INDOOR PATH LOSS MODELING FOR FIFTH GENERATION APPLICATIONS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JULY 2018

Dedicated to my beloved parents and family,

my beloved wife Noor, my son Yosuf and my daughter Razan

ACKNOWLEDGMENT

Firstly, I thank Allah SWT, for giving me this opportunity of life, and for everything I was able to achieve.

This thesis would not have been possible without the kind support and encouragement of Professor Dr. Tharek Abd. Rahman. I am very grateful to him for his caring supervision, his enthusiastic involvement in this thesis and his supportive suggestions and comments. I wish to express my thanks to my co-supervisor Dr. Omar Abdul Aziz for his helpful comments during my research and careful reviews of this thesis.

I owe special thanks to my wife Noor for her patience and understanding, and I also would like to thank my parents for continuous encouragement and support.

Finally, I would like to express my most sincere gratitude to all those who have helped me directly or indirectly to complete this work.

ABSTRACT

The demand for high data rate transmission for the future wireless communication technology is increasing rapidly. Due to the congestion in the current bands for cellular network, it may not be able to satisfy the user requirements. For the future cellular networks, the millimeter wave (mm-wave) bands are the promising candidate bands because of the large available bandwidth. The 28 GHz and 38 GHz bands are the strongest candidate for fifth generation (5G) cellular networks. The channel needs to be characterized based on large-scale characterization to know the channel behavior in mm-wave bands in indoor environment. The narrowband channel is characterized based on the path loss model. For the development of new 5G systems to operate in bands up to 100 GHz, there is a need for accurate radio propagation models, which are not addressed by existing channel models developed for bands below 6 GHz. This attempt was conducted through extensive measurement campaigns and by using Information and Communication Solutions (ICS) Telecom simulation tool. The measurement environments were a closed-plan scenario in two buildings that included a line-of-sight (LOS) and non-line-of-sight (NLOS) corridor, a hallway, a cubicle room, and different adjacent-rooms communication links. The main limitation of the study was the limited distance range of LOS and NLOS environments because of the building structure design. Well-known single-frequency and multi-frequency directional and omnidirectional large-scale path loss models such as close-in free space reference (CI), floating intercept (FI) and alpha-beta-gamma (ABG) models and modified model are presented in this thesis. The modified model has a correction factor for different environments and it provides physically-based and efficient estimated path loss data points for the reference distance. Directional path loss model was done in co-polarized and cross-polarized antenna orientations, while omnidirectional path loss model was done in co-polarized antenna orientation only. The ICS Telecom simulation results show very high compatibility when compared with measurement campaign results. Also, it is found that the CI model is simpler, more convenient and more accurate for path loss prediction comparing with FI and ABG models. Also, the results show that the modified large-scale path loss model has the smallest path loss exponent (PLE), n and standard deviation, σ values compared to the CI model. The results suggest that the modified path loss model can provide a sound estimation of path loss prediction and act as a reference analysis for developing mm-wave for wireless communication planning in indoor environments.

ABSTRAK

Permintaan untuk penghantaran data dengan kadar yang tinggi bagi teknologi komunikasi tanpa wayar masa depan sedang meningkat pesat. Kesesakan penggunaan jalur frekuensi yang digunakan pada waktu kini bagi kegunaan rangkaian selular mungkin mengakibatkan ketidakmampuan menampung keperluan pengguna pada masa akan datang. Untuk rangkaian selular masa depan, jalur gelombang milimeter (gelombang-mm) adalah jalur frekuensi terbaik kerana keluasan lebar jalurnya. Jalur 28 GHz dan 38 GHz merupakan calon jalur frekuensi paling sesuai untuk rangkaian selular generasi kelima (5G). Saluran pada jalur tersebut perlu dicirikan berdasarkan pencirian berskala besar bagi menentukan karakteristik gelombang mm di persekitaran dalam bangunan. Pencirian saluran adalah berpaksikan model kehilangan laluan. Bagi pembangunan sistem 5G baru yang beroperasi dalam jalur sehingga 100 GHz, model perambatan gelombang yang lebih tepat diperlukan kerana model sedia ada hanya sesuai untuk julat di bawah 6 GHz. Pembentukan model ini telah dilakukan berdasarkan kempen pengukuran yang ekstensif dan menggunakan perisian simulasi *Information and Communication Solutions* (ICS) *Telecom*. Persekitaran pengukuran adalah senario pelan tertutup dalam dua bangunan termasuk untuk keadaan garis nampak (LOS), garis tak nampak (NLOS), laluan lorong luas, bilik berkubikel serta hubungan komunikasi bilik berhampiran. Kekangan utama kajian adalah julat jarak yang terhad dari persekitaran LOS dan NLOS disebabkan reka bentuk struktur bangunan. Model kehilangan laluan berskala besar satu dan berbilang frekuensi terarah dan semua arah yang diketahui seperti rujukan ruang bebas (CI), pemantauan terapung (FI) dan *alpha-beta-gamma* (ABG) serta model yang diubah suai telah dibentang dalam tesis ini. Model yang diubah suai mempunyai faktor pembetulan bagi persekitaran yang berbeza dan memberikan titik data kehilangan laluan secara fizikal dan cekap untuk jarak rujukan. Model kehilangan laluan terarah telah dilakukan bagi orientasi antena sama-kutub dan silang-kutub, manakala model kehilangan laluan pemancaran antena pelbagai-arah dilakukan untuk orientasi antena sama-kutub sahaja. Hasil simulasi ICS *Telecom* menunjukkan keserasian yang sangat tinggi dibandingkan dengan hasil pengukuran. Juga, didapati bahawa model CI adalah lebih mudah, ringkas dan tepat untuk ramalan kehilangan laluan membandingkan dengan model FI dan ABG. Selain itu, keputusan menunjukkan bahawa model kehilangan laluan dikemukakan mempunyai eksponen kehilangan laluan (PLE), n dan sisihan piawai, σ lebih kecil berbanding dengan model CI. Dapatan kajian menunjukkan model yang diubah suai dapat meramal kehilangan laluan dengan tepat dan menjadi analisis rujukan untuk membangunkan aplikasi gelombang-mm bagi perancangan komunikasi tanpa wayar dalam persekitaran dalam bangunan.

