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Study and Analysis Indoor Path Loss Models for Low-Terahertz mmWaves

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ABSTRACT

Due to growing demand for data by subscribers of cellular networks and expected increases to dozens of times by the year 2030. Many research organizations in the field of cellular networks has motivated to search for a new frequency spectrum to confront this challenge in data and to reduce the time access. D-band is the low terahertz spectrum (110-170 GHz) which has very short wavelengths from 1.7 mm to 2.3 mm, and not been used in cellular communications and is expected to be proposed by the International Telecommunication Union (ITU) for next generation. In this paper, path loss models were studied and analyzed to the indoor environment (offices and shopping malls) at three points of frequencies within the D-band including the start band, the middle band, and the end of the band (110, 150, and 170) GHz. The study included a number of path loss models for both LOS and NLOS scenarios, including free space, 3GPP, 5GCM, mmMAGIC, METIS, and IEEE.

1. INTRODUCTION

After the growing demand for more data through the Internet, day after day, especially with the advent of the Internet of Things era, which stimulated research organizations to think hard about the next generation of wireless communications to connect millions of people and billions of devices and a range of application systems, such as autonomous vehicles and virtual reality [1-3]. According to the forecasts of the International Telecommunication Union (ITU), by 2030 global data capacity is expected to reach five zettabytes [1]. Short-range communications in the sub-terahertz frequency spectrum are potential candidates for achieving wireless communications that meet future requirements for high data rates. Bandwidths between 90 and 200 GHz have been identified as available for terrestrial radio communications. But before this is possible, there are many challenges that must be addressed. The most prominent of these challenges are propagation losses in free space with the square of the frequency [4-6].

The 95 GHz to 3 terahertz wide spectrum granted by the FCC has been a research hotspot in recent years [7]. There are a number of experiments and increasing interest in the D band operating at frequency 110-170 GHz as a potential spectrum resource because of its advantages such as higher capacities, higher antenna gains and narrower transmission beam. Also, under standard environment, the atmospheric attenuation in the D band does not exceed 2 dB/km [8]. To overcome the high losses experienced at higher frequencies such as high reflection and propagation losses and high free space, which means future wireless networks may rely on line-of-sight (LOS) transmission and highly directional high-gain steerable antennas [9].

To facilitate infrastructure design for 6G and beyond, and since indoor environments including office environments and shopping malls are crowded places for scattered objects to scatter radio channels, characterization of THz channels for indoor scenarios propagation attenuation [10], so the characteristics of propagation channels, especially those associated with path loss, must be modeled and studied carefully. Several universities, such as New York University, have been working on measurements within the D band. In 2021, researchers at NYU Wireless examined the propagation of waves at 140 GHz and measured the reflection and scattering properties [11]. Aalto University in 2018 reported on a GHz directional channel for a large indoor shopping center environment at 140 GHz that the spatiotemporal characteristics are remarkably consistent for the robust path between the 28 and 140 GHz channels and that the channel parameters are comparable at both frequencies [12].

University of Southern California (USC), conducted a LOS measurement experiment in the frequency range of 140 to 220 GHz for the CI model using the measurement data and estimated the path loss exponent and the standard deviation of the shading factor in the range of only 100 m [13]. Shanghai Jiao Tong University (SJTU) developed a measurement system at 140 GHz. They conducted channel measurements in a typical indoor meeting room with a directional solution with Tx/Rx distances of 1.8 to 7.3 m and in an office room with Tx/Rx distances of 3.75 to 20 m [14]. This paper introduces the study of short-distance internal channels in the D band, and the analysis of the applicability of 3GPP TR 38.901, 5G (5GCM), 5G (mmMAGIC), (METIS) (IEEE) models in the D band, and all comparisons and results were achieved using MATLAB(M-file). The objects of the paper are organized as follows: The second section presents the probability of LOS propagation condition. The third section presents a review of path loss models for the indoor environment. In Section four, path loss and channel models for indoor scenarios are compared considering actual measurements and Section five presents the main conclusions of the paper.

2. METHOD

One of the main thinks upon which cellular communications networks in the fifth generation and subsequent generations were founded is the deployment of small networks of different sizes and in a dense manner, cost-effective and efficient for subscribers' demand to the data; but it is suffered from blocking and barriers those are located between the base stations and the subscribers.

Most studies have been concerned with path loss for dense networks for both line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. LOS transmission is known for short distances between transmitter and receiver. In office environments and central shopping mall, transmission beyond line-of-sight is common [14].

2.1 LOS probability propagation

In this section, the definition of sub-LOS is discussed along with other LOS propagation. The state of LOS is determined by looking at the positions of the transmitter (AP) and the receiver (UE) and whether any natural or artificial barriers separate the AP and the UE, for example, buildings or walls that block the path between the AP and the UE, or the human body, chairs and desks [15]. Office furniture causes shading in the very high frequency spectrum. We observe LOS models that are independent of frequency, and depend only on the separation distance between the transmitter and the receiver only. In this paper, the most important LOS probability models, which are included Table 1, have been studied and compared [16].

