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Path Loss Models for 5G Communications System in Corridors Environment

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ABSTRACT

This paper presents the propagation path loss channel models, developed from real-field measurement in Universiti Teknologi Malaysia (UTM) Kuala Lumpur, Malaysia. The purpose of the study is to characterize the channel at 28 GHz for 5G communications system in line-of-sight (LOS) corridors environment. Measurement campaigns were conducted to measure the wireless signal of received signal strength at three different construction of straight corridors, narrow, wide and open corridors. The large-scale path loss models are developed using the closed-in reference distance (CI) and floating – intercept (FI) modelling approaches. Besides contributing path loss (PL) models at 28 GHz for different corridors dimension, the result found in this work discovered the breakpoint distance (dbp) of radio propagation is seen varies differently at those corridors. PLE in CI model, open corridor significantly exaggerates of 1.92 compared to the narrow and wide corridor of 1.60 and 1.83 PLEs respectively. The lower than free-space (PLE is 2) in the corridors, attributes to the waveguide phenomenon within the corridors.

1. Introduction

The rapidly increasing demands for higher mobile data rates and ubiquitous data access have led to a spectrum crunch over the traditional wireless communication frequency bands, i.e., below 6 GHz [1]. As the current technology is expected unable to cope with the demand, the new standardization toward fifth generation (5G) communication is aggressively studied [2-6]. However, many aspects of 5G propagation channel have not yet been thoroughly evaluated [7-11].

The key to achieving future generation mobile communication of 5G, the technology has to move to the higher frequency band of millimetre-wave [12,13], where the availability of very large bandwidth in frequency bands. ITU has revealed the attractive focus of 5G deployment range between 24.25-86 GHz in WRC’15 for IMT-2020 [14-18]. As the existing channel model are evaluated

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for as high as 6 GHz [19], the application of the new spectrum bands draws special attention to channel characterization [20-26]. In a closed environment for LOS scenario, the multipath reflection from surrounding environment, such as ceiling, wall, and floor rise the effect of channel waveguiding [27]. Measurement at 915 MHz and 2.4 GHz in the corridor environment shows the construction of the wide corridor increase the path loss exponent (PLE), compared to narrow construction corridor [28,29]. In [30], the measurement campaigns conducted to study the path loss (PL) at L-shaped and straight corridor particularly MIMO application. PL study was conducted at 5 GHz. The short- range channel characterization was conducted at 15 GHz for a different construction of indoor corridor. The closed and semi-closed corridor have been evaluated for PLE and shadow fading, where the authors agree PLE is unreliable to the carrier frequency in LOS case [31].

In channel characterization, the existence of obstacle may degrade the received signal strength (RSS) due to deflecting effect that bounces the [32-36]. In [37], the propagation work on the NLOS link due to deflection obstacle was measured in the T-shape corridor at 60 GHz. In the non-straight corridor environment, the multipath fading comes through reflection, diffraction, and transmission. The study performed in [38] presented the narrowband *PL* models base on measurement campaigns and ray-tracing approach at 900 MHz and 2.44 GHz.

The similar approach of ray-tracing is applied to characterize corridor in non-line-of-sight (NLOS) scenario [39]. Many of empirical models are developed for corridor environment, especially below 6 GHz. To the author's best knowledge, there is none work literature studied the *PL* propagation model for the different structure of corridor, particularly at 28 GHz. In this paper, the measurement base channel propagation was conducted to evaluate and model PL and shadow fading, for 5G communication system at 28 GHz. Three types of corridors were measured, open structure outdoor corridor, narrow structure indoor corridor, and wide structure tunnel corridor.

The author in [40] has discussed about the propagation for third-order closed-in PL model for indoor corridor measurement campaign. The path loss for similar enclosed corridor has been measured at 28 GHz and 38 GHz with different antenna polarization, vertical-to-vertical and vertical-to-horizontal [29]. The indoor radio wave frequency has been studied for various campaign as discussed in [42-45].

The overall observation acknowledges that CI and FI model are the best for millimetre-wave channel propagation model range between 28 GHz to 100 GHz. The CI and FI model are widely used in measurement campaign for Line-of-sight (LOS) and Non-line-of-sight (NLOS) [21,40,46-51].

The remainder of the paper is organized as follows. Measurement description and scenario are described in Section 2 and the PL models are presented in Section 3. In Section 4, the numerical result and discussion are drawn, before the conclusion of the paper in Section 5.