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LIST OF ABBREVIATIONS

2D	-	2 Dimensional
3D	-	3 Dimensional
3GPP	-	3rd Generation Partnership Project
4G	-	Fourth Generation
5G	-	Fifth Generation
ABG	-	Alpha-Beta-Gamma Path Loss Model
BSs	-	Base Stations
CI	-	Close-In Reference Path Loss Model
CIF	-	Close-In Frequency-Dependent Path Loss Model
CMOS	-	Complementary Metal-Oxide-Semiconductor
CW	-	Continuous Wave
D2D	-	Device-To-Device
DEM	-	Data Elevation Model
ELA	-	Enhanced Local Area
FDD	-	Frequency Division Duplex
FI	-	Floating Intercept Path Loss Model
FSPL	-	Free Space Path Loss
GSCM	-	Geometry Centered Stochastic Channel Model
HDTV	-	High-Definition Television
ICS Telecom	-	Information and Communication Solutions Telecom
IMT	-	International Mobile Telecommunications
IoT	-	Internet of Things
ITU-R	-	International Telecommunication Union for Radiocommunication
LMDS	-	Local Multipoint Distribution Service

LOS	-	Line of Sight
LTE	-	Long-Term Evolution
METIS	-	Mobile and Wireless Communications Enablers For The Twenty-Twenty Information Society
MIMO	-	Multiple-Input Multiple-Output
MMSE	-	Minimum Mean Square Error
mmWave	-	Millimeter Wave
MU-MIMO	-	Multi User- Multiple Input-Multiple Output
NLOS	-	Non-Line of Sight
PC	-	Personal Computer
PDPs	-	Power Delay Profiles
PL	-	Path Loss
PLE	-	Path Loss Exponent
QoS	-	Quality of Service
RATs	-	Radio Access Technologies
RF	-	Radio Frequency
RX	-	Receiver
TDM	-	Time-Division Multiplexing
TX	-	Transmitter
UE	-	User Equipment
V2V	-	Vehicle-To-Vehicle
VNA	-	Vector Network Analyzer
WCC	-	Wireless Communication Center
WiFi	-	Wireless Fidelity
WiGig	-	Wireless Gigabit Alliance
WLAN	-	Wireless Local Area Network
WPAN	-	Wireless Personal Area Network
WRC	-	World Radio Conference

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The frequency spectrum is a valuable natural resource, which has been swiftly utilized for worldwide, regional and national telecommunication infrastructures [1], [2]. In light of this, the World Radio Conference (WRC-15) and the International Telecommunication Union for Radiocommunication (ITU-R) have been established as the main guidelines for the worldwide spectrum allocation for the next generation of cellular systems [3]. In addition, the International Mobile Telecommunications (IMT)-advanced requirements for the fourth generation (4G) terrestrial mobile telecommunication were affirmed by the ITU-R in January 2012. Simultaneously, the tremendous evolution of cellular data services supported by wireless internet and smart devices has prompted the research on the fifth generation (5G) designed for the next generation of terrestrial cellular telecommunications [4].

The field of wireless communications technology has advanced rapidly in recent years. The wider application of wireless communications technology is mainly due to its capability in fulfilling the specifications for the modern methods. Nevertheless, there has been increasing demand for the high data rate and fast communication nowadays [5]. In light of this, wireless data traffic is projected to rise by 1000 fold and 10,000 fold by the year 2020 and 2025, respectively [6]. In the case of cellular communication, is it essential to enhance the cellular capacity to address the dynamic need of the traffic. Moreover, rising demand for usage of the smart devices (e.g., smart-phone, tablet, personal computer (PC), and etc.) and tremendous growth of applications urge huge data traffics. These factors have contributed exponentially towards increase of the support for wireless data traffic.

In recent years, there has been an enormous advancement in cellular data traffic owing to the development of smartphones, tablets, and devices that deliver, oversee, convey, and save Zettabytes of data annually [7]-[9]. Moreover, the smartphone adoption rates are markedly rising as carriers and service providers are striving to engage more clients [10], [11]. Fundamentally, the arrival of smartphones and "wireless fidelity" (WiFi) supported devices have expedited the growth of wireless technologies and utilization. Nevertheless, it has formed the bottleneck in the sub-6 GHz spectrum, wherein most of these devices function [12]-[15].

From the beginning of 2000's, there has been an extensive utilization of 2.4 GHz and 5 GHz WiFi bands for indoor wireless communications in common workplace settings, eateries, and lodging houses [16], [17]. Nonetheless, the heavy deployment of indoor hotspots and latest wireless multimedia devices have caused high bottleneck and traffic over indoor networks [18]. Moreover, the 60 GHz mmWave band is applied for wireless gigabit alliance (WiGig) along with the 2.4 GHz and 5 GHz WiFi bands, to enable high-data-rate uses. As such, the broad bandwidth at 60 GHz has promoted widespread 60 GHz indoor propagation analysis to determine the essential attributes of the channel for inventing indoor wireless local area network (WLAN) systems. It should be noted that the WLAN systems that have potential for attaining multi-gigabits per- second throughputs [19], [20].

In general, the wireless spectrum more than 6 GHz, particularly amongst 30 GHz and 300 GHz, is known as the mmWave spectrum. The mmWave spectrum encompasses a substantial volume of fresh bandwidth that is rarely used. Nevertheless, it could be feasible for unlicensed or licensed utilization in the near future [12], [13], [21]. Presently, the unlicensed 60 GHz band is the only millimeter wave band applied for extensive commercial utilization. In this case, oxygen absorption generates loss larger than free space in comparison with the alternative millimeter wave bands. Consequently, this lowers the signal strength across the extended array (up to a few hundreds of meters) of propagation distances [22].

The observation gained through existing mobile and wireless communications networks leads to unexpected growth of the data traffic. Resultantly, it contributes to a significant challenge towards further advancement of mobile and wireless communication networks. The future IMT systems are anticipated to support extremely high-throughput data networks to withstand the progress on the data traffic [23]. In light of this, many studies and development are in the pipeline to discover feasible mobile broadband systems with frequency bands more than 6 GHz.

The band more than 6 GHz at millimeter wave band is proposed as a promising candidate for the latest cellular 5G communication system [4]. Accordingly, the system capability of the 5G cellular communication system will be enhanced. Consequently, the cellular devices functioned through base station could be provided with enhanced service environment with high-speed broadband transmission with low latency compared to the existing cellular communication systems. Hence, the utilization of millimeter wave band for 5G cellular communication system will lead to innovative multimedia facilities [24].

The imminent spectrum and capacity crunch intended for outdoor cellular may ultimately result in the 28 GHz and 38 GHz millimeter wave frequency bands. This is considered as an expansion of 5G outdoor and indoor communications, particularly owing to the nature of shrinking cell sizes. On the occasion of 28 GHz and 38 GHz bands turn out to be unlicensed like the 60 GHz band, the comprehensive utilization and occasions they could support would extremely decline the load on cellular and backhaul networks conforming to the phase of the internet of things (IoT) [25].