Table 1. Summary of LOS probability models [17-19]

Model	LOS Probability as a Function of *d* [m]
ITU model	$P_{los} = \begin{cases} 1, & d \leq 18 \\ \exp\left(-\frac{d-18}{27}\right) & 18 < d < 37 \\ 0.5, & d \geq 37 \end{cases}$
WINNER II model (B3)	$P_{los} = \begin{cases} 1, & d \leq 10 \\ \exp\left(-\frac{d-10}{45}\right) & d > 10 \end{cases}$
WINNER II model (A1)	$P_{los} = \begin{cases} 1, & d \leq 2.5 \\ 1 - 0.9(1-(1.24-0.61log_{10}(d))^3)^{\frac{1}{3}} & d > 2.5 \end{cases}$
3GPP model	$P_{los} = \begin{cases} 1, & d \leq 1.2 \\ \exp\left(-\frac{d-18}{27}\right) & 1.2 < d < 6.5 \\ 0.5, & d \geq 6.5 \end{cases}$
NYUSIM model	$P_{los} = \begin{cases} 1, & d \leq 5 \\ \exp\left(-\frac{d-5}{70.8}\right) & 5 < d \leq 49 \end{cases}$

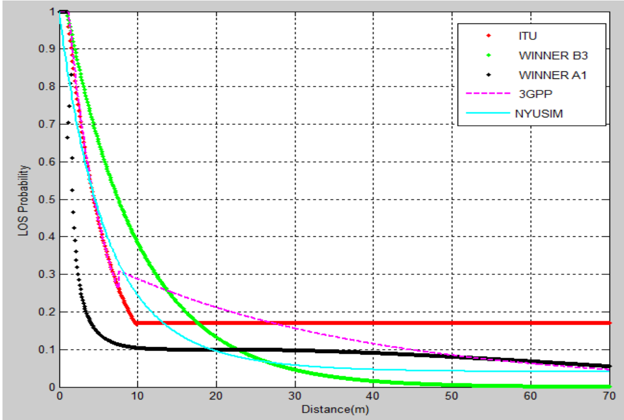


Figure 1. Indoor office LOS probability

A summary of LOS probability models in Table 1 is compared in Figure 1. The comparison between the models clear differences appear in performance, ITU model has a better performance compared to the other of the models proposed in Table 1, where we notice that the probability of LOS is constant for the distance after 10 meters at a probability of 0.18. For the 3gpp model, we notice that the probability of LOS is almost identical to the ITU model until a distance of approximately 8 meters, after that it begins to decrease in inversely appropriate with respect to distance. WINNER A1 remain to constant at a probability 0.1approximately up to a distance of 40m between the Tx and the Rx, after that the performance begins to decline gradually. WINNER B3 has better performance compared to the models up to a distance of 14 meters, then it drops sharply by increasing the distance until it becomes the worst model after a distance of 30m.

2.2 Indoor path loss models

To understand the propagation models of radio signals at D band, many research organizations have conducted studies on understanding the behavior of the most popular indoor environment path loss models for frequencies above 6 GHz (millimeter waves). The increasing demand for download data and modern applications that current networks cannot within frequencies below 100 GHz requires searching for new frequency bands licensed to work in cellular networks. Most research organizations suggest that frequencies greater than 100 GHz and below 300 GHz are the most promising frequencies. To design radio systems and compare them accurately in order to provide stable and accurate predictions, in this section, five channel models presented by five organizations were studied, namely IEEE, 5GCM, 3GPP, METIS, and mmMAGIC for the indoor office environment, and for the shopping center environment, which is 5GCM, METIS, where a comparison was made with the outer space model.

2.2.1 IEEE 802.11ad

Describes IEEE 802.11ad channel models for high millimeter frequencies above 60 GHz according to standard experimental results in indoor environments which we will try to test it in D band. In both LOS and NLOS scenarios, experimental measurements show that the InH scenario consists of a constrained environment and a model Path loss is similar to the CI model. In the case of LOS, the shading term is not provided because the path loss in different antenna configurations matches very closely to each other. For NLOS conditions, the obtained channel model presents a σSF equal to 1 dB. d_{2D} is used in both cases [20, 21].

IEEE 802.11ad model for InH Office case/ LOS:

$$P_L = 32.5 + 20\ log_{10}(f_c) + 20\ log_{10}(d_{2D}) \quad (1)$$

InH Office/ NLOS case:

$$P_L = 44.2 + 20\ log_{10}(f_c) 18\ log_{10}(d_{2D}) \quad (2)$$

where, f_c is the carrier freq., d_{2D} is 2D distance between BS and UE. Figure 2 explains 2D and 3D distances.

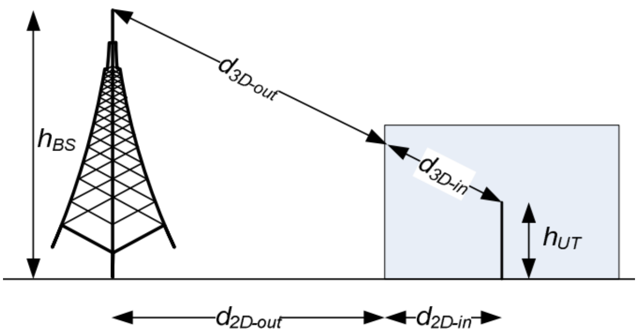


Figure 2. Definition of $d_{2D\text{-}out}$, $d_{2D\text{-}in}$ and $d_{3D\text{-}out}$, $d_{3D\text{-}in}$ for indoor UTs [22]

2.2.2 3GPP TR 38.901

For the 3GPP TR 38.901 channel models, standard experiments have proven that they are applicable to the frequency range after 6GHz in general and have many important scenarios. For indoor office scenarios, model 3GPP TR 38.901 is valid for spaces up to 150 meters in the form of open spaces, walled offices and corridors. However, base stations (BS) are installed either on ceilings or walls at a height of 2-3 metres. A 3-D Tx-Rx d3D separation distance representing base station (hBS) height and user equipment (UE) height for both LOS and NLOS conditions is used for these path loss models [22].