2. Channel Measurement

2.1 Open Corridor

The open corridor located outdoor, without wall enfold. The open corridor is constructed from metal zinc ceiling and covered by porcelain tile floor. Apart of that, the corridor is implanted with the permanent metal pole at every 1.5 m, as depicted in Figure. The dimension of the open corridor is 3.5 m height, 2.5 m width, and 100 m length.

2.2 Wide Corridor

The wide corridor is a tunnel-like corridor, constructed of 30 m reinforced concrete walls and ceiling, while the corridor floor is covered by cement tile. The dimension of the wide corridor is 2.5

m height, 3.6 m width, and 60 m length. Furthermore, the corridor is built with openings structure particularly at 13 m (0.3 m width), 14 m (1 m width) and 15 m (1 m width) of the corridor.

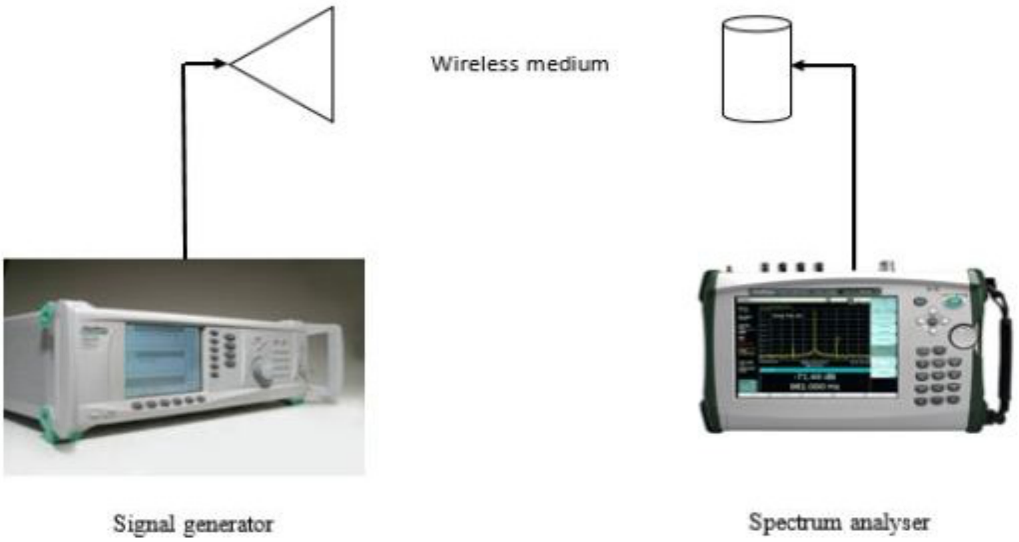
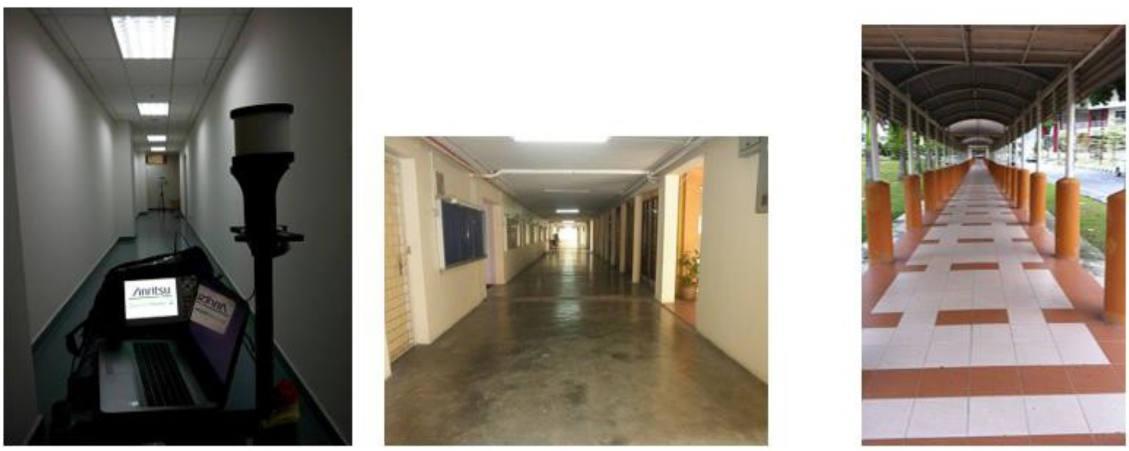


Fig. 1. Measurement setup for 28 GHz

2.3 Narrow Corridor

For narrow corridor, the corridor is located at 4th floor of Malaysia-Japan International Institute of Technology in UTM-Kuala Lumpur campus. The wall is enclosed by reinforced concrete wall, of 23 cm thickness, the ceiling is made of asbestos, and the floor is covered by porcelain tile. The dimension of the narrow corridor is 3.5 m height, 1.5 widths, and 40 lengths. The corridor structure as depicted in Figure 2 (a) to (c) [18].