The 5G wireless networks are anticipated to be a combination of network tiers of diverse magnitudes, transmit powers, backhaul connections, and diverse radio access technologies (RATs) that are retrieved by remarkable quantities of smart and heterogeneous wireless devices. This architectural improvement in addition to the cutting-edge physical communications technology like high-order spatial multiplexing multiple-input multiple-output (MIMO) communications will offer sophisticated comprehensive capability for additional immediate customers, or greater spectral efficacy in comparison with the 4G networks [26].

The transceivers in 5G should warrant a protected communication with a steadfast connection speed of Gigabit per second at all ubiquitously. In the vicinity of the entire transceiver modules for millimeter wave (30GHz-300GHz) for 5G cellular communication, the antenna design needs major modifications. This is for the reason that the entire cellular communication criterions up to 4G have functioned in the series of the microwave spectrum 300MHz-3GHz [27].

1.2 Problem Statement

The expansion of 5G cellular communication networks concentrates towards contributing sophisticated bandwidth and elongated array together with advanced capability. Therefore, the spectrum usable in the millimeter wave frequency bands offers multi-gigabit-per-second data rates. Nevertheless, the recognized communication scope is limited by a number of aspects, such as the setting (indoor or outdoor), the functioning frequency, antenna categories, and designs, etc.

For the development of the new 5G systems to operate in bands above 6 GHz, there is a need for accurate radio propagation models for these bands which are not fully modelled by existing channel models below 6 GHz, because of the difference of signal propagation characteristics in different frequencies. Thus, it is important to investigate the channel characterization and path loss modeling in frequency bands above 6 GHz (millimeter wave bands).

The problem is to investigate the practical usefulness of IMT in different frequency bands and in millimeter wave bands specifically 28 GHz and 38 GHz and investigating the channel characteristics and path loss modeling in these bands under different propagation conditions and scenarios in indoor environment, e.g. LOS, NLOS, and different rooms, also for directional and omnidirectional path loss models for co- and cross-antenna polarizations. Also, for different antenna types like horn and omni antennas, to examine and evaluate the effect of changing the antenna type (horn or omni) and changing the antenna orientation (co- and cross-polarized) on the path loss.

1.3 Research Objective

In this research the main objective is aiming to investigate the channel characteristics and path loss modeling, and usefulness of IMT in bands more than 6 GHz (28 GHz and 38 GHz). This aim was meant to support and further enrich literature on path loss modeling for 5G mobile networks in millimeter wave frequency bands. The other objectives to achieve the aim aforementioned are outlined below:

- To measure received signal strength then conduct and modeling path loss for different path loss models (CI, FI and ABG) in different indoor environments at 4.5 GHz, 28 GHz and 38 GHz.
- To perform path loss modeling by using ATDI-ICS Telecom simulation, to compare and verify the measurement and simulation results. Also, develop a modified path loss model in same environments at 28 GHz and 38 GHz.

- To evaluate and verify the developed model and to find most suitable and accurate path loss model in corresponding bands for various propagation settings based on different path loss coefficients and parameters, such as path loss exponent PLE.

1.4 Scope of Work

The study is aimed to examine and deliver data on the practical usefulness of IMT in the bands more than 6 GHz in millimeter wave bands (28 GHz and 38 GHz). In addition, the study purposed to form propagation models for the indoor settings. The practical usefulness to be measured are inclusive of details, the existing IMT systems, their development, and/or possibly innovative IMT radio technologies and system methodologies could be applicable for operation in the bands more than 6 GHz. This is in view of the effect of the propagation features associated with the potential upcoming operation of IMT in those bands. All necessary formulas that should be applied for this study have to be analyzed and the required parameters are going to be determined. The scope of the research has been listed as follows:

- Literature reviews have been carried out on radio propagation model, frequency bands, propagation losses, path loss models, millimeter wave frequency bands, 5G channel modeling and current literature related to this study.
- Illustrating the specifications and parameters of the proposed system for TX and RX for different scenarios.
- Identifying the path loss models' formulas in order to find the relationship between path loss with distance and frequency for different scenarios and frequencies.

- Measure the received signal strength and characterize path loss for two different indoor environments inside Universiti Teknologi Malaysia (UTM), Johor campus.
- Path loss measurements carried out at three frequency bands 4.5 GHz, 28 GHz and 38 GHz.
- ATDI-ICS Telecom simulation for planning and designing telecommunication network to do coverage calculation and path loss modeling for same environments and scenarios of measurement.

1.5 Research Contribution

A few measurements have been conducted, and few studies have been investigated on the millimeter wave propagation and path loss modeling at 28 GHz and 38 GHz for typical indoor settings. In light of this, the current research is emphasized on path loss modeling in diverse indoor settings and schemes. Appropriately, the findings of the current study would contribute towards model path loss and channel features. These contributions are as outlined below:

- A significant study based on measurements and experimental setup, and coverage analysis in ATDI-ICS Telecom simulation have been performed for path loss modeling and channel characterization.
- The study conducted in LOS, NLOS and in different rooms environments in the two buildings with different obstacles, to examine signal attenuation when penetrating different obstacles, in order to accurately characterize the channel and model path loss to design indoor systems at mmWave frequency band.
- The study showed a comparison results in different path loss models between the frequency below 6 GHz (4.5 GHz) and frequencies above 6 GHz (28 GHz and 38 GHz).

- New path loss model has been modified and validated for different scenarios, in directional and omnidirectional path loss models for co- and cross-antenna polarization. Experimental works and analysis on path loss in indoor environment in this research study have produced path loss model that is more precise for the examined scenarios relative to standard indoor empirical models.

1.6 Thesis Outlines

This thesis comprises of six chapters to cover the whole research work that has been conducted.

The second chapter provides a summary of literature review on radio propagation model, deterministic and empirical indoor propagation models, applications of millimeter wave communications. Also, topics on 5G channel modeling, challenges and requirements are then explained. It includes results of the most recent studies in indoor channel modeling for different frequencies.

The third chapter proposes a methodology of path loss modeling in measurements and simulation software in different indoor environments and frequencies for directional and omnidirectional models. It includes the closed-form expression for formulas of single and multi-frequency path loss models that used in this research study. Also shows the measurement environments and experiment procedures. The modified model for 28 GHz and 38 GHz frequency bands has been presented.

