expressed as

$$\begin{aligned} \langle S^s \rangle &= \frac{1}{2} Y_1 \langle E^s \overline{E^s} \rangle \\ &= \frac{1}{2} Y_1 |E^r|^2 \langle \rho \bar{\rho} \rangle \end{aligned} \quad (8.20)$$

where

$$E^r = \Gamma_{\perp}^b E^i \quad (8.21)$$

$$= j \frac{2\beta_1 E^i e^{j\beta_1 R_0} XY \cos \theta_i}{\pi R_0} \quad (8.22)$$

Y_1 is the admittance of the dielectric medium in S, R_0 is the distance of the point of observation from the origin, which lies on the mean plane interface but not necessarily on the interface, X and Y are the dimensions of the rough boundary, the angular brackets $\langle \rangle$ indicate mean value, and the bar $(-)$ denotes complex conjugate. E^r is of $\perp$ polarization because when the reflection is initiated by linearly polarized $\mathbf{E}^i$ and upon smooth interfaces, $\mathbf{E}^r$ preserve the linear polarization properties. (8.22) is also calculated exercising the Helmholtz integral for the assumptions given in the definition of ρ .

Let the interface between the media be rough in two dimensions and the surface is given by a random stationary process $\zeta(x, y)$, whose values designate the level z of the surface at points (x, y) on the xy plane boundary. If ζ is normally distributed with zero mean value, standard deviation ς , which represents the roughness of the surface, and correlation distance D , signifying the separation between two variable points for which the autocorrelation coefficient reduces to e^{-1} , and so the density of the irregularities, $\langle \rho \bar{\rho} \rangle$ is computed as

$$\langle \rho \bar{\rho} \rangle = e^{-g} \left(\rho_0^2 + \frac{\pi D^2 F^2}{A} \sum_{m=1}^{\infty} \frac{g^m}{m! m} e^{\frac{-(v_x^2 + v_y^2) D^2}{4m}} \right) \quad (8.23)$$

where

$$g = \left[\frac{2\pi\varsigma}{\lambda} (\cos \theta_i + \cos \theta_r) \right]^2 \quad (8.24)$$

$$\rho_0 = \frac{\sin(v_x X) \sin(v_y Y)}{v_x X v_y Y} \quad (8.25)$$

$$F = \frac{1 + \cos \theta_i \cos \theta_r - \sin \theta_i \sin \theta_r \cos \theta_s}{\cos \theta_i (\cos \theta_i + \cos \theta_r)} \quad (8.26)$$

$$v_x = \frac{2\pi}{\lambda} (\sin \theta_i - \sin \theta_r \cos \theta_s) \quad (8.27)$$

$$v_y = \frac{-2\pi}{\lambda} (\sin \theta_r \sin \theta_s) \quad (8.28)$$

$$\lambda = \frac{2\pi}{\beta_1} \quad (8.29)$$

g is the Rayleigh roughness parameter, ρ_0 is the scattering coefficient of a smooth interface of area $A = XY$, F is a factor from the general Kirchhoff solution for ρ ,

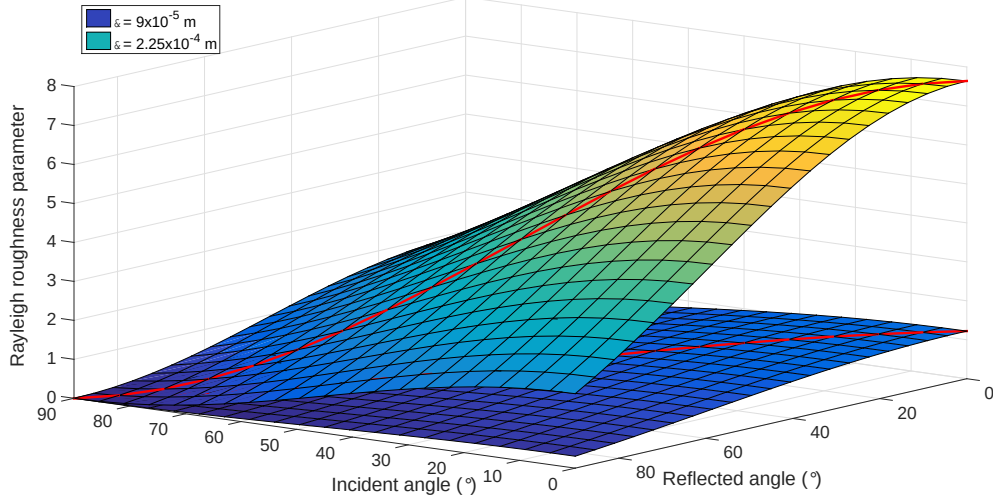


Figure 8.2: Rayleigh roughness parameter, calculated for a uniform plane EM wave propagating in air at 293.089 GHz and for incident rough surfaces with standard deviations of 0.09 and 0.225 mm, where red lines demonstrate the cases of specular reflection.

v_x and v_y are the x and y components of the vector $\mathbf{v} = \boldsymbol{\beta}^i - \boldsymbol{\beta}^r$, respectively, m is the index introduced by an exponential series expansion step during the derivation of (8.23), and λ is the wavelength of the EM wave in the dielectric medium in m [145].

To the best of authors' knowledge, there are three publications in the literature which propose or include a channel model for the THz band. While the emphasis is on ergodic capacity calculation of a THz band communication system that utilizes hybrid beamforming on its antenna subarrays, a channel model nevertheless is available in [146]. It builds on the famous work of Saleh and Valenzuela, which primarily proposed that rays arrive in clusters in indoor transmissions. In [146], arrival time mechanisms are kept the same as Poisson processes, whereas gain of the rays are detailed to contain gaseous attenuation. Angular characteristics and beamforming related antenna components are also included from related works. However, the model is of unknown use since its accuracy is not validated against correct channel measurements.

Of the two papers which put forward a THz band channel model, the more recent

one is strictly analytical [147]. Formed on the proposal to divide a wideband THz channel into narrow enough subbands that do not exhibit frequency selectivity, the channel response of each such subband is claimed to be the addition of LoS, reflection, diffraction and scattering components. Since the transfer functions and test data sets of all these propagation mechanisms are mostly based on existing work, the channel is yet to be independently analytically modelled and verified.

The only low-THz band channel model that is constructed on top of both the theoretical and experimental work of a single research group is [135]. Outputs of an internally developed ray tracing software are used for modelling instead of real channel measurements, while omitting diffraction and scattering components. Analytical probability density functions approximating the amplitude and polarization parts of the channel transfer function are parametrized in full. However, the formulated model is scenario-specific, hence the provided time and angle of arrival and angle of departure information are of no general use and can be deterministically calculated. Altogether, while it is far from final with many issues that need to be resolved, [135] still presents the first true low-THz band channel model in the literature.

8.4 Open Research Issues

Investigations on low-THz band for wireless communication purposes began nearly a decade ago. Consequently, the research area is only emergent with several problems which need to be solved before real world deployments. The foremost of these can be described as follows:

- **Realistic channel models:** As previously explained, for low-THz band there is only one channel model candidate that incorporates serious inadequacies. Multiple new models which target potential WPAN and WLAN use cases should be devised based on actual channel measurements performed in various environments including outdoors, where the effects of meteorological phenomena also ought to be accounted for. In addition to providing a complete and accurate elucidation of the small- and large-scale space-time-frequency characteristics of the

channel, the models need to be adaptable to analytical and empirical analyses for higher communication layer research subjects.

- **Multiple channel access:** The very high data rate and zero-latency requirements from the low-THz band for IoT applications are achievable through multi-hop communication over dense ad hoc networks, and the multiple access scheme should be compliant. Multiple, hybrid and random access methods need to be investigated for varying channel bandwidth, equipment density and usage models. While intersymbol interference is probably insignificant since multipath is confined in the THz band, results of multiple access interference ought to be examined for different access techniques.
- **Baseband signal processing:** For successful low-THz band system realizations, TRX design and communication methods are equally important. However, baseband processing of a 40/100 Gb/s wireless link solely in the digital domain is a major challenge in its own right. Analogue implementations of various TRX components should be investigated as mixed-signal baseband operation can theoretically result in simpler, faster and more energy efficient circuitries. Another research area is parallel data transmission using OFDM or parallel sequence spread spectrum, because utilizing multiple streams would lower the performance requirements on the baseband processor in return for increased number of circuit elements.
- **Multiple antenna systems:** Since the effective area of an antenna is inversely proportional to the square of signal frequency, advanced multiple antenna methods are both critical in augmenting the link budget of and practicable for low-THz band IoT services. Beam forming and steering algorithms for phased array antennas are among the prioritized investigation directions as those will aid the problems of device discovery and propagation in susceptible THz channels. Massive MIMO also necessitates further research to resolve predicaments such

as pilot contamination and reciprocity calibration prior to becoming an enabling technology.

- **Access network architecture:** Additional losses intrinsic to the THz band limit the range of individual devices. However, network densification which accompanies IoT and expanding universal Internet access present new design opportunities for uninterrupted connectivity. Last-mile network architectures should be capable of supporting the expected escalating capacity needs of each small cell, where wavelength-division multiplexing passive optical networks can become the bottleneck. Moreover, short-range communication techniques for the low-THz band need to be researched as complementary device-to-device links are effective in avoiding brief shadowing events like human blockage [148].

8.5 Conclusion

With no end of wireless communication upsurge in sight, neither throughput nor data rate requirements of 5G systems can be provided by just concentrating on spectral efficiency solutions. Due to the constantly improving low-cost device technologies, the first transmission window within the THz band is no longer out of reach of widespread communication systems. As the THz standardization activities for WPANs recently progressed to second stage, research efforts in the area are to intensify even more. While the initially arising difficulties for low-THz indoor access network architecture can be resolved using the already laid out concepts, the proposed frequency leap is not small and the work has just begun. Realistic channel models, optimum multiple access algorithms and Si CMOS devices all separately yet simultaneously need development. However, the question is not the possibility of commonplace low-THz band communications, but the timetable.

Chapter 9

ATTENUATION CONSTANT MEASUREMENTS OF CLEAR AND FROSTED GLASS SAMPLES AT THE LOW TERAHERTZ BAND

9.1 *Introduction*

The usage of wireless communications is continually growing. IP traffic carried over all access network technologies is anticipated to rise, along with the projected increase in the shares of the mobile and wireless local area networks (WLANs). The amount of data transferred using fixed connections is forecasted to grow at 11% compound annual growth rate (CAGR) from 2014 to 2019. During this period the expected CAGRs for mobile and Wi-Fi links are 62% and 22%, respectively, rising their parts to 29% and 37% in 2019 from their 2014 values of 7% and 38%. Also, approximately 55% of the total mobile traffic is going to be off-loaded onto WLANs in 2020, which amount was 51% in 2015[1].

The rise in the wireless data traffic and the associated network connection speed growth necessitate notably improved radio interface capabilities. Because the existing spectral efficiency techniques are already highly advanced [35], operation bandwidth expansion by means of carrier frequency increase is prioritized. In fact, the first IEEE WLAN standard for the 60 GHz band was ratified in 2012, and the World Radiocommunication Conference 2015 (WRC-15) selected the 24.25-86 GHz frequency range to be considered for primary service allocation to mobile communications at WRC-19 [62].

The next band explored for general wireless communications is the spectrum beyond 275 GHz, which is the low end of the THz band and unallocated for any active

services by the ITU. WRC-15 identified the 275-450 GHz frequency range for land mobile and fixed services as well, while the IEEE 802.15 Task Group 3d is developing a switched point-to-point physical layer for the 252.72-321.84 GHz band for close proximity, intra-device, mobile backhaul and fronthaul, and data center communication applications [62].

The initial research activity towards utilization is channel modelling. Transmission through materials is one of the fundamental electromagnetic (EM) wave propagation mechanisms that depends on media's attenuation constants, which are a function of the frequency and materials' constitutive parameters and, represented with α . Therefore, correct quantities of the α of materials that are commonly present in wireless communication channels are essential for THz band investigations.

To the best of authors' knowledge, there are only three publications in the literature which include α measurement results of customary building materials in the THz range [63, 149, 64]. All three articles are established on time domain spectroscopy (TDS) and compute $\alpha(f)$ from the Fourier spectra of the ultrashort EM pulses. [149] has the largest measurement span, extending from 0.1 to 2 THz, though just one gypsum board and two mineral wool samples are evaluated. All papers contain graphs of the calculated α outcomes using sparsely assessed data points. However, exact values are provided only in [64] and for 100, 350, 500 and 700 GHz frequencies.

Accordingly, this is the first publication that demonstrates the complete α results of the clear and frosted glasses in the low-THz band by the use of an original method which employs a scattering matrix element. The rest of this chapter is organized as follows. Section 9.2.1 formulates the theoretic model of the α measurement, and Section 9.2.2 explains the novel α computation technique. Section 9.3 describes the experimentation setup and glass specimens. The α results and comparative analyses are presented in Section 9.4, and the article concludes with summarizing remarks.

9.2 Attenuation Constant

9.2.1 Electromagnetic Wave Transmission Through Lossy Media

Assume a plane EM wave with parallel ($\parallel$) polarization propagating in a perfect dielectric medium is incident normally upon a lossy medium with smooth interface, as illustrated in Fig. 9.1. The incident, reflected and transmitted electric field components, $\mathbf{E}^i$, $\mathbf{E}^r$ and $\mathbf{E}^t$, in V/m, and the corresponding average power densities, $\mathbf{S}_{\text{av}}^i$, $\mathbf{S}_{\text{av}}^r$ and $\mathbf{S}_{\text{av}}^t$, in W/m², are

$$\mathbf{E}^i = \hat{\mathbf{a}}_x E^i e^{-j\beta_1 z} \quad (9.1)$$

$$\mathbf{E}^r = \hat{\mathbf{a}}_x \Gamma^b E^i e^{+j\beta_1 z} \quad (9.2)$$

$$\mathbf{E}^t = \hat{\mathbf{a}}_x T^b E^i e^{-\alpha_2 z} e^{-j\beta_2 z} \quad (9.3)$$

$$\mathbf{S}_{\text{av}}^i = \hat{\mathbf{a}}_z \frac{|E^i|^2}{2\eta_1} \quad (9.4)$$

$$\mathbf{S}_{\text{av}}^r = -\hat{\mathbf{a}}_z |\Gamma^b|^2 \frac{|E^i|^2}{2\eta_1} \quad (9.5)$$

$$\mathbf{S}_{\text{av}}^t = \hat{\mathbf{a}}_z |T^b|^2 \frac{|E^i|^2}{2} e^{-2\alpha_2 z} \text{Re} \left(\frac{1}{\eta_2} \right) \quad (9.6)$$

where

$$\Gamma^b = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \quad (9.7)$$

$$T^b = \frac{2\eta_2}{\eta_2 + \eta_1} \quad (9.8)$$

$$\alpha = w\sqrt{\mu\varepsilon} \left\{ \frac{1}{2} \left[\sqrt{1 + \left(\frac{\sigma}{w\varepsilon} \right)^2} - 1 \right] \right\}^{1/2} \quad (9.9)$$

$$\eta = \sqrt{\frac{jw\mu}{\sigma + jw\varepsilon}} \quad (9.10)$$

E^i is the amplitude of $\mathbf{E}^i$, β is the phase constant in rad/m, Γ^b and T^b are the reflection and transmission coefficients at the interface, α is in neper/m (Np/m), η is the intrinsic impedance in ohms, w is the angular frequency in rad/s, μ is the permeability in H/m, ε is the permittivity in F/m, σ is the conductivity in S/m, and the bar ($\bar{}$) denotes complex conjugate.

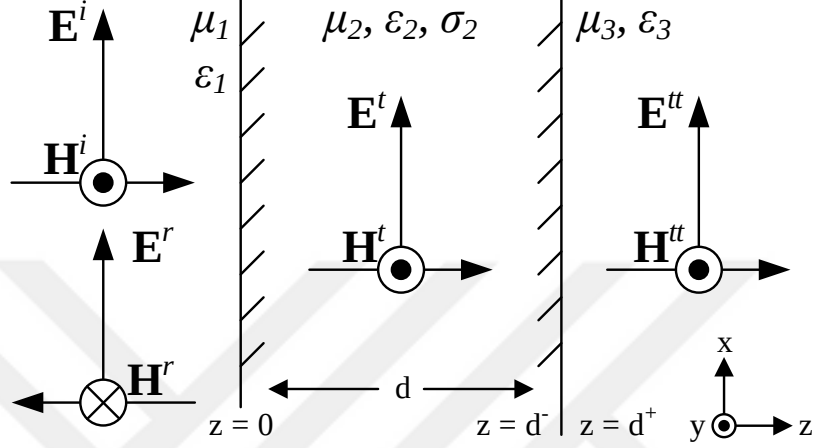


Figure 9.1: Normal incidence of a uniform plane electromagnetic wave with parallel polarization on smooth interfaces and its transmission through media.

Suppose the EM wave propagates further for a distance of d up to the second plane boundary and transmits into the medium 3, which is also lossless as the medium 1. Then, $\mathbf{E}^t$ at $z = d^-$ and the twice transmitted electric field component, $\mathbf{E}^{tt}$, are

$$\mathbf{E}^t|_{z=d^-} = \hat{\mathbf{a}}_x T_{21}^b E^i e^{-\alpha_2 d} e^{-j\beta_2 d} \quad (9.11)$$

$$\mathbf{E}^{tt} = \hat{\mathbf{a}}_x T_{32}^b (T_{21}^b E^i e^{-\alpha_2 d}) e^{-j\beta_1(z-d)} \quad (9.12)$$

where T_{21}^b and T_{32}^b are the transmission coefficients at the interface from media 1 to 2 and 2 to 3, respectively [136].

9.2.2 Attenuation Constant Calculation Using the S_{21} Parameter

Elements of a scattering matrix $[S]$ are defined as

$$S_{ij} = \left. \frac{V_i^-}{V_j^+} \right|_{V_k^+ = 0 \text{ for } k \neq j} \quad (9.13)$$

where V_i^- and V_j^+ are the amplitudes of the voltage waves reflected from port i and incident on port j , respectively.

Assume the S_{21} parameter of a single input single output wireless communication system that emits vertically polarized EM waves is measured with and without a single layer of slab. This block has smooth interface, and is positioned perpendicular to the line-of-sight (LoS) path on the direction of maximum antenna radiation intensity between the transmitter (TX) and receiver (RX) antennae, easily obstructing the projected areas of the first few Fresnel zones onto its boundary. Also, suppose the following conditions hold:

1. The TX and RX antennae have narrow half-power beamwidths (HPBW), therefore the rays collected by the RX antenna can assumed to be normally incident upon the interfaces.
2. The slab is short, thus the EM waves can assumed to propagate in the same trajectory regardless of the presence of the slab.
3. The power input to the TX is equal for a measurement pair, hence V_1^+ remains unchanged for measurements at specific settings for both cases of the existence of slab.

Then, for this situation, (9.1) and (9.12) express the EM wave propagation, the induced voltages on the RX antenna are proportional to the E^i and E^{tt} for the free-space and blocked instances, respectively, and the relative value of the S_{21} parameter for the two cases of a particular measurement setting is sufficient to establish the ratio.