For this measurement campaigns, TX was kept stationary at one end of the corridor, while RX is a move for each 1 m adjacent away toward the end of another corridor side, to capture RSS at every 1 m distance. The repeated measurements are performed to obtain a precise value of RSS. The average of RSS was then used to compute the PL and shadow fading and hence the PLEs are further extracted. To verify the measured results, the measurements campaign was conducted repeated, where the TX and RX are aligned to each other boresight. Moreover, the measurements campaign was conducted during the off-hour, to avoid human induce and movement interference.



(a) (b) (c)

Fig. 2. The construction of (a) narrow corridor, (b) wide corridor and (c) open corridor

3. Path Loss Models

The CI path loss model is presented as statistical path loss model of a single frequency, which is derived from the measurement dataset and as is shown as follow:

$$PL^{CI}[dB] = PL_{d_0} + 10n\log_{10}\left(\frac{d}{d_0}\right) + \chi_{\sigma}^{CI} \tag{1}$$

where PL_{d0} is the free-space reference distance at d_0=1 m, d is the distance of 3-D TX-RX separation, n is the path loss exponent parameter that derived from least-square error approach which fits the measurement data, and $X\sigma^{CI}$ is a zero-mean Gaussian random variable with standard deviation σ in decibels.

Another path loss model is called the floating-intercept (FI) path loss model which used in the WINNER II and 3GPP standards [14,15]. It is based on the floating-intercept (α) and line slope (β) to provide the best minimum error fit of collected path losses as follows:

$$PL^{FI}[dB] = \alpha + 10 \cdot \beta \log_{10}(d) + \chi_{\sigma}^{FI} \tag{2}$$

where χ_{σ}^{FI} is a zero mean Gaussian (in dB) shadow fading random variable, which describes large-scale signal fluctuations about the mean path loss over distance.

4. Results and Discussion

The following Figure 3 to Figure 5 provide the measured and models parameterization of PL and shadow fading obtained for three differently dimensional corridors at 28 GHz.