Chapter four describes the details and shows the results of an experimental setup for propagation and path loss modeling in Wireless Communication Center

(WCC P15a) new building and (WCC P15) old building in Universiti Teknologi Malaysia (UTM), Skudai, Johor. The experimental setup comprises of fixing the TX in a location and distribute the RX points in LOS, NLOS and six rooms in the building. Single frequency (CI and FI) models and multi frequency (ABG) model as well as modified model results are presented for directional and omnidirectional path loss models. Also, indoor plan designing and path loss modeling by using ATDI-ICS Telecom simulation software are presented. Moreover, the comparison results between measurements and simulation are presented also.

Chapter five presents the overall conclusions of this research study and give the recommendations on future work and development related to channel characterization and path loss modeling for 5G communication networks.

REFERENCES

1. Laster JD, Reed JH. Interference rejection in digital wireless communications. *IEEE signal processing magazine*. 1997 May;14(3):37-62.
2. Yoon HG, Chung WG, Jo HS, Lim J, Yook JG, Park HK. Spectrum requirements for the future development of IMT-2000 and systems beyond IMT-2000. *Journal of Communications and Networks.* 2006 Jun;8(2):169-74.
3. Kerczewski RJ, Jonasson L. Outcomes of the 2015 world radiocommunication conference for aeronautical spectrum and applications. In *Integrated Communications Navigation and Surveillance* (ICNS), 2016 2016 Apr 19 (pp. 5D1-1). IEEE.
4. Akdeniz MR, Liu Y, Samimi MK, Sun S, Rangan S, Rappaport TS, Erkip E. Millimeter wave channel modeling and cellular capacity evaluation. *IEEE journal on selected areas in communications*. 2014 Jun;32(6):1164-79.
5. Andrews JG, Buzzi S, Choi W, Hanly SV, Lozano A, Soong AC, Zhang JC. What will 5G be?. *IEEE Journal on selected areas in communications*. 2014 Jun;32(6):1065-82.
6. Cudak M, Ghosh A, Kovarik T, Ratasuk R, Thomas TA, Vook FW, Moorut P. Moving towards mmWave-based beyond-4G (B-4G) technology. *In Vehicular Technology Conference (VTC Spring)*, 2013 IEEE 77th 2013 Jun 2 (pp. 1-5). IEEE.
7. Pi Z, Khan F. An introduction to millimeter-wave mobile broadband systems. *IEEE communications magazine*. 2011 Jun;49(6).
8. Li Y, Yang J, Ansari N. Cellular smartphone traffic and user behavior analysis. In *Communications (ICC), 2014 IEEE International Conference on* 2014 Jun 10 (pp. 1326-1331). IEEE.

9. Rappaport TS. Millimeter wave wireless communications: the renaissance of computing and communications. In *IEEE International Conference on Communications, Sydney* 2014 Jun.
10. Aldhaban F. Exploring the adoption of Smartphone technology: Literature review. In Technology Management for Emerging Technologies (PICMET), 2012 Proceedings of PICMET'12: 2012 Jul 29 (pp. 2758-2770). IEEE.
11. Gartner. Gartner Says by 2018, More Than 50 Percent of Users Will Use a Tablet or Smartphone First for All Online Activities. (Dec. 2014). [Online]. Available: http://www.gartner.com/newsroom/id/2939217
12. Rappaport TS, Sun S, Mayzus R, Zhao H, Azar Y, Wang K, Wong GN, Schulz JK, Samimi M, Gutierrez F. Millimeter wave mobile communications for 5G cellular: It will work! *IEEE access*. 2013; 1:335-49.
13. T. S. Rappaport, R. W. Heath, Jr., R. C. Daniels, and J. N. Murdock, Millimeter Wave Wireless Communications. Englewood Cliffs, NJ, USA: Prentice-Hall, 2015.
14. CISCO. (2007). 20 Myths of Wi-Fi Interference: Dispel Myths to Gain High Performing and Reliable Wireless. http://www.cisco.com/c/en/us/products/collateral/wireless/spectrum-expert-wi-_/prod_white_ paper0900aecd807395a9.pdf
15. Hays Z, Richter G, Berger S, Baylis C, Marks RJ. Alleviating airport WiFi congestion: A comparison of 2.4 GHz and 5 GHz WiFi usage and capabilities. In *Wireless and Microwave Circuits and Systems (WMCS), 2014 Texas Symposium on* 2014 Apr 3 (pp. 1-4). IEEE.
16. Na C, Chen JK, Rappaport TS. Hotspot traffic statistics and throughput models for several applications. In *Global Telecommunications Conference, 2004. GLOBECOM'04. IEEE* 2004 Dec (Vol. 5, pp. 3257-3263). IEEE.
17. Na C, Chen JK, Rappaport TS. Measured traffic statistics and throughput of IEEE 802.11 b public WLAN hotspots with three different applications. *IEEE Transactions on Wireless Communications*. 2006 Nov;5(11).
18. Sergiou C, Antoniou P, Vassiliou V. A comprehensive survey of congestion control protocols in wireless sensor networks. *IEEE Communications Surveys & Tutorials*. 2014 Nov;16(4):1839-59.

19. Xu H, Kukshya V, Rappaport TS. Spatial and temporal characteristics of 60-GHz indoor channels. *IEEE Journal on selected areas in communications*. 2002 Apr;20(3):620-30.
20. Maltsev A, Maslennikov R, Sevastyanov A, Khoryaev A, Lomayev A. Experimental investigations of 60 GHz WLAN systems in office environment. *IEEE Journal on Selected Areas in Communications*. 2009 Oct;27(8).
21. Rappaport TS, Murdock JN, Gutierrez F. State of the art in 60-GHz integrated circuits and systems for wireless communications. *Proceedings of the IEEE*. 2011 Aug;99(8):1390-436.
22. Daniels RC, Murdock JN, Rappaport TS, Heath RW. 60 GHz wireless: Up close and personal. *IEEE Microwave magazine*. 2010 Dec;11(7):44-50.
23. Report ITU-R M.2243, Characteristics Assessment of the global mobile broadband deployments and forecasts for International Mobile Telecommunications. November, 2011. http://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2243-2011-PDF-E.pdf.
24. Recommendation ITU-R P.452-12. Prediction Procedure for the Evaluation of Microwave Interference between Stations on the Surface of the Earth at Frequencies above about 0.7 GHz. Geneva, Switzerland. May, 2007.
25. Ge X, Cheng H, Guizani M, Han T. 5G wireless backhaul networks: challenges and research advances. *IEEE Network*. 2014 Nov;28(6):6-11.
26. Wang CX, Haider F, Gao X, You XH, Yang Y, Yuan D, Aggoune H, Haas H, Fletcher S, Hepsaydir E. Cellular architecture and key technologies for 5G wireless communication networks. *IEEE Communications Magazine*. 2014 Feb;52(2):122-30.
27. Chen S, Zhao J. The requirements, challenges, and technologies for 5G of terrestrial mobile telecommunication. *IEEE Communications Magazine*. 2014 May;52(5):36-43.
28. Maltsev A. Channel Modeling and Characterization-MiWEBA," Deliverable 5.1 EU Contract No. FP7-ICT-608637; 2014.
29. Rappaport TS. Wireless Communications Principles and Practice. *2nd ed Up Saddle River, NJ Prentice Hall*, 2002.
30. https://www.ctia.org/docs/default-source/default-document-library/5g-high-band-white-paper.pdf