9.3 Channel Measurements

The set of circumstances explained in Section 9.2 are emulated as follows. Analog signal in the low-THz band between 260 and 350 GHz, which frequency range is sufficient to cover the first two THz band transmission windows [60], is generated by mixing the intermediate frequency (IF) signal to the up-converted THz local oscillator (LO) signal. Anritsu Company MS4647B model vector network analyzer (VNA) creates the

Table 9.1: VNA measurement parameters

Parameter	Value	Unit
Starting frequency	10	MHz
Stopping frequency	1	GHz
Bandwidth	990	MHz
Measurement points	991	
Intermediate frequency power	5	dBm
Mean noise floor power	-107.26	dBm
Noise floor standard deviation	6.94	dB

IF signal according to the parameters demonstrated in Table 9.1. Virginia Diodes, Inc. (VDI) frequency synthesizer produces the LO signal from 10.875 to 14.54167 GHz, which is input to the VDI WR-2.8 mixer-amplifier-multiplier chain (MAMC) pair. The latter constitute the TX and RX of the wireless communication system, executing block up-conversion and down-conversion, respectively, via frequency multiplication by 24. The connected diagonal horn antennae are 21.4 mm long and have 4.6 mm aperture diameter. These radiators possess a HPBW of 12° and like the waveguides of the MAMCs, $\parallel$ polarization. A photograph of the measurement instruments in experimentation setup is provided in Fig. 9.2.

There are various methods to calibrate a VNA. The common purpose is measuring the known calibration standards with exact electrical characteristics in order to compute an error model that will be used to eliminate the systematic errors while testing. However, since the LO signal is generated and multiplied independent of the VNA and IF signal, a conventional vector error correction algorithm is not applicable to our measurement system. Therefore, the original α calculation technique in Section 9.2.2 which works with response calibration is devised.

Common window glasses belonging to the soda-lime-silica glass category are selected for α measurements. Three clear glass specimens having different thicknesses

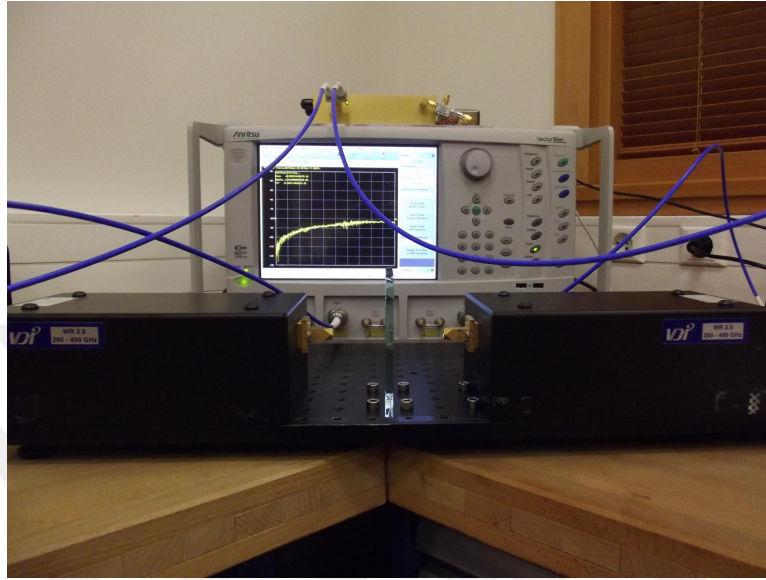
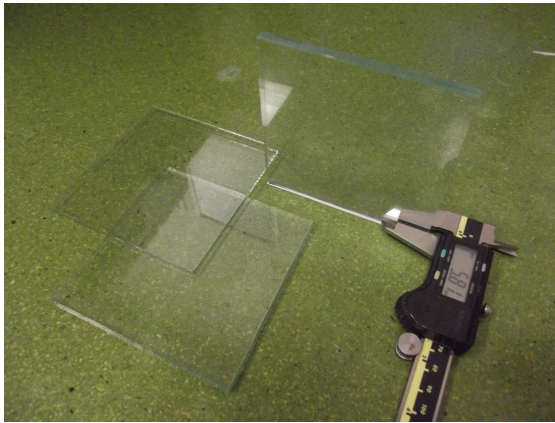
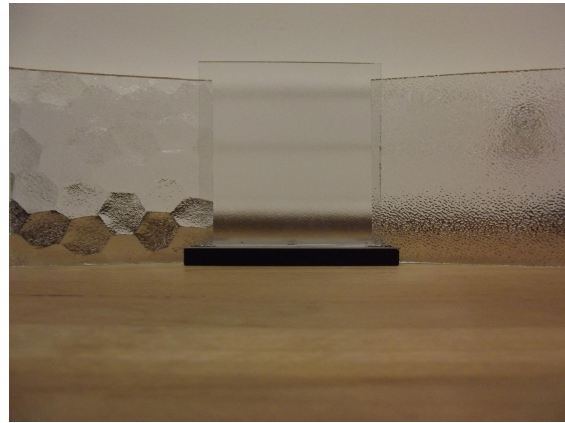


Figure 9.2: The measurement setup.



(a)



(b)

Figure 9.3: (a) Clear glass samples, and (b) Frosted glass samples with hexagon, blur and dot patterned irregularities, respectively.

and three frosted glass specimens with distinct irregularity form and depths are used. The examples have a relative permittivity of 6, and are presumed to be nonmagnetic and insulators with a σ of 10^{-12} S/m. The samples' thicknesses, d , are gauged manually using a Mitutoyo Corporation Absolute Digimatic model caliper at 8 separate positions and the ensuing sample mean, $\langle d \rangle$, and standard deviations, (s) , are given

Table 9.2: Descriptive statistics of the samples' thicknesses

Quantity	Clear Glass			Frosted Glass		
	1	2	3	Blurred	6-gon	Dotted
$\langle d \rangle$ (mm)	1.8925	3.8338	5.7988	1.9938	3.8088	3.8675
s_d (μm)	8.8641	7.4402	9.9103	14.079	121.59	8.8641

in Table 9.2. In addition, the surface dimensions of all of the specimens are approximately $0.1 \text{ m} \times 0.1 \text{ m}$, which makes the interfaces broad enough to refract the entirety of the EM wave emission due to the short testing path length and the narrow TX antenna radiation pattern. Pictures of the evaluated clear and frosted glass samples are presented in Fig. 9.3a and Fig. 9.3b, respectively.

9.4 Results and Discussion

9.4.1 Clear Glass

The S_{21} parameter of the wireless communication system with the three clear glass samples placed as described in Section 9.2.2 and without any blocks is quantified at 45 carrier frequency values that are uniformly 2 GHz apart. The differences between the extrema of the individual S_{21} outcome lines are 51.974, 42.812, 35.086 and 30.36 decibel (dB), for free-space and increasing specimen thickness cases, respectively. This variation is because of the frequency dependent conversion loss performance of the MAMCs and does not affect the α calculations since the relative values of the S_{21} parameters are employed.

In accordance with (9.1) and (9.12), any two of the four S_{21} parameter results are adequate to compute the α at a frequency. Moreover, the magnitude of the S_{21} parameter at a frequency must reduce as the slab depth rises, and the very low number of points which do not comply with this verifies the reliability of the experiments. Therefore, initially α is calculated at every frequency for each S_{21} combination that

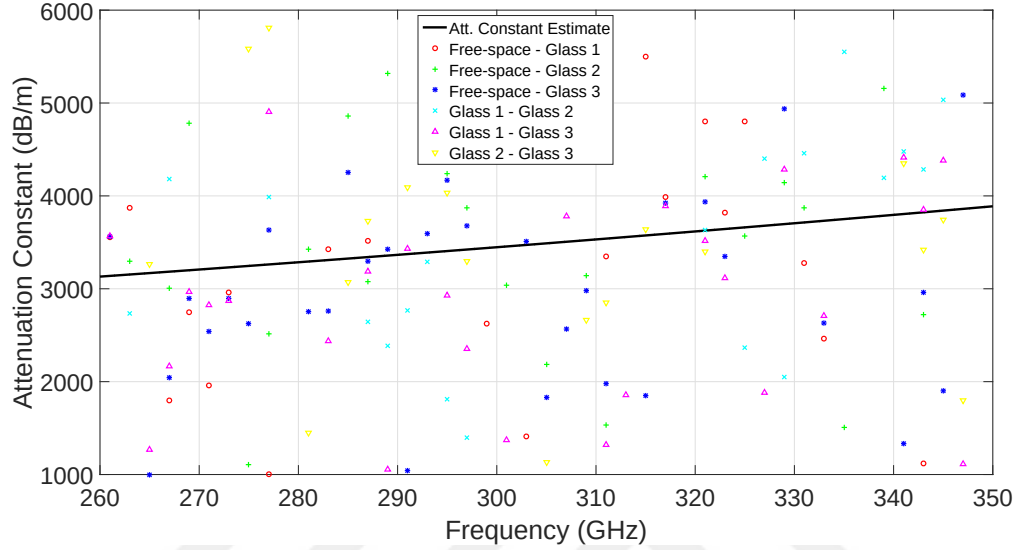


Figure 9.4: Clear glass α estimate and the calculated clear glass α data set, which is color- and marker-coded according to the originating S_{21} parameter pairs.

satisfies the magnitude constraint. Then, the statistical outliers are removed from the data, and a one-term exponential model is fitted to the final set. The resulting function is

$$\alpha(f) = 1675 \exp \left[(2.406 \times 10^{-12}) f \right] \quad (9.14)$$

where f is the operation frequency in Hz, and $\alpha(f)$ is determined in dB/m for simpler interpretation. (9.14) has a root-mean-square error (RMSE) of 1053, and it is illustrated in Fig. 9.4 together with the α data set, which are color- and marker-coded consistent with the originating S_{21} parameter pairs, utilized by the non-linear least squares fitting method.

There are two publications by the same research groups available in the literature that include α results of clear glass in the low-THz band using actual measurements [63, 64]. Neither the exact unit of α , Np/m or dB/m, nor the accurate type of the glass samples, other than the inexplicit designation of window, is provided in the publications. Additionally, precise values are obtainable only from the second publication and just for 100, 350 and 500 GHz frequencies. Nevertheless, to present

an exemplary comparison, α is given as 995 m^{-1} in [64] and estimated to be 3888.071 dB/m by (9.14). Whereas the almost three times difference between the quantities is significant, the reasons can be unlike kind of glasses quantified, or inferior performance of the laser-based THz TDS measurement system, especially at the low-THz band, employed in [63, 64]. Overall, for the computation of α of soda-lime-silica category clear glasses in the low-THz band between 260 and 350 GHz, (9.14) is the most dependable and only equation in the literature.

9.4.2 Frosted Glass

In contrast to the clear glass specimens whose both interfaces are smooth, frosted glass specimens' TX-facing interfaces replicate the roughness patterns of the glasses. Due to the randomly irregular boundary and media, even if the EM waves are normally incident upon the mean plane boundary, the rays will not transmit perpendicular to the interface but rather be refracted and scattered arbitrarily. Thus, (9.12) no longer explains the EM wave transmission, as the distribution of a rough surface is required for the deterministic solution [145]. Yet, the method devised in Section 9.2, which is valid for homogeneous materials with smooth interfaces, is also applied to the particular free-space-frosted glass S_{21} parameter pairs, and the results are

$$\alpha(f) = \begin{cases} 3465 \exp \left[(1.427 \times 10^{-12}) f \right], & \text{for blurred} & (9.15) \\ 462.2 \exp \left[(6.275 \times 10^{-12}) f \right], & \text{for hexagon} & (9.16) \\ 3112 \exp \left[(9.796 \times 10^{-13}) f \right], & \text{for dotted} & (9.17) \end{cases}$$

where the consequent RMSEs are 3015, 1226 and 1996, respectively. (9.15)–(9.17), which are shown in Fig. 9.5 in conjunction with their corresponding α data sets, are not generalizable since the formulae are reliant on the specific irregularity forms, and their goodness-of-fit statistics are considerably poorer than (9.14). Furthermore, the α comprise the frosted glasses' random effects on the EM wave propagation too. Altogether, the predominantly higher α results of the frosted glasses compared to the clear glass plainly indicate the ray spreading impact of the rough boundary and media.

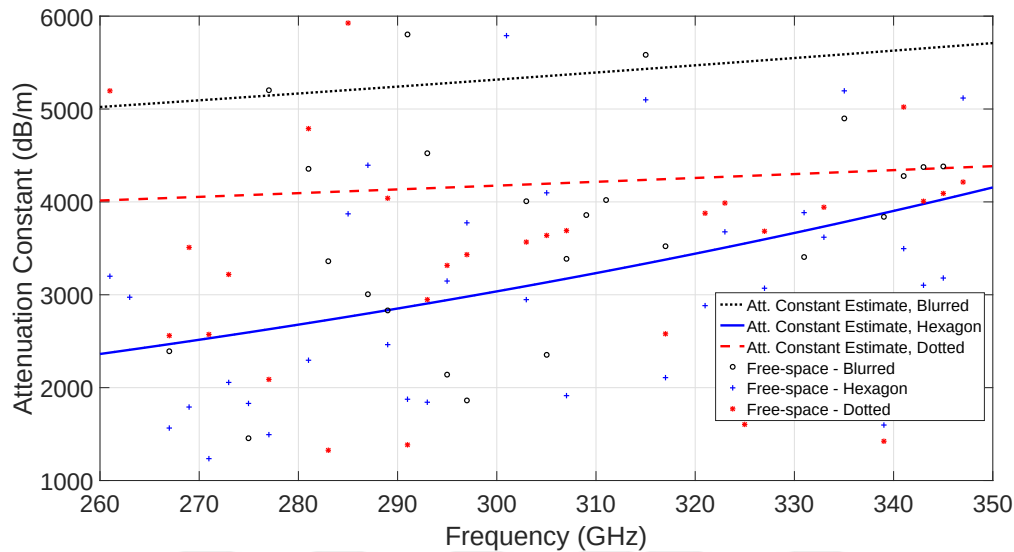


Figure 9.5: Frosted glass α estimates and the calculated frosted glass α data sets.

9.5 Conclusion

EM wave propagation through any medium is a function of the medium's α . In this chapter, for the first time in the literature, exponential models of the α of ordinary clear window glass and three different forms of frosted glasses, based on channel measurements between 260 and 350 GHz and making use of an original calculation technique are presented. α is computable from the change in the S_{21} parameter tested with and without a material blocking the propagation path, if the EM waves are normally incident upon the material's interface. High-priced VNA frequency extenders are needed for experimentation in the low-THz band. Whereas the α calculation method and clear glass result are directly applicable to the entire THz band research subjects, frosted glass outcomes are confined to the distinct irregularity patterns.

Chapter 10

ENERGY-EFFICIENT MODULATION AND PHYSICAL LAYER DESIGN FOR LOW TERAHERTZ BAND COMMUNICATION CHANNEL

10.1 *Introduction*

Over the last two decades mobile communications have radically progressed from just being a luxury service for business people. The subscriber number of mobile telephony passed both the 1 billion mark and its fixed-line counterpart in 2002 permanently: As of 2014, mobile device and connections reached to 7.4 billion globally, resulting a penetration rate over 100% for the first time, and expected to grow to 11.6 billion by 2021 [150, 70, 57].

Technical performance requirements of the fourth generation (4G) of mobile telecommunication systems, IMT-Advanced [151], were identified in 2008 by the report International Telecommunication Union (ITU) Radiocommunication Sector (ITU-R) M.2134 [2]. LTE-Advanced and WirelessMAN-Advanced were specified as the two complying standards on 18 January 2012, and this date can be considered to be the beginning of the standardization activities on the 5G systems.

There are some ever-present expectations from the next-generation of cellular systems, the foremost of which can claimed to be peak data rate increase. The highest data rate for the third generation systems was defined as 20 Mb/s in 1997 by the report ITU-R M.1034-1 [122], whereas, this value for the 4G downlink is 1500 Mb/s [2]. However, the latter assumes an extended operation bandwidth of 100 MHz and 4×4 multiple-input multiple-output (MIMO) antenna array, though the current industry norm is 2-stream MIMO and 4-stream MIMO is only perceived to be possible

by the time 5G telecommunication systems arise. Thus, in view of the advancement of the wireless standards, peak data rate designation of beyond 4G systems is expected to be on the order of 10 Gb/s.

Besides performance, mobile telecommunication market and applications are continuously evolving too. The increase in the number of user equipments (UEs) is led by smartphones, and this trend is expected to continue, as the share of smart devices among total connections is predicted to rise from its 2014 value of 26% to 74.7% by 2021. Such an upsurge does not just alter the composition of principal mobile application and services, but also adds additional growth pressure on network capacity and connection speeds, since average data usage per smart devices range between 37 and 132 times that of a basic mobile phone, depending on the device and connection types[70, 57].

Increasing the carrier frequency, f_c , to the low end of the THz band has been proposed as one alternative method to meet the radio interface performance requirements of the 5G systems [152, 153]. Research activities in this spectrum are increasing, as the channel characterization and semiconductor device behaviors are already being examined. However, unlike the 60 GHz industrial, scientific and medical radio band, modulation schemes for the THz band communications are yet to be defined. In [154], a distance aware modulation scheme which uses distance and frequency dependent behavior of the THz band channel to adaptively utilize the bandwidth is proposed. An important factor in the selection of the modulation technique for the THz band is the higher amount of energy that is required for data transmission. Thus, minimizing the energy consumption factor is necessary to make the communications viable and cost-effective. Most of the literature on wireless communication energy consumption is focused on transmitting small amounts of data at sub 6 GHz bands. For example, in [155], energy consumption analysis of a communication system operating at 2.5 GHz is analyzed by including the transmission and circuit energy consumptions. It is shown that for short-range applications, M-ary quadrature amplitude modulation (MQAM) is more energy efficient than M-ary frequency-shift keying (MFSK).

In this chapter, use cases that contain large amounts of data transmission in the low-THz band are investigated in order to determine the best performing and lowest energy consuming modulation methods. The analyses are extended towards optimal physical layer (PHY) parameters which can further minimize energy consumption, and to propose ideal parameters required for general THz band transceiver (TRX) design. The used models are also based on semiconductor technology, since silicon (Si) complementary metal-oxide-semiconductor (CMOS) is still the best choice for bulk fabrication of inexpensive products.

The remainder of this chapter is organized as follows. Section 10.2 provides state-of-the-art THz device technologies that operate in room temperature and hold promise for use in commercial 5G products. In Section 10.3, the THz band TRX model used for energy consumption analyses is described. Energy consumption characteristics of MQAM and MFSK are researched in Section 10.4. Optimization of modulation parameters, together with the comparison of the MQAM and MFSK simulation results, are provided in Section 10.5. Optimization of PHY parameters is examined in Section 10.6, and the chapter is concluded following a précis on associated open research issues in Section 10.7.

10.2 THz Band Device Technologies

While the THz band seems to offer an abundant spectrum for every radio service conceivable, it actually presents a very harsh environment for electromagnetic (EM) wave propagation. Although prohibitively high attenuation by atmospheric gases is advantageous for some small number of specific applications, like intersatellite communications links because it assists those to be isolated from any possible interference from the Earth, THz band is yet to be utilized for communication purposes. However, this has not been the case for the whole scientific field as the THz band contains some unique and valuable information that are within the research interests of different areas. For example, temperatures of the interstellar dust clouds range between 10 and 200°K, which corresponds to about 0.21 and 4.3 THz, respectively. Therefore, energy

radiated from interstellar gas, which is used for star formation research, lies entirely within the THz band. Gases that make up the Earth's atmosphere also have thermal emission lines in the THz band, creating Earth science's need for measurement instruments working at THz frequencies.