3GPP TR 38.901 model for InH Office/ LOS:

$$P_L = 32.4 + 20\ log_{10}(f_c) + 17.3\ log_{10}(d_{3D}) \quad (3)$$

InH Office/ NLOS case:

$$P_L = 32.4 + 20\ log_{10}(f_c) + 31.9\ log_{10}(d_{2D}) \quad (4)$$

where, $D_{3d} = \sqrt{{d_{2d}}^2 + (h_{bs} - h_{ue})^2}$, which is shown in Figure 2.

h_{bs}=base station high(10m).
h_{ue}=user high. (5)

2.2.3 5GCM

An extension of existing 3GPP models is 5GCM which supports frequency bands up to 200 GHz [23]. In this research, different scenarios were studied, such as offices and open and closed corridors inside shopping centers. Access points in an office environment, which often consists of walled cubicles and offices, are installed either on ceilings or walls at a height of between 2 and 3 metres. As for shopping malls, which generally consist of two to five floors and include an open area, access points are installed on the walls or ceilings of corridors and shops at a height of about 3 meters. LOS and NLOS 5GCM model for both InH Office and InH Shopping-Mall as in the equations below [23]:

For both InH (Office and Shopping-Mall) / LOS:

$$P_L = 32.4 + 20\ log_{10}(f_c) + 17.3\ log_{10}(d_{3D}) \quad (6)$$

InH Office/NLOS:

1. 5GCM Single Slope

a) CIF model:

$$p_l = 32.4 + 31.9\left(1 + 0.06\left(\frac{f_c - 24.2}{24.2}\right)\right) log_{10}(d_{3D}) + 20 log_{10}(f_c) \quad (7)$$

b) ABG model:

$$p_l = 38.3 log_{10}(d_{3D}) + 17.30 + 24.9 log_{10}(f_c) \quad (8)$$

2. 5GCM Dual Slope

a) CIF model:

$$P_L = \begin{cases} LFS\ +\ 25.1(1 + 0.12\left(\frac{f_c - 24.1}{24.1}\right) log_{10}(d) \\ \text{for } 1\ <\ d\ \leq\ 7.8\text{ m} \\ LFS\ +\ 25.1(1 + 0.12\left(\frac{f_c - 24.1}{24.1}\right) log_{10}(7.8) + \\ 25.1(1 + 0.04\left(\frac{f_c - 24.1}{24.1}\right) log_{10}\left(\frac{d}{7.8}\right) \\ \text{for d } >\ 7.8\text{ m} \end{cases} \quad (9)$$

b) ABG model:

$$P_L = \begin{cases} 17\ log_{10}\ (\text{d}) +\ 33\ +\ 24.9\ \text{log10 (fc)}, \\ \text{for } 1\ <\ \text{d}\ \leq\ 6.9\text{ m} \\ 17\ log_{10}\ (6.9) +\ 33\ +\ 24.9\ \text{log10 (fc)} + \\ 41.7\ log_{10}\left(\frac{d}{6.9}\right), \\ \text{for d } >\ 6.9\text{ m} \end{cases} \quad (10)$$

InH Shopping-Mall / NLOS:

1. 5GCM Single Slope InH Shopping Mall

a) CIF model:

$$P_L = 32.4 + 25.9\left(1 + 0.01\left(\frac{f_c - 39.5}{39.5}\right)\right) log_{10}(d_{3D}) + 20 log_{10}(f_c) \quad (11)$$

b) ABG model:

$$p_l = 32.1 log_{10}(d_{3D}) + 18.09 + 22.4 log_{10}(f_c) \quad (12)$$

2. 5GCM Dual Slope InH Shopping Mall

a) CIF model:

$$P_L = \begin{cases} LFS + 24.3(1 - 0.01\left(\frac{f_c - 39.5}{39.5}\right) log_{10}(d), \\ for\ 1\ < d \leq 110\ m \\ LFS + 24.3(1 + 0.01\left(\frac{f_c - 39.5}{39.5}\right) log_{10}(110) \\ +83.6(1 + 0.39\left(\frac{f_c - 39.5}{39.5}\right) log_{10}\left(\frac{d}{110}\right), \\ for\ d\ >\ 110\ m \end{cases} \quad (13)$$

b) ABG model:

$$P_L = \begin{cases} 29\ log_{10}\,(d) +\ 22.17 + 24.9\ log10\ (fc\ ), \\ for\ 1\ <\ d\ \leq\ 147\ m \\ 29\ log_{10}\,(147) +\ 22.17\ + \\ 22.4\ log10\ (fc\ )14.7\ log_{10}\left(\frac{d}{147}\right) \\ for\ d\ >\ 147\ m \end{cases} \quad (14)$$

