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Review Article

A Brief Review of Path Loss Models for mmWave Channels

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Abstract

It is planned to use millimeter wave (mm-wave) communication in 5th Generation (5G) communication systems, as it allows high bandwidth and accordingly high speed data communication. Path loss is one of the most important factors affecting system performance in mm-wave communication. Therefore, path loss must be taken into account in order to create an efficient and reliable mm-wave communication system and to obtain high data rates. It is very important for 5G systems to accurately determine the propagation characteristics and path loss models of the mm-wave communication channel. Many methods have been proposed in the literature to predict path loss with high accuracy and precision in 5G systems. In this review, it is aimed to provide researchers a clear knowledge about path loss in 5G mm-wave communication systems. Papers published between 2018-2021 which based on machine learning, deep learning, neural networks and propagation measurement approach were presented, and the main results of researches related to main path loss models Close-in (CI), and Alpha, Beta, Gamma (ABG) or Floating Intercept (FI) and papers that discussed 3-D ray tracing method were summarized in clear and precise manner.

Keywords: mmWave, 5G, Path loss models, Propagation measurements.

mm-Dalga Kanallarındaki Yol Kaybı Modelleri Üzerine Kısa Bir Derleme

Öz

Yüksek bant genişliğine ve buna bağlı olarak yüksek hızlı veri iletişimine olanak tanıması nedeniyle milimetre dalga (mm-dalga) haberleşmesinin 5. Nesil (5G) haberleşme sistemlerinde kullanılması planlanmaktadır. Yol kaybı, mm-dalga haberleşmesinde sistem başarımını etkileyen en önemli faktörlerden biridir. Bu nedenle etkin ve güvenilir mm-dalga haberleşme sistemini oluşturmak, yüksek veri hızları elde etmek için yol kaybı dikkate alınmalıdır. mm-dalga haberleşme kanalının yayılım özelliklerinin ve yol kaybı modellerinin doğru bir biçimde belirlenmesi 5G sistemleri için oldukça önemlidir. 5G sistemlerininde, yol kaybını yüksek doğruluk ve hassasiyetle tahmin etmek için literatürde birçok yöntem önerilmiştir. Bu derleme çalışmasında araştırmacılara, 5G mm-dalga haberleşme sistemlerinde yol kaybı hakkında bilgi sağlamak hedeflenmiştir. 2018-2021 yılları arasında yapılmış, makine öğrenmesi, derin öğrenme, sinir ağları ve yayılım ölçümü yaklaşımına dayanan birçok çalışma sunulmuş, CI, ABG veya FI gibi temel yol kaybı modellerini, 5G'de üç boyutlu ışın izleme yöntemlerini inceleyen çalışmalar açık ve anlaşılır bir biçimde özetlenmiştir.

Anahtar Kelimeler: mm-dalga, 5. Nesil, Yol kaybı modelleri, Yayılım ölçümleri.

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1. Introduction

Wireless communication technology has changed the way we communicate and socialize in a remarkable way since its inception. It helped us to transmit data and information over a distance without any wires or cables. Also, the ability to communicate with people on move has developed arrestingly. Wireless communication has experienced different generations of technology starting from 0G to 5G (fifth generation). The target of 5G is to improve the scalability, connectivity, security, data rate and efficiency of the network [1, 2]. As the development of technology, the demands of the users are increasing. So, more bandwidth should be granted to satisfy the demand of users.

Millimeter wave (mmWave) frequencies (i.e., the frequency range of 3 GHz to 300 GHz) are expected to be used in 5G networks. The unused mmWave spectrum provides an excellent chance to excess mobile broadband capacity, thereby providing better quality of service to users. However, according to a number of studies, mmWave frequencies have implementation issues, particularly with regards to path loss due to multiple factors, such as obstacles in the environment, weather condition, and atmosphere. Therefore, to find the best position of 5G base stations, investigation of the path loss model at these 5G mmWave frequencies is of crucial importance [3, 4]. Surveys on mmWave [5, 6] have discussed propagation features, different channel models, parameters that affect system such as mediums, and operating frequency, and [7] for indoor environments have provided a general review of the radio propagation research at mmWave.