Several device technologies are available today which jointly cover the transmitter (TX) and receiver (RX) needs of the entire THz spectrum, ranging from metamorphic high electron mobility transistors to quantum cascade lasers; however, only a very small percentage of these possess the potential to be used for 5G communication systems. If 5G systems are to acquire high market penetration rates, respective UE and network devices must be robust, lightweight, highly integrated and most importantly, low-cost. Taking into account the technologies which are currently used to manufacture the hardware of virtually all mainstream communication devices and after a review of the currently available THz device technologies, Si CMOS appear as the only viable candidates for 5G despite their shortcomings in practically all electronic performance criteria.

Compared to the III-V semiconductor compounds, Si has worse material properties than many. Lower electron mobility, smaller energy band gap and higher resistivity of Si result in devices with inferior figures of merit. CMOS, likewise, has poorer transistor and passive performances than the corresponding components produced using III-V compound processes. However, there are plenty of critical reasons that have caused Si and CMOS to dominate the global semiconductor market, and with the current development rate in corresponding areas, their places look secure. Si, first of all, is vastly available all around the world and its purification is simple. Mechanical characteristics of Si make it a sturdy material, thus easy to manufacture and handle. Si also has high thermal conductivity enabling efficient thermal management of devices. It is simple to form insulators with exceptional dielectric properties like silicon dioxide that are used as CMOS transistor gates among many other functions. The doping concentration of Si has a very high range and with the already established manufacturing capacity and continued demand, low-cost production is ensured. On the

other hand, since CMOS technology is essentially the same for all devices regardless of the frequency of operation, CMOS's intrinsic advantages like integration of higher frequency circuits with baseband circuitry, digital calibration for better performance, high yield and built-in self test also holds true for the THz range devices.

Initial IEEE mm-wave standards 802.11ad and 802.15.3c were ratified in December 2012 and October 2009, respectively. Furthermore, considering the fact that the first submm-wave standard, IEEE 802.15.3d, was approved in September 2017, it will be safe to say we are at least a decade away from commercial low-THz band products [61, 77, 142]. Nevertheless, research activities on both circuitry and communication domains are starting to accelerate, which includes MIMO systems as well. Emerging THz band applications that also develop Si CMOS technology include imaging [156], sensors [157] and chip interconnection [158]. Artificial dielectric layers are proposed to improve performance of on-chip antennas radiating at the low-THz band [159]. However, in line with the subject of the chapter, in the following subsections a complete survey is presented on the state-of-the-art Si CMOS THz circuit blocks and modules designed for communication purposes. Moreover, devices whose operation frequencies are contained by the first 3 transmission windows of the low-THz band, which, approximately, range from 275 to 420 GHz [60, 62], are selected in order to demonstrate the potential for 5G in the THz region. This limitation imposed the exclusion of a number of notable Si CMOS studies that are just outside the frequency range [160, 161].

10.2.1 Signal Sources

THz signal source fabrication using CMOS is probably the most difficult field of the THz electronics research and only recently implementations with acceptable power, high stability and frequency tuning have started appearing in the scientific literature. Depending on the power gain cutoff frequency (f_{max}) of the transistors that are used, low-THz band can be reached through either frequency multiplication or direct generation. If the f_{max} of a device is large enough for the intended THz application, direct

generation is commonly preferred since the power efficiency is better and smaller chip area is needed compared to frequency multiplication. However, especially for Si CMOS devices, this is predominantly not the case. Therefore, signal sources are specifically designed to efficiently generate power at the harmonic frequencies of built-in non-linear diodes, so that appropriate harmonics of the fundamental frequency (f_0) can be output.

One Si CMOS source employing a triple-push architecture is reported in [162]. An N-push oscillator consists of N coupled oscillators which use a shared resonator and output $2\pi/N$ phase-shifted signals. When these signals are combined, N^{th} harmonic components are constructively added, whereas the rest, in theory, are negated. Even though this method is useful for higher frequency generation, discontinuous tuning is observed in the event of uneven phase-shift [163].

In [162], the same 2 triple-push oscillator cores are locked by magnetic coupling, and the power is conveyed to the differential ring antenna through a matching stage. The device is realized in a 65-nm CMOS process over a $500 \times 570 \mu\text{m}^2$ die area, with oscillators occupying $120 \times 150 \mu\text{m}^2$ of the total. Output frequency is measured to be tunable from 284 to 288 GHz by reducing the supply voltage from 1.4 to 0.7 volts (V), and the source can generate a peak output power of -1.5 dBm at the upper limit of the tuning range by consuming 275 milliwatts (mW) of DC power. The circuitry was also packaged with a Si lens on an FR-4 board, but since the aim was demonstration and did not involve original design, that part is omitted.

Another novel CMOS source that is implemented in a 65-nm low-power bulk CMOS process is presented in [123]. For frequency tuning, placing varactors inside the LC resonator is a common practice that is shown to work satisfactorily up to 0.1 THz [164]. However, at higher frequencies varactor performance degrades. The significance of the design of [123] originates from eliminating varactors from the voltage-controlled oscillator (VCO), but still delivering a frequency tunable source with high output power which functions at the beginning of the submm-wave band. By adding phase shifters to the proposed 4 core coupled oscillator system, locking frequency of the

VCO is made adjustable in accordance with the phase shifts between each core and the respective injected signal. Even though the provided simulation result illustrated that the third harmonic generates higher current around 300 GHz, fourth harmonic is chosen also for the symmetry it brings. One of the two VCOs that are fabricated for the study radiates peak output power of -1.19 dBm around its 13 GHz of tuning range centered at 290 GHz, therefore achieving the highest output power and tunability for all the oscillators available in the literature which operate in and beyond the low-THz band, even including the ones using compound semiconductor technologies. DC-to-RF conversion efficiency stands at 0.23% due to the 325 mW DC power input, and the chip is printed on an area of $600 \times 600 \mu\text{m}^2$.

10.2.2 Transmitters

Not just sources but also complete TXs are being developed for THz frequencies. One latest example is a phased array [165] that is expanded over the delay-coupled oscillator method by the authors of [123]. The idea of controlling the oscillator frequency through the phase shift between adjacent cores works on a one-dimensional ring. To extend this effect over two dimensions, a 2×2 central loop is connected to 4 other similar loops solely through one of its vertices, creating a 4×4 coupled array. Adjacent nodes are situated at a fixed distance which equals half of the radiation wavelength, and the oscillators are linked with phase shifters. Patch antennas are used for radiation to prevent substrate coupling. A sample, likewise [123], is manufactured in a 65-nm bulk CMOS process over an area of $1.95 \times 2 \text{ mm}^2$. Peak total radiated power is measured at 338 GHz as 0.8 mW, or -0.97 dBm, and equivalent isotropically radiated power (EIRP) as 51 mW, or 17.1 dBm, using 1.54 W of DC power. 12 dB of the 18 dB antenna directivity is due to array gain, and the rest due to patch antenna directivity. Beam steering is feasible across 45° in azimuth (Φ), and 50° in elevation (Θ) angles. Center frequency tuning measurements are performed between 337 and 339 GHz. However, the authors claim that 2.1% tuning is possible via altering the coupler supply voltage, which results in a 7.1 GHz spectrum around

338 GHz.

Another architecture is tunable at second harmonic frequencies which are between 276 and 285 GHz [166]. Distributed active radiator (DAR) [167] and inverse design approach lies at the core of this design. Typically, power generation and radiation are implemented by different circuit blocks. However, in [166], surface currents on Si chip metal layers are first calculated for a specific EM field, and then synthesized using a DAR, which is made of 4 cross-coupled transistor pairs located symmetrically along 2 loops that are shaped into a Möbius strip. This way, second harmonic signal is radiated, while fundamental and other harmonic signals are filtered. The implementation consists of 16 DAR cores in a 4×4 array, and it is realized in a 45-nm CMOS silicon on insulator process. The output of the center VCO, which is tunable from 91.8 to 96.5 GHz using a 1.1 V supply voltage, is distributed to 4 separate divide-by-two frequency dividers that generate quadrature in-phase (I) and quadrature (Q) signals. Signal is then transferred through phase rotator and frequency triplers to drive the DARs. The resulting circuit, which has a chip area of $2.7 \times 2.7 \text{ mm}^2$, is capable of beam steering nearly 80° in both Θ and Φ planes and provides an EIRP of 9.4 dBm at 280.8 GHz via the 16 dBi maximum directivity.

10.2.3 Transceivers

The final integrated TRX model [168] is included to provide a TRX example, even though the device is implemented in 130-nm silicon-germanium bipolar CMOS process. Moreover, its 367 to 382 GHz working range is around an atmospheric attenuation local maximum, thus making the device unsuitable for communication purposes. The TRX design is a homodyne frequency-modulated continuous wave radar using triangular modulation signal. Differential Colpitts VCO generates the fundamental signal at 92.7 GHz with 8.3% tuning radius, which is followed by drive amplifiers. Inside the TX, initially, balanced quadrature I and Q signals are coupled through transformers to the frequency quadrupler. 2 push-push pairs compose the quadrupler, which outputs the fourth harmonic frequency, and separate patch antennas, each

containing 2 patches, radiates and receives the signal. On the RX side a subharmonic mixer, driven by second harmonic quadrature I and Q signals, down-converts to intermediate frequency (IF), before the concluding IF amplifier stage. The TX translates 3 dBm VCO output power into -14 to -11 dBm EIRP, the RX noise figure (N_f) is assessed to be between 35 and 38 dB, and the entire TRX consumes 380 mW power above a total space of $2.2 \times 1.9 \text{ mm}^2$.

10.3 THz Band Communication System Model

We modeled a communication link between 2 THz band nodes in order to analyze the energy consumption of a THz band wireless system. A generic wireless communications system can be decomposed into 5 main components: TX, RX, synthesizer, power amplifier (PA) and antenna. All signal processing blocks need to be considered in the energy consumption analysis too. THz band signal generation requires a special synthesizer, and thus it should also be examined in detail. Contrariwise, bandwidth in the THz spectrum is abundant and the small electrical length enables highly directive communication. Therefore, complicated signal processing techniques such as multiuser detection or time division multiplexing are not very advantageous and hence neglected in our model. The resulting system model of the THz band TRX is shown in Fig. 10.1. This system can easily be modified to analyze the energy consumption in a full-dimension MIMO (FD-MIMO).

THz band signal synthesizer mainly consists of a local oscillator (LO), balun, buffer amplifier (BA) and multiplier [169]. The multiplying factor depends on the generated frequency. The baseband digital signal is first converted to analog signal using a digital-to-analog (DAC) converter. This signal modulates the frequency synthesizer signal in the mixer. Subsequently, the modulated signal is amplified using a PA and transmitted into the channel through the antenna. Usually, antennas in the THz band devices are connected to the circuit using special interconnects whose power dissipation is considerable and cannot be neglected. On the RX side, the THz signal is first filtered inherently by the interconnect and then amplified by the low noise

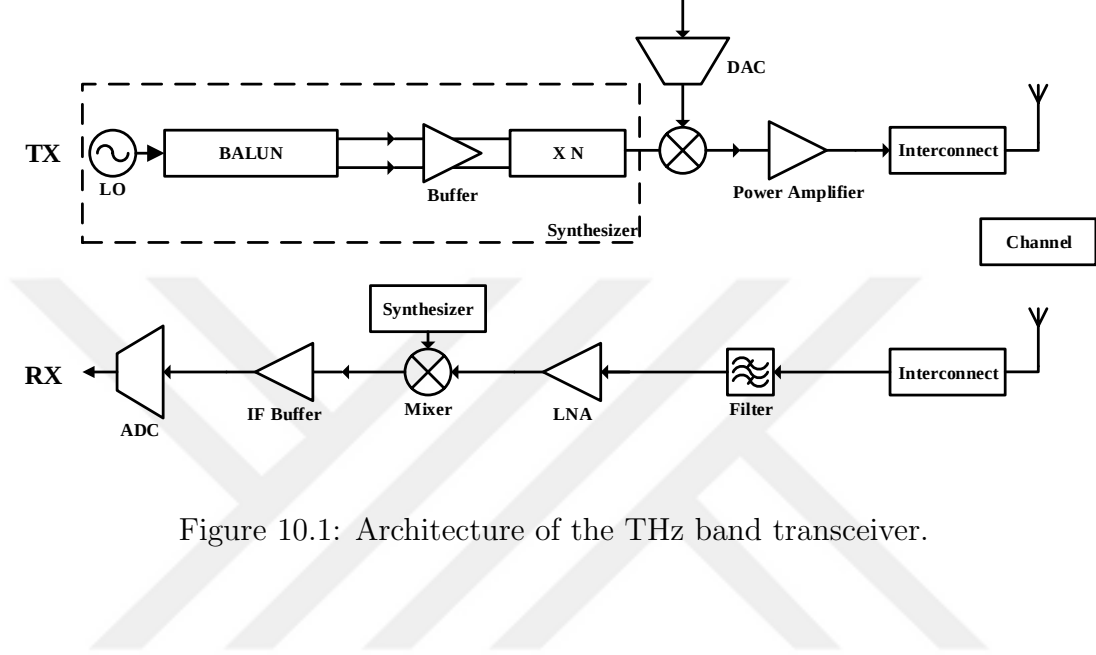


Figure 10.1: Architecture of the THz band transceiver.

amplifier (LNA), downconverted by the mixer and amplified by the IF buffer. Finally, the IF signal is converted back to digital signal using an analog-to-digital converter (ADC).

TRX is assumed to be operating on a hybrid mode basis. When there is a signal to transmit, all the TRX components operate in active mode and consume full power. Conversely, when there is no signal to transmit, TRX switches to inactive mode, which saves energy. When switching from the inactive mode to the active mode there is a transient mode, which is the time required to turn all the components into the active state.

To calculate the power consumption, a simplified case of wireless communication is considered where one of the nodes has I bits to transfer in time T . TX turns on for active mode time, T_{act} , to transmit these bits and then returns back to the inactive mode. T_{act} parameter needs to be optimized based on the modulation scheme. The transmission period consists of $T = T_{act} + T_{settl} + T_{off}$, where, T_{settl} is the transient time whose duration depends mainly on the phase lock loop settling time in the frequency synthesizer and T_{off} is the inactive mode duration. In this scenario, the

total energy consumption, E_{total} , required to send I bits can be written as

$$E_{total} = P_{act}T_{act} + P_{off}T_{off} + P_{settl}T_{settl} \quad (10.1)$$

where the active mode power, P_{act} , is composed of the transmitted power and the circuit power consumption. Power consumed by LO, balun, BA, mixer, LNA, filter, IF buffer, ADC, DAC and PA are all included in the circuit power use. The power consumption of PA is $P_{amp} = \alpha P_t$, where $\alpha = (\xi/\eta) - 1$, ξ is the peak-to-average power ratio (PAPR) which depends on the modulation scheme, and η is the drain efficiency. Thus, the corresponding active mode power can be expressed as

$$P_{act} = P_t + P_{amp} + P_{ct} + P_{cr} \quad (10.2)$$

where P_{ct} and P_{cr} are the circuit power consumptions at the TX and RX, respectively. Moreover, $P_{ct} = P_{LO} + P_{balun} + P_{buffer} + P_{\times N} + P_{mix} + P_{DAC} + P_{interconnect}$ and $P_{cr} = P_{LO} + P_{balun} + P_{buffer} + P_{\times N} + P_{mix} + P_{LNA} + P_{interconnect} + P_{IFBuffer} + P_{ADC} + P_{fil}$.

The inactive mode power consumption is orders of magnitude smaller than the other 2 states and can be neglected in the current comparison [170]. In contrast, when turning on the TX, first the LO is activated until it settles and then the other circuitries are started. Hence, the transient state power depends on the power consumed by the LO at the TX and RX, which can be approximated to $P_{settl} \approx 2P_{LO}$.

Using these defined parameters, energy consumption per information bit, $E_b = E_{total}/I$, is computed as

$$E_b \approx \frac{(1 + \alpha)E_t + P_cT_{act} + 2P_{LO}T_{settl}}{I} \quad (10.3)$$

where $E_t = P_tT_{act}$ is the energy transmitted, and $P_c = P_{ct} + P_{cr}$ is the circuit power consumption, whereas P_{LO} and T_{settl} are constants [171]. Here, the optimal T_{act} needs to be determined to obtain the ideal constellation size for any modulation scheme. From (10.3), E_b is directly proportional to the PAPR of the modulation technique. Thus, the modulation scheme must be selected carefully. In addition, it has been shown that the energy per bit increases as the bandwidth efficiency rises, which is defined by $B_e = I/BT_{act}$, where B is modulation bandwidth [171].

Employing a log-distance path loss model, the transmitted power, P_t , can be defined as

$$P_t = P_r d^\gamma M_l G_1 \quad (10.4)$$

where P_r is the received power, d is the link distance, γ is the path loss exponent, M_l is the link margin compensation used to account for any variations in the system and G_1 is the gain factor for unit distance, which includes the gains of the TX and RX antennas and the path loss at 1 m. For an indoor office environment, γ can be assumed 4 [172]. Furthermore, the free-space path loss for 1 m at 300 GHz is approximately 82 dB and since an antenna gain of 22 dBi is already demonstrated [173], we utilized G_1 as 38 dB in our analyses.

10.4 Energy Consumption Analyses of MQAM and MFSK Modulations

Bandwidth is not scarce in the THz spectrum. Therefore, to transmit large amounts of data, the most energy efficient modulation scheme should be utilized. To find the optimum modulation method, the model given in the Section 10.3 is evaluated for the MQAM and MFSK [35]. Both techniques are analyzed over an additive white Gaussian noise (AWGN) channel.

10.4.1 MQAM

For a communication system that uses MQAM, the number of symbols required to send I bits are $I_s = I/b$, where $b = \log_2 M$ is the number of bits assigned per symbol. Moreover, I_s can also be represented in terms of the symbol period T_s , such as $I_s = T_{act}/T_s$. If the system utilizes square pulses, then $T_s \approx 1/B$ and hence the relationship can be expressed as

$$b \approx \frac{I}{BT_{act}} = B_e \quad (10.5)$$

The required P_r for a specific set of constellation size, N_f , bandwidth and probability of error for MQAM operating in an AWGN channel is also determined using

the upper bound on the error probability given by

$$P_r = \frac{4}{3} N_f B \sigma^2 (2^b - 1) \ln \left[\frac{4 \left(1 - \frac{1}{\sqrt{2^b}} \right)}{b P_b} \right] \quad (10.6)$$

where σ^2 is the power spectral density of the AWGN channel and P_b is the bit error probability [172].

For MQAM, PAPR is calculated using $\xi = 3(\sqrt{M}-1)/(\sqrt{M}+1)$ and $M = 2^{I/BT_{act}}$. Finally, by substituting all the necessary parameters for MQAM in (10.3), energy per bit is expressed as

$$E_b = \frac{4}{3} (1 + \alpha) N_f \sigma^2 (2^b - 1) \frac{G_1}{b} \ln \left[\frac{4 \left(1 - \frac{1}{\sqrt{2^b}} \right)}{b P_b} \right] + \frac{P_c T_{act} + 2 P_{LO} T_{settl}}{I} \quad (10.7)$$

System parameters for the THz band TRX are given in Table 10.1 [174, 175, 176]. The DAC and ADC are also assumed to be the Texas Instruments Inc. models DAC1220 and ADC08D500, respectively. Due to high PAPR, MQAM requires linear PA. Amplification in the THz band is hard to achieve using solid state devices due to their low transistor cut off frequency. Hence, class-A PA is selected whose efficiency is $\eta_{MQAM} = 0.15$ [176]. I is found using $b_{min} = L/BT$ and the fact that minimum constellation size, b_{min} , equals 2. Here, B and T are chosen for the specific case of Internet of Things.