2.2.4 mmMAGIC

In millimeter wave frequency band (6-100) GHz, the mmMAGIC project has been at the forefront of research and development. A wide range of technologies in the mm wave field are covered and implemented in mmMAGIC, starting with spectrum suitability and identifying use cases [24]. mmMAGIC channel model is to develop advanced channel models for the frequency range may exceed 100GHz [24]. For the InH scenarios, different measurements of channels at multiple frequencies were performed. In this research, the channels will be tested for a range of frequencies exceeding 100GHz. BS is installed at 1-5m height for all InH scenarios which includes closed and open air office buildings and offices. For indoor airport scenarios, duct models have been developed where the BS has to be installed close to the ceiling at a height of 4-9 metres. Most scenarios of the mmMAGIC channel model are defined as follows [25]:

mmMAGIC InH Office/ LOS:

$$P_L = 33.6 + 20.3\ log_{10}(f_c) + 13.8\ log_{10}(d_{3D}) \quad (15)$$

mmMAGIC InH Office/ NLOS:

$$P_L = 15.2 + 26.8\ log_{10}(f_c) + 36.9\ log_{10}(d_{3D}) \quad (16)$$

2.2.5 METIS

At a time when the volume of required data is increasing, which may reach in the near few years to 1000 times what it is currently in each region, and the number of connected devices from 10 to 100 times, it was necessary to work on developing realistic and high-quality radio propagation models, and one of these models is the METIS model. In this paper, the METIS channel model was verified, where the propagation measurements and simulations of frequencies within the D-band of the internal environment were analyzed for both LOS and NLOS cases, as follows [26]:

METIS InH Shopping Mall/ LOS:

$$P_L = 68.8 + 18.4\ log_{10}(d_{2D}) \quad (17)$$

METIS InH Shopping Mall/ NLOS:

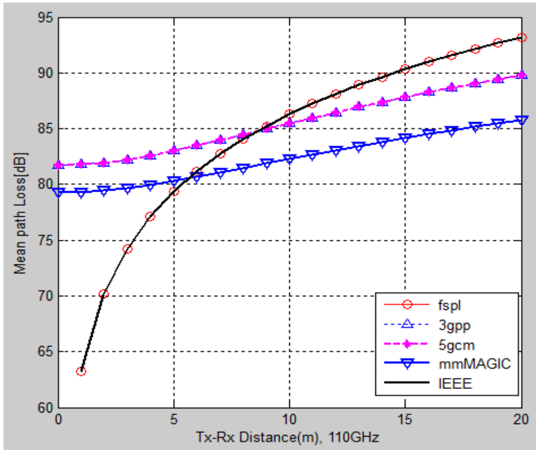
$$P_L = 94.3 + 3.59\ log_{10}(d_{2D}) \quad (18)$$

3. RESULTS AND DISCUSSION

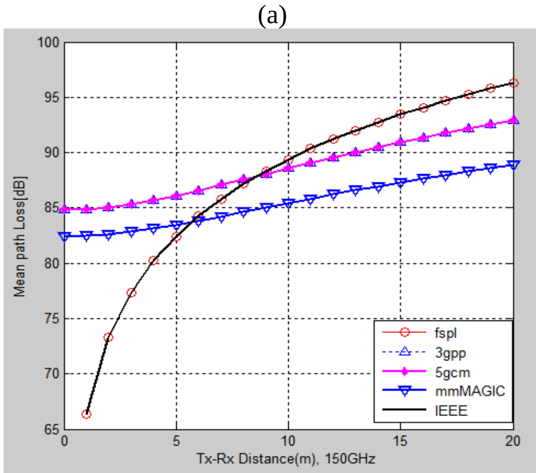
3.1 LOS/InH Office Scenario

The mean path loss versus distance (Tx-Rx) are compared in Figure 3. Three D-band frequencies were selected to compare the performance of FSPL, 3GPP, 5GCM, mmMAGIC, and IEEE 802.11ad channel models in the LOS scenario (110,150 and 170) GHz respectively.

In Figure 3(a), at the carrier frequency of 110GHz, we notice the path loss rate for both free space models, IEEE matches in performance along the distance between Tx-Rx, starting from the distance of 1 meter, and with a path loss starting from 63 dB and then gradually increasing until it reaches approximately 94 dB at 20 meters distance. For the 3gpp, 5gcm, and mmMAGIC models, the path loss rate for them starts between 80-82 dB, with a relative advantage over mmMAGIC with a difference ranging from (2-4) dB. Figure 3(b) shows the performance of the proposed models at a frequency of 150 GHz. We note the performance of all models that perform the same behavior within Figure 3, but with an increase in the path loss rate of 2 dB over the distance between Tx-Rx, and this is what we notice in the performance of the path loss models for the proposed models in Figure 3(c), with an increase in the same amount of path loss as Figure 3(b).



(a)



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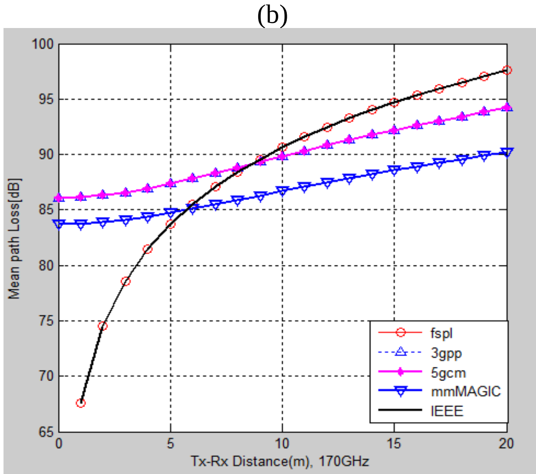
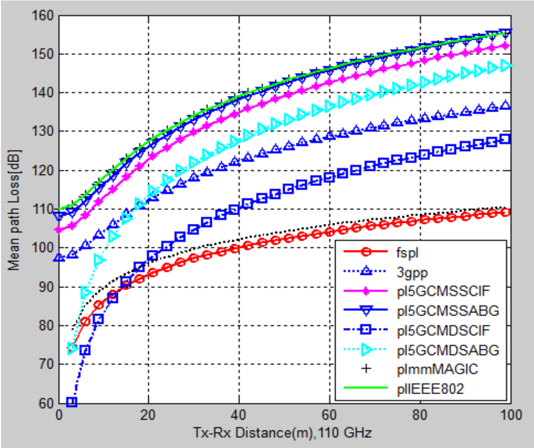
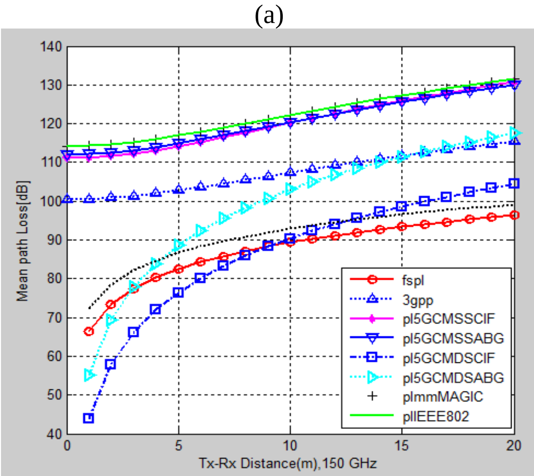