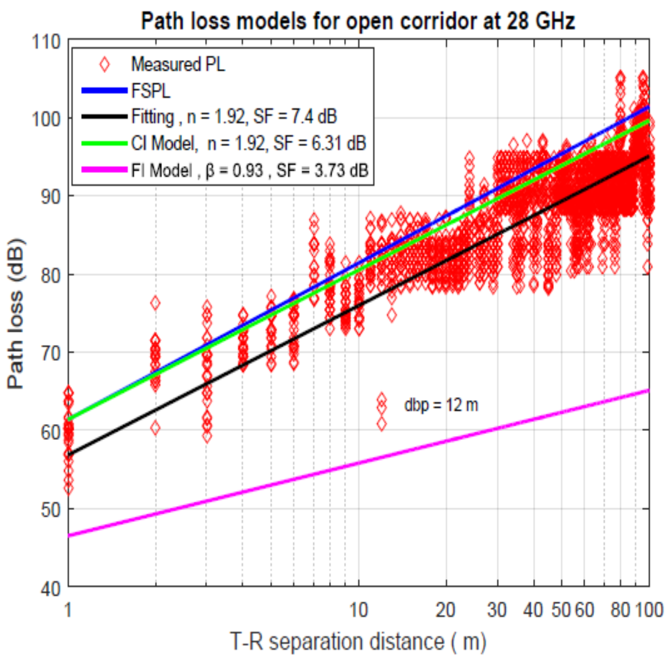


Fig. 3. Path loss models for open corridor

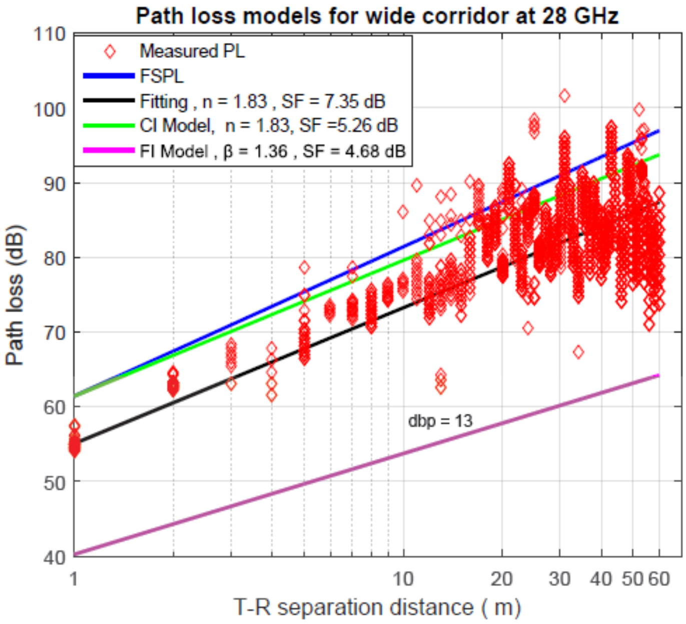


Fig. 4. Path loss models for wide corridor

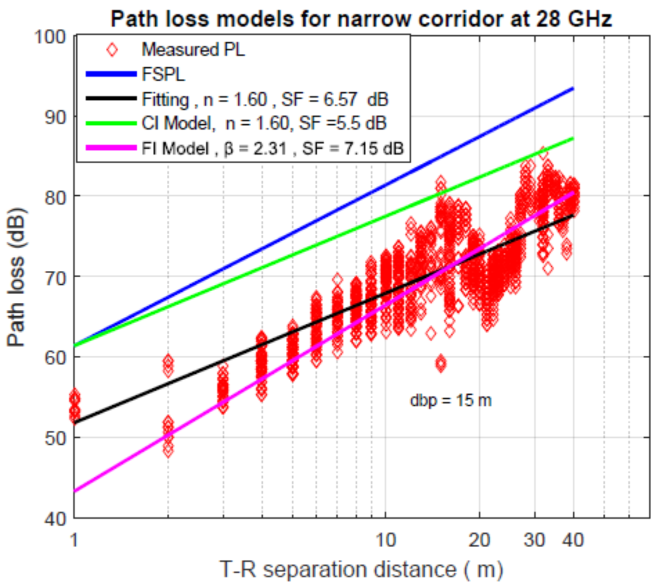


Fig. 5. Path loss models for narrow corridor

As given in Table 1, the $PLdo$ for CI and FI model varies differently as CI considers 1 m reference distance, while FI model estimates the non-physical PL. PLE in CI model, open corridor significantly exaggerates of 1.92 compared to the narrow and wide corridor of 1.60 and 1.83 PLEs respectively. The lower than free-space (PLE is 2) in the corridors, attributes to the waveguide phenomenon within the corridors. However, the open corridor indicates high attenuation compared to the wide and narrow corridor, as the PLE of the open corridor is near to free-space.

For shadow fading, the fading in corridors varies typically for surround environments, range from 4.68 dB to 7.15 dB. Among of three corridors, PL in open corridor PL varies closely to free-space path loss (FSPL), followed by a wide corridor and narrow corridor respectively. This is due to multipath reflection in the narrow corridor, which is a constructive rise, the RSS within the corridor.

On the other hand, the multipath reflection is lowest at the open corridor and moderate at the wide corridor, thus the range of average PL is insignificant compared to a narrow corridor.

For the case of breakpoint distance (dbp), despite short T-R separation distance within 100 m, the result reveal diverges dbp can be observed for short range communication at 28 GHz. For narrow corridor, the result shows 17 m dbp, while 12 m for open corridor and 15 m for wide corridor respectively. This indicates the tapered environment able to contain strongest RSS within to enhance the coverage wider and longer, compared to open environment. The high attenuation fluctuation is observed after the dbp, due to high destruction multipath reflection of corridor surrounding. This behavior promotes the relaying approach at certain a distance within the corridor or tunnel to enhance the RSS for better end user experience.