To determine the optimum active time for transmission at different d , E_b is plotted against the normalized T_{act} in Fig. 10.2. For low d , the energy consumption is less for smaller T_{act} . Hence, significant amount of energy can be saved by optimum T_{act} .

10.4.2 MFSK

In MFSK, the number of orthogonal carriers equals the constellation size M , with a minimum intercarrier separation of $1/2T_s$. Hence, the total bandwidth is $B \approx 2^b/2T_s$, and the bandwidth efficiency is $B_e = 2b/2^b$. By comparing the bandwidth efficiency

Table 10.1: System parameters

Parameter	Value	Parameter	Value
B	1 GHz	γ	4
η_{MQAM}	0.15	η_{MFSK}	0.35
G_1	38 dB	M_l	40 dB
N_f	10 dB	f_c	300 GHz
σ^2	-174 dBm/Hz	I	200 Mb
T_{settl}	10 μ s	T_{MQAM}	100 ms
T_{MFSK}	1.07 s	P_b	10^{-3}
P_{LNA}	6.75 mW	P_{maxt}	53 mW
P_{LO}	100 mW	P_{fil}	1 mW
P_{ADC}	1.4 W	P_{mix}	7.9 mW
P_{DAC}	2.5 mW	P_{balun}	1.2 mW
$P_{IFBuffer}$	5 mW	P_{buffer}	8 mW
$P_{\times N}$	13 mW	$P_{interconnect}$	1.8 mW

of MFSK with the general bandwidth efficiency equation $B_e = I/BT_{act}$, the following equation for T_{act} in MFSK is obtained

$$T_{act} = \frac{2^b I}{B 2b} \quad (10.8)$$

The relation between required P_r for a given probability of error, bandwidth, constellation size and N_f for MFSK can be determined using the upper bound on error probability, which is calculated as [172]

$$P_r = 4N_f \sigma^2 \frac{2B}{2^b} \ln \left(\frac{2^{b-2}}{P_b} \right) \quad (10.9)$$

Unique nature of MFSK modulation requires some modification in the circuit parameters and model. In MFSK, $\xi = 1$ due to the constant signal amplitude. This allows the amplifier to be used in saturation and achieve maximum efficiency. Furthermore, it allows the use of non-linear amplifiers, such as class-B amplifiers

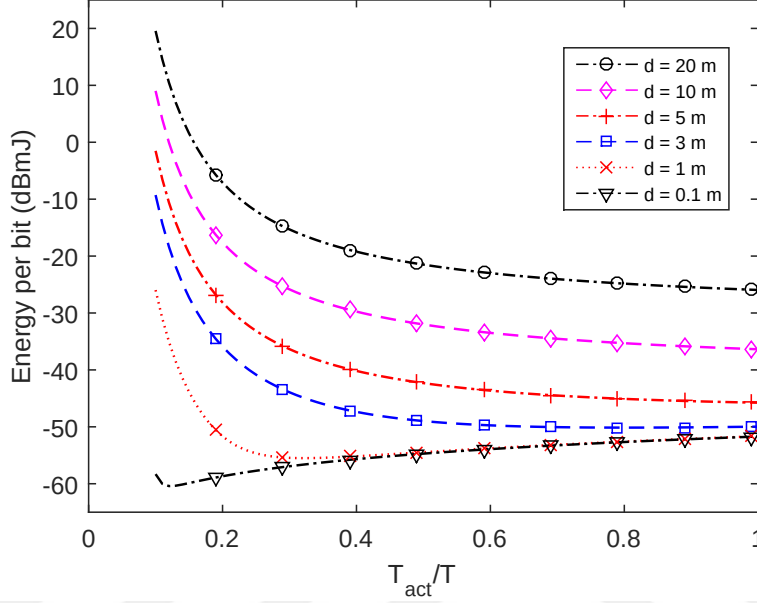


Figure 10.2: Energy consumption per information bit at various distances vs. normalized T_{act} for the MQAM system.

that provide better drain efficiency. Hence $\eta = 0.35$ is kept for the THz band PA. Conversely, in the TX, the mixer and DAC need to be removed since frequency modulation is carried out directly in the synthesizer. When all the required MFSK parameters are placed in (10.3), E_b becomes

$$E_b = 4(1 + \alpha)N_f\sigma^2\frac{G_d}{b}\ln\left(\frac{2^{b-2}}{P_b}\right) + \frac{P_cT_{act} + 2P_{LO}T_{settl}}{I} \quad (10.10)$$

where G_d is the power gain factor, and the bandwidth and packet size for MFSK are kept similar to the MQAM configuration. However, the maximum time delay, T_{MFSK} , was changed to 1.07 s, which restricts the maximum value of b to 6. Unlike MQAM, MFSK modulation is less bandwidth efficient and thus it requires more transmission time for the same number of bits and a given bandwidth.

E_b for MFSK modulation scheme is shown in Fig. 10.3. For low d , smaller b value is more energy efficient, and energy consumption rises with growing b . This is due to the effect of circuit power consumption, which increases for higher b . Yet, for distances higher than 10 m, transmission power dominates the circuit power consumption and

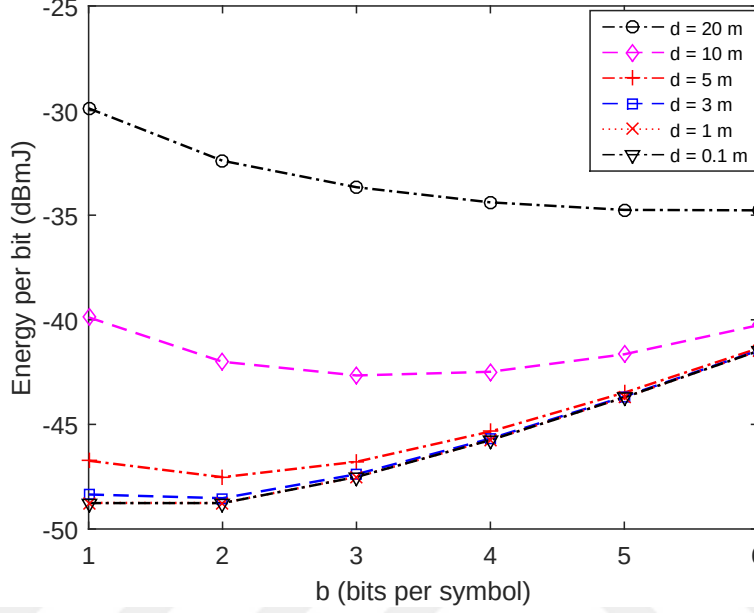


Figure 10.3: Energy consumption per information bit at various distances vs. bits per symbol (b) for the MFSK system.

thus larger b becomes more energy efficient. In an AWGN channel, the larger the M is, the more energy efficient MFSK becomes, leading to our result of reduction in transmission energy at higher d . To illustrate, about 50% energy saving is achieved for $b = 4$ in the $d = 10$ m case.

10.5 Modulation Parameters Optimization

MQAM is a bandwidth efficient modulation scheme, requiring less time to transmit a given amount of data. The energy consumption analysis of MQAM in the THz band shows that for $d < 1$ m, T_{act} should be small enough to reduce the energy consumption. However, for $d > 3$ m, a higher T_{act} will decrease E_b . This is due to the fact that at longer distances, transmission power outweighs the effect of circuit power. Hence, for $d > 3$ m, optimizing T_{act} does not help with energy saving, and therefore the maximum value of T_{act} should be used.

MFSK is less efficient in terms of transmission time, and therefore the time re-

Table 10.2: Optimized parameters for the MQAM and MFSK systems at various distances

Parameter	d = 0.1 m		d = 1.1 m		d = 5.1 m		d = 25.1 m	
	MQAM	MFSK	MQAM	MFSK	MQAM	MFSK	MQAM	MFSK
b_{opt}	16.66	2	5.88	2	2	2	2	6
T_{act} (s)	0.012	0.2	0.034	0.2	0.1	0.2	0.1	1.067
E_b (nJ)	0.909	13.29	3.04	13.31	27.94	18	5609.1	652.47
Rate (Gbps)	16.66	1	5.88	1	2	1	2	0.1875

quired to send a certain amount of bits is higher. But, the constant envelope ($\xi = 1$) significantly relaxes the PA linearity requirement and thus a power efficient transmission can be achieved. The energy consumption analysis of MFSK in the THz band shows that for $d < 7$ m, $b = 2$ is the optimum choice. Whereas, for $d > 7$ m, higher b value yields better energy efficiency.

A comparison of TRX energy consumption using MQAM and MFSK modulation schemes is shown in Fig. 10.4. For each d in the MQAM TRX, optimum T_{act} value is used to minimize energy consumption. These parameters are obtained from the energy per bit analysis of MQAM. For example, for the $d = 0.1$ m case, $T_{act} = 12$ ms is used and for $d = 4$ m, $T_{act} = 100$ ms is employed. Similarly, optimum b is selected during the MFSK modulation energy consumption analysis. The comparison of both modulation techniques show that for $d < 4$ m, MQAM requires less E_b , given optimum T_{act} is used. However, for $d > 4$ m, MFSK is more efficient and hence consumes less energy than MQAM for the low-THz band operation. The optimized parameters for the MQAM and MFSK systems operating at different d are given in Table 10.2.

The potential usage models for THz band can be divided into 3 main categories. The first category is very short distance communication which includes applications such as gadgets connected to a computer, ultra high definition (UHD) displays, ultra

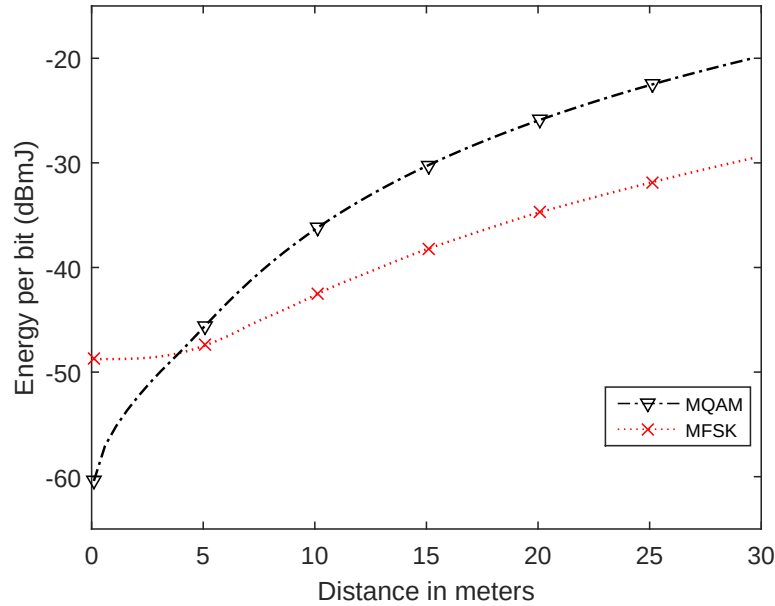


Figure 10.4: Energy consumption per information bit at various distances for the optimized MQAM and MFSK systems.

fast portable data drives and mobile data synchronization. In these applications, the distance between the TX and RX is usually less than 2 m. Hence, to minimize the energy consumption of the information transmission, we propose the utilization of MQAM, which can lead to greater than 90% energy saving. The second category is THz band 5G indoor wireless communications, that will enable femtocells with ultra high speed communications for a coverage range of 10 m. Specific usage models include UHD multimedia streaming, UHD video conferencing and ultra-high speed wireless data transfer. Due to the higher mobility and distance requirements in these applications, MFSK is propositioned for adoption. The third category is wireless backhaul that operates over distances greater than 10 m. Like the second category, the characteristics of this application also necessitates the use of MFSK [16, 13, 38, 141].

Table 10.3: Normalized system parameters

Parameter	Normalized Value					
	0	0.2	0.4	0.6	0.8	1
<i>Amplifier effic. (η, %)</i>	0	20	40	60	80	100
<i>Link margin (M_l, dB)</i>	40	32	24	16	8	0
<i>Path loss exponent (γ)</i>	8	6.6	5.2	3.8	2.4	1
<i>Noise figure (N_f, dB)</i>	20	16	12	8	4	0

10.6 PHY Parameters Optimization

PHY consists of the main communication hardware and is the most complex layer of any communication architecture. Optimizing the parameters of PHY can significantly reduce energy consumption in a communication link. Hence, we analyzed the effects of PHY on energy consumption. The key components of PHY are solid state circuits, amplifiers, antenna gains, RX noise, bit error rate and path loss. By examining their effect on the energy consumption, optimal hardware parameters which will reduce it can be determined. To observe the behavior of all major parameters, the values of the hardware are normalized between 0 and 1, i.e., from worst to best, respectively. The corresponding values are shown in Table 10.3. To provide an example, the normalized value 0 of an amplifier corresponds to 0% efficiency, whereas 1 corresponds to 100% efficiency. Furthermore, a higher efficiency means an expensive amplifier design. Therefore, any parameter with a normalized value close to 1 will perform better, but at the expense of higher cost and complexity; whereas, lower normalized value might consume higher energy, but the implementation would be easier. The comparison of MQAM parameters for $d = 1.5$ m and MFSK parameters for $d = 10$ m are shown in Fig. 10.5 and Fig. 10.6, respectively.

Solid state circuits working in the THz frequency range are rapidly being developed and considered as the core technology that will enable THz band wireless communica-

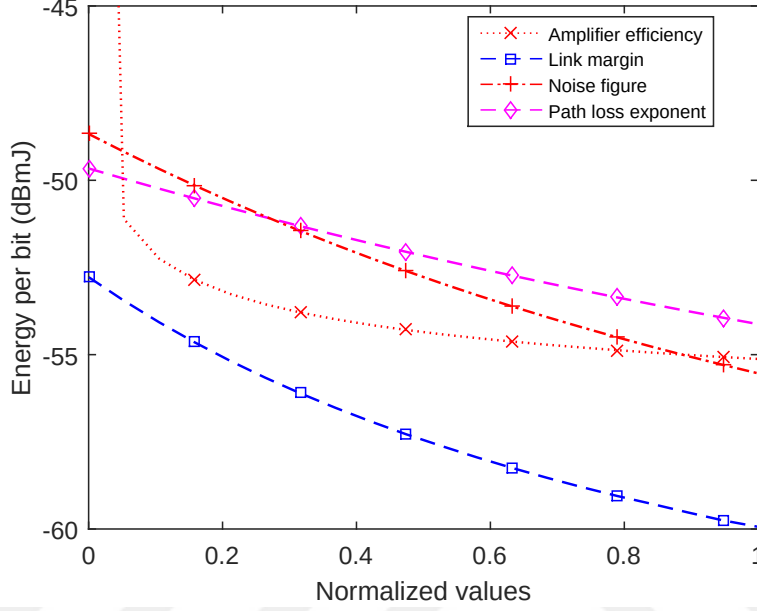


Figure 10.5: PHY components parameter sweep on normalized scale vs. energy consumption per bit of the MQAM system for $d = 1.5$ m.

tions. Many successful TRXs have been published in recent years [177, 169]. However, the amplifiers operating in the THz band require further improvement since their efficiency values are not sufficient. As power consumption of PA dominates circuit power consumption after a certain distance, their higher efficiency can improve the energy consumption for the THz band communications. The non-linear behavior of η can be observed from Fig. 10.5. In the MQAM system, 15% efficient amplifier consumes a significant amount of energy and is graded as very poor. Moreover, the non-linearly decreasing behavior depicts that after 40% efficiency, there is not considerable energy saving in MQAM. In contrast, for MFSK, PA efficiency of 60% is adequate as higher efficiency does not reduce the energy consumption substantially.

Small aperture size at high frequency allows the use of highly directional antennas that can reduce path loss. To observe the effect of antenna gain, link margin is swept from 40 to 0 dB, which corresponds to an increase in antenna gain from 22 to 42 dBi. It is obvious that MQAM is effected by the change in power transmitted,

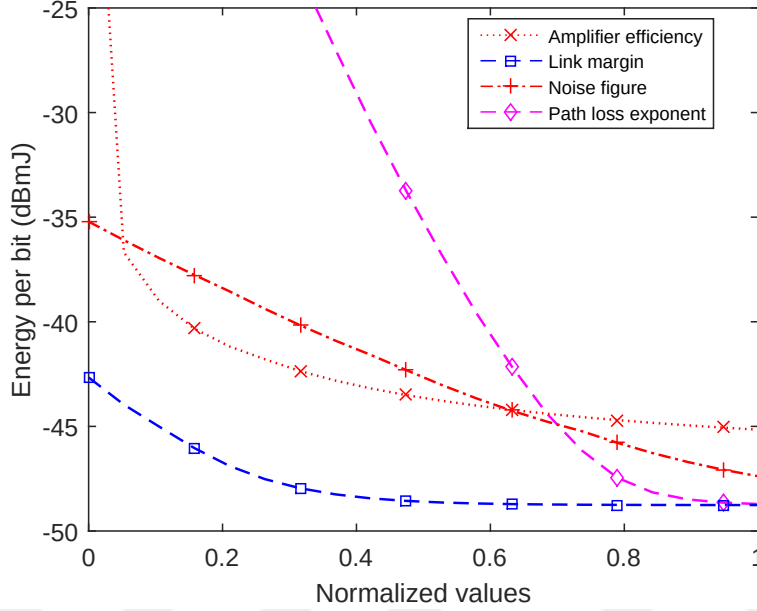


Figure 10.6: PHY components parameter sweep on normalized scale vs. energy consumption per bit of the MFSK system for $d = 10$ m.

hence in Fig. 10.5 the behavior of M_l variation is linear. Furthermore, MFSK is prone to power variations, and after a certain value of M_l , any significant reduction in energy consumption is not achieved. This is confirmed by the non-linear behavior of M_l illustrated in Fig. 10.6. Thus, the higher the antenna gain, the better the performance of an MQAM communication system. Whereas, for the case of MFSK, 34 dBi would be an optimum gain value for both the TX and RX.

The path loss exponent γ has vast effects on a communication link. It is a function of f_c , obstructions, environment and weather conditions, among others. It can range from 1.4 to 8. Usually γ for a furnished room is considered as 4. To observe its effect on energy consumption, γ is changed from 8 to 1, which corresponds to 0 and 1 on normalized scale, respectively. In Fig. 10.5, the behavior of γ is approximately linear for the MQAM system. However, in MFSK γ behaves non-linearly, as shown in Fig. 10.6, and hence higher value of γ increases energy consumption rapidly. Moreover, the plot shows that for the MFSK system to perform well, γ needs to be smaller than

2.4.

N_f is the amount of noise introduced by the RX front end to the signal received. It depicts the degradation in signal-to-noise ratio caused by the hardware components of the RX. The major components affecting N_f are the antenna interconnects and LNA. The attenuation causing noise in the interconnects can be reduced by designing high quality interconnects that attach the antenna to the circuit, while also assisting with the out of band signal rejection. Also, the noise of amplifier can be reduced by selecting proper transistor technology and stability network of the amplifier. The ideal N_f of a RX front end is 0 dB which corresponds to 1 on our normalized scale; whereas, 20 dB is considered to be the worst case. The behavior of N_f is approximately linear in both Fig. 10.5 and Fig. 10.6. Hence, the lower the noise is, the less E_b will be.