(c)

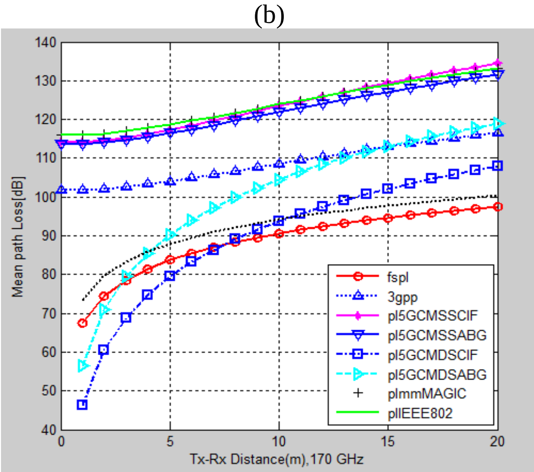
Figure 3. Path loss versus Tx-Rx distance comparison for LOS InH office scenario at (a) 110GHz, (b) 150GHz and (c) 170GHz



(a)

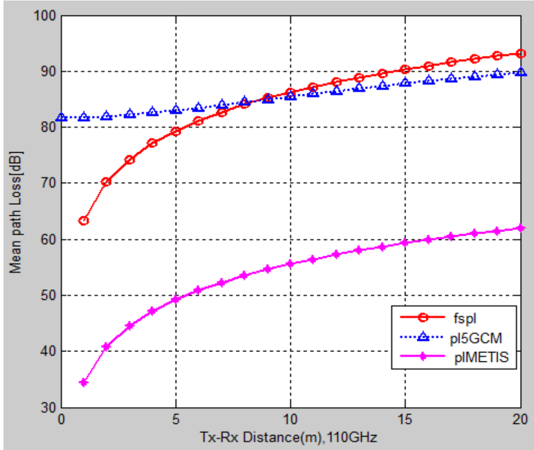


(b)

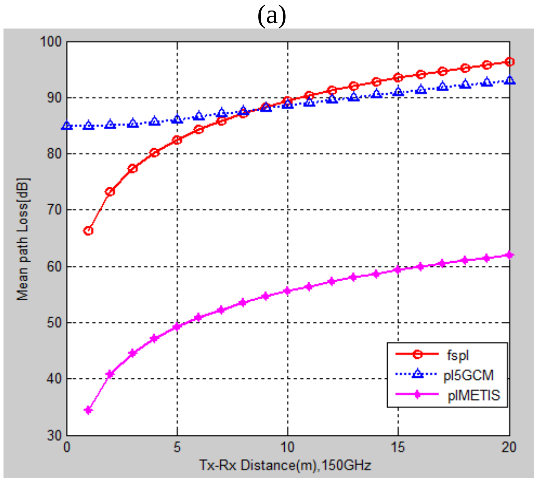


(c)

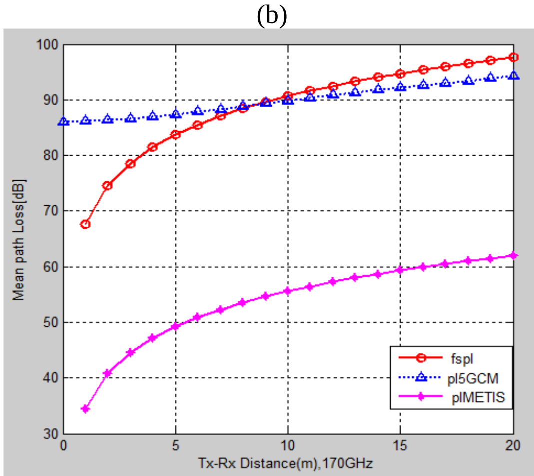
Figure 4. Path loss versus Tx-Rx distance comparison for NLOS InH office scenario at (a) 110GHz; (b) 150GHz and (c) 170GHz



(a)



(b)