Table 1
Path loss models parameters for open, wide and narrow corridors at 28 GHz

Open			
CI	$PLdo$	PLE	Shadow fading
	61.39	1.92	6.31
FI	α	β	Shadow fading
	46.51	0.93	3.73
Wide			
CI	$PLdo$	PLE	Shadow fading
	61.39	1.83	5.26
FI	α	β	Shadow fading
	40.22	1.36	4.68
Narrow			
CI	$PLdo$	PLE	Shadow fading
	61.36	1.6	5.5
FI	α	β	Shadow fading
	43.29	2.37	7.15

5. Conclusion

This paper presents the measurement of PL and shadow fading models at three-dimensional different corridors at 28 GHz. The parameter of PL, PLE and shadow fading are studied, additionally with the characterization of breakpoint distance. The average PL values show the multipath reflection in narrow corridor escalates the RSS values, thus extend the coverage for longer distance. Furthermore, the result of dbp distance promotes the similar extension of radio signal in narrow corridor. As the multipath reflection is less attributed in the open corridor and wide corridor, the PLEs are observed higher than in narrow corridor. Moreover, the $dbps$ are seen shorter than in narrowband, indicate the higher attenuation of RF losses characterization.

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References
[1] Abdullah Al-Ahmadi, Abdusamea, I. A. Omer, Muhammad Ramlee Kamarudin, and Tharek Bin Abdul Rahman. "Multi-floor indoor positioning system using Bayesian graphical models." *Progress In Electromagnetics Research B* 25 (2010): 241-259. https://doi.org/10.2528/PIERB10081202

[2] Azar, Yaniv, George N. Wong, Kevin Wang, Rimma Mayzus, Jocelyn K. Schulz, Hang Zhao, Felix Gutierrez, DuckDong Hwang, and Theodore S. Rappaport. "28 GHz propagation measurements for outdoor cellular communications using steerable beam antennas in New York city." In *2013 IEEE international conference on communications (ICC)*, pp. 5143-5147. IEEE, 2013. https://doi.org/10.1109/ICC.2013.6655399
[3] Bakirtzis, Stefanos, Ian Wassell, Marco Fiore, and Jie Zhang. "Stochastic Evaluation of Indoor Wireless Network Performance with Data-Driven Propagation Models." In *GLOBECOM 2022-2022 IEEE Global Communications Conference*, pp. 3587-3592. IEEE, 2022. https://doi.org/10.1109/GLOBECOM48099.2022.10001717
[4] Bangerter, Boyd, Shilpa Talwar, Reza Arefi, and Ken Stewart. "Networks and devices for the 5G era." *IEEE Communications Magazine* 52, no. 2 (2014): 90-96. https://doi.org/10.1109/MCOM.2014.6736748
[5] Bureau, Radiocommunication. “Preparations for Purpose of ITU WRCs,”
[6] Circular, Administrative, and Radiocommunication Sector Members. “Radiocommunication Bureau (BR),” (2015): 1–51.
[7] Dehos, Cedric, Jose Luis González, Antonio De Domenico, Dimitri Ktenas, and Laurent Dussopt. "Millimeter-wave access and backhauling: The solution to the exponential data traffic increase in 5G mobile communications systems?." *IEEE communications magazine* 52, no. 9 (2014): 88-95. https://doi.org/10.1109/MCOM.2014.6894457
[8] Docomo, N. T. T. *5G Channel Model for bands up to100 GHz*. Technical report, 2016.
[9] Ghaddar, Mohamad, Larbi Talbi, Gilles Y. Delisle, and Jules LeBel. "Deflecting-obstacle effects on signal propagation in the 60 GHz band." *IEEE Transactions on antennas and propagation* 61, no. 1 (2012): 403-414. https://doi.org/10.1109/TAP.2012.2216852
[10] Imoize, Agbotiname Lucky, Augustus Ehiremen Ibhaze, Aderemi A. Atayero, and K. V. N. Kavitha. "Standard propagation channel models for MIMO communication systems." *Wireless Communications and Mobile Computing* 2021 (2021): 1-36. https://doi.org/10.1155/2021/8838792
[11] Jesus, Paulo, Albena D. Mihovska, Sofoklis Kyriazakos, George Karetsos, Yutao Zhu, and Marc Werner. "IST-4-027756 WINNER II Deliverable D6. 11.4 Final WINNER II System Requirements: http://www. ist-winner. org/deliverables. html." (2007).
[12] MacCartney, George R., Junhong Zhang, Shuai Nie, and Theodore S. Rappaport. "Path loss models for 5G millimeter wave propagation channels in urban microcells." In *2013 IEEE global communications conference (GLOBECOM)*, pp. 3948-3953. IEEE, 2013. https://doi.org/10.1109/GLOCOM.2013.6831690
[13] El Khaled, Zayan, Wessam Ajib, and Hamid Mcheick. "Log distance path loss model: Application and improvement for sub 5 ghz rural fixed wireless networks." *IEEE Access* 10 (2022): 52020-52029. https://doi.org/10.1109/ACCESS.2022.3166895
[14] Lei, Mingyang, Jianhua Zhang, Tian Lei, and Detao Du. "28-GHz indoor channel measurements and analysis of propagation characteristics." In *2014 IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC)*, pp. 208-212. IEEE, 2014. https://doi.org/10.1109/PIMRC.2014.7136161
[15] Lertwiram, Namzilp, Gia Khanh Tran, Keiichi Mizutani, Kei Sakaguchi, and Kiyomichi Araki. "MIMO Radio Propagation Measurement for Two-Hop Relay Network on L-Shaped Corridor with Network Performance Analysis." In *2010 IEEE 71st Vehicular Technology Conference*, pp. 1-5. IEEE, 2010. https://doi.org/10.1109/VETECS.2010.5493698
[16] Liu, Bo. "LTE wireless network coverage optimisation based on corrected propagation model." *Applied Mathematics and Nonlinear Sciences*.
[17] Liu, Hui, Houshang Darabi, Pat Banerjee, and Jing Liu. "Survey of wireless indoor positioning techniques and systems." *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* 37, no. 6 (2007): 1067-1080. https://doi.org/10.1109/TSMCC.2007.905750
[18] Lodro, Mir. “Channel Characterization of Reconfigurable Intelligent Radio Environment.” (2021).
[19] Löwenstein, Uwe. “ITU-R Activities towards 5G between WRC-15 and WRC-19,” (2016).
[20] Nguyen, Sinh LH, Jonas Medbo, Michael Peter, Aki Karttunen, Katsuyuki Haneda, Aliou Bamba, Raffaele D'Errico, Naveed Iqbal, Cheikh Diakhate, and J-M. Conrat. "On the frequency dependency of radio channel's delay spread: Analyses and findings from mmMAGIC multi-frequency channel sounding." (2018): 634-5. https://doi.org/10.1049/cp.2018.0993
[21] Maccartney, George R., Theodore S. Rappaport, Mathew K. Samimi, and Shu Sun. "Millimeter-wave omnidirectional path loss data for small cell 5G channel modeling." *IEEE access* 3 (2015): 1573-1580. https://doi.org/10.1109/ACCESS.2015.2465848
[22] Maccartney, George R., Theodore S. Rappaport, Shu Sun, and Sijia Deng. "Indoor office wideband millimeter-wave propagation measurements and channel models at 28 and 73 GHz for ultra-dense 5G wireless networks." *IEEE access* 3 (2015): 2388-2424. https://doi.org/10.1109/ACCESS.2015.2486778