To find the optimal PHY parameter values for the least energy consumption in the THz band, the model is evaluated with 1 and 3 dB back-off values for all the parameters. 1 dB back-off point corresponds to the parameter value that consumes 1 dB less energy than the energy consumed at the ideal state, i.e., for the normalized value of 1. This is calculated as $|E_{b1}| - 1$, where $|E_{b1}|$ is E_b with the parameter having its ideal value. Similarly, 3 dB back-off point corresponds to the parameter value that consumes 3 dB less energy than the energy consumed at the ideal state and is computed by $|E_{b1}| - 3$. These optimum values for the MQAM and MFSK systems are given in Table 10.4.

The total energy consumption per bit for optimized modulation parameters and PHY with 1 dB back-off point over different d is shown in Fig. 10.7a. Optimized PHY parameters save significant amount of energy and can increase the distance where MFSK performs better than MQAM. For the stated parameters, MQAM is more efficient in terms of energy consumption till 143 m, and after that MFSK becomes more energy efficient. Yet, in this situation the hardware parameters are very stringent and expensive. The total energy consumption per bit for 3 dB back-off point is shown in Fig. 10.7b. These PHY parameters save significant amount of energy too, and MQAM is more energy efficient for $d < 12$ m.

Table 10.4: Optimized PHY parameters for the MQAM and MFSK systems for 1 and 3 dB back-off points

Parameter	1 dB back-off		3 dB back-off	
	MQAM	MFSK	MQAM	MFSK
η (%)	40	65	20	42
M_l (dB)	8	30	17	31
γ	3	2.4	4	2.8
N_f (dB)	4.2	3.15	7.5	5.2

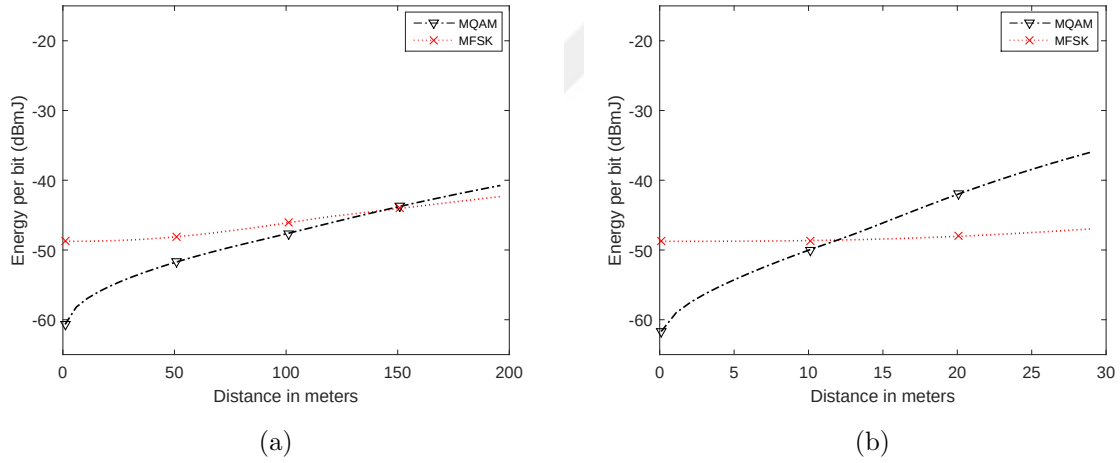


Figure 10.7: Energy consumption per bit for MQAM and MFSK PHY parameters optimized at (a) 1 dB, and (b) 3 dB back-off points.

As previously discussed, higher normalized value leads to a more expensive circuit. To compare the values of both of the modulation schemes, the average normalized parameter is calculated using

$$\Theta = \frac{1}{N} \sum_{i=1}^N X_i \quad (10.11)$$

where X_i is the normalized value of the parameter i . Average normalized values of the communication system operating with 1 dB back-off point are calculated as 0.6725 and 0.6356 for MQAM and MFSK, respectively. Whereas, for 3 dB back-off

point, these average values are 0.4925 and 0.53125, again, for MQAM and MFSK. This shows that the 3 dB back-off PHY components of MQAM is on average both cheaper and more energy efficient than the MFSK. Since the THz band is expected to operate in femtocells where d will be tens of meters, MQAM is deduced to be the superior modulation scheme for future THz band communications.

10.7 Open Research Issues

Number of bits being utilized per unit area is growing exponentially. Data usage is expected to increase by a thousandfold in 5G. Supporting the required amount of energy can become exigent if not handled properly. Adaptive modulation that saves energy is definitely useful, however, it is not sufficient to minimize energy consumption by itself. Other methods should also be inspected. One of the candidate techniques is reflecting antennas. It reduces the power consumption at the remote device by up to 100 times. In reflecting antennas technology, the mobile device reflects wireless signals instead of using regular TXs to generate them. This eliminates the need of PA in the UE, but consumes more energy at the base station [178].

Another interesting research topic that can significantly reduce power consumption is full-duplex wireless communications. In a full-duplex system, transmission and reception is carried out simultaneously which makes the detection of received signal very difficult. This is because the signal from the local transmitting antenna is immensely stronger than the transmission from other the node. The predicament can be handled by using a signal inversion cancellation method [179]. Full-duplex systems reduce the time of communication, and hence the energy usage. By introducing full-duplex transmission in the THz band for 5G communication applications, E_b can be reduced significantly with improved system latency whereas the data throughput can be doubled [180].

10.8 Conclusion

In this chapter, the total energy consumption of a wireless communication system operating in the THz band channel is analyzed. A comprehensive THz band system model is developed in order to determine the energy consumption of a TRX operating using MQAM and MFSK. Based on the performed analyses, it is deduced that short-range THz band applications should use MQAM modulation scheme, whereas, medium- and long-range applications should employ MFSK modulation method to minimize the energy consumption per bit. Moreover, optimization of the PHY of a wireless system substantially affects the energy consumption factor. Different PHY parameters are evaluated in order to generate a set of best-functioning parameters which can further reduce the energy consumption factor by 81%. Finally, it is shown that for wireless systems with optimal PHY parameters, the distance at which MFSK performs better than MQAM significantly increases, and consequently for the low-THz band usage models MQAM is the most optimal modulation scheme.

Chapter 11

A HEXAGONAL GRID BASED HUMAN BLOCKAGE MODEL FOR THE LOW TERAHERTZ BAND COMMUNICATIONS

11.1 Introduction

Mobile data traffic is increasing globally. It rose 63% in 2016 and expected to achieve a compound annual growth rate (CAGR) of 47% until 2021. The projection is also similar for the global average mobile network connection speed, as the expected 5-year 24% CAGR will increase that data rate to 20.4 megabits per second (Mb/s)[57].

This subscriber demand for higher data volume and rates necessitates new methods to extend communication network capacities. Since modern encoding techniques and higher modulations are readily employed, only limited spectral efficiency gains are possible. Another main method to expand communication capacity is increasing the operation bandwidth. Current fourth generation (4G) mobile systems and common wireless networks all operate below 6 GHz carrier frequency and within overcrowded bands. Therefore, higher spectra at mm- and submm-wave frequency ranges are being investigated.

Electromagnetic (EM) wave propagation properties of the THz band are different from conventional bands. Free-space path loss and atmospheric and material attenuations are higher, whereas reflection coefficients are reduced. Consequently, THz band transmissions are unable to penetrate any solid objects [181, 60, 13, 77, 62, 61]. This situation has the potential to change usage habits, as novel access network configuration schemes are needed. New communication techniques would be required to enable seamless connection as well.

Widespread THz band communication applications should be preceded also by blockage investigations of ordinary users over realistic motion models. One previously introduced such model for mm-wave communications portrays human blockage utilizing knife edge diffraction and generates a stochastic model over random walk [182]. Two other attempt to compute the number of blockers present in the direct link between the base station (BS) and user equipment (UE) by applying distinct statistical distributions [183, 184]. However, THz band communications intrinsically have a limited range and this chapter explores indoor deployment scenarios.

In line with these, this is the first publication that puts forward a human blockage model relevant to the 5G low-THz band communications. Section 11.2 elucidates the model. The effect of the user direction on the link stability is examined in a setting where the UE is always within the range of the BS. Direction and distance are both included in the derivation via hexagonal grid. A specific environment, along with simulation results are given in Section 11.3, followed by the conclusion.

11.2 The Model

11.2.1 Motion Description

In an open setting, signal blockage is often caused by the user himself. Whether one is in motion or just standing still, UE is operated in front of the user. As one moves or changes direction, the signal between the UE and BS can be inadvertently obstructed.

The height and width of the user, as well as how high or close the UE is held, all affect the existence of a line-of-sight (LoS) communication path. When a user faces the opposite direction of the BS, signal from the BS to UE is impeded and LoS communication is not possible. In view of both the authors' previous works and the available literature, in this article it is assumed that for all practical purposes THz band communication is lost when there is a person blocking the direct path of EM waves between the BS and UE [80, 34, 38, 35, 185, 142, 186]. Thus, the analysis environment is established as follows. While r and d are the distances between the BS and user and the user and UE, respectively, α is defined as the angle between



The height of a user blocks the signal even when one is very close to the BS, so height is disregarded as a parameter and derivations are conducted over the two-dimensional (2D) geometry of the system. Communication is unattainable if ϕ is smaller than the threshold ϕ_{th} , which are written as

$$\phi_{th} = \arctan \left(\frac{(w/2) \cos \alpha}{r - (w/2) \sin \alpha} \right) \quad (11.2)$$

$$P_L = \frac{\int_0^{r_{\max}} 2r\alpha_{\max}(r)dr}{\pi r_{\max}^2} \quad (11.3)$$

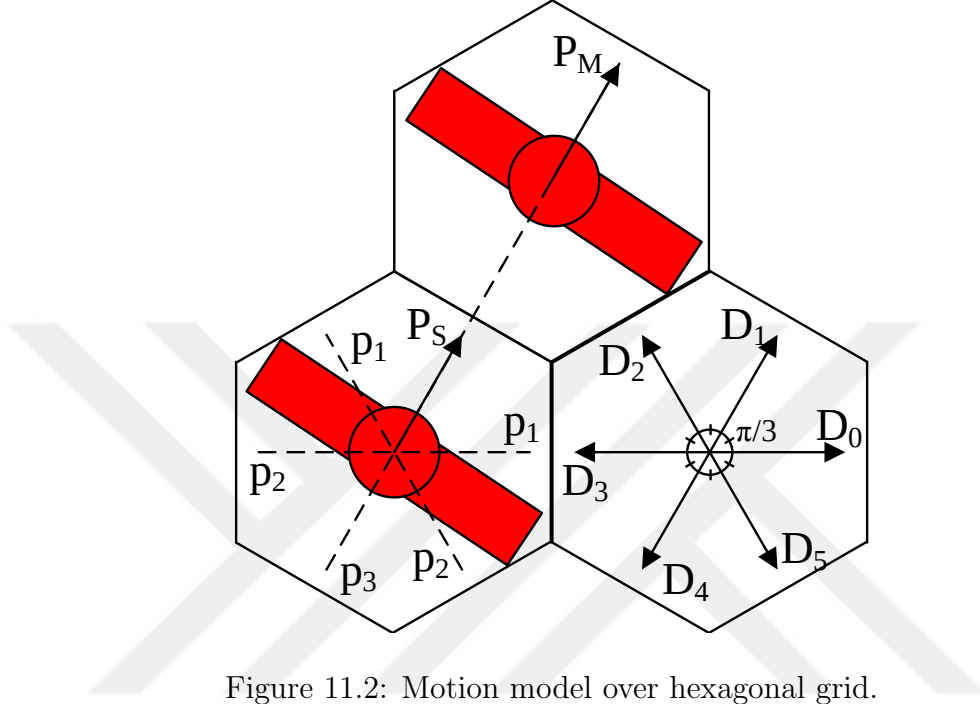


Figure 11.2: Motion model over hexagonal grid.

However, the user position seldom fits uniform distribution and this chapter tries to develop a broad blockage model which incorporates user movement and direction. Therefore, the behavior of a user is parametrized. At any time t_n , during a time step interval a user can stand still, change direction or move in the direction he is facing with probabilities P_S , P_D and P_M , respectively. The 2D space is split into hexagonal grid consistent with the coordinates given in [187]. In this geometry, a user can only be located at the center of a tile, can shift to the adjacent tile and has six possible directions, looking towards the midpoints of each edge of the hexagon he is in. The probabilities of user direction change are labelled by angles of $\pi/3$, $2\pi/3$ and π with p_1 , p_2 and p_3 , respectively, and the motion model is illustrated in Fig. 11.2.

11.2.2 Coordinate System

To simplify the execution of the described motion model, the coordinate system used in [188] is implemented in 2D, as shown in Fig. 11.3. The directions are termed from D_0 to D_5 , where D_i is at an $i(\pi/3)$ angle with the x-axis. The $\pi/3$ rad region between

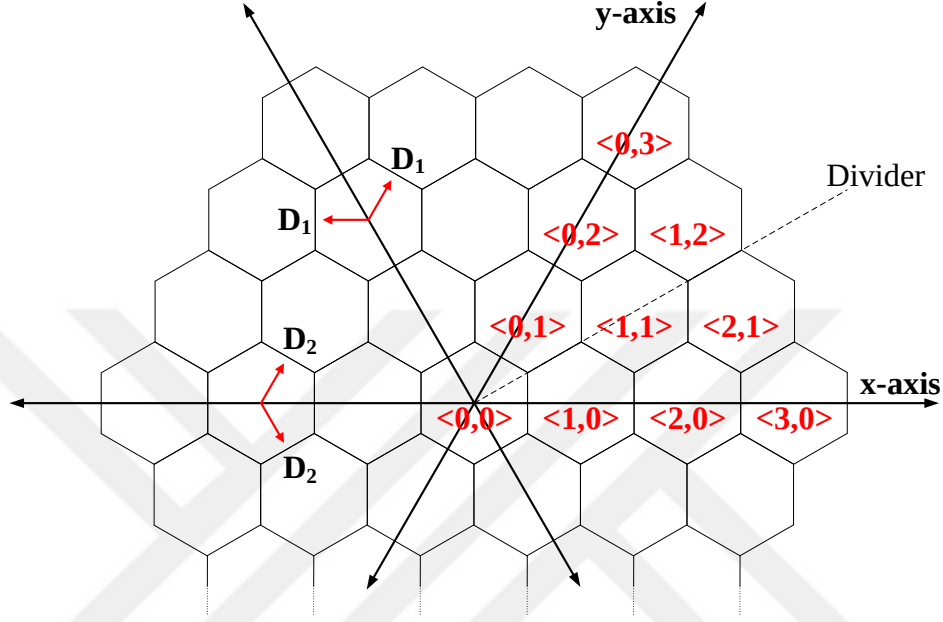


Figure 11.3: Hexagonal coordinate system.

the axes, named a sextant, is repeated symmetrically six times over the plane, leading to only two directions with a probability of communication loss.

Every action is produced in a sextant. If the direction is D_4 or D_5 for the points on the x-axis, user moves to the adjoining sextant with the same coordinates and new directions D_2 or D_1 , respectively, since the sextants are symmetric and adjacent sextants share the same x- or y-axis. Similarly, if the direction is D_2 or D_3 on the y-axis, user moves to the neighboring sextant with new directions D_0 or D_5 , respectively, and retaining his coordinates.

User position changes in hexagonal grid following a move is presented in Table 11.1. α at each user location is calculated via $D_i - \theta$, where θ is defined as the angle between the line connecting the BS and user and the x-axis, and expressed as

$$\theta = \arctan \left(\frac{(3/2)y}{\sqrt{3}(x + y/2)} \right) \quad (11.4)$$

In the first sextant, communication loss probability only exists for D_0 and D_1 . Because the maximum θ value is $\pi/3$ rad, for a user facing D_1 any preceding moves towards D_4 , D_5 or D_0 have reduced θ , and vice versa. In this case higher θ results

Table 11.1: Coordinate change of point $\langle x, y \rangle$ after moving in direction D_i

D_0	D_1	D_2	D_3	D_4	D_5
$\langle x+1, y \rangle$	$\langle x, y+1 \rangle$	$\langle x-1, y+1 \rangle$	$\langle x-1, y \rangle$	$\langle x, y-1 \rangle$	$\langle x+1, y-1 \rangle$

in lower α , which decreases ϕ and increases ϕ_{th} according to (11.1) and (11.2), respectively, hence creating the circumstances for communication loss. Additionally, an analogous argument is valid for D_0 direction.

11.2.3 Half-Sextant

A further simplification of the coordinate system is achievable by taking advantage of the internal symmetry of each sextant. The divider exhibited in Fig. 11.3 separates the first sextant into two equivalent and symmetrical areas, which will be called half-sextants (HSs). Since only the $|\alpha|$ is considered when $\alpha \in (-\pi/3, \pi/3)$, each HS contains identical communication loss probabilities.

Shifting between adjoining HSs generates extra actions. If a user's direction is D_1 , D_2 or D_3 for the points on the divider, which are of the form $\langle x, x \rangle$, it is altered to D_0 , D_5 or D_4 , respectively. If one faces D_4 or D_5 on the x-axis, his direction is converted to D_2 or D_1 , again, respectively. A move from the coordinates $\langle x+1, x \rangle$ towards D_2 causes just a direction change to D_5 . Finally, coordinate change is not required at HS crossings.

11.3 Performance Evaluation

To investigate a deployment scenario, a boundary on the communication environment needs to be set. In line with the hexagonal grid selection, the simulation setting is assumed to be a hexagonal room. Therefore, if the x-axis is bounded by a constant $X_{\max} \in \mathbb{Z}^+$, the coordinates are limited to $(x+y) \leq X_{\max}$. Under these conditions, if a user's direction is D_0 or D_1 on the HS border, he cannot move, thus $P_M^b = 0$.

Table 11.2: Direction change transition matrix of the points on the x-axis

$M_D^{\langle x,0 \rangle}$	$\langle x, 0 \rangle_{D_0}$	$\langle x, 0 \rangle_{D_1}$	$\langle x, 0 \rangle_{D_2}$	$\langle x, 0 \rangle_{D_3}$
$\langle x, 0 \rangle_{D_0}$	P_S	$2p_1$	$2p_2$	p_3
$\langle x, 0 \rangle_{D_1}$	p_1	$P_S + p_2$	$p_1 + p_3$	p_2
$\langle x, 0 \rangle_{D_2}$	p_2	$p_1 + p_3$	$P_S + p_2$	p_1
$\langle x, 0 \rangle_{D_3}$	p_3	$2p_2$	$2p_1$	P_S

Table 11.3: Direction change transition matrix of the points on divider

$M_D^{\langle x,x \rangle}$	$\langle x, x \rangle_{D_0}$	$\langle x, x \rangle_{D_4}$	$\langle x, x \rangle_{D_5}$
$\langle x, x \rangle_{D_0}$	$P_S + p_1$	$p_2 + p_3$	$p_1 + p_2$
$\langle x, x \rangle_{D_4}$	$p_2 + p_3$	$P_S + p_1$	$p_1 + p_2$
$\langle x, x \rangle_{D_5}$	$p_1 + p_2$	$p_1 + p_2$	$P_S + p_3$

Also, while in general $P_D = 2p_1 + 2p_2 + p_3$, the user direction change and stand still probabilities become $p_i^b = p_i/(1 - P_M)$ and $P_S^b = P_S/(1 - P_M)$, respectively, on the HS borders for D_0 and D_1 directions.