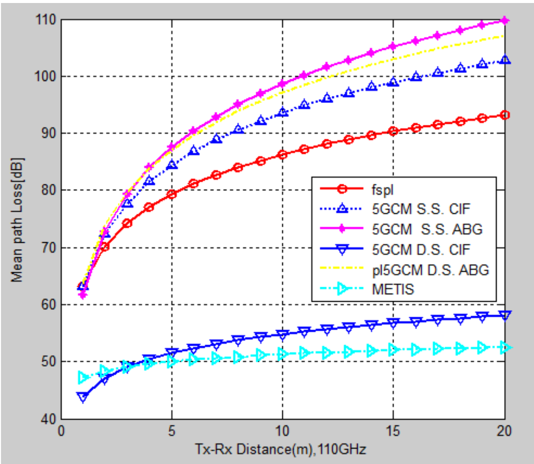
(c)

Figure 5. Path loss versus Tx-Rx distance comparison for LOS InH shopping mall scenario at (a) 110GHz; (b) 150GHz and (c) 170GHz

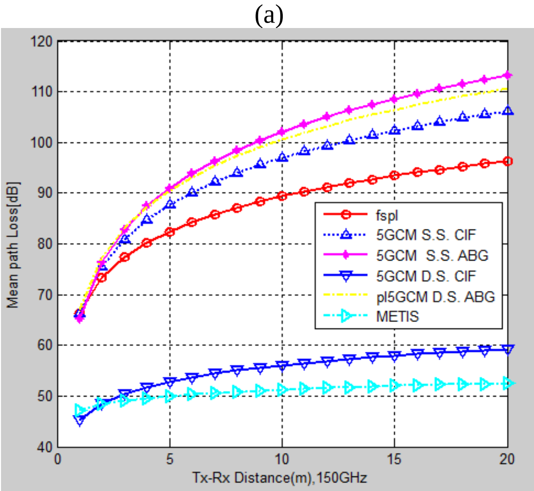
3.2 NLOS/InH Office scenario

In Figure 4, the mean path loss is pointed versus the distance between Tx and Rx. Also, at (110, 150 and 170) GHz are D-band frequencies were selected to compare the performance of channel models in the NLOS scenario.

In Figure 4(a), the path loss models were compared at the carrier frequency of 110 GHz, where we notice the path loss rate for the 5GCMDSCIF model starts from 60dB, while the rest of the models have a path loss rate ranging from 72-110 dB. At a distance of 20 meters, the performance of fs becomes the best, followed by mmMAGIC and 5GCMDSCIF, while the worst model is IEEE802 and 3gpp. In Figure 4(b), the internal path loss models were compared at a frequency of 150 GHz, where we notice the performance of the 5GCMDSCIF model, the best performance compared to the rest of the models, as it starts from approximately 43 dB at a distance of 1 meter up to 90 dB at a distance of 10 meters. After 10 meters, the fs model becomes the best. The worst performance is for the models IEEE802, 5GCMSSABG, 5GCMSSCIF, where the path loss starts from 110 dB to 130 dB at a distance of 20 meters. In Figure 4(c), the path loss models were compared at the frequency of 170 GHz. In this figure, we notice that the performance of 5GCMDSCIF is the best up to a distance of approximately 7 meters, as its path loss rate starts from approximately 46 dB at a distance of approximately 1 meter. After a distance of 7 meters, the fs model becomes the best, while the rest of the models have a path loss rate ranging from 56-115 dB at a distance of 1 meter to a path loss rate of 110-135 dB at a distance of 20 meters between the transmitter and the receiver.



(a)



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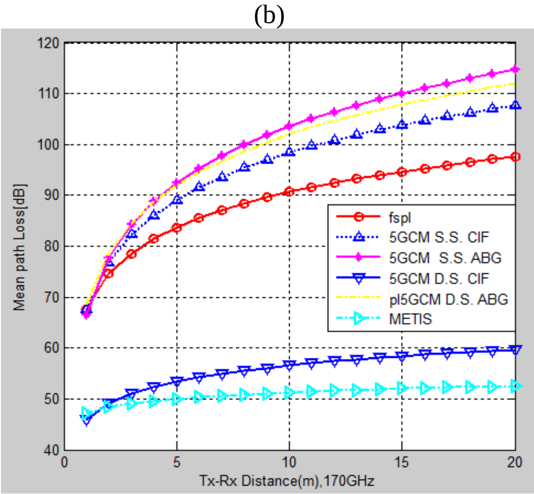

(c)

Figure 6. Path loss versus Tx-Rx distance comparison for NLOS InH shopping mall scenario at (a) 110GHz; (b) 150GHz and (c) 170GHz

3.3 LOS/Shopping-Mall scenario

In Figure 5, the average path loss is compared against the distance between the transmitter and the receiver for a shopping mall environment. At frequencies 110, 150 and 170 the three path loss models 5GCM, METIS and fs were studied for LOS scenario.

In Figure 5(a), we note that the METIS model has a better performance than the 5GCM model. Its average path loss starts from approximately 34 dB at a distance of 1 meter, while the 5GCM model's average path loss starts from 81 dB, which is higher than that of the outer space model. In Figures 5(b) and (c), we notice that the METIS model is not affected by the frequency change and remains constant, while the 5GCM model and the fs model give the same performance, but with a slight change in the path loss rate compared to Figure 5(a).

3.4 NLOS/Shopping-Mall scenario

In Figure 6, the average path loss is compared to the distance between the transmitter and the receiver in a shopping mall environment at three frequencies 110, 150 and 170 within the D band. Five path loss models are studied fs, 5GCM S.S. CIF, 5GCM S.S. ABG, 5GCM D.S. CIF ,5GCM D.S. ABG, METIS for the NLOS case.