[23] Rappaport, Theodore S., George R. MacCartney, Mathew K. Samimi, and Shu Sun. "Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design." *IEEE transactions on Communications* 63, no. 9 (2015): 3029-3056. https://doi.org/10.1109/TCOMM.2015.2434384

[24] Majed, Mohammed Bahjat, Tharek Abd Rahman, Omar Abdul Aziz, Mohammad Nour Hindia, and Effariza Hanafi. "Channel characterization and path loss modeling in indoor environment at 4.5, 28, and 38 GHz for 5G cellular networks." *International Journal of Antennas and Propagation* 2018 (2018). https://doi.org/10.1155/2018/9142367

[25] Majed, Mohammed Bahjat, Tharek Abd Rahman, Omar Abdul Aziz, Mohammad Nour Hindia, and Effariza Hanafi. "Channel characterization and path loss modeling in indoor environment at 4.5, 28, and 38 GHz for 5G cellular networks." *International Journal of Antennas and Propagation* 2018 (2018). https://doi.org/10.1155/2018/9142367

[26] Marks, Roger, and Ethairnet Associates. “IEEE 802 5G Spectrum Considerations.” (2016). https://Mentor.Ieee.Org/802- Ec/Dcn/16/Ec-16-0068-00-5GSG-Ieee-802-5g-Spectrum-Considerations.Pdf

[27] Miura, Yuko, Yasuhiro Oda, and Tokio Taga. "Outdoor-to-indoor propagation modelling with the identification of path passing through wall openings." In *The 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 1, pp. 130-134. IEEE, 2002.