The site boundary is designated as $X_{\max} = 3$, which yields 6 tiles in each HS. The simulations are processed on the first HS utilizing the methods devised in Section 11.2. Normally a user is positioned at the center of a hexagon and can face any of the directions, whereas, there are some restrictions for the points on the location edges. To exemplify, the direction change transition matrices of the coordinates on the x-axis, $M_D^{\langle x,0 \rangle}$, and divider, $M_D^{\langle x,x \rangle}$, are provided in Tables 11.2 and 11.3.

A single simulation run involves randomly originating multitude of action steps, operating the user appropriately and computing the state of communication at every period. This procedure is reiterated, again, multitude of times, and for that group of values, P_L is calculated as the average P_L over all the time steps of the entire simulation runs.

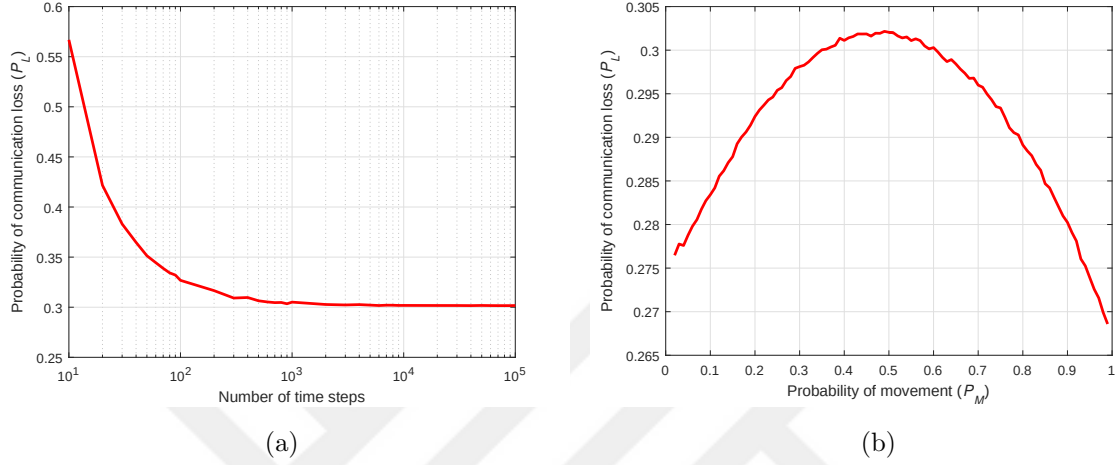


Figure 11.4: P_L for growing (a) Total time steps, and (b) Movement probability.

11.3.1 Results and Discussion

The parameters for the primary simulation case are determined as follows. Consistent with the men's body measurements given in [189], for a male of 1.75 m average height, w and d are chosen to be 0.5 and 0.35 m, respectively. Furthermore, the distance between the centers of any two adjacent hexagons is equated to one walking step length of 0.75 m. Lastly, throughout the entirety of simulations, the probabilities of the non-movement actions are decided using the presumption $P_S = 2p_1 = 4p_2 = 8p_3$.

The first simulation comprises rising time steps from 10 to 10^5 for the constant quantities 10^3 runs and $P_M = 0.5$, and the result is displayed in Fig. 11.4a. P_L decreases from 0.567 to its stationary value 0.302 at 2×10^3 action steps and onwards. Hence, the number of time steps is set to 10^4 during the rest of the simulations and in this circumstance, regardless of the simulation run increase from 10 to 10^4 , P_L always approximately amounts to 0.302.

The alteration in P_L with respect to P_M , excluding its limits, is shown in Fig. 11.4b. The outcome is a concave function, beginning at 0.276, maximizing at 0.302 for $P_M = 0.5$ and ending at 0.269. The minute variation in P_L demonstrates the pronounced effect of the user direction on link setup.

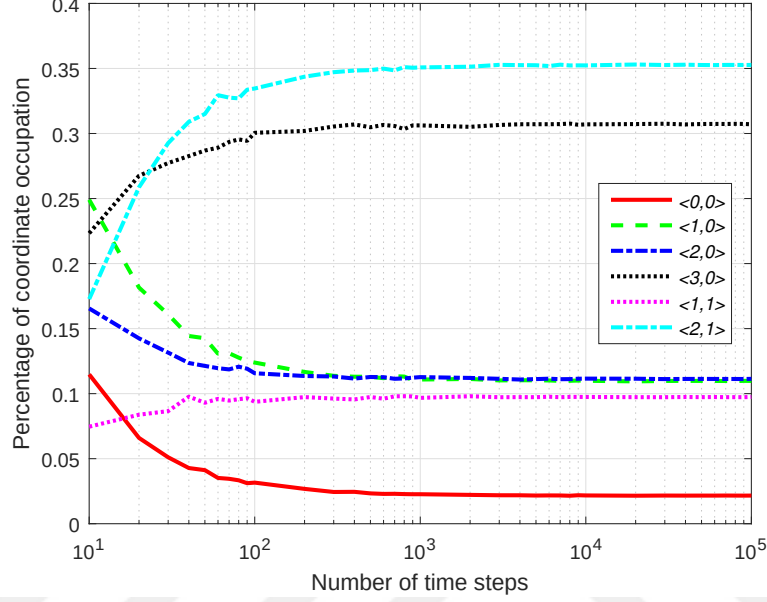


Figure 11.5: Distribution of user position for growing total time steps.

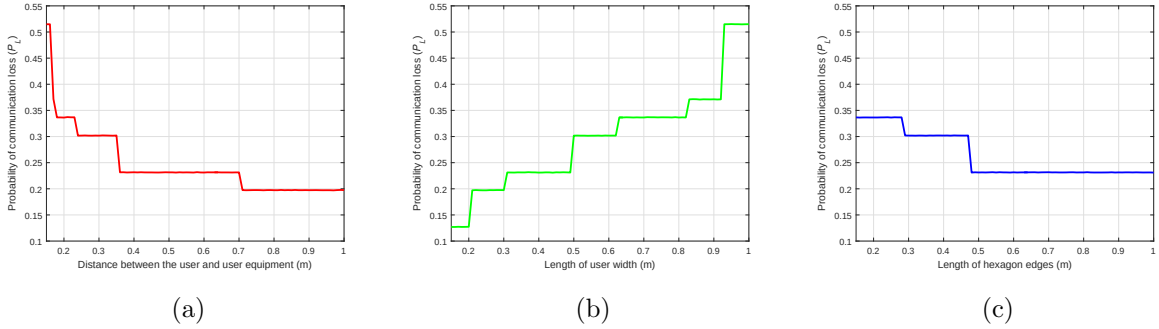


Figure 11.6: Probability of communication loss for growing (a) Distance between the user and user equipment, (b) User width, and (c) Hexagon edge length.

The mean number of time steps needed to reach the first communication state is 4.6, because the origin is presumed to be non-communicating, and the distribution of user position is illustrated in Fig. 11.5. Location of the user is not uniformly distributed. Coordinates on the environment boundary, $\langle 2, 1 \rangle$ and $\langle 3, 0 \rangle$, are occupied more frequently, whereas the origin is the least stayed point.

Finally, the impacts of d , w and hexagon edge length, so r , on P_M are presented

in Fig. 11.6. The parameters each span 0.15 to 1 m. As anticipated, the obstruction likelihood of direct communication path rises with increasing w , and the contrary is true for d and r . The lines change in steps since communication states of coordinate-direction pairs switch at particular group of variable quantities.

11.4 Conclusion

In this chapter, a human blockage model for the 5G low-THz band communications with emphasis on the location and direction of the user in relation to the BS is provided for the first time in the literature. The propositioned motion model is more suitable to the THz band communications than any random walk model because, unlike legacy sub-6 GHz bands, user direction change can cause communication loss for a submm-wave link. The studies can be expanded by integrating height and 3D domain into the analyses and adding other deployment scenarios with larger usage spaces.

Chapter 12

CONCLUSION

The detailed conclusion reached in the chapters is given in the following.

12.1 State-of-the-Art and Research Challenges for Consumer Wireless Communications at 60 GHz

This chapter is focused to the efforts on the utilization of the 60 GHz ISM band for consumer wireless communications. Standardization activities that began in 2006 are completed by the end of 2012 for both WPAN and WLANs. During these actions, EM wave transmission properties and channel models of the 60 GHz band are developed. Low-cost 60 GHz devices are also produced, as commercial products are expected to go on sale in 2016. Overall, the 60 GHz ISM band is ready for both widespread adoption and further use in B4G systems.

12.2 Employing 60 GHz ISM Band for 5G Wireless Communications

In this chapter utilization of 60 GHz ISM band for the forthcoming 5G wireless communication systems is explored. Following a broad assessment on the current wireless and mobile communication networks, physical layer properties of 60 GHz band is explained. A realistic indoor simulation along the lines of ITU-R guidelines and commercial off-the-shelf circuitry is set for comparing present 4G and proposed 60 GHz 5G systems. From the results the suitability of 60 GHz for in-room communications can be deduced. However, the need for a novel indoor access network architecture to establish an uninterrupted communications link in 60 GHz band is also apparent.

12.3 Millimeter Wave Communication for 5G IoT Applications

In this chapter, the use of mm-wave band for 5G IoT applications is examined. In general, path losses of different propagation mechanisms are increased in the mm-wave band. While OFDM is extensively and reliably used in current communication systems, modulation techniques with better spectral efficiency are needed to meet the data rate and network capacity requirements of B4G systems. Mm-wave channel coding is an active research area that does not currently exhibit a commonly favored solution for 5G. Theory of MIMO systems is thoroughly researched; though, real world massive MIMO implementations are distant. To sum up, utilization of mm-wave band is necessary for efficient IoT applications within 5G mobile networks, and correspondingly, the research efforts in the area continues to steadily intensify.

12.4 On the Use of the Millimeter Wave and Low Terahertz Bands for Internet of Things

Channel capacity and attainable data rates are examined in this chapter for 4 different legacy and mm-wave band links, using a simulation environment significant for the IoT applications. Lower frequency bands are more efficient in terms of channel capacity, which increases with transmission distance too. However, the amounts are incomparable to the effect of the vast spectrum available within the mm-wave band. Path length boundaries for maximum bit rate also decrease as the carrier frequency or modulation technique increases; though, the calculated distances are still useful for IoT services. For these reasons, mm-wave band is not just an option, but a performance improving enabling technology for the IoT.

12.5 Utilizing THz Band for Local and Personal Area Wireless Communication Systems

In this chapter, the use of THz band for wireless communication systems is investigated. Subsequent to a general introduction on the current state of wireless and

mobile communication systems, the realistic simulation environment of [16] is extended across 700 GHz. According to the results, transmission windows up to 500 GHz are capable of supporting WPANs, which can theoretically provide peak data rates between 10 and 20 Gb/s. Severe material absorption on the higher frequencies is the principal reason against coverage expansion. Towards that end, indoor access network architectures featuring multiple APs that support a handover mechanism and building materials with workable absorption coefficients should be investigated.

12.6 On the Use of Low Terahertz Band for 5G Indoor Mobile Networks

The suitability of the low-THz band for 5G mobile communication systems is examined in this chapter using both theoretical analyses and numerical simulations. Free-space path loss, atmospheric attenuation and absorption and reflection losses are all higher for the THz band compared to the sub 6 GHz bands, limiting the coverage area of BSs. However, this can be offset by the network densification expected from the 5G. Simulation results clearly show that it is possible to achieve peak data rates on the order of 10 Gb/s using the low-THz band, though THz band signals are confined within the room containing the AP. There are still several important challenges that need to be solved during the standardization processes before actual deployments. High-performance and low-cost devices are needed to be able to implement the communication systems. Novel access network architecture solutions should be devised to overcome the greater losses in the THz band. A practical channel model is also compulsory for the continuation of the theoretical research efforts.

12.7 On the 5G Wireless Communications at the Low Terahertz Band

With no end of wireless communication upsurge in sight, neither throughput nor data rate requirements of 5G systems can be provided by just concentrating on spectral efficiency solutions. Due to the constantly improving low-cost device technologies, the first transmission window within the THz band is no longer out of reach of widespread communication systems. As the THz standardization activities for WPANs recently

progressed to second stage, research efforts in the area are to intensify even more. While the initially arising difficulties for low-THz indoor access network architecture can be resolved using the already laid out concepts, the proposed frequency leap is not small and the work has just begun. Realistic channel models, optimum multiple access algorithms and Si CMOS devices all separately yet simultaneously need development. However, the question is not the possibility of commonplace low-THz band communications, but the timetable.

12.8 Attenuation Constant Measurements of Clear and Frosted Glass Samples at the Low Terahertz Band

EM wave propagation through any medium is a function of the medium's α . In this chapter, for the first time in the literature, exponential models of the α of ordinary clear window glass and three different forms of frosted glasses, based on channel measurements between 260 and 350 GHz and making use of an original calculation technique are presented. α is computable from the change in the S_{21} parameter tested with and without a material blocking the propagation path, if the EM waves are normally incident upon the material's interface. High-priced VNA frequency extenders are needed for experimentation in the low-THz band. Whereas the α calculation method and clear glass result are directly applicable to the entire THz band research subjects, frosted glass outcomes are confined to the distinct irregularity patterns.

12.9 Energy-efficient Modulation and Physical Layer Design for Low Terahertz Band Communication Channel

In this chapter, the total energy consumption of a wireless communication system operating in the THz band channel is analyzed. A comprehensive THz band system model is developed in order to determine the energy consumption of a TRX operating using MQAM and MFSK. Based on the performed analyses, it is deduced that short-range THz band applications should use MQAM modulation scheme, whereas, medium- and long-range applications should employ MFSK modulation method to

minimize the energy consumption per bit. Moreover, optimization of the PHY of a wireless system substantially affects the energy consumption factor. Different PHY parameters are evaluated in order to generate a set of best-functioning parameters which can further reduce the energy consumption factor by 81%. Finally, it is shown that for wireless systems with optimal PHY parameters, the distance at which MFSK performs better than MQAM significantly increases, and consequently for the low-THz band usage models MQAM is the most optimal modulation scheme.

12.10 A Hexagonal Grid Based Human Blockage Model for the Low Terahertz Band Communications

In this chapter, a human blockage model for the 5G low-THz band communications with emphasis on the location and direction of the user in relation to the BS is provided for the first time in the literature. The propositioned motion model is more suitable to the THz band communications than any random walk model because, unlike legacy sub-6 GHz bands, user direction change can cause communication loss for a submm-wave link. The studies can be expanded by integrating height and 3D domain into the analyses and adding other deployment scenarios with larger usage spaces.

BIBLIOGRAPHY

- [1] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015-2020. Report, Cisco Systems, Inc., 2016.
- [2] Report ITU-R M.2134: Requirements related to technical performance for IMT-Advanced radio interface(s). *ITU, Geneva, CHE*, 2008.
- [3] 2020: Beyond 4G - Radio evolution for the Gigabit experience. Report, Nokia Networks, 2011.
- [4] Farhang-Boroujeny, B. OFDM Versus Filter Bank Multicarrier. *IEEE Signal Processing Magazine*, 28(3):92–112, 2011.
- [5] The World in 2009: ICT Facts and Figures. Report, International Telecommunication Union, 2009.
- [6] The World in 2015: ICT Facts and Figures. Report, International Telecommunication Union, 2015.
- [7] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2010-2015. Report, Cisco Systems, Inc., 2011.
- [8] Turker Yilmaz, Naveed A. Abbasi, and Ozgur B. Akan. *Millimeter Wave 5G-Enabled Internet of Things*. CRC Press, 2019.
- [9] Ajung, Kim and Young Hun, Joo and Yungsoo, Kim. 60 GHz wireless communication systems with radio-over-fiber links for indoor wireless LANs. *IEEE Transactions on Consumer Electronics*, 50(2):517–520, 2004.

- [10] Rangan, S. and Rappaport, T. S. and Erkip, E. Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges. *Proceedings of the IEEE*, 102(3):366–385, 2014.
- [11] Tianyang, Bai and Alkhateeb, A. and Heath, R. Coverage and capacity of millimeter-wave cellular networks. *IEEE Communications Magazine*, 52(9):70–77, 2014.
- [12] Perahia, E. and Gong, M. X. Gigabit wireless LANs: an overview of IEEE 802.11ac and 802.11ad. *SIGMOBILE Mob. Comput. Commun. Rev.*, 15(3):23–33, 2011.
- [13] Yilmaz, Turker and Akan, Ozgur B. Utilizing terahertz band for local and personal area wireless communication systems. In *2014 IEEE 19th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, pages 330–334, 2014.
- [14] ETSI. EN 300 328 V1.9.1 (2015-02). *Electromagnetic compatibility and Radio spectrum Matters (ERM); Wideband transmission systems; Data transmission equipment operating in the 2,4 GHz ISM band and using wide band modulation techniques; Harmonized EN covering essential requirements of article 3.2 of the R&TTE Directive*, 2015.
- [15] ETSI. EN 301 893 V.1.7.1 (2012-06). *Broadband Radio Access Networks (BRAN); 5 GHz high performance RLAN; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive*, 2012.
- [16] Yilmaz, Turker and Fadel, Etimad and Akan, Ozgur B. Employing 60 GHz ISM band for 5G wireless communications. In *2014 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom)*, pages 77–82, 2014.

- [17] Amending Decision 2006/771/EC on harmonisation of the radio spectrum for use by short-range devices, 2011.
- [18] Daniels, R. C. and Heath, R. W. 60 GHz wireless communications: emerging requirements and design recommendations. *IEEE Vehicular Technology Magazine*, 2(3):41–50, 2007.
- [19] Consortium, WirelessHD. WirelessHD Specification Version 1.1. 2010.
- [20] Wonjin, Lee and Kwangseok, Noh and Saejoon, Kim and Jun, Heo. Efficient cooperative transmission for wireless 3D HD video transmission in 60GHz channel. *IEEE Transactions on Consumer Electronics*, 56(4):2481–2488, 2010.
- [21] Standard ECMA-387: High Rate 60 GHz PHY, MAC and HDMI PALs. pages 1–302, 2010.
- [22] Recommendation ITU-R P.676-9: Attenuation by atmospheric gases. *ITU, Geneva, CHE*, 2012.
- [23] Charfi, E. and Chaari, L. and Kamoun, L. PHY/MAC Enhancements and QoS Mechanisms for Very High Throughput WLANs: A Survey. *IEEE Communications Surveys & Tutorials*, 15(4):1714–1735, 2013.
- [24] Verma, L. and Fakharzadeh, M. and Sunghyun, Choi. Wifi on steroids: 802.11ac and 802.11ad. *IEEE Wireless Communications*, 20(6):30–35, 2013.
- [25] Rappaport, T. S. and Heath, R. W. and Daniels, R. C. and Murdock, J. N. *Millimeter Wave Wireless Communications*. Prentice Hall, 2014.
- [26] Seyed, A. TG3c System Requirements. *IEEE P802.15-07-0583-01-003c*, 2007.
- [27] IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific

- requirements. Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs) Amendment 2: Millimeter-wave-based Alternative Physical Layer Extension. *IEEE Std 802.15.3c-2009 (Amendment to IEEE Std 802.15.3-2003)*, pages c1–187, 2009.
- [28] IEEE Standard for Information technology–Telecommunications and information exchange between systems–Local and metropolitan area networks–Specific requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band. *IEEE Std 802.11ad-2012 (Amendment to IEEE Std 802.11-2012, as amended by IEEE Std 802.11ae-2012 and IEEE Std 802.11aa-2012)*, pages 1–628, 2012.
- [29] Grodzinsky, M. Amendment to WFA VHT Study Group Consolidation of Usage Models. *IEEE 802.11-09/0583r0*, 2009.
- [30] The Radio Regulations, Edition of 2012, 2012.
- [31] Recommendation ITU-R P.838-3: Specific attenuation model for rain for use in prediction methods. *ITU, Geneva, CHE*, 2005.
- [32] Lamb, James W. Miscellaneous data on materials for millimetre and submillimetre optics. *International Journal of Infrared and Millimeter Waves*, 17(12):1997–2034, 1996.
- [33] Langen, B. and Lober, G. and Herzig, W. Reflection and transmission behaviour of building materials at 60 GHz. In *1994 IEEE 5th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pages 505–509 vol.2.