Table 2. A summary of the comparison between the path loss models for LOS case

Location	Link Distance (m)	Carrier Freq. (GHz)	Path Loss Models	Mean Path Loss (dB)
InH Office	1m	110	fs	64
		150	fs	66
		170	fs	68
	5m	100	fs	79
		150	fs	82.5
		170	fs	84
	10m	110	mmMAGIC	82.5
		150	mmMAGIC	85
		170	mmMAGIC	87
InH Shopping Malls	1m	110	METIS	34
		150	METIS	34
		170	METIS	34
	5m	110	METIS	50
		150	METIS	50
		170	METIS	50
	10m	110	METIS	56
		150	METIS	56
		170	METIS	56

In Figure 6(a), we note that the 5GCM D.S. CIF starts with a path loss rate of 43 dB, which is the best performance from the METIS model up to a distance of approximately 3 meters, and then the METIS model becomes better after 3 meters distance between the sender and the receiver. As for the rest of the path loss models fs, 5GCM S.S. CIF, 5GCM S.S. ABG, 5GCM D.S. ABG we notice the path loss rate for it at approximately 1 meter, all of which start from 61 dB, so that fs has a better performance compared to the rest of the models along the distance between the sender and the receiver. In Figures 6(b) and (c), we notice 5GCM D.S. CIF remains the best performance of the METIS model up to a distance of approximately 3 meters, and then the METIS model becomes better after 3 meters distance between the sender and the receiver, and this makes them the best two models of path loss for the environment of shopping centers among the five models that were studied for the case of NLOS.

Table 3. A summary of the comparison between the path loss models for NLOS case

Location	Link Distance (m)	Carrier Freq. (GHz)	Path Loss Models	Mean Path Loss (dB)
InH Office	1m	110	5GCMDSCIF	60
		150	5GCMDSCIF	43
		170	5GCMDSCIF	46
	5m	110	5GCMDSCIF	72
		150	5GCMDSCIF	77
		170	5GCMDSCIF	80
	10m	110	5GCMDSCIF	81
		150	fs	90
		170	fs	90
Shopping malls	1m	110	5GCMDSCIF	43
		150	5GCMDSCIF	45
		170	5GCMDSCIF	46
	5m	110	METIS	50
		150	METIS	50
		170	METIS	50
	10m	110	METIS	51
		150	METIS	51
		170	METIS	51

A summary of the comparison between the path loss models for the free space environment and the indoor environment (office and shopping malls) at 150 GHz within D band at 5m distance between transmitter and receiver as an example for both LOS case in Table 2 and NLOS case in Table 3.

4. CONCLUSION

Despite the crowding of space with various signals carried at various frequencies, the bandwidth of cellular communication networks remains restricted by the license of the International Telecommunication Union (ITU) and the American Telecommunication Union; The demand for data downloading has increased at a rapid pace after the emergence of artificial intelligence systems and the Internet of Things, which made the cellular networks of the fifth generation by 2030 may be unable to provide the needs of subscribers, which prompted research institutions to study frequency bands within the high millimeter frequencies that reach parts of the terahertz. The D bandwidth is one of the proposed bands to be used for telecommunications in the near future. In this paper, a set of path loss models are studied for important organizations and standard bodies such as 3GPP, 5GCM, mmMAGIC, METIS, and IEEE for the indoor environment (office and shopping center) for both cases of LOS and NLOS, and to determine which models are suitable for each environment. The comparison between the models was made at three frequency points within the D range (110, 150, 170).

After conducting a comparison between the models, the results indicate that the mmMAGIC and METIS models are the most suitable for the LOS case of the office and shopping mall environments, respectively. While for NLOS case, 5GCMDSCIF and METIS model provided the best results for path loss rate for 5m distance between transmitter and receiver.

REFERENCES

[1] Kumar, S., Tiwar, P., Zymbler, M. (2019). Internet of things is a revolutionary approach for future technology enhancement: A review. Journal of Big Data, 6(111): 2019. http://doi.org/10.1186/s40537-019-0268-2

[2] Haleem, A., Javaid, M., Qadri, M.A., Suman, R. (2022). Understanding the role of digital technologies in education: A review. Sustainable Operations and Computers, 3: 275-285. http://doi.org/10.1016/j.susoc.2022.05.004

[3] Sestino, A., Prete, M.I., Piper, L., Guido, G. (2020). Internet of things and big data as enablers for business digitalization strategies. Technovation, 98: 102173. http://doi.org/10.1016/j.technovation.2020.102173

[4] Musey, J.A., Keener, E.B. (2018). The Spectrum Handbook 2018. Smmuit Ridge Group, LLC, New York, USA. https://summitridgegroup.com/wp-content/uploads/Spectrum-Handbook-2018.pdf.

[5] Rao, S.K. (2018). Socio-Economic Impact of 5G Technologies. Thesis, School of Business and Social Sciences Aarhus University, Herning, Denmark. https://btech.au.dk/fileadmin/AU_Herning/Pdf/Ph.d.-afhandlinger/PhD_dissertation_Sriganesh_Rao.pdf.