31. Yacoub, M. D. Foundations of Mobile Radio Engineering. *New York: CRC Press*.1993, 67-70.
32. https://www.mathworks.com/help/phased/examples/modeling-the-propagation-of-rf-signals.html?requestedDomain=www.mathworks.com
33. Lee, W. C. Y. *Integrated wireless propagation models*. United State, USA: Mc Graw Hill. 2015.
34. http://web.uettaxila.edu.pk/cms/aut2012/tewcnms/notes/2%20-%20Wireless%20Physical%20Media.ppt
35. Zhang, J., and De la Roche, G. *Femtocells. Technologies and Deployment*. New York: Wiley. 2011.
36. Sarkar TK, Ji Z, Kim K, Medouri A, Salazar-Palma M. A survey of various propagation models for mobile communication. *IEEE Antennas and propagation Magazine*. 2003 Jun;45(3):51-82.
37. Austin AC, Neve MJ, Rowe GB. Modeling propagation in multifloor buildings using the FDTD method. *IEEE Transactions on Antennas and Propagation*. 2011 Nov;59(11):4239-46.
38. Lawton MC, McGeehan JP. The application of a deterministic ray launching algorithm for the prediction of radio channel characteristics in small-cell environments. *IEEE Transactions on Vehicular Technology*. 1994 Nov;43(4):955-69.
39. McKown JW, Hamilton RL. Ray tracing as a design tool for radio networks. *IEEE Network*. 1991 Nov;5(6):27-30.
40. Seidel SY, Rappaport TS. 914 MHz path loss prediction models for indoor wireless communications in multifloored buildings. *IEEE transactions on Antennas and Propagation*. 1992 Feb;40(2):207-17.
41. Zyoud A, Chebil J, Habaebi MH, Islam MR, Zeki AM. Comparison of empirical indoor propagation models for 4G wireless networks at 2.6 GHz. *In Proceedings Engineering & Technology* 2013 Jun (Vol. 3, pp. 7-11).
42. Rappaport TS, Murdock JN, Michelson DG, Shapiro R. An open-source archiving system. *IEEE Vehicular Technology Magazine*. 2011 Jun;6(2):24-32.
43. Report ITU-R P.525, Calculation of Free-Space Attenuation. August, 1994. http://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.525-2-199408-I!!PDF-E.pdf

44. Recommendation ITU-R P.837-6, Characteristics of precipitation for propagation modeling, February, 2012. https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.837-6-201202-I!!PDF-E.pdf
45. Gutierrez F, Agarwal S, Parrish K, Rappaport TS. On-chip integrated antenna structures in CMOS for 60 GHz WPAN systems. *IEEE Journal on Selected Areas in Communications*. 2009 Oct;27(8).
46. Rappaport TS, Ben-Dor E, Murdock JN, Qiao Y. 38 GHz and 60 GHz angle-dependent propagation for cellular & peer-to-peer wireless communications. *In Communications (ICC), 2012 IEEE International Conference* on 2012 Jun 10 (pp. 4568-4573). IEEE.
47. Rusek F, Persson D, Lau BK, Larsson EG, Marzetta TL, Edfors O, Tufvesson F. Scaling up MIMO: Opportunities and challenges with very large arrays. *IEEE Signal Processing Magazine*. 2013 Jan;30(1):40-60.
48. Seidel SY, Arnold HW. Propagation measurements at 28 GHz to investigate the performance of local multipoint distribution service (LMDS). *In Global Telecommunications Conference, 1995. GLOBECOM'95*., IEEE 1995 Nov 14 (Vol. 1, pp. 754-757). IEEE.
49. Qingling Z, Li J. Rain attenuation in millimeter wave ranges. *In Antennas, Propagation & EM Theory, 2006. ISAPE'06. 7th International Symposium* on 2006 Oct 26 (pp. 1-4). IEEE.
50. Rappaport, T. S. Special session on mmWave communications. *In Proceedings of the ICC*. Budapest, Hungary. 2013
51. Baldemair R, Irnich T, Balachandran K, Dahlman E, Mildh G, Selén Y, Parkvall S, Meyer M, Osseiran A. Ultra-dense networks in millimeter-wave frequencies. *IEEE Communications Magazine*. 2015 Jan;53(1):202-8.
52. Qiao J, Cai LX, Shen X, Mark JW. STDMA-based scheduling algorithm for concurrent transmissions in directional millimeter wave networks. *In Communications (ICC), 2012 IEEE International Conference* on 2012 Jun 10 (pp. 5221-5225). IEEE.
53. Chen Q, Tang J, Wong DT, Peng X, Zhang Y. Directional cooperative MAC protocol design and performance analysis for IEEE 802.11 ad WLANs. *IEEE Transactions on Vehicular Technology*. 2013 Jul;62(6):2667-77.