[28] Murdock, James N., Eshar Ben-Dor, Yijun Qiao, Jonathan I. Tamir, and Theodore S. Rappaport. "A 38 GHz cellular outage study for an urban outdoor campus environment." In *2012 IEEE wireless communications and networking conference (WCNC)*, pp. 3085-3090. IEEE, 2012. https://doi.org/10.1109/WCNC.2012.6214335

[29] Solahuddin, Y. F., and R. Mardeni. "Indoor empirical path loss prediction model for 2.4 GHz 802.11 n network." In *2011 IEEE International Conference on Control System, Computing and Engineering*, pp. 12-17. IEEE, 2011. https://doi.org/10.1109/ICCSCE.2011.6190487

[30] Nie, Shuai, George R. MacCartney, Shu Sun, and Theodore S. Rappaport. "72 GHz millimeter wave indoor measurements for wireless and backhaul communications." In *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pp. 2429-2433. IEEE, 2013. https://doi.org/10.1109/PIMRC.2013.6666553

[31] Oladimeji, Tolulope T., Pradeep Kumar, and Mohamed K. Elmezughi. "Path Loss Measurements and Model Analysis in an Indoor Corridor Environment at 28 GHz and 38 GHz." *Sensors* 22, no. 19 (2022): 7642. https://doi.org/10.3390/s22197642

[32] Oladimeji, Tolulope T., Pradeep Kumar, and Mohamed K. Elmezughi. "Performance analysis of improved path loss models for millimeter-wave wireless network channels at 28 GHz and 38 GHz." *Plos one* 18, no. 3 (2023): e0283005. https://doi.org/10.1371/journal.pone.0283005

[33] Oladimeji, Tolulope T., Pradeep Kumar, and Nicholas O. Oyie. "Propagation path loss prediction modelling in enclosed environments for 5G networks: A review." *Heliyon* 8, no. 11 (2022). https://doi.org/10.1016/j.heliyon.2022.e11581

[34] Osseiran, Afif, Federico Boccardi, Volker Braun, Katsutoshi Kusume, Patrick Marsch, Michal Maternia, Olav Queseth *et al.,* "Scenarios for 5G mobile and wireless communications: the vision of the METIS project." *IEEE communications magazine* 52, no. 5 (2014): 26-35. https://doi.org/10.1109/MCOM.2014.6815890

[35] Mardeni, R., and Y. Solahuddin. "Path loss model development for indoor signal loss prediction at 2.4 GHz 802.11 n network." In *2012 International Conference on Microwave and Millimeter Wave Technology (ICMMT)*, vol. 2, pp. 1-4. IEEE, 2012. https://doi.org/10.1109/ICMMT.2012.6230089

[36] Priebe, Sebastian, Marius Kannicht, Martin Jacob, and Thomas Kürner. "Ultra broadband indoor channel measurements and calibrated ray tracing propagation modeling at THz frequencies." *Journal of Communications and Networks* 15, no. 6 (2013): 547-558. https://doi.org/10.1109/JCN.2013.000103

[37] Rao, T. Rama, Dhanavanthan Balachander, and Nishesh Tiwari. "Short-range near floor path gain measurements in indoor corridors at UHF for wireless sensor communications." In *2012 IEEE International Conference on Communication Systems (ICCS)*, pp. 189-193. IEEE, 2012.

[38] Rao, Thipparaju Rama, and Balachander Dhanavanthan. "RF propagation investigations at 915/2400 MHz in indoor corridor environments for wireless sensor communications." *Progress in Electromagnetics Research B* 47 (2013): 359-381. https://doi.org/10.2528/PIERB12102908

[39] Rappaport, Theodore S., Eshar Ben-Dor, James N. Murdock, and Yijun Qiao. "38 GHz and 60 GHz angle-dependent propagation for cellular & peer-to-peer wireless communications." In *2012 IEEE international conference on communications (ICC)*, pp. 4568-4573. IEEE, 2012. https://doi.org/10.1109/ICC.2012.6363891

[40] Roh, Wonil, Ji-Yun Seol, Jeongho Park, Byunghwan Lee, Jaekon Lee, Yungsoo Kim, Jaeweon Cho, Kyungwhoon Cheun, and Farshid Aryanfar. "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results." *IEEE communications magazine* 52, no. 2 (2014): 106-113. https://doi.org/10.1109/MCOM.2014.6736750