- [34] Jacob, M. and Priebe, S. and Dickhoff, R. and Kleine-Ostmann, T. and Schrader, T. and Kurner, T. Diffraction in mm and Sub-mm Wave Indoor Propagation Channels. *IEEE Transactions on Microwave Theory and Techniques*, 60(3):833–844, 2012.
- [35] Turker Yilmaz, Gokce Gokkoca, and Ozgur B. Akan. *Millimetre Wave Communication for 5G IoT Applications*, pages 37–53. Springer International Publishing, Cham, 2016.
- [36] Wooncheol, Hwang and Kiseon, Kim. Performance analysis of OFDM on the shadowed multipath channels. *IEEE Transactions on Consumer Electronics*, 44(4):1323–1328, 1998.
- [37] Jacob, M. and Mbianke, C. and Kürner, T. A dynamic 60 GHz radio channel model for system level simulations with MAC protocols for IEEE 802.11ad. In *2010 IEEE 14th International Symposium on Consumer Electronics (ISCE)*, pages 1–5.
- [38] Yilmaz, Turker and Akan, Ozgur B. On the use of the millimeter wave and low terahertz bands for Internet of Things. In *2015 IEEE 2nd World Forum on Internet of Things (WF-IoT)*, pages 177–180, 2015.
- [39] Proakis, J. G. *Digital Communications*. McGraw-Hill, 4 edition, 2001.
- [40] Patel, P. K. and Mentall, J. The Advanced Microwave Sounding Unit-A (AMSU-A). In *1993 IEEE Topical Symposium on Combined Optical, Microwave, Earth and Atmosphere Sensing*, pages 159–164.
- [41] Vurgaftman, I. and Meyer, J. R. and Ram-Mohan, L. R. Band parameters for III-V compound semiconductors and their alloys. *Journal of Applied Physics*, 89(11):5815–5875, 2001.

- [42] Li, T. and Mastro, M. and Dadgar, A. *III-V Compound Semiconductors: Integration with Silicon-Based Microelectronics*. CRC Press, 2010.
- [43] Chow, T. P. and Tyagi, Ritu. Wide bandgap compound semiconductors for superior high-voltage unipolar power devices. *IEEE Transactions on Electron Devices*, 41(8):1481–1483, 1994.
- [44] Jae-Sung, Rieh and Dong-Hyun, Kim. An Overview of Semiconductor Technologies and Circuits for Terahertz Communication Applications. In *2009 IEEE GLOBECOM Workshops (GC Wkshps)*, pages 1–6.
- [45] Saito, N. and Tsukizawa, T. and Shirakata, N. and Morita, T. and Tanaka, K. and Sato, J. and Morishita, Y. and Kanemaru, M. and Kitamura, R. and Shima, T. and Nakatani, T. and Miyanaga, K. and Urushihara, T. and Yoshikawa, H. and Sakamoto, T. and Motozuka, H. and Shirakawa, Y. and Yosoku, N. and Yamamoto, A. and Shiozaki, R. and Takinami, K. A Fully Integrated 60-GHz CMOS Transceiver Chipset Based on WiGig/IEEE 802.11ad With Built-In Self Calibration for Mobile Usage. *IEEE Journal of Solid-State Circuits*, 48(12):3146–3159, 2013.
- [46] Mitomo, T. and Tsutsumi, Y. and Hoshino, H. and Hosoya, M. and Wang, T. and Tsubouchi, Y. and Tachibana, R. and Sai, A. and Kobayashi, Y. and Kurose, D. and Ito, T. and Ban, K. and Tandai, T. and Tomizawa, T. A 2-Gb/s Throughput CMOS Transceiver Chipset With In-Package Antenna for 60-GHz Short-Range Wireless Communication. *IEEE Journal of Solid-State Circuits*, 47(12):3160–3171, 2012.
- [47] Okada, K. and Kondou, K. and Miyahara, M. and Shinagawa, M. and Asada, H. and Minami, R. and Yamaguchi, T. and Musa, A. and Tsukui, Y. and Asakura, Y. and Tamonoki, S. and Yamagishi, H. and Hino, Y. and Sato, T. and Sakaguchi, H. and Shimasaki, N. and Ito, T. and Takeuchi, Y. and Li, N.

- and Bu, Q. and Murakami, R. and Bunsen, K. and Matsushita, K. and Noda, M. and Matsuzawa, A. Full Four-Channel 6.3-Gb/s 60-GHz CMOS Transceiver With Low-Power Analog and Digital Baseband Circuitry. *IEEE Journal of Solid-State Circuits*, 48(1):46–65, 2013.
- [48] Linfoot, S. L. and Sherratt, R. S. Analysis of a DVB-T compliant receiver simulation under various multipath conditions. *IEEE Transactions on Consumer Electronics*, 46(1):201–206, 2000.
- [49] Choi, J. H. and Kwon, H. and Kim, J. and Lee, W. Y. and You, Y. Implementation of a seamless uncompressed video transmission system in 60GHz bands. In *2013 IEEE International Conference on Consumer Electronics (ICCE)*, pages 422–423.
- [50] Park, Y. H. and Kim, J. and Kim, M. and Lee, W. and Lee, S. Programmable multimedia platform based on reconfigurable processor for 8K UHD TV. *IEEE Transactions on Consumer Electronics*, 61(4):516–523, 2015.
- [51] Xie, F. and Pourazad, M. T. and Nasiopoulos, P. and Slevinsky, J. Determining bitrate requirement for UHD video content delivery. In *2016 IEEE International Conference on Consumer Electronics (ICCE)*, pages 241–242.
- [52] Resolution ITU-R 229: Use of the bands 5 150-5 250 MHz, 5 250-5 350 MHz and 5 470-5 725 MHz by the mobile service for the implementation of wireless access systems including radio local area networks. *ITU, Geneva, CHE*, 2012.
- [53] IEEE Standard for Information technology–Local and metropolitan area networks–Specific requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment 8: Medium Access Control (MAC) Quality of Service Enhancements. *IEEE Std 802.11e-2005 (Amendment to IEEE Std 802.11, 1999 Edition (Reaff 2003))*, pages 1–212, 2005.

- [54] Spectrum value of 800MHz, 1800MHz and 2.6GHz. Report, DotEcon Ltd., Aetha Consulting Ltd., 2012.
- [55] Ofcom. Ofcom announces winners of the 4G mobile auction, 2013.
- [56] IEEE Standard for Information technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. *IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007)*, pages 1–2793, 2012.
- [57] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021. Report, Cisco Systems, Inc., 2017.
- [58] Daqing, Gu and Jinyun, Zhang. QoS enhancement in IEEE 802.11 wireless local area networks. *IEEE Communications Magazine*, 41(6):120–124, 2003.
- [59] Stone, William C. NIST Construction Automation Program Report No. 3: Electromagnetic Signal Attenuation in Construction Materials. *Building Fire Res. Lab., Nat. Inst. Standards Technol., Gaithersburg, MD, Tech. Rep. NISTIR*, 6055, 1997.
- [60] Yilmaz, Turker and Akan, Ozgur B. On the use of low terahertz band for 5G indoor mobile networks. *Computers & Electrical Engineering*, 48:164–173, 2015.
- [61] Yilmaz, T. and Akan, O. B. State-of-the-art and research challenges for consumer wireless communications at 60 GHz. *IEEE Transactions on Consumer Electronics*, 62(3):216–225, 2016.
- [62] Yilmaz, Turker and Akan, Ozgur B. On the 5G Wireless Communications at the Low Terahertz Band. *arXiv preprint arXiv:1605.02606*, 2016.

- [63] Piesiewicz, R. and Kleine-Ostmann, T. and Krumbholz, N. and Mittleman, D. and Koch, M. and Kurner, T. Terahertz characterisation of building materials. *Electronics Letters*, 41(18):1002–1004, 2005.
- [64] Piesiewicz, R. and Jansen, C. and Wietzke, S. and Mittleman, D. and Koch, M. and Kurner, T. Properties of Building and Plastic Materials in the THz Range. *International Journal of Infrared and Millimeter Waves*, 28(5):363–371, 2007.
- [65] Maltsev, A. and Erceg, V. and Perahia, E. and Hansen, C. and Maslennikov, R. and Lomayev, A. and Sevastyanov, A. and Khoryaev, A. and Morozov, G. and Jacob, M. and Priebe, S. and Kürner, T. and Kato, S. and Sawada, H. and Sato, K. and Harada, H. Channel models for 60 GHz WLAN systems. *IEEE 802.11-09/0334r8*, 2010.
- [66] Report ITU-R M.2135-1: Guidelines for evaluation of radio interface technologies for IMT-Advanced. *ITU, Geneva, CHE*, 2009.
- [67] Ding, Xu and Jianhua, Zhang and Xinying, Gao and Ping, Zhang and Yufei, Wu. Indoor Office Propagation Measurements and Path Loss Models at 5.25 GHz. In *2007 IEEE 66th Vehicular Technology Conference (VTC Fall)*, pages 844–848.
- [68] Maltsev, A. and Maslennikov, R. and Sevastyanov, A. and Lomayev, A. and Khoryaev, A. Statistical channel model for 60 GHz WLAN systems in conference room environment. In *2010 4th European Conference on Antennas and Propagation (EuCAP)*, pages 1–5.
- [69] Corporation, Hittite Microwave. HMC6000LP711E - 60 GHz Tx with Integrated Antenna, 2013.
- [70] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2014-2019. Report, Cisco Systems, Inc., 2015.

- [71] Atzori, Luigi and Iera, Antonio and Morabito, Giacomo. The Internet of Things: A survey. *Computer Networks*, 54(15):2787–2805, 2010.
- [72] Karjalainen, J. and Nekovee, M. and Benn, H. and Kim, W. and Park, J. and Sungsoo, H. Challenges and opportunities of mm-wave communication in 5G networks. In *2014 9th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, pages 372–376.
- [73] Ortiz, S. The Wireless Industry Begins to Embrace Femtocells. *Computer*, 41(7):14–17, 2008.
- [74] Rappaport, T. S. and Gutierrez, F. and Ben-Dor, E. and Murdock, J. N. and Yijun, Qiao and Tamir, J. I. Broadband Millimeter-Wave Propagation Measurements and Models Using Adaptive-Beam Antennas for Outdoor Urban Cellular Communications. *IEEE Transactions on Antennas and Propagation*, 61(4):1850–1859, 2013.
- [75] Chandrasekhar, V. and Andrews, J. G. and Gatherer, Alan. Femtocell networks: a survey. *IEEE Communications Magazine*, 46(9):59–67, 2008.
- [76] Torkildson, E. and Madhow, U. and Rodwell, M. Indoor Millimeter Wave MIMO: Feasibility and Performance. *IEEE Transactions on Wireless Communications*, 10(12):4150–4160, 2011.
- [77] Turker Yilmaz and Ozgur B. Akan. *Millimeter-Wave Communications for 5G Wireless Networks*, pages 425–440. CRC Press, 2016. doi:10.1201/b19698-20.
- [78] Recommendation ITU-R P.835-5: Reference standard atmospheres. *ITU, Geneva, CHE*, 2012.
- [79] Friis, H. T. A note on a simple transmission formula. *Proc. IRE*, 34(5):254–256, 1946.

- [80] Jansen, C. and Priebe, S. and Moller, C. and Jacob, M. and Dierke, H. and Koch, M. and Kurner, T. Diffuse Scattering from Rough Surfaces in THz Communication Channels. *IEEE Transactions on Terahertz Science and Technology*, 1(2):462–472, 2011.
- [81] Songlin, Sun and Yanhong, Ju and Yamao, Y. Overlay cognitive radio OFDM system for 4G cellular networks. *IEEE Wireless Communications*, 20(2):68–73, 2013.
- [82] Priyanto, B. E. and Codina, H. and Rene, S. and Sorensen, Troels B. and Mogensen, P. Initial Performance Evaluation of DFT-Spread OFDM Based SC-FDMA for UTRA LTE Uplink. In *2007 IEEE 65th Vehicular Technology Conference (VTC Spring)*, pages 3175–3179.
- [83] Akyildiz, Ian F. and Gutierrez-Estevez, David M. and Reyes, Elias Chavarria. The evolution to 4G cellular systems: LTE-Advanced. *Physical Communication*, 3(4):217–244, 2010.
- [84] Banelli, P. and Buzzi, S. and Colavolpe, G. and Modenini, A. and Rusek, F. and Ugolini, A. Modulation Formats and Waveforms for 5G Networks: Who Will Be the Heir of OFDM?: An overview of alternative modulation schemes for improved spectral efficiency. *IEEE Signal Processing Magazine*, 31(6):80–93, 2014.
- [85] Schaich, F. and Wild, T. Waveform contenders for 5G - OFDM vs. FBMC vs. UPMC. In *2014 6th International Symposium on Communications, Control and Signal Processing (ISCCSP)*, pages 457–460.
- [86] Wunder, G. and Jung, P. and Kasparick, M. and Wild, T. and Schaich, F. and Yejian, Chen and Brink, S. and Gaspar, I. and Michailow, N. and Festag, A. and Mendes, L. and Cassiau, N. and Ktenas, D. and Dryjanski, M. and Pietrzyk, S. and Eged, B. and Vago, P. and Wiedmann, F. 5GNOW: non-orthogonal,

- asynchronous waveforms for future mobile applications. *IEEE Communications Magazine*, 52(2):97–105, 2014.
- [87] Wunder, G. and Kasparick, M. and ten Brink, S. and Schaich, F. and Wild, T. and Gaspar, I. and Ohlmer, E. and Krone, S. and Michailow, N. and Navarro, A. and Fettweis, G. and Ktenas, D. and Berg, V. and Dryjanski, M. and Pietrzyk, S. and Eged, B. 5GNOW: Challenging the LTE Design Paradigms of Orthogonality and Synchronicity. In *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*, pages 1–5.
- [88] Fusco, T. and Petrella, A. and Tanda, M. Sensitivity of multi-user filter-bank multicarrier systems to synchronization errors. In *2008 3rd International Symposium on Communications, Control and Signal Processing (ISCCSP)*, pages 393–398.
- [89] Farhang, A. and Marchetti, N. and Figueiredo, F. and Miranda, J. P. Massive MIMO and waveform design for 5th generation wireless communication systems. In *2014 1st International Conference on 5G for Ubiquitous Connectivity (5GU)*, pages 70–75.
- [90] Vakilian, V. and Wild, T. and Schaich, F. and ten Brink, S. and Frigon, J. F. Universal-filtered multi-carrier technique for wireless systems beyond LTE. In *2013 IEEE Globecom Workshops (GC Wkshps)*, pages 223–228.
- [91] Andrews, J. G. and Buzzi, S. and Wan, Choi and Hanly, S. V. and Lozano, A. and Soong, A. C. K. and Zhang, J. C. What Will 5G Be? *IEEE Journal on Selected Areas in Communications*, 32(6):1065–1082, 2014.
- [92] Schaich, F. and Wild, T. and Yejian, Chen. Waveform Contenders for 5G - Suitability for Short Packet and Low Latency Transmissions. In *2014 IEEE 79th Vehicular Technology Conference (VTC Spring)*, pages 1–5.

- [93] Czylik, A. Comparison between adaptive OFDM and single carrier modulation with frequency domain equalization. In *1997 IEEE 47th Vehicular Technology Conference*, volume 2, pages 865–869 vol.2.
- [94] Benvenuto, N. and Dinis, R. and Falconer, D. and Tomasin, S. Single Carrier Modulation With Nonlinear Frequency Domain Equalization: An Idea Whose Time Has Come - Again. *Proceedings of the IEEE*, 98(1):69–96, 2010.
- [95] Myung, H. G. and Junsung, Lim and Goodman, D. Peak-To-Average Power Ratio of Single Carrier FDMA Signals with Pulse Shaping. In *2006 IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications*, pages 1–5.
- [96] Jianfei, Li and Du, Yan and Liu, Yang. Comparison of Spectral Efficiency for OFDM and SC-FDE under IEEE 802.16 Scenario. In *2006 11th IEEE Symposium on Computers and Communications (ISCC)*, pages 467–471.
- [97] Benvenuto, N. and Tomasin, S. On the comparison between OFDM and single carrier modulation with a DFE using a frequency-domain feedforward filter. *IEEE Transactions on Communications*, 50(6):947–955, 2002.
- [98] Marinkovic, M. and Piz, M. and Chang-Soon, Choi and Panic, G. and Ehrig, M. and Grass, E. Performance evaluation of channel coding for Gbps 60-GHz OFDM-based wireless communications. In *2010 IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, pages 994–998.
- [99] Costello Jr., D. J. and Pusane, A. E. and Bates, S. and Zigangirov, K. Sh. A Comparison Between LDPC Block and Convolutional Codes. In *Information Theory and Applications Workshop*.