There are three basic models of path loss in 5G include Close-in Free Space with Reference Distance (CI), and Alpha, Beta, Gamma (ABG) or Floating Intercept (FI) [8, 9]. These models were built based on the traditional statistical approaches. However, data-dependent machine learning methods has also used for path loss predictions recently. In [10] path loss estimation was done through machine learning, and metrics used to compare the performances of random forest, artificial neural network, support vector regression forest models. [11] compares traditional channel models with a channel model obtained through deep learning techniques using satellite images supported by a simple path loss model for 2.6 GHz mobile communication systems.

In [12] a novel method for modeling mmWave path losses was presented (Convolutional Neural Network, CNN). A new CNN structruce was proposed and it’s superior performance over empirical models and deterministic models was shown [12]. Path loss predictions in urban areas were performed using the tabular data and images for machine learning models as two diverse types of inputs [13]. In [14] the path loss was predicted at different frequencies ranged 0.8 GHz to 70 GHz for urban and suburban environment, and in non-line of sight (NLOS) scenario. The proposed path loss model based on a deep neural network was shown to provide improved mean square error and higher prediction accuracy compared to the multi-frequency ABG path loss model.

A deep learning approach was applied in [15] for path loss modeling in urban environments for 5G systems, and proposes a combined method of the log-distance path loss model and a deep-learning-based model. Based on the simulation results the proposed path loss model outperforms the conventional models in the 3.5 GHz frequency band. In [16] a new path loss model has been proposed for 5G communication in suburban settings using deep learning with advanced convolution and attention. From the experimental results, it was shown that the proposed attention-augmenting convolutional neural network performed better in test scenarios than modern empirical and deterministic methods in terms of the root mean square error.

In this study, we focused on the studies on path loss models in different environments and frequencies. A brief information about path loss models for wireless communications is given, and comparisons of models are presented under various measurement scenarios (indoor, outdoor) and frequencies.

2. Material and Method

2.1. Methodology

To determine the studies included in this review, some inclusion criteria were defined and the articles published between 2018 and 2021 were concerned. Some basic and mostly cited papers were also included. Search process was shortened to three academic databases as shown in Table 1. The articles most relevant to the study, and highly cited were selected from among a large number of articles.

Table 1. Search Tools.

Academic database	**URL address**
Google Scholar	https://scholar.google.com/
IEEE Explore	https://ieeexplore.ieee.org/Xplore/home.jsp
Web of Science	https://apps.webofknowledge.com

2.1.1. Related Work

In [8] The properties of 5G radio communication systems were specified and propagation parameters, channel models, path losses in large areas and penetration losses in buildings were modeled by various standardization bodies and compared in the range 0.5 to 100 GHz. Additionaly, the various models suggestted by several independent groups based on extensive measurements and ray-tracing methods were compared. The details and applications of channel simulation software (NYUSIM) which helps generate realistic spatial and temporal channel responses was given in [17], channel spatial modeling for 5G mmWave was simulated for various mmWave bands (28, 38, 60, and 73 GHz and channel model parameters like received power, path loss exponent and path loss for the specified frequencies were estimated using NYUSIM [18]. A statistical channel modelling was also simulated in [19] for urban microcell simulated in LOS condition at 28 GHz operating frequency using NYUSIM, and best direction was determined according to parameters like path loss, path loss exponent and standard deviation.

In view of the high path loss [20] focus on studying mmWave frequencies, that allow mmWave to scale to high-density deployments and to consistently achieve high data rates. Also, in [21] the author discusses the fundamental characteristics of mmWave and two basic channel modeling methods to investigate the channel characteristics at mmWave bands. In [22] the author also focuses on how one can achieve less path loss through studying the impact of transmitter antenna height on the signal propagation.

In [23,24] the authors conducted the experiment at 26, 32, and 39 GHz frequency bands in line of sight (LOS) indoor conditions. The measurement was carried out for two antenna configurations obtaining a constant referred to the free space path loss (FSPL) condition for each band. Then a comparison between regression fitting and mmWave models were made. It inferred at 39GHz a higher path loss was acquired for the horn configuration, also path loss 3dB difference between frequencies. Another study proposes a new frequency attenuation (FA) path loss model. In this model, ultra-wideband measurements are made for various frequencies in the 10–40 GHz in an outdoor environment for LOS scenarios, also in this study the three basic path loss models and FA path loss model are compared for single-frequency and multi-frequency schemes [25]. In the paper presented in [26] CI and FI models in indoor LOS/NLOS condition were applied. Further, using the same measurement parameters the 2-ray model is inspected for 40 GHz band. Also, it inferred path loss exponent (PLE) for CI and FI models for both scenarios are identical at 40 GHz.