54. Ghosh A, Thomas TA, Cudak MC, Ratasuk R, Moorut P, Vook FW, Rappaport TS, MacCartney GR, Sun S, Nie S. Millimeter-wave enhanced local area systems: A high-data-rate approach for future wireless networks. *IEEE Journal on Selected Areas in Communications*. 2014 Jun;32(6):1152-63.
55. Singh H, Oh J, Kweon C, Qin X, Shao HR, Ngo C. A 60 GHz wireless network for enabling uncompressed video communication. *IEEE Communications Magazine*. 2008 Dec;46(12).
56. Wu D, Wang J, Cai Y, Guizani M. Millimeter-wave multimedia communications: challenges, methodology, and applications. *IEEE Communications Magazine*. 2015 Jan;53(1):232-8.
57. Rangan S, Rappaport TS, Erkip E. Millimeter-wave cellular wireless networks: Potentials and challenges. *Proceedings of the IEEE*. 2014 Mar;102(3):366-85.
58. Rappaport TS, Gutierrez F, Ben-Dor E, Murdock JN, Qiao Y, Tamir JI. Broadband millimeter-wave propagation measurements and models using adaptive-beam antennas for outdoor urban cellular communications. *IEEE transactions on antennas and propagation*. 2013 Apr;61(4):1850-9.
59. Bai T, Alkhateeb A, Heath RW. Coverage and capacity of millimeter-wave cellular networks. *IEEE Communications Magazine*. 2014 Sep;52(9):70-7.
60. Bai T, Heath RW. Coverage and rate analysis for millimeter-wave cellular networks. *IEEE Transactions on Wireless Communications*. 2015 Feb;14(2):1100-14.
61. Singh S, Ziliotto F, Madhow U, Belding E, Rodwell M. Blockage and directivity in 60 GHz wireless personal area networks: From cross-layer model to multihop MAC design. *IEEE Journal on Selected Areas in Communications*. 2009 Oct;27(8).
62. Sulyman AI, Nassar AT, Samimi MK, Maccartney GR, Rappaport TS, Alsanie A. Radio propagation path loss models for 5G cellular networks in the 28 GHz and 38 GHz millimeter-wave bands. *IEEE Communications Magazine*. 2014 Sep;52(9):78-86.
63. Son IK, Mao S, Gong MX, Li Y. On frame-based scheduling for directional mmWave WPANs. *In INFOCOM, 2012 Proceedings IEEE* 2012 Mar 25 (pp. 2149-2157). IEEE.

64. Niu Y, Li Y, Jin D, Su L, Vasilakos AV. A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges. *Wireless Networks*. 2015 Nov 1;21(8):2657-76.
65. Taori R, Sridharan A. Point-to-multipoint in-band mmwave backhaul for 5G networks. *IEEE Communications Magazine*. 2015 Jan;53(1):195-201.
66. Bernardos CJ, De Domenico A, Ortin J, Rost P, Wübben D. Challenges of designing jointly the backhaul and radio access network in a cloud-based mobile network. *In Future Network and Mobile Summit (Future Network Summit)*, 2013 2013 Jul 3 (pp. 1-10). IEEE.
67. Niu Y, Gao C, Li Y, Su L, Jin D, Vasilakos AV. Exploiting device-to-device communications in joint scheduling of access and backhaul for mmWave small cells. *IEEE Journal on Selected Areas in Communications*. 2015 Oct;33(10):2052-69.
68. METIS M. Wireless Communications Enablers for the Twenty twenty Information Society, *EU 7th Framework Programme project*. ICT-317669-METIS.
69. M. Fallgren, B. Timus (Editors), "Future Radio Access Scenarios, Requirements and KPIs," Deliverable D1.1, V1.0, ICT-317669, METIS project, 1st May 2013. Project.
70. Osseiran A, Boccardi F, Braun V, Kusume K, Marsch P, Maternia M, Queseth O, Schellmann M, Schotten H, Taoka H, Tullberg H. Scenarios for 5G mobile and wireless communications: the vision of the METIS project. *IEEE Communications Magazine*. 2014 May;52(5):26-35.
71. "Guidelines for evaluation of radio interface technologies for IMT-Advanced," International Telecommunication Union (ITU), Geneva, Switzerland, Report ITU-R M.2135-1, 12/2009.
72. P. Kyösti et al., "WINNER II Channel Models," IST-4-027756 WINNER II Deliverable D1.1.2 v.1.2.4.2.2008. (http://www.istwinner.org/deliverables.html).
73. P. Heino et al., "WINNER+ Final Channel Models," V1.0, CELTIC CP5-026 WINNER+ Project, Deliverable D5.3, 30.6.2010 (http://projects.celtic-initiative.org/winner+/deliverables_winnerplus.html).
74. Fraunhofer Gesellschaft, "QuaDRiGa - Quasi Deterministic Radio Channel Generator," http://hhi.fraunhofer.de/quadriga.

75. Verdone R, Zanella A, editors. Pervasive mobile and ambient wireless communications: COST action 2100. *Springer Science & Business Media*; 2012 Jan 2.
76. Maltsev A. Channel models for 60GHz WLAN systems. *IEEE P802*. 11-09-0334-04. 2010 May.
77. Nurmela V, Karttunen A, Roivainen A, Raschkowski L, Hovinen V, EB JY, Omaki N, Kusume K, Hekkala A, Weiler R, HHI MP. Deliverable D1. 4 METIS Channel Models. *Mobile Wireless Commun. Enablers Twenty-Twenty Inf. Soc.(METIS)*. 2014 Apr.
78. Medbo J, Asplund H, Berg JE, Jalden N. Directional channel characteristics in elevation and azimuth at an urban macrocell base station. *In Antennas and Propagation (EUCAP), 2012 6th European Conference* on 2012 Mar 26 (pp. 428-432). IEEE.
79. Haneda K, Tian L, Asplund H, Li J, Wang Y, Steer D, Li C, Balercia T, Lee S, Kim Y, Ghosh A. Indoor 5G 3GPP-like channel models for office and shopping mall environments. *In Communications Workshops (ICC), 2016 IEEE International Conference* on 2016 May 23 (pp. 694-699). IEEE.
80. 3GPP, “Study on 3D channel model for LTE,” Tech. Rep. 3GPP 36.873 (V12.2.0), July 2015.
81. Rappaport TS, MacCartney GR, Samimi MK, Sun S. Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design. *IEEE Transactions on Communications*. 2015 Sep;63(9):3029-56.
82. Anderson CR, Rappaport TS, Bae K, Verstak A, Ramakrishnan N, Tranter WH, Shaffer CA, Watson LT. In-building wideband multipath characteristics at 2.5 and 60 GHz. *In Vehicular Technology Conference, 2002. Proceedings. VTC 2002-Fall*. 2002 IEEE 56th 2002 (Vol. 1, pp. 97-101). IEEE.
83. Sun S, Thomas TA, Rappaport TS, Nguyen H, Kovacs IZ, Rodriguez I. Path loss, shadow fading, and line-of-sight probability models for 5G urban macro-cellular scenarios. *In Globecom Workshops (GC Wkshps)*, 2015 IEEE 2015 Dec 6 (pp. 1-7). IEEE.
84. Maccartney GR, Rappaport TS, Sun S, Deng S. Indoor office wideband millimeter-wave propagation measurements and channel models at 28 and 73 GHz for ultra-dense 5G wireless networks. *IEEE Access*. 2015; 3:2388-424.

