Review article

Propagation path loss prediction modelling in enclosed environments for 5G networks: A review

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ABSTRACT

Millimeter wave path loss modeling is essential for reliable system design and accurate link budget calculations. The motivation for this research is that channel modeling in 5G millimeter wave propagation in an indoor environment is a current research topic in which capacity differences have been noticed as a result of different models being utilized. Existing models for future millimeter wave propagation must be tested and improved in order to aid link design. The improvements in the path loss models will allow engineers and researchers to budget for 5G wireless networks with better quality in an indoor environment. In this paper, we discuss the survey of indoor environment undertaking for both line of sight (LOS) and non-line of sight (NLOS) scenarios as well as the comparison of path loss performance analysis of the three commonly used models: Close-In (CI) free space reference model, Floating Intercept (FI), and Alpha-Beta-Gamma (ABG) models at some selected frequencies. The review looked at how to determine efficient path loss models which is a major challenge in millimeter wave propagation. The paper also focuses on the measurement work done in millimeter wave research in interior environments. The analysis of path loss and shadow fading in different frequency bands are presented. The researchers whose publications were examined for this study used a range of methodologies to forecast path loss models and propagation parameters of millimeter wave communication channel. This will help design engineers and researchers calculate budgets for a suitable 5G and even forecasted 6G wireless network in an inside environment. This will help design engineers and researchers calculate budgets for a suitable 5G and even forecasted 6G wireless network in an inside environment. The researchers whose publications were examined for this study used a range of methodologies to forecast path loss models and propagation parameters of millimeter wave communication channel. This will help design engineers and researchers calculate budgets for a suitable 5G and even forecasted 6G wireless network in an inside environment.

1. Introduction

In recent years, the rate of increase in wireless data traffic per subscriber has been above 50% per year, and due to the continued use of video and internet of things (IoT) it is predicted to continue to rise over the next ten years [1]. It has also been predicted that by 2030, mobile data traffic will be increased by a factor of 5000 [1]. This anticipated rise in traffic may, however, be managed by increasing link capacity, spectrum availability, and significant small-cell densification [1]. To meet this demand, the wireless industry will need to shift to fifth-generation cellular technology which will use millimeter wave (mmWave) frequencies to provide unprecedented spectrum and multi-Gigabit-per-second (Gbps) data speeds to mobile devices [2]. Furthermore, as gigabit Ethernet and desktop connections have become inexpensive for server connections, the communication sector made a disclosure in 2007 of the empty 10 GB for usage [3, 4, 5]. In addition, gigabit Ethernet became the standard for servers, requiring systems to be ordered with gigabit network interface cards on a regular basis [5]. Over the time, the cost of wireless gigabit lines has about equaled the cost of wireless, which provides superior output in older wireless applications as well as other feasible uses at gigabit speeds. Wireless communications have become increasingly relevant in the
business world, particularly in Universal Serial Bus (USB) 2.0, gigabit rates, and long-range connectivity, with the significant applications in high-quality multi-media, phone, and data services [5].

Previous wireless local area network (WLAN) speeds were just 54 Mb/s with IEEE 802.1 and achieved 150–300 Mb/s in some applications. However, when it comes to higher access speeds from rich media content, even 500 Mb/s is insufficient. In the near future, home Audio/Video (A/V) networks will require Gb/s data speeds to help deliver uncompressed high-definition video at resolutions of up to 1920–1080 progressive scan, with latencies ranging from 5 to 15 ms [5, 6]. In addition, the technical requirements for the high-speed wireless systems must consider the following factors:

(a) The requirement for higher data rates will continue to grow as the demand for multimedia networks grows.
(b) The demand for shared resources has increased as a result of data streaming for both personal and mobile devices.

Although numerous approaches have been adopted, including IEEE 802.1, IEEE 802.16 WiMax, and Ultra-wideband (UWB). However, the effectiveness of wireless communications has not been sufficient to meet the expectations placed on them, particularly in fifth generation (5G) networks [7]. A better way to tackle these challenges is to make proper use of frequencies that are not employed in millimeter waves but have a lot of application potential. Despite the fact that millimeter wave technology has been in use for some time. With the advent of process technology, this technique has begun to garner a lot of traction among academics and businesses.