In [27], the authors presented a directional horn and omnidirectional antenna used at the transmitter and receiver, respectively. Also, according to the acquired measurement data, the path loss was examined at 19, 28 and 38 GHz. At these frequencies, the path loss exponent is low and in NLOS channel the propagation signal was strong with a low delay. In [28] the authors examine the band of 5, 31and 90 GHz under different channel condition and antenna CI and FI model were used to compare path loss simulation results (ray-tracing simulations) and measurement data. It deduced for LOS and NLOS conditions, CI model slopes show the difference between ray-tracing and measurements for slope is less than 0.3 and 0.6 respectively.

In another paper [29] the authors have made their study in the band of 38 GHz in both LOS/NLOS conditions. Measurements were performed using a directional horn antenna, then based on the comparison of CI and FI path loss models they suggest that CI model is more suitable in the outdoor semi-corridor environment then FI model. Another measurement method was used in [30] within the band of 18 GHz. By using a horn antenna radiation, the omnidirectional path loss synthesis has been confirmed, then in the measured data, the dual slope (DS) and CI path loss models were structured. Through these measurements they inferred that DS model is more suitable in the indoor corridors environment as compared to CI model.

The approach in [31] has relied on using a directional horn and omnidirectional antenna at the transmitter and receiver. Measurements were conducted, respectively for 3 scenarios, direct toward wall and toward window in the band of 28 and 38 GHz to study the basic path loss models. It concluded that the modified CI model is simpler than the models compared to the FI and ABG model. Also, for the PLE there is no big difference between the models. In [32] outdoor LOS/NLOS measurements were performed at five different mmWave frequencies and a new path loss model was proposed. They also suggest that a communication link can be build up in 20 and 30 GHz bands using the prosed model for certain TX-RX separation distance. Furthermore in [33] authors have conducted the study in the band of 26, 28, 36, and 38 GHz. The experiment has studied the path loss model FI and CI in both LOS/NLOS. The result show that CI provides better performance than FI model.

The band of 26, 28, 32 and 38 GHz in the scenario of indoor (emergency stairwell) were analyzed in [34] for single and multi-frequency; physical-anchor stair (PAS) and FI, ABG and close-in model with frequency-weighted path loss exponent (CIF) model were used, respectively. It concluded that in the emergency stairwell FI model is not that much beneficial compared to the proposed PAS model. Similarly, at single and multi-frequency, CI, FI, ABG and CIF path loss model are used in [35] to examine two different propagation mediums (stairwell), and the result provided can be helpful to understand the radio propagation in the studied environment. Also, in [36] measurements are performed in an indoor corridor and stairwell at 26 GHz and 38 GHz. An omnidirectional and directional horn antenna were used at the transmitter and receiver, respectively. Path loss exponents are analyzed with respect to LOS/NLOS scenarios, co-polarization and cross-polarization and frequencies. It is reported that the directional PLEs are greater than omnidirectional PLEs. Also, PLEs for NLOS are greater than LOS and PLEs for stairwell are larger than that for corridor.

In [37] the author, discussed the characterization of 28 GHz by using the computer simulation for the indoor office environment. Through analyzing the path loss model parameters, it shown that in the indoor environment many multipath waves were received in the LOS environment. Furthermore in [38] the author discussed the characteristics of 60 GHz based on the method of shooting and bouncing ray tracing/image method (SBR/IM) in LOS/ NLOS scenarios. According to the results, PLE in LOS environments vary between 1.56 and 1.78 while 3.87 in NLOS. In [39] CI, FI, and CIF path loss models were used to study the received signal in the condition of LOS indoor stairwell. It reported that the models used, fit the measured data well in the band of 3.5 and 28 GHz with the path loss exponent are found near to the FSPL. The band of 14 and 22 GHz were analyzed in [40] that the authors made a measurement for different heights of TX and RX antenna for two path loss model. It concluded that the proposed dual slope path loss model is more outclass in all measurement scenarios compared to CI. Also, the same band and scenarios were reported in [41] but using different path loss model that it inferred in all scenarios the ABG model show a good foretelling of path loss.