[41] Schmidt, Ingo, Jaouhar Jemai, Radoslaw Piesiewicz, Robert Geise, Martin Schwark, Thomas Kurner, Martin Schirrmacher, and Patrick Thielker. "UWB propagation channels within an aircraft and an office building environment." In *2008 IEEE Antennas and Propagation Society International Symposium*, pp. 1-4. IEEE, 2008. https://doi.org/10.1109/APS.2008.4619553

[42] Seidel, Eiko. "3GPP LTE-A Standardization in Release 12 and beyond." *Nomor Research GmbH, Munich, Germany, Tech. Rep* 1 (2013): 2013-01.

[43] Shuminoski, Tomislav, and Toni Janevski. "Radio network aggregation for 5G mobile terminals in heterogeneous wireless networks." In *2013 11th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services (TELSIKS)*, vol. 1, pp. 225-228. IEEE, 2013. https://doi.org/10.1109/TELSKS.2013.6704923

[44] Digiworld Summit. “Verticals and 5G Evolution,” (2016).

[45] Sun, Shu, George R. MacCartney, Mathew K. Samimi, Shuai Nie, and Theodore S. Rappaport. "Millimeter wave multi-beam antenna combining for 5G cellular link improvement in New York City." In *2014 IEEE International Conference on Communications (ICC)*, pp. 5468-5473. IEEE, 2014. https://doi.org/10.1109/ICC.2014.6884191

[46] Sun, Shu, George R. MacCartney, Mathew K. Samimi, and Theodore S. Rappaport. "Synthesizing omnidirectional antenna patterns, received power and path loss from directional antennas for 5G millimeter-wave communications." In *2015 IEEE Global Communications Conference (GLOBECOM)*, pp. 1-7. IEEE, 2015. https://doi.org/10.1109/GLOCOM.2015.7417335

[47] Tarng, Jenn-Hwan, W. R. Chang, and B. J. Hsu. "Three-dimensional modeling of 900-MHz and 2.44-GHz radio propagation in corridors." *IEEE Transactions on Vehicular Technology* 46, no. 2 (1997): 519-527. https://doi.org/10.1109/25.580790

[48] Yoon, Youngkeun, and Hyoung Jin Park. "Excess loss by urban building shadowing and empirical slant path model." *IEEE Antennas and Wireless Propagation Letters* 21, no. 2 (2021): 237-241. https://doi.org/10.1109/LAWP.2021.3124233

[49] Zhang, Bei, Zhangdui Zhong, Xin Zhou, Ke Guan, and Ruisi He. "Path loss characteristics of indoor radio channels at 15 GHz." In *2016 10th European Conference on Antennas and Propagation (EuCAP)*, pp. 1-5. IEEE, 2016. https://doi.org/10.1109/EuCAP.2016.7481177

[50] Zhang, Yue Ping, and H. J. Hong. "Ray-optical modeling of simulcast radio propagation channels in tunnels." *IEEE transactions on vehicular technology* 53, no. 6 (2004): 1800-1808. https://doi.org/10.1109/TVT.2004.836920

[51] Zhao, Hang, Rimma Mayzus, Shu Sun, Mathew Samimi, Jocelyn K. Schulz, Yaniv Azar, Kevin Wang, George N. Wong, Felix Gutierrez, and Theodore S. Rappaport. "28 GHz millimeter wave cellular communication measurements for reflection and penetration loss in and around buildings in New York city." In *2013 IEEE international conference on communications (ICC)*, pp. 5163-5167. IEEE, 2013. https://doi.org/10.1109/ICC.2013.6655403

[52] Zhong, Zhimeng, Chao Li, Jianyao Zhao, and Xiaomei Zhang. "Height-dependent path loss model and large-scale characteristics analysis of 28 GHz and 38.6 GHz in urban micro scenarios." In *2017 11th European Conference on Antennas and Propagation (EUCAP)*, pp. 1818-1822. IEEE, 2017. https://doi.org/10.23919/EuCAP.2017.7928640

[53] Zulkefly, Nor Raihan, Tharek Abdul Rahman, Marwan Hadri Azmi, and Omar Abd Aziz. "6.5 GHz and 10.2 GHz path loss measurements and modeling for 5G communications system prediction." *International Journal of Research in Engineering and Technology* (2017). https://doi.org/10.15623/ijret.2017.0611002