85. Piersanti S, Annoni LA, Cassioli D. Millimeter waves channel measurements and path loss models. *In Communications (ICC), 2012 IEEE International Conference* on 2012 Jun 10 (pp. 4552-4556). IEEE.
86. Andersen JB, Rappaport TS, Yoshida S. Propagation measurements and models for wireless communications channels. *IEEE Communications Magazine*. 1995 Jan;33(1):42-49.
87. MacCartney GR, Zhang J, Nie S, Rappaport TS. Path loss models for 5G millimeter wave propagation channels in urban microcells. *In Global Communications Conference (GLOBECOM), 2013 IEEE* 2013 Dec 9 (pp. 3948-3953). IEEE.
88. Sun S, Rappaport TS, Rangan S, Thomas TA, Ghosh A, Kovacs IZ, Rodriguez I, Koymen O, Partyka A, Jarvelainen J. Propagation path loss models for 5G urban micro-and macro-cellular scenarios. *In Vehicular Technology Conference (VTC Spring), 2016 IEEE* 83rd 2016 May 15 (pp. 1-6). IEEE.
89. Thomas TA, Rybakowski M, Sun S, Rappaport TS, Nguyen H, Kovacs IZ, Rodriguez I. A prediction study of path loss models from 2-73.5 GHz in an urban-macro environment. *In Vehicular Technology Conference (VTC Spring), 2016 IEEE* 83rd 2016 May 15 (pp. 1-5). IEEE.
90. Samimi MK, Rappaport TS. Local multipath model parameters for generating 5G millimeter-wave 3GPP-like channel impulse response. *In Antennas and Propagation (EuCAP), 2016 10th European Conference* on 2016 Apr 10 (pp. 1-5). IEEE.
91. Siddique U, Tabassum H, Hossain E, Kim DI. Wireless backhauling of 5G small cells: challenges and solution approaches. *IEEE Wireless Communications*. 2015 Oct;22(5):22-31.
92. T. S. Rappaport, “The massively broadband future,” Spectrum 20/20 conference, June 2012. (http://www.spectrum2020.ca/presentations/Rappaport.pdf).
93. Maltsev A, Sadri A, Pudeyev A, Nicholls R, Arefi R, Davydov A, Bolotin I, Morozov G, Sakaguchi K, Haustein T. MmWave smallcells is a key technology for future 5G wireless communication systems. *In European Conference on Networks and Communications* (EuCNC’2014) 2014 Jun.
94. Samimi MK, Rappaport TS. Statistical channel model with multi-frequency and arbitrary antenna beamwidth for millimeter-wave outdoor

communications. *In Globecom Workshops (GC Wkshps), 2015 IEEE* 2015 Dec 6 (pp. 1-7). IEEE.

95. Cassioli D, Win MZ, Molisch AF. The ultra-wide bandwidth indoor channel: from statistical model to simulations. *IEEE Journal on selected areas in Communications*. 2002 Aug;20(6):1247-57.
96. Hindia M, Rahman T, Ojukwu H, Hanafi E, Fattouh A. Enabling Remote Health-Caring Utilizing IoT Concept over LTE-Femtocell Networks. *PloS one.* 2016;11(5):e0155077.
97. Al-Samman A, Rahman T, Azmi M, Hindia M, Khan I, Hanafi E. Statistical modelling and characterization of experimental mm-wave indoor channels for future 5G wireless communication networks. *PloS one*. 2016;11(9):e0163034.
98. Sun S, Rappaport TS, Thomas TA, Ghosh A, Nguyen HC, Kovács IZ, et al. Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications. *IEEE Transactions on Vehicular Technology*. 2016;65(5):2843-60.
99. Alexander SE. Characterising buildings for propagation at 900 MHz. *Electronics Letters*. 1983 Sep 29;19(20):860.
100. Akerberg D. Properties of a TDMA pico cellular office communication system. In *Vehicular Technology Conference*, 1989, IEEE 39th 1989 May 1 (pp. 186-191). IEEE.
101. Saleh AA, Valenzuela R. A statistical model for indoor multipath propagation. *IEEE Journal on selected areas in communications*. 1987 Feb;5(2):128-37.
102. Bultitude R. Measurement, characterization and modeling of indoor 800/900 MHz radio channels for digital communications. *IEEE communications magazine*. 1987 Jun;25(6):5-12.
103. Motley AJ, Keenan JM. Personal communication radio coverage in buildings at 900 MHz and 1700 MHz. *Electronics Letters*. 1988 Jun 9;24(12):763-4.
104. Rappaport TS. Characterization of UHF multipath radio channels in factory buildings. *IEEE Transactions on Antennas and Propagation*. 1989 Aug;37(8):1058-69.
105. Rappaport TS, Hawbaker DA. Effects of circular and linear polarized antennas on wideband propagation parameters in indoor radio channels. In *Global Telecommunications Conference, 1991. GLOBECOM'91.'Countdown to the*

New Millennium. Featuring a Mini-Theme on: Personal Communications Services 1991 Dec 2 (pp. 1287-1291). IEEE.

106. Ho CP, Rappaport TS, Koushik MP. Antenna effects on indoor obstructed wireless channels and a deterministic image-based wide-band propagation model for in-building personal communication systems. *International Journal of Wireless Information Networks*. 1994 Jan 1;1(1):61-76.
107. Ghassemzadeh SS, Jana R, Rice CW, Turin W, Tarokh V. Measurement and modeling of an ultra-wide bandwidth indoor channel. *IEEE Transactions on Communications.* 2004 Oct;52(10):1786-96.
108. Rappaport TS, Sandhu S. Radio-wave propagation for emerging wireless personal-communication systems. *IEEE Antennas and Propagation Magazine*. 1994 Oct;36(5):14-24.
109. Alvarez A, Valera G, Lobeira M, Torres RP, Garcia JL. Ultra-wideband channel model for indoor environments. *Journal of Communications and Networks.* 2003 Dec;5(4):309-18.
110. Athanasiadou GE, Nix AR, McGeehan JP. A ray tracing algorithm for microcellular wideband propagation modelling. In *Vehicular Technology Conference, 1995 IEEE 45th* 1995 Jul 25 (Vol. 1, pp. 261-265). IEEE.
111. Schaubach KR, Davis NJ, Rappaport TS. A ray tracing method for predicting path loss and delay spread in microcellular environments. In *Vehicular Technology Conference, 1992, IEEE 42nd* 1992 May 10 (pp. 932-935). IEEE.
112. Seidel SY, Rappaport TS. A ray tracing technique to predict path loss and delay spread inside buildings. In *Global Telecommunications Conference, 1992. Conference Record., GLOBECOM'92. Communication for Global Users.,* IEEE 1992 Dec 6 (pp. 649-653). IEEE.
113. Seidel SY, Rappaport TS. Site-specific propagation prediction for wireless in-building personal communication system design. *IEEE transactions on Vehicular Technology*. 1994 Nov;43(4):879-91.
114. Seidel S, Schaubach K, Tran T, Rappaport T. Research in site-specific propagation modeling for PCS system design. In *Vehicular Technology Conference, 1993., 43rd* IEEE 1993 May 18 (pp. 261-264). IEEE.
115. Skidmore RR, Rappaport TS, Abbott AL. Interactive coverage region and system design simulation for wireless communication systems in multifloored indoor environments: SMT Plus. In *Universal Personal Communications,*