In [42] the basic frequency attenuation (FA) and CIF models were used to evaluate the path loss in bands of 19, 28 and 38 GHz. It concludes that the PLE for all the studied models are smaller than the ones for free space path loss exponent (FSPLE). A study of [43] applied the measurements at 38 GHz for two different antenna polarization scenarios, and FI and CI models were used to study the action of path loss at the studied frequency. Through the measurement CI showed a good result in both LOS and NLOS while FI give a good result just in the LOS. A new approach in [44] was applied to study path loss in the band of 26 GHz for two scenarios, and the authors deduce that path loss difference of LOS and obstructed LOS is about 5dB. In addition to the basic path loss models a new approach was reported in [45] to examine both of loss due to high frequency and edge shadow in the band of 3.5 and 28 GHz. The authors concluded that at the both bands in the studied scenarios, single and multi-frequency FI and ABG models show a good execution for path loss, and also PLE is less than FSPLE. In different antenna polarization, for directional and omnidirectional, CI, FI, ABG and a proposed path loss model were applied in [46] to examine the effect of path loss in the band of 4.5, 28 and 38 GHz. According to the results the proposed model had showed an average progress compared to the basic path loss models.

In [47] a new technique, the 3-D ray tracing method was applied to study the path loss of wave propagation. According to the measurement and simulation the new proposed method had shown more agreement with it compared to the other. In [48] the author presents an outdoor/ indoor environment at 60 GHz by using the method of Smart Cognitive 3D Ray Tracer. It was shown that as the separation between the transmitter and the receiver increase, the mmWave's propagation attenuation increase. Also, obstacles in the path of waves cause reflection and diffraction that can increase the path loss. In [49] the author presented a new path loss model as 3GPP and mmMAGIC. According to the experiment and measurement after calibration, the path loss mean absolute error for LOS and NLOS decreased. Also, the use of machine learning algorithms reduces the mean absolute errors of path loss in both LOS/ NLOS. Furthermore in [50] the author presents a performance analysis method of mmWave cellular network based on 3-D Poisson point process (PPP) model, and analyses the impact of path loss and other parameters. It shows that the performance of 3-D PPP model is very accurate in the urban environment.

In order to be able to easily examine and compare the articles given in this study, the important details of the studies are summarized and given in Table 2.

Table 2. Comparative evaluations of related works

Frequency	Indoor/Outdoor	LOS/NLOS	Methodologies	Model	Important Results	Ref.
26,39 GHz / 26,32 and 39GHz	Indoor	LOS	two antenna configurations, comparison between regression fitting and mmWave models	CI, FI path loss models and mm Wave model.	At 39GHz a higher PL was acquired for the horn configuration, also pathloss 3dB difference between frequencies	[23]-[24]
40 GHz / 5, 31 and 90 GHz	Indoor	Both	CI and FI models are used and the 2-ray model is inspected for 40GHz band / Comparison between CI, FI models and ray-tracing simulations under different channel condition and antenna.	CI, FI path loss model and two-ray model / CI and FI path loss model	PLE for CI and FI models for LOS, NLOS are identical / LOS, NLOS conditions, CI model slopes show the difference between ray-tracing and measurements	[26]-[28]
19, 28 and 38 GHz	Indoor to Outdoor	NLOS	A directional horn and omnidirectional antenna were used on transmitter and receiver, respectively. Also, according to the acquired measurement data, path loss was examined.	CI, ABG path loss model	The path loss exponent is low and in NLOS channel the propagation signal was strong with a low delay.	[27]
38 GHz	Outdoor (semi-corridor)	Both	A measurement of a directional horn antenna was performed, then	CI and FI path loss model	Compared to FI model, CI model is more appropriate for	[29]