Even though the IEEE 802.11n standard will improve the reliability of wireless communications, the data rate will remain modest (even below 1 Gbps) [5, 7, 8]. Millimeter wave technology has emerged as a critical field of research that has aided in the advancement of 5G wireless communications in broadband, with applications in ultrahigh and high definition technology [9]. Millimeter wave technology operates in the electromagnetic spectrum between 30 GHz and 300 GHz, with wavelength ranging from 10 mm to 1 mm [10]. This accessible spectrum at these frequencies is more than 200 times larger than all of the present cellular network allocations [11]. This technology is characterized by a huge quantity of idle bandwidth that can enhance the data rate available to end users, allowing it to meet the two major requirements for 5th Generation (5G) Networks: ultra-high peak throughput (20 Gbps) and average user experience rate (50–100 Mbps) [12]. The generality of millimeter wave frequency ranges is found between microwaves and infrared waves in the electromagnetic spectrum regions that lie between 30 GHz (10 mm) and 300 GHz (1 mm) as shown in Figures 1 and 2 [13, 14]. As shown in Figure 3, the 4G cellular network has served as a cornerstone for 5G networks, as small cells, wideband data, and WiFi rely on servers at network edges to enable the adoption of lower latency applications in new scenarios [1].

The 5G millimeter wave wireless channel bandwidths will be substantially more efficient than the current 4G LTE 20 MHz cellular channels. Even though diffraction and material penetration will cause an increase in attenuation at millimeter wave frequencies compared to today’s 4G microwave frequencies, boosting the relevance of LOS propagation, reflection, and scattering. The usage of accurate propagation models is critical for the development of new mm wave signaling protocols e.g. air interfaces, as it is required for the proper operation of new millimeter-band 5G systems. The corresponding path loss models must be set up for link budget evaluation and signal strength proposal in the process of generating reliable models for 5G systems and determining standard performance measurements, with the addition of directional and beam forming antenna arrays and co-channel interference, which statistical models cannot adequately assess [12].

The path loss is a measure of the degeneration of the propagated signals over a distance range in both LOS and NLOS scenarios. The path loss exponent is a key indicator of any communication system’s performance in wireless channel propagation. Wireless system design, planning, and simulation were all part of the model application. Different path loss model ideas have been proposed by numerous scholars for investigation, notably in indoor environments [15, 16]. Path loss models are used in a variety of applications, the most important of which include power budget calculations, modulation, cellular coverage/interference forecasts, and the design of coding schemes [17]. The data from the various measurements and models used in this work will also aid researchers in the standardization of 5G millimeter wave channel models, particularly in the link budget estimates described previously.

Although the main goal is to find an acceptable model with the best line of fit and the simplest application for path loss model estimate in both LOS and NLOS scenarios. However, this research will continue to work in the future to improve the FI and CI models which are user-friendly in a wide frequency range in order to achieve a higher level of accuracy while maintaining high energy efficiency, allowing for very robust and stable transmission capacity in both LOS and NLOS. Excessive path loss particularly in

![Electromagnetic Radiation Spectrum](image)

**Figure 1.** Electromagnetic frequency spectrum [13].
NLOS will be corrected by the use of high gain antennas, which has been one of the key flaws in previous works [17, 18, 19, 20, 21, 22].

The reason for this study stems from the fact that channel modeling in 5G millimeter wave propagation in an indoor environment is a current research area in which variations in capacity have been observed as a result of different models being used. As a result, existing models must be validated and improved for future millimeter wave propagation in order to aid link design and to enable engineers and researchers in budget

Figure 2. ITU 5G frequency bands [14].

Figure 3. Evolving mobile networks from 4G toward 5G multifier architecture [1].
Table 1. Comparison of general works on millimeter wave propagation.

| Ref  | Frequency (GHz) | Scenario  | Environment | Area of Focus/Methodology | Important results |
|------|----------------|-----------|-------------|----------------------------|------------------|
| [1]  | 0.5–100        | LOS and NLOS | Indoor and Outdoor | Rappaport et al. did a thorough investigation of the fundamental propagation modelling techniques for the 5G networks in millimetre wave wireless communication systems. | The data gathered on shadowing and path loss will help with the improvement expected knowing fully well that millimetre wave is still in the research era especially in the use for 5G propagation. |
| [16] | 14, 18 and 22  | LOS and NLOS | Indoor       | The measurements for two different path loss models at frequencies 14 GHz, 18 GHz and 22 GHz in an indoor situation for LOS and NLOS communication scenarios. | Analysis in the LOS indicates that CI and FI models are similar in execution at all frequencies used. In the CI model, a notable increment of the PLE was observed with the increase in frequency. |
| [25] | 60             | NLOS and LOS | Indoor       | Analysis for the deployment of wireless high-speed local and personal area networks (WLANs/ WPANs) | The millimetre wave propagation was observed to be characterised with propagation loss due to obstructions like walls, furniture and human blockage, to the level of between 25-30 dB. |
| [26] | 23, 25, 28, and 38 | LOS | Outdoor | Dynamic rain-aware link adaptation scheme to allow the system to fit the modulation and coding scheme for rain intensity levels | Result shows that the improbability lies between the theoretical and practical signal induced with rain in the range 1.5–4.5 dB, which was attenuation due to unstable conditions of the weather. |
| [27] | 55–65          | NLOS      | Outdoor     | On-chip wireless channel characteristics in conjunction with antenna implementation with near field and multipath propagation effects | It shows that the near field/transition region is where the propagation in the on-chip wireless channel is located thus making the channel complicated. It was also observed on antennas that the directional antennas are less affected by channel time dispersion, however, there are higher losses. The characteristics are reversed for omnidirectional antennas. |
| [28, 29, 30] | 28 and 73 | NLOS and LOS | Indoor | Analysis of millimetre wave propagation at different frequency bands | This implies that a rise in the path loss brings about a corresponding increase in the separation distance as a result of issues associated with the directivity of the antenna. Also, the scheme has been able to surmount the problem of bandwidth in electronic devices and open the room for the development of low-cost infrastructure demand for the broadband mobile devices. |
| [32] | 73             | LOS and NLOS | Outdoor and Indoor | Proposed a new technique known as Q learn-based scheme which encompasses edge computing function in an adjustable power and angle, which uses sub-6 GHz user equipment (UE) | The result from this investigation indicates that the user equipment with this scheme was able to achieve high energy efficiency and thus creating a room for a very robust and stable capacity in transmission. |
| [33] | 60             | NLOS and LOS | Outdoor and Indoor | Made us to realise that there are unallocated spectrum in the millimetre wave bands which is not making the full opportunity of the use of large antenna arrays for high speed data rates to be achievable. | It was discovered that millimetre wave communication has played a vital role in the deployment of 5G and it is expected that the fundamental improvement in radio and network will be made to help in the deployment of the upcoming 6G. |
| [34] | 6 and 70       | LOS and NLOS | Indoor       | Fuschini et al. [32] studied the narrowband and wideband features of in-room 70 GHz wireless channel using Ray Tracing (RT) simulations and making the measurement to be directional. | Observations show that reflection is the most pronounced mode of propagation, scattering is still present and it appears more than when the frequencies are below 6 GHz. |
| [35] | 60             | LOS        | Indoor       | The use of vector network analyser (VNA) was adopted to verify the response of three different types of antennas to the parameters of power loss. | The investigation shows that large aperture antennas has a significant guided wave effect than those with the narrow apertures, thus making the latter to have a more accurate path loss model. The measurements also indicate that placing an omnidirectional antenna in the access point (AP) gives an improved radiation than at a corner in the meeting room, since the shadowing effects caused by human obstruction are reduced. |
| [36] | 2.4 and 60     | LOS        | Indoor       | Wang et al. validated the eligibility of the SBR modelling method. The SBR method makes use of some propagation parameters such as path loss, RMS delay speed etc. | The results show that strong attenuation leads to smaller coverage area for millimetre waves than lower frequencies. |
| [37] | 60             | LOS and NLOS | Indoor | Verification of multipath effects in an indoor environment | This investigation shows that the multipath effect is more pronounced in indoor NLOS surroundings because the reflection effect on the received power is more as compared to the diffraction effect. |
| [38] | 73             | LOS and NLOS | Indoor | The work uses simulated surroundings at a frequency of 73 GHz in LOS as well as NLOS situations using SBR method. | The measured results are put in comparison with the simulated results of path loss to be able to authenticate the correctness of the SBR method. The profiles of the power angle as well as the power delay were critically examined. |

estimates for good wireless networks in the 5G wireless network propagation in an indoor environment. The findings of this paper will aid design engineers and researchers in calculating budgets for the high performing 5G wireless networks and even the anticipated 6G network in an indoor environment. Another purpose of this article is to gain a comprehensive understanding of the best path loss model, particularly for indoor environments, and to improve on it in future research to provide a better line of fit and simplicity among the three basic path loss models: CI, ABG, and FI. The rest of the paper is organized as follows: Sections 2 and 3 cover fundamental characteristics of mm waves and review of literatures on mm waves, respectively. The path loss in mm wave propagation is explained in Section 4. The overview of the accuracy and viability of models of propagation for outdoor as well as indoor environments in LOS...
| Ref | Frequency (GHz) | Environment | Scenario | Methodologies | Model | Important Reasons |
|-----|----------------|-------------|----------|---------------|-------|------------------|
| [36] | 60 | Indoor and LOS | NLOS | Efforts were made to properly scrutinize the workability and the performance of the SBR/IM method on the basis of accuracy, reliability and the ease of use. The simulation of the important components of the channel propagation such as RMS delay spread and the path loss was carried out. | SBR/IM method | It was inferred that the RMS delay spread has a very low value and a rise in the coherent bandwidth at a frequency of 60 GHz, but at 2.4 GHz, there is a tendency for anti-interference. |
| [38] | 2-73 | Urban microcell | LOS and NLOS | The analysis of millimetre-wave channel characteristics in urban microcell environment based on the SBR method adopts a vertically polarized antenna which is omnidirectional in nature in the transmitter and the receiver section. | SBR technique | The results of this method indicate that some of the features of the millimetre wave channel in UMi is a good background for propagation but only in the outdoor scenarios. |
| [39] | 28 and 73 | Indoor | LO and NLOS | An experiment on ultra-wide band propagation with the statistics of the large scale path loss for present as well as future use was conducted by adopting directional horn antennas. | CI and FI | It was observed during analysis that simple CI and FI models can be used to model large scale path loss (with distance and frequency) in millimetre wave indoor wireless channels with the correctness intact while using one or two functions that have a connection with the transmitted power. |
| [42] | 2.735 | Indoor | LO and NLOS | Data were obtained from about 20 measurement campaigns for frequency bands 2 GHz and 73.5 GHz over a path of distances starting at 5 m and stopping at 1429 m. | CI and ABG | Observation of the analysis of the result shows that the simulation accuracy of the CI model is better than the ABG model even though it is a three parameter model. The former offers more stable and acceptable performance in all the frequencies and the range of distance considered in the course of the experiment which is not so in the latter. |
| [43] | 2-73 | Urban microcell, shopping malls and indoor office | LO and NLOS | The analogy of three most common models of path loss that is CI, CIF and ABG models was done in the range of data sets of distance ranging from 4 m to 1238 m and frequency of 2-73 GHz. | CI, CIF and ABG | It was concluded that for outdoor use, the CI model is more preferable but in the case of indoor modelling, the CIF is the better model. |
| [45] | 0.5-100 | LOS and NLOS | LOS and NLOS | A study of rural macrocell path loss models for millimetre wave wireless communications gives a comprehensive understanding of the present 3GPP RMa LOS as well as NLOS scenarios of models of path loss in range of frequencies of 0.5 GHz–100 GHz. The use of directional antennas was adopted for real-time measurement campaign in a rural area. | CI and CIH | The observation queries continued application of the present 3GPP RMa path loss models for frequencies above 6 GHz. The result of the measured data validates the accuracy, reliability and frequency dependence of the CIH model even beyond the first meter distance of propagation. |
| [46] | 6.5, 10.5, 15, 19, 28 and 38 | Indoor | LO and NLOS | Characteristics analysis of millimetre wave channels in the frequency bands of 6.5 GHz, 10.5 GHz, 15 GHz, 19 GHz, 28 GHz and 38 GHz in an indoor scenario was done with measurement campaign taken across 4000 power delay profiles using horn directional antenna in the receiver and an omnidirectional antenna in the transmitting section. | Path loss models, known as frequency attenuation model ABG, CIX as well as ABG with XPD were proposed. | The results of this model show its simplicity, less path loss exponents, better RMS delay spread and good dispersion factor values. |
| [47] | 19 | Outdoor | LO and NLOS | Examination of the features of millimetre wave 5G channels in order to find out the components of path loss together with dispersion of time for an outdoor scenario was carried out. | Free space path loss model | This experiment deduced that there is a very great drop in the mean values of the delay spread in both LOS and NLOS situations when adopting the use of horn-horn as well as Horn-Omni antenna applications. It indicates that the influence of the delay spread is minimal to the directional horn antenna at the transmitting side. |
| [48] | 40 | Indoor | LO and NLOS | Measurements were conducted in order to access the functionality of 5G wireless propagation and the path loss exponent. | CI and FI Models | Results of this experiment show that in both the LOS as well as NLOS the FI together with CI models have similar values for the PLE and slope line. This is a very strong indication that the FI together with the CI model have the best performance for indoor use at the frequency band of 40 GHz in a 5G propagation system. |

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and NLOS is reviewed in Section 5, while Section 6 discusses findings on path loss propagation in different antenna polarizations using the CI, FI, and ABG models. Finally, Section 7 presents the concluding remarks.

2. Fundamental characteristics of mmWaves

Heavy path loss, increased bandwidth, reduced wavelength, increased penetration loss, and wavelengths in the millimeter range characterize millimeter wave communication. These characteristics are addressed below [21].

2.1. Abundant bandwidth

At the moment, the overall bandwidth available for the mobile networks is insufficient to meet the high data demand of devices, in fact the available bandwidth is less than 780 MHz for 2G, 3G and 4G networks. The biggest advantage of the millimeter communication over the microwave communication is the large bandwidth, which allows communication at high frequencies and provides the large bandwidth for wireless systems [23].

2.2. Short wavelength

Because the mm wave signal has a short wavelength on the order of millimeters, it is necessary to communicate it via MIMO technology, and it is also appropriate for cramming a high number of half-wavelength spaced antennas into a small space. The combination of mm Wave with massive MIMO technology may considerably improve wireless access and throughput performance [23].

2.3. Propagation loss

There are two types of propagation loss: path loss and penetration loss. According to the Friis transmission expression for the assumption of LOS, the free space path loss is proportional to the square of the carrier frequency. Because microwave frequencies start at 26.5 GHz, there is a larger propagation loss than in the microwave band. For example, at 60 GHz, the propagation loss is 28 dB higher than at 2.4 GHz. This has been a key drawback of mm wave, but with the introduction of D2D communications, a high gain directional antenna may compensate for the loss, improving network capacity and enhancing security against eavesdropping and jamming. There is a larger penetration loss in NLOS circumstances, making it harder for mm wave nodes put outdoors to cover indoor spaces. Signals/propagation may suffer a large penetration loss in the case of indoor users with outdoor base stations (BSs), lowering data throughput, spectrum efficiency and energy efficiency. As a result, it's unavoidable to separate outside and indoor scenarios [23, 24].

3. Literature review on mmWave propagation

Salous et al. [2] pointed out that there is unallocated spectrum in the millimeter wave bands, prohibiting the full use of huge antenna arrays for high-speed data transfers. Despite the fact that gigabit data transmission in these bands necessitates accurate channel modeling, the shadowing effect and the need for adaptive beam formation in areas with significant mobility persist. As a result, it was suggested that in addition to end channel sounders, detailed measurements for full radio characterization should include angular spread and delay time in the characterization of multipath made-ups. The lack of channel models, on the other hand, must be addressed in order to provide the inputs to the standards organizations.

Hajj et al. [25] emphasized the relevance of millimeter bands as a proven solution for high-data-rate transmission, particularly in indoor environments. However, millimeter wave propagation technology has been reported to suffer from propagation loss of 25 dB–30 dB due to the impediments such as walls, furniture, and human blocking. Another study used a frequency domain and a vector network analyzer (VNA) to investigate millimeter wave propagation at 60 GHz in an indoor environment.
| Ref  | Frequency (GHz) | Environment | Scenario | Polarization | Distance range (m) | Model | PLE (∇) | β (dB) | σ (dB) | γ |
|------|----------------|-------------|----------|--------------|-------------------|-------|---------|--------|---------|----|
| [18, 20] | 15 | LOS Indoor Corridor | V-H | 1.00–40.00 | CI | 1.90 | — | 2.40 | — | — |
|       |     | FI | 63.50 | 1.10 | 2.90 | — | — | — | — | — |
|       |     | ABG | — | — | — | — | — | — | — | — |
| [18, 20] | 14 | LOS Indoor Corridor | V-V | 2.00–24.00 | CI | 1.37 | — | 2.19 | — | — |
|       |     | FI | 55.41 | 1.37 | 2.19 | — | — | — | — | — |
| [18, 20] | 18 | LOS Indoor Corridor | V-V | 2.00–24.00 | CI | 1.58 | — | 1.53 | — | — |
|       |     | FI | 57.48 | 1.59 | 1.53 | — | — | — | — | — |
| [46] | 22 | LOS Indoor Corridor | V-V | 2.00–24.00 | CI | 1.66 | — | 1.31 | — | — |
|       |     | FI | 61.04 | 1.50 | 1.12 | — | — | — | — | — |
| [46] | 6.5 | LOS Indoor Corridor | V-H | 1.00–40.00 | CI | 1.00 | — | 3.10 | — | — |
|       |     | FI | 40.70 | 1.00 | 3.10 | — | — | — | — | — |
|       |     | ABG | 1.10 | 15.70 | 3.20 | — | — | — | — | — |
| [46] | 10.5 | LOS Indoor Corridor | V-V | 2.00–24.00 | CI | 1.40 | — | 2.80 | — | — |
|       |     | FI | 51.90 | 1.40 | 2.80 | — | — | — | — | — |
|       |     | ABG | 1.10 | 15.70 | 3.20 | — | — | — | — | — |
| [46] | 6.5 | LOS Indoor Corridor | V-H | 1.00–40.00 | CI | 1.20 | — | 2.00 | — | — |
|       |     | FI | 48.50 | 1.40 | 2.00 | — | — | — | — | — |
|       |     | ABG | — | — | — | — | — | — | — | — |
| [46] | 10.5 | LOS Indoor Corridor | V-V | 2.00–24.00 | CI | 1.00 | — | 2.50 | — | — |
|       |     | FI | 45.40 | 1.30 | 2.30 | — | — | — | — | — |
|       |     | ABG | 1.10 | 15.70 | 3.20 | — | — | — | — | — |
| [46] | 15 | LOS Indoor Corridor | V-V | 2.00–24.00 | CI | 0.60 | — | 2.20 | — | — |
|       |     | FI | 56.60 | 0.90 | 2.10 | — | — | — | — | — |
|       |     | ABG | 1.10 | 15.70 | 3.20 | — | — | — | — | — |
| [46] | 19 | LOS Indoor Corridor | V-V | 2.00–24.00 | CI | 1.40 | — | 3.00 | — | — |
|       |     | FI | 63.30 | 1.10 | 2.80 | — | — | — | — | — |
|       |     | ABG | — | — | — | — | — | — | — | — |
| [46] | 28 | LOS Indoor Corridor | V-V | 2.00–24.00 | CI | 0.90 | — | 2.10 | — | — |
|       |     | FI | 58.70 | 1.20 | 2.00 | — | — | — | — | — |
|       |     | ABG | 1.10 | 15.70 | 3.20 | — | — | — | — | — |
| [46] | 28 | LOS Indoor Corridor | V-H | 1.00–40.00 | CI | 1.80 | — | 3.80 | — | — |
|       |     | FI | 69.10 | 1.10 | 3.10 | — | — | — | — | — |
|       |     | ABG | — | — | — | — | — | — | — | — |
| [46] | 40 | LOS Indoor Corridor | V-V | 2.00–2.70 | CI | 1.80 | — | 4.70 | — | — |
| [46] | 4.5 | LOS Indoor Office | V-V | 1.00–22.70 | CI | 0.70 | — | 3.14 | — | — |
|       |     | FI | 41.45 | 1.32 | 1.79 | — | — | — | — | — |
|       |     | ABG | 0.43 | 1.56 | 0.24 | — | — | — | — | — |
| [46] | 4.5 | LOS Indoor Office | V-H | 1.00–22.70 | CI | 1.13 | — | 2.63 | — | — |
| [46] | 4.5 | LOS Indoor Office | V-Omni | 1.00–22.70 | CI | 2.31 | — | 6.64 | — | — |
|       |     | FI | 71.0 | 0.88 | 1.79 | — | — | — | — | — |
|       |     | ABG | 0.90 | 35.77 | 0.19 | 3.02 | — | — | — | — |
| [46] | 28 | LOS Indoor Office | V-V | 1.00–22.70 | CI | 0.92 | — | 2.18 | — | — |
|       |     | FI | 60.10 | 1.06 | 2.15 | — | — | — | — | — |
|       |     | ABG | 0.43 | 1.56 | 0.24 | — | — | — | — | — |
| [46] | 28 | LOS Indoor Office | V-H | 1.00–22.70 | CI | 3.87 | — | 7.83 | — | — |
| [46] | 28 | LOS Indoor Office | V-Omni | 1.00–22.70 | CI | 2.49 | — | 4.38 | — | — |
|       |     | FI | 68.23 | 1.77 | 3.97 | — | — | — | — | — |
|       |     | ABG | 0.90 | 35.77 | 0.19 | 3.02 | — | — | — | — |
resulting in improved performance of system to dynamic rain-aware link adaptation method was developed to allow the forecasting and monitoring in real time was founded. As a result, the recorded signal attenuation during rainfall was studied. The idea of rain between the theoretical rain-induced signal attenuation and the practically compared. This had the disadvantage of not allowing different linkages to be predictable in both practical and theoretical settings, ranging from 1.5 schemes. The results demonstrate that the rain-induced signal is un-

tions. This had the disadvantage of not allowing different linkages to be predictable in both practical and theoretical settings, ranging from 1.5 schemes. The results demonstrate that the rain-induced signal is un-

The performance of millimeter waves for indoor communication at multiple bands between 28 GHz and 73 GHz was thoroughly examined for LOS and NLOS conditions considering the effects of various building and frequency sensitive materials. The link between separation distances and the duo of receive power and the delay spread was predicted to be inverse. By increasing the antenna's directivity, the separation distance can be increased. The system has also been able to solve the problem of bandwidth in electronic devices which is allowing the growth of the low-cost infrastructure for broadband mobile devices. The main limitation of this approach is that it tends to fail as separation distance and the communication capacity increase [28, 29, 30].

Table 3 (continued)

| Ref | Frequency (GHz) | Environment | Scenario | Polarization | Distance range (m) | Model | PLE (α) | β (dB) | σ (dB) | γ |
|-----|----------------|-------------|----------|--------------|-------------------|-------|---------|--------|--------|---|
| [48] | 26 | LOS | Indoor Office | V-V | 1.00–22.70 | CI | 2.29 | — | 5.6 | — |
|       |     |   |            |       |       | FI | 82.53 | 0.33 | 2.57 | — |
|       |     |   |            |       |       | ABG | 0.43 | 1.56 | 0.24 | 4.83 |
| [48] | 38 | LOS | Indoor Office | V-H | 1.00–22.70 | CI | 4.81 | — | 12.67 | — |
| [48] | 38 | LOS | Indoor Office | V-Omni | 1.00–22.70 | CI | 3.25 | — | 5.27 | — |
|       |     |   |            |       |       | FI | 83.79 | 1.12 | 2.04 | — |
|       |     |   |            |       |       | ABG | 0.90 | 35.77 | 0.19 | 3.02 |
| [59] | 26 | LOS | Indoor Office(Horn Antenna) | V-V | 1.00–50.00 | CI | 1.46 | — | 4.94 | — |
|       |     |   |            |       |       | FI | 62.12 | 1.36 | 4.94 | — |
|       |     |   |            |       |       | ABG | 30.51 | 1.32 | 4.81 | 2.25 |
| [59] | 32 | LOS | Indoor office(Horn Antenna) | V-V | 1.00–