1996. Record., 1996 5th IEEE International Conference on 1996 Oct (Vol. 2, pp. 646-650). IEEE.

116. Seidel SY, Rappaport TS. Path loss prediction in multifloored buildings at 914 MHz. *Electronics Letters*. 1991 Jul 18;27(15):1384-7.
117. Durgin G, Patwari N, Rappaport TS. Improved 3D ray launching method for wireless propagation prediction. *Electronics Letters*. 1997 Jul 31;33(16):1412-3.
118. Xu H, Kukshya V, Rappaport TS. Spatial and temporal characterization of 60 GHz indoor channels. In *Vehicular Technology Conference, 2000. IEEE-VTS Fall VTC 2000. 52nd* 2000 (Vol. 1, pp. 6-13). IEEE.
119. Zwick T, Beukema TJ, Nam H. Wideband channel sounder with measurements and model for the 60 GHz indoor radio channel. *IEEE transactions on Vehicular technology*. 2005 Jul;54(4):1266-77.
120. Geng S, Kivinen J, Vainikainen P. Propagation characterization of wideband indoor radio channels at 60 GHz. In *Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications, 2005. MAPE 2005. IEEE International Symposium* on 2005 Aug 8 (Vol. 1, pp. 314-317). IEEE.
121. Anderson CR, Rappaport TS. In-building wideband partition loss measurements at 2.5 and 60 GHz. *IEEE transactions on wireless communications.* 2004 May;3(3):922-8.
122. Wu X, Zhang Y, Wang CX, Goussetis G, Alwakeel MM. 28 GHz indoor channel measurements and modelling in laboratory environment using directional antennas. In *Antennas and Propagation (EuCAP), 2015 9th European Conference on* 2015 May 13 (pp. 1-5). IEEE.
123. Lei M, Zhang J, Lei T, Du D. 28-GHz indoor channel measurements and analysis of propagation characteristics. *In Personal, Indoor, and Mobile Radio Communication (PIMRC), 2014 IEEE 25th Annual International Symposium* on 2014 Sep 2 (pp. 208-212). IEEE.
124. Zhao H, Mayzus R, Sun S, Samimi M, Schulz JK, Azar Y, Wang K, Wong GN, Gutierrez F, Rappaport TS. 28 GHz millimeter wave cellular communication measurements for reflection and penetration loss in and around buildings in New York City. In *Communications (ICC), 2013 IEEE International Conference on* 2013 Jun 9 (pp. 5163-5167). IEEE.

125. Deng S, Samimi MK, Rappaport TS. 28 GHz and 73 GHz millimeter-wave indoor propagation measurements and path loss models. *In Communication Workshop (ICCW), 2015 IEEE International Conference on* 2015 Jun 8 (pp. 1244-1250). IEEE.
126. Deng S, MacCartney GR, Rappaport TS. Indoor office plan environment and layout-based mmWave path loss models for 28 GHz and 73 GHz. *In Vehicular Technology Conference (VTC Spring), 2016 IEEE 83rd* 2016 May 15 (pp. 1-6). IEEE.
127. Kim M, Konishi Y, Chang Y, Takada JI. Large scale parameters and double-directional characterization of indoor wideband radio multipath channels at 11 GHz. *IEEE Transactions on Antennas and Propagation*. 2014 Jan;62(1):430-41.
128. Lee J, Liang J, Kim MD, Park JJ, Park B, Chung HK. Measurement-Based Propagation Channel Characteristics for Millimeter-Wave 5G Giga Communication Systems. *ETRI Journal*. 2016 Dec 1;38(6):1031-41.
129. Yu Y, Dong J, Ye AP, Yang B, Liu J, Liu Y, Lu WJ, Zhu HB. Effect of antenna height on propagation characteristics under indoor stair environment. In *Antennas and Propagation (APCAP), 2014 3rd Asia-Pacific Conference on* 2014 Jul 26 (pp. 710-712). IEEE.
130. Valcarce A, Zhang J. Empirical indoor-to-outdoor propagation model for residential areas at 0.9–3.5 GHz. *IEEE Antennas and Wireless Propagation Letters.* 2010; 9:682-5.
131. MacCartney GR, Samimi MK, Rappaport TS. Exploiting directionality for millimeter-wave wireless system improvement. In *Communications (ICC), 2015 IEEE International Conference on* 2015 Jun 8 (pp. 2416-2422). IEEE.
132. Sun S, Rappaport TS, Heath RW, Nix A, Rangan S. MIMO for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both? *IEEE Communications Magazine*. 2014 Dec;52(12):110-21.
133. Sun S, Rappaport TS. Multi-beam antenna combining for 28 GHz cellular link improvement in urban environments. In *Global Communications Conference (GLOBECOM), 2013 IEEE* 2013 Dec 9 (pp. 3754-3759). IEEE.
134. Sun S, MacCartney GR, Samimi MK, Nie S, Rappaport TS. Millimeter wave multi-beam antenna combining for 5G cellular link improvement in New York

City. In *Communications (ICC), 2014 IEEE International Conference on* 2014 Jun 10 (pp. 5468-5473). IEEE.

135. Allen KC, DeMinco N, Hoffman JR, Lo Y, Papazian P. Building penetration loss measurements at 900 MHz, 11.4 GHz, and 28.8 GHz. *US Department of Commerce, National Telecommunications and Information Administration Rep*. 1994 May:94-306.
136. Alejos AV, Sanchez MG, Cuinas I. Measurement and analysis of propagation mechanisms at 40 GHz: Viability of site shielding forced by obstacles. *IEEE Transactions on Vehicular Technology*. 2008 Nov;57(6):3369-80.
137. Series P. Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz. *Recommendation ITU-R*. 2012 Feb:1238-7.