- [100] Tirouvengadam, B. and Radhakrishnan, R. and Nayak, A. CAAHR: Content aware adaptive HARQ retransmission scheme for 4G/LTE network. In *2012 4th International Conference on Ubiquitous and Future Networks (ICUFN)*, pages 456–461.
- [101] Zukang, Shen and Papasakellariou, A. and Montojo, J. and Gerstenberger, D. and Fangli, Xu. Overview of 3GPP LTE-advanced carrier aggregation for 4G wireless communications. *IEEE Communications Magazine*, 50(2):122–130, 2012.
- [102] Popovski, P. and Stefanovic, C. and Yomo, H. and Pratas, N. and Schaich, F. and Santos, A. and Braun, V. and Gozalvez-Serrano, D. and Strom, E. and Svensson, T. and Sun, W. and Weitkemper, P. and Benjebbour, A. and Saito, Y. and Kishiyama, Y. and He, N. and Lin, H. and Siaud, I. and Siohan, P. and Schellmann, M. and Zhao, Z. and Schubert, M. and Lahetkangas, E. and Vihriala, J. and Pajukoski, K. and Ascheid, G. and Heinen, S. and Ashok, A. and Ishaque, A. and Luecken, V. and Dekorsy, A. and Bockelmann, C. and Quint, F. and Rajatheva, N. and Pirinen, P. and Baghdadi, A. and Guilloud, F. Requirement analysis and design approaches for 5G air interface. Report, 2013.
- [103] Swindlehurst, A. L. and Ayanoglu, E. and Heydari, P. and Capolino, F. Millimeter-wave massive MIMO: the next wireless revolution? *IEEE Communications Magazine*, 52(9):56–62, 2014.
- [104] Larsson, E. and Edfors, O. and Tufvesson, F. and Marzetta, T. Massive MIMO for next generation wireless systems. *IEEE Communications Magazine*, 52(2):186–195, 2014.
- [105] Talwar, S. and Choudhury, D. and Dimou, K. and Aryafar, E. and Bangerter,

- B. and Stewart, K. Enabling technologies and architectures for 5G wireless. In *2014 IEEE MTT-S International Microwave Symposium (IMS)*, pages 1–4.
- [106] Andrews, J. G. and Wan, Choi and Heath, R. W. Overcoming interference in spatial multiplexing MIMO cellular networks. *IEEE Wireless Communications*, 14(6):95–104, 2007.
- [107] Telatar, E. Capacity of Multi-antenna Gaussian Channels. *European Transactions on Telecommunications*, 10(6):585–595, 1999.
- [108] Chin, Woon Hau and Zhong, Fan and Haines, R. Emerging technologies and research challenges for 5G wireless networks. *IEEE Wireless Communications*, 21(2):106–112, 2014.
- [109] Ngo, H. Q. and Larsson, E. G. and Marzetta, T. L. Energy and Spectral Efficiency of Very Large Multiuser MIMO Systems. *IEEE Transactions on Communications*, 61(4):1436–1449, 2013.
- [110] Marzetta, T. L. Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas. *IEEE Transactions on Wireless Communications*, 9(11):3590–3600, 2010.
- [111] Ngo, Hien Quoc and Marzetta, T. L. and Larsson, E. G. Analysis of the pilot contamination effect in very large multicell multiuser MIMO systems for physical channel models. In *2011 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pages 3464–3467.
- [112] Muller, R. R. and Cottatellucci, L. and Vehkaperä, M. Blind Pilot Decontamination. *IEEE Journal of Selected Topics in Signal Processing*, 8(5):773–786, 2014.
- [113] Haifan, Yin and Gesbert, D. and Filippou, M. and Yingzhuang, Liu. A Coordinated Approach to Channel Estimation in Large-Scale Multiple-Antenna

- Systems. *IEEE Journal on Selected Areas in Communications*, 31(2):264–273, 2013.
- [114] Fettweis, G. P. The Tactile Internet: Applications and Challenges. *IEEE Vehicular Technology Magazine*, 9(1):64–70, 2014.
- [115] Commission implementing decision of 2 May 2014 on amending Decision 2008/411/EC on the harmonisation of the 3 400-3 800 MHz frequency band for terrestrial systems capable of providing electronic communications services in the Community, 2014.
- [116] IEEE Standard for Information technology–Telecommunications and information exchange between systems–Local and metropolitan area networks–Specific requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications–Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz. *IEEE Std 802.11ac-2013 (Amendment to IEEE Std 802.11-2012, as amended by IEEE Std 802.11ae-2012, IEEE Std 802.11aa-2012, and IEEE Std 802.11ad-2012)*, pages 1–425, 2013.
- [117] Haibing, Yang and Smulders, P. F. M. and Herben, M. H. A. J. Frequency Selectivity of 60-GHz LOS and NLOS Indoor Radio Channels. In *2006 IEEE 63rd Vehicular Technology Conference (VTC Spring)*, volume 6, pages 2727–2731.
- [118] Jornet, J. M. and Akyildiz, I. F. Channel Modeling and Capacity Analysis for Electromagnetic Wireless Nanonetworks in the Terahertz Band. *IEEE Transactions on Wireless Communications*, 10(10):3211–3221, 2011.
- [119] Breit, G. and Sampath, H. and Vermani, S. and Van Nee, R. and Cheong, M. and Kwak, B.-J. and Kim, M. D. and Park, J. J. and Honma, N. and Yasushi, T. and Seok, Y. and Choi, S. and Chambelin, P. and Benko, J. and Cariou, L.

- and Jones, VK and Van Zelst, A. and Yang, L. and Kenney, T. and Perahia, E. and Erceg, V. TGac Channel Model Addendum. *IEEE 802.11-09/0308r12*, 2010.
- [120] HMC6000 - Millimeterwave Transmitter IC, 57 - 64 GHz, 2012.
- [121] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2013-2018. Report, Cisco Systems, Inc., 2014.
- [122] Report ITU-R M.1034-1: Requirements for the radio interface(s) for International Mobile Telecommunications-2000 (IMT-2000). *ITU, Geneva, CHE*, 1997.
- [123] Tousi, Y. M. and Momeni, O. and Afshari, E. A Novel CMOS High-Power Terahertz VCO Based on Coupled Oscillators: Theory and Implementation. *IEEE Journal of Solid-State Circuits*, 47(12):3032–3042, 2012.
- [124] Priebe, S. and Jacob, M. and Kurner, T. The impact of antenna directivities on THz indoor channel characteristics. In *2012 6th European Conference on Antennas and Propagation (EUCAP)*, pages 478–482.
- [125] Sarkar, T. K. and Zhong, Ji and Kyungjung, Kim and Medouri, A. and Salazar-Palma, M. A survey of various propagation models for mobile communication. *IEEE Antennas and Propagation Magazine*, 45(3):51–82, 2003.
- [126] HDMI Licensing, LLC. High-Definition Multimedia Interface Specification Version 2.0. 2013.
- [127] Fettweis, G. and Guderian, F. and Krone, S. Entering the path towards terabit/s wireless links. In *2011 Design, Automation & Test in Europe Conference & Exhibition (DATE)*, pages 1–6.
- [128] The World in 2014: ICT Facts and Figures. Report, International Telecommunication Union, 2014.

- [129] MacCartney, G. R. and Rappaport, T. S. 73 GHz millimeter wave propagation measurements for outdoor urban mobile and backhaul communications in New York City. In *2014 IEEE International Conference on Communications (ICC)*, pages 4862–4867.
- [130] Rappaport, T. S. and Shu, Sun and Mayzus, R. and Hang, Zhao and Azar, Y. and Wang, K. and Wong, G. N. and Schulz, J. K. and Samimi, M. and Gutierrez, F. Millimeter Wave Mobile Communications for 5G Cellular: It Will Work! *IEEE Access*, 1:335–349, 2013.
- [131] Roh, W. and Ji-Yun, Seol and Jeongho, Park and Byunghwan, Lee and Jaekon, Lee and Yungsoo, Kim and Jaeweon, Cho and Kyungwhoon, Cheun and Aryanfar, F. Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results. *IEEE Communications Magazine*, 52(2):106–113, 2014.
- [132] Jastrow, C. and Munter, K. and Piesiewicz, R. and Kurner, T. and Koch, M. and Kleine-Ostmann, T. 300 GHz Transmission System. *Electronics Letters*, 44(3):213–214, 2008.
- [133] Jastrow, C. and Priebe, S. and Spitschan, B. and Hartmann, J. and Jacob, M. and Kurner, T. and Schrader, T. and Kleine-Ostmann, T. Wireless digital data transmission at 300 GHz. *Electronics Letters*, 46(9):661–663, 2010.
- [134] Chung, Tae Jin and Lee, Won-Hui. 10-Gbit/s Wireless Communication System at 300 GHz. *ETRI Journal*, 35(3):386–396, 2013.
- [135] Priebe, S. and Kurner, T. Stochastic Modeling of THz Indoor Radio Channels. *IEEE Transactions on Wireless Communications*, 12(9):4445–4455, 2013.
- [136] Balanis, C. A. *Advanced Engineering Electromagnetics*. John Wiley and Sons, New York City, NY, 1989.

- [137] Recommendation ITU-R M.2083-0: IMT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond. *ITU, Geneva, CHE*, 2015.
- [138] Recommendation ITU-R M.2410-0: Minimum requirements related to technical performance for IMT-2020 radio interface(s). *ITU, Geneva, CHE*, 2017.
- [139] Mobile traffic forecasts 2010-2020. Report, UMTS Forum, 2011.
- [140] Report ITU-R M.2290: Future spectrum requirements estimate for terrestrial IMT. *ITU, Geneva, CHE*, 2014.
- [141] Turker Yilmaz. *Advanced Image Coding Algorithms: Beyond JPEG2000*. Thesis, 2009.
- [142] Yilmaz, Turker and Kaygan, Arda and Akan, Ozgur B. Attenuation Constant Measurements of Clear Glass Samples at the Low Terahertz Band. *Electronics Letters*, 2018.
- [143] Paris, D. T. and Hurd, F. K. *Basic Electromagnetic Theory*. McGraw-Hill, New York City, NY, 1969.
- [144] Piesiewicz, R. and Jansen, C. and Mittleman, D. and Kleine-Ostmann, T. and Koch, M. and Kurner, T. Scattering Analysis for the Modeling of THz Communication Systems. *IEEE Transactions on Antennas and Propagation*, 55(11):3002–3009, 2007.
- [145] Beckmann, P. and Spizzichino, A. *The Scattering of Electromagnetic Waves from Rough Surfaces*. Artech House, Norwood, 1986.
- [146] Cen, Lin and Li, G. Ye. Indoor terahertz communications with antenna subarrays. In *2014 IEEE Global Communications Conference (GLOBECOM)*, pages 3790–3795.

- [147] Han, C. and Bicen, A. O. and Akyildiz, I. F. Multi-Ray Channel Modeling and Wideband Characterization for Wireless Communications in the Terahertz Band. *IEEE Transactions on Wireless Communications*, 14(5):2402–2412, 2015.
- [148] Erturk, Onur and Yilmaz, Turker. A Hexagonal Grid Based Human Blockage Model for the 5G Low Terahertz Band Communications. In *2018 IEEE 1st 5G World Forum (5GWF)*, 2018.
- [149] Hiromoto, N. and Fukasawa, R. and Hosako, I. Measurement of Optical Properties of Construction Materials in the Terahertz Region. In *2006 Joint 31st International Conference on Infrared Millimeter Waves and 14th International Conference on Terahertz Electronics (IRMMW-THz)*, pages 157–157.
- [150] World Telecommunication Development Report 2002: Reinventing Telecoms. Report, International Telecommunication Union, 2002.
- [151] Resolution ITU-R 56-1: Naming for International Mobile Telecommunications. *ITU, Geneva, CHE*, 2012.
- [152] Akyildiz, Ian F. and Jornet, Josep Miquel and Han, Chong. Terahertz band: Next frontier for wireless communications. *Physical Communication*, 12(0):16–32, 2014.
- [153] Akyildiz, I. F. and Jornet, J. and Han, C. TeraNets: ultra-broadband communication networks in the terahertz band. *IEEE Wireless Communications*, 21(4):130–135, 2014.
- [154] Han, C. and Akyildiz, I. F. Distance-aware multi-carrier (DAMC) modulation in Terahertz Band communication. In *2014 IEEE International Conference on Communications (ICC)*, pages 5461–5467.

- [155] Cui, S. and Goldsmith, A. J. and Bahai, A. Energy-constrained modulation optimization. *IEEE Transactions on Wireless Communications*, 4(5):2349–2360, 2005.
- [156] Uzunkol, M. and Gurbuz, O. D. and Golcuk, F. and Rebeiz, G. M. A 0.32 THz SiGe 4x4 Imaging Array Using High-Efficiency On-Chip Antennas. *IEEE Journal of Solid-State Circuits*, 48(9):2056–2066, 2013.
- [157] Karolyi, G. and Gergelyi, D. and Foldesy, P. Sub-THz Sensor Array With Embedded Signal Processing in 90 nm CMOS Technology. *IEEE Sensors Journal*, 14(8):2432–2441, 2014.
- [158] Gu, Q. J. THz interconnect: the last centimeter communication. *IEEE Communications Magazine*, 53(4):206–215, 2015.
- [159] Syed, W. H. and Fiorentino, G. and Cavallo, D. and Spirito, M. and Sarro, P. M. and Neto, A. Design, Fabrication, and Measurements of a 0.3 THz On-Chip Double Slot Antenna Enhanced by Artificial Dielectrics. *IEEE Transactions on Terahertz Science and Technology*, 5(2):288–298, 2015.
- [160] Ruonan, Han and Afshari, E. A CMOS High-Power Broadband 260-GHz Radiator Array for Spectroscopy. *IEEE Journal of Solid-State Circuits*, 48(12):3090–3104, 2013.
- [161] Yen-Ju, Chen and Ta-Shun, Chu. 2-D Direct-Coupled Standing-Wave Oscillator Arrays. *IEEE Transactions on Microwave Theory and Techniques*, 61(12):4472–4482, 2013.
- [162] Grzyb, J. and Yan, Zhao and Pfeiffer, U. R. A 288-GHz Lens-Integrated Balanced Triple-Push Source in a 65-nm CMOS Technology. *IEEE Journal of Solid-State Circuits*, 48(7):1751–1761, 2013.

- [163] Rohde, U. L. and Poddar, A. K. and Schoepf, J. and Rebel, R. and Patel, P. Low noise low cost ultra wideband N-push VCO. In *2005 IEEE MTT-S International Microwave Symposium Digest*, pages 1171–1174.
- [164] Shinwon, Kang and Jun-Chau, Chien and Niknejad, A. M. A W-Band Low-Noise PLL With a Fundamental VCO in SiGe for Millimeter-Wave Applications. *IEEE Transactions on Microwave Theory and Techniques*, 62(10):2390–2404, 2014.
- [165] Tousi, Y. and Afshari, E. A High-Power and Scalable 2-D Phased Array for Terahertz CMOS Integrated Systems. *IEEE Journal of Solid-State Circuits*, 50(2):597–609, 2015.
- [166] Sengupta, K. and Hajimiri, A. A 0.28 THz Power-Generation and Beam-Steering Array in CMOS Based on Distributed Active Radiators. *IEEE Journal of Solid-State Circuits*, 47(12):3013–3031, 2012.
- [167] Sengupta, K. and Hajimiri, A. Distributed active radiation for THz signal generation. In *2011 IEEE International Solid-State Circuits Conference Digest of Technical Papers (ISSCC)*, pages 288–289.
- [168] Jung-Dong, Park and Shinwon, Kang and Niknejad, A. M. A 0.38 THz Fully Integrated Transceiver Utilizing a Quadrature Push-Push Harmonic Circuitry in SiGe BiCMOS. *IEEE Journal of Solid-State Circuits*, 47(10):2344–2354, 2012.
- [169] Chakraborty, A. and Trotta, S. and Wuertele, J. and Weigel, R. A D-band transceiver front-end for broadband applications in a 0.35 μ m SiGe bipolar technology. In *2014 IEEE Radio Frequency Integrated Circuits Symposium*, pages 405–408.
- [170] Itoh, T. and Haddad, G. and Harvey, J. *RF Technologies for Low-Power Wireless Communications*. Wiley-IEEE Press, 2001.

- [171] Cui, Shuguang and Goldsmith, A. J. and Bahai, A. Modulation optimization under energy constraints. In *2003 IEEE International Conference on Communications (ICC)*, volume 4, pages 2805–2811 vol.4.
- [172] Goldsmith, A. *Wireless Communications*. Cambridge University Press, 2005.
- [173] Li, C. H. and Chao, T. Y. and Lai, C. W. and Chen, W. C. and Ko, C. L. and Kuo, C. N. and Cheng, Y. T. and Kuo, M. C. and Chang, D. C. A 37.5-mW 8-dBm-EIRP 15.5-HPBW 338-GHz Terahertz Transmitter Using SoP Heterogeneous System Integration. *IEEE Transactions on Microwave Theory and Techniques*, 63(2):470–480, 2015.
- [174] Thomas, B. and Maestrini, A. and Beaudin, G. A low-noise fixed-tuned 300-360-GHz sub-harmonic mixer using planar Schottky diodes. *IEEE Microwave and Wireless Components Letters*, 15(12):865–867, 2005.
- [175] Samoska, L. A. An Overview of Solid-State Integrated Circuit Amplifiers in the Submillimeter-Wave and THz Regime. *IEEE Transactions on Terahertz Science and Technology*, 1(1):9–24, 2011.
- [176] Diebold, S. and Wagner, S. and Massler, H. and Pahl, P. and Leuther, A. and Tessmann, A. and Zwick, T. and Kallfass, I. A Novel 1x4 Coupler for Compact and High-Gain Power Amplifier MMICs Around 250 GHz. *IEEE Transactions on Microwave Theory and Techniques*, 63(3):999–1006, 2015.
- [177] Deng, X. and Li, Y. and Li, J. and Wu, W. and Xiong, Y. Z. A 340 GHz fully integrated transmitter for high-speed communications. In *2014 International Symposium on Integrated Circuits (ISIC)*, pages 300–303.
- [178] Tang, A. and Kim, Y. and Chang, M. C. F. A 65 nm CMOS 330 Mb/s Microwave Backscatter Link at 2.4 to 2.9 GHz With Ambient Blocker Cancellation. *IEEE Microwave and Wireless Components Letters*, 26(1):61–63, 2016.

- [179] Broek, D. J. van den and Klumperink, E. A. M. and Nauta, B. A self-interference cancelling front-end for in-band full-duplex wireless and its phase noise performance. In *2015 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, pages 75–78.
- [180] Debaillie, B. and Liempd, B. van and Hershberg, B. and Craninckx, J. and Rikkinen, K. and Broek, D. J. van den and Klumperink, E. A. M. and Nauta, B. In-band full-duplex transceiver technology for 5G mobile networks. In *2015 41st European Solid-State Circuits Conference (ESSCIRC)*, pages 84–87.
- [181] Piesiewicz, R. and Kleine-Ostmann, T. and Krumbholz, N. and Mittleman, D. and Koch, M. and Schoebel, J. and Kurner, T. Short-Range Ultra-Broadband Terahertz Communications: Concepts and Perspectives. *IEEE Antennas and Propagation Magazine*, 49(6):24–39, 2007.
- [182] Jacob, M. and Priebe, S. and Maltsev, A. and Lomayev, A. and Erceg, V. and Kurner, T. A ray tracing based stochastic human blockage model for the IEEE 802.11ad 60 GHz channel model. In *5th European Conference on Antennas and Propagation (EUCAP)*, pages 3084–3088.
- [183] Abouelseoud, M. and Charlton, G. The Effect of Human Blockage on the Performance of Millimeter-Wave Access Link for Outdoor Coverage. In *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*, pages 1–5.
- [184] Gapeyenko, M. and Samuylov, A. and Gerasimenko, M. and Moltchanov, D. and Singh, S. and Aryafar, E. and Yeh, S. p. and Himayat, N. and Andreev, S. and Koucheryavy, Y. Analysis of human-body blockage in urban millimeter-wave cellular communications. In *2016 IEEE International Conference on Communications (ICC)*, pages 1–7.
- [185] Khalid, Nabil and Yilmaz, Turker and Akan, Ozgur B. Energy-efficient Modulation Scheme for THz-band 5G Femtocell Internet of Things. In *2017 1st*

- International Balkan Conference on Communications and Networking (BalkanCom)*, 2017.
- [186] Khalid, Nabil and Yilmaz, Turker and Akan, Ozgur B. Energy-efficient modulation and physical layer design for low terahertz band communication channel in 5G femtocell Internet of Things. *Ad Hoc Networks*, 79:63–71, 2018.
- [187] Luczak, E. and Rosenfeld, A. Distance on a Hexagonal Grid. *IEEE Transactions on Computers*, C-25(5):532–533, 1976.
- [188] Bell, Sarah B. M. and Holroyd, Fred C. and Mason, David C. A digital geometry for hexagonal pixels. *Image and Vision Computing*, 7(3):194–204, 1989.
- [189] Neufert, E. and Neufert, P. *Architects' Data*. Blackwell Science, 2000.