			based on a comparison of these measurement between the CI and FI path loss models were extract the result.		the outdoor environment	
18 GHz	Indoor	LOS	By using a horn antenna radiation, the omnidirectional path loss synthesis has been confirmed, then in the measured data, the DS and CI path loss model were structured.	CI and DS path loss model	Compared to the CI model, the DS model is better suited to interior corridors	[30]
28 and 38 GHz	Indoor (dining room)	LOS	A directional horn and an omnidirectional antenna were used on the transmitter and receiver, respectively for 3 scenarios, and single and multi-band basic path loss models were studied.	The proposed and the CI, FI and ABG path loss model	The M-CI model compared to the FI and ABG model is simpler. There is no big difference for PLE between the models.	[31]
26,28,36 and 38 GHz	Outdoor	Both	A measurement for a different scenario for 20 and 30 GHz bands were taken to compare the proposed model with the basic path loss models.	Proposed model and CI, FI and ABG path loss model	A communication link can be established using prosed model for certain TX-RX separation	[32]
26,28,32 and 38 GHz	Indoor (emergency stairwell) / Indoor (stairwell) /	LOS	Single and multifrequency	FI, ABG, FAS and CIF path loss models / The basic path loss model and CIF	FI model is not that much beneficial compared to the PAS / Measurement data is helpful to understand propagation mechanism in the studied medium	[34]-[35]
26 and 38 GHz	Indoor corridor and stairwell	Both	An omnidirectional biconical as transmitter and a steerable directional horn as receiver used for both co-polarization, cross-polarization LOS/NLOS measurement scenarios	CI model in V-V polarization, CIX model in V-H	Omnidirectional PLEs are smaller than directional PLEs	[36]
3.5 and 28 GHz	Indoor (stairwell)	LOS	CI, FI, and CIF path loss models were used to study the received signal in the stairwell according to the measured data	CI, FI and CIF path loss model	The models that used fit the measured data well, path loss exponent are close to FSPL.	[39]

14 and 22 GHz	Indoor	Both	A measurement in the band of 14 and 22 GHz for different heights of TX and RX antenna were examined for two/multi frequency path loss model.	CI and proposed dual slope (DS) path loss model / DS and ABG path loss model	Dual slope path loss model is better than CI / ABG model shows a good foretelling of path loss at 14 and 22GHz and DS needs less modeling parameters	[40]-[41]
19,28 and 38 GHz	Indoor	Both	The basic path loss model, FA and CIF models were used to study path loss in bands of 19, 28 and 38 GHz	CIF, FA and the basic path loss model	The PLE are smaller for all the studied models compared to the FSPLE	[42]
38 GHz	Outdoor	Both	In two different antenna polarization scenarios the basic path loss model, FI and CI models were used to study the action of path loss at 38GHz	FI and CI model	Through the measurement CI showed a good result in both LOS and NLOS while FI give a good result just in the LOS.	[43]
26 GHz	Indoor(office)	LOS and OLOS	FI and CI model were implemented in the frequency band of 26GHz that they made a measurement through the MMSE approach to derived the parameters of the models	FI and CI model	Through the results, they deduce that between LOS and OLOS theirs path loss difference about 5 dB	[44]
3.5 and 28 GHz / 4.5, 28 and 38 GHz	Indoor	Both	Single and multi-frequency, CI, FI, ABG and CIF path loss models / For different antenna polarization CI, FI, ABG and proposed path loss models	FI, CI, ABG and CIF model / The CI, FI and ABG and proposed path loss model	At the both bands single and multi-frequency FI and ABG models show a good execution, PLE is less than the FSPLE / the proposed model yielded an average improvement compared to the basic path loss models	[45]-[46]
28 GHz	Indoor	Both	Using a new technique, the 3-D ray tracing method to study the path loss of wave propagation	3-D ray tracing method	According to the measurement and simulation the new proposed method had shown more agreement with it compared to the other.	[47]

3. Conclusions and Recommendations

In this review, we present the studies that examine the performance of various path loss models at candidate mmWave frequencies for 5G wireless communication systems. We have discussed the three basic path loss models CI, FI, ABG, and some other path loss models that have been derived by modifying the values of these three basic models. Furthermore, the studies that cover different measurements scenarios such as, LOS/NLOS, or both, indoor/outdoor at different frequencies 5, 3.5, 4.5, 14, 18, 19, 22, 26, 28, 31, 32, 36, 38, 39, 40, 90 GHz were included.

Even though some paper investigates the same frequency band, their models or method were different. Additionally, the studies that uses data dependent machine learning methods or neural network to predict path loss were also presented. Finally, we presented a clear knowledge about path loss models in 5G to the readers, that we briefly summarized the main results of each studied papers. This provides the opportunities for researchers to modify the previous pathloss models and propose new pathloss models, that can be more beneficial compared to the previous ones

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