[6] Wu, Y.L., Huang, H.J., Wang, C.X. (2019). 5G Enabled Internet of Things. Taylor & Francis Group. https://doi.org/10.1201/9780429199820

[7] Alsharif, M.H., Albreem, M.A., Solyman, A.A.A., Kim, S. (2021). Toward 6G communication networks: Terahertz frequency challenges and open research issues. Computers, Materials & Continua, 66(3): 2831-2842. http://doi.org/10.32604/cmc.2021.013176

[8] Wang, X.Y., Li, W.P., Wang, M.X., Bian, C.Z., Wei, Y., Zhou, W. (2022). Research on penetration loss of D-band millimeter wave for typical materials. Sensors, 22(19): 7666. http://dx.doi.org/10.3390/s22197666

[9] Al-Saman, A., Mohamed, M., Cheffena, M., Moldsvor, A. (2021). Wideband channel characterization for 6G networks in industrial environments. Sensors, 21(6): 2015. https://doi.org/10.3390/s21062015

[10] Tripathi, S., Sabu, N.V., Gupta, A.K., Dhillon, H.S. (2021). Millimeter-wave and terahertz spectrum for 6G wireless. In 6G Mobile Wireless Networks, Cham: Springer International Publishing, pp. 83-121. http://doi.org/10.1007/978-3-030-72777-2_6

[11] Saleem, A., Zhang, X., Xu, Y., Albalawi, U.A., Younes, O.S. (2023). A critical review on channel modeling: Implementations, challenges and applications. Electronics, 12(9): 2014. https://doi.org/10.3390/electronics12092014

[12] Gustafson, C. (2014). 60 GHz wireless propagation channels: Characterization, modeling and evaluation. Lund University. https://lucris.lub.lu.se/ws/portalfiles/portal/5361183/4810453.pdf.

[13] Abbasi, N.A., Hariharan, A., Nair, A.M., Molisch, A.F. (2020). Channel measurements and path loss modeling for indoor THz communication. In 2020 14th European conference on antennas and propagation (EUCAP), Copenhagen, Denmark. https://doi.org/10.23919/EuCAP48036.2020.9135643

[14] Han, C., Wang, Y., Li, Y., Chen, Y., Abbasi, N.A., Kürner, T., Molisch, A.F. (2022). Terahertz wireless channels: A holistic survey on measurement, modeling, and analysis. IEEE Communications Surveys & Tutorials, 24(3): 1670-1707. https://doi.org/10.1109/COMST.2022.3182539

[15] Aboagye, S., Ndjiongue, A.R., Ngatched, T.M., Dobre, O.A., Poor, H.V. (2022). RIS-assisted visible light communication systems: A tutorial. IEEE Communications Surveys & Tutorials, 25(1): 251-288. http://doi.org/10.1109/COMST.2022.3225859

[16] Imam-Fulani, Y.O., Faruk, N., Sowande, O.A., Abdulkarim, A., Alozie, E., Usman, A.D., Taura, L.S. (2023). 5G frequency standardization, technologies, channel models, and network deployment: Advances, challenges, and future directions. Sustainability, 15(6): 5173. https://doi.org/10.3390/su15065173

[17] Li, J. (2016). LOS probability modeling for 5G indoor scenario. In 2016 International Symposium on Antennas and Propagation (ISAP), pp. 204-205. https://www.ieice.org/cs/isap/ISAP_Archives/2016/pdf/2D1-3.pdf.

[18] Aleksiejunas, R. (2020). Statistical approximations of LOS/NLOS probability in urban environment. arXiv:2001.11813. https://doi.org/10.48550/arXiv.2001.11813

[19] Aydın, V., Çavdar, İ.H., Hasırcı, Z. (2016). Line of sight (LOS) probability prediction for satellite and haps communication in Trabzon, turkey. International Journal of Applied Mathematics Electronics and Computers, (Special Issue-1), pp. 155-160. http://doi.org/10.18100/ijamec.269190

[20] Carneiro de Souza, L., de Souza Lopes, C.H., de Cassia Carlleti dos Santos, R., Cerqueira Sodré Junior, A., Mendes, L.L. (2022). A study on propagation models for 60 GHz signals in indoor environments. Frontiers in Communications and Networks, 2: 757842. https://doi.org/10.3389/frcmn.2021.757842

[21] Perahia, E., Cordeiro, C., Park, M., Yang, L.L. (2010). IEEE 802.11 ad: Defining the next generation multi-Gbps Wi-Fi. In 2010 7th IEEE Consumer Communications and Networking Conference, pp. 1-5. IEEE. https://doi.org/10.1109/CCNC.2010.5421713

[22] Study on channel model for frequencies from 0.5 to 100 GHz. (3GPP TR 38.901 version 14.3.0 Release 14). In 3rd Generation Partnership Project (3GPP). https://www.etsi.org/deliver/etsi_tr/138900_138999/138901/16.01.00_60/tr_138901v160100p.pdf.

[23] Haneda, K., Nguyen, S.L., Karttunen, A., Järveläinen, J. (2017). Measurement Results and Final mmMAGIC Channel Models. Edited by Gunter Blamberger and Dietrich Boshujng, 20: 2015. https://www.researchgate.net/publication/320403581.

[24] Pimienta-del-Valle, D., Mendo, L., Riera, J.M., Garcia-del-Pino, P. (2020). Indoor LOS propagation measurements and modeling at 26, 32, and 39 GHz millimeter-wave frequency bands. Electronics, 9(11): 1867. https://doi.org/10.3390/electronics9111867

[25] Sudhamani, C., Roslee, M., Chuan, L.L., Waseem, A., Osman, A.F., Jusoh, M.H. (2023). Performance analysis of a millimeter wave communication system in urban micro, urban macro, and rural macro environments. Energies, 16(14): 5358. https://doi.org/10.3390/en16145358

[26] Raschkowski, L., Kyösti, P. (2020). Mobile and wireless communications Enablers for the Twenty-twenty (2020) Information Society-II. https://doi.org/10.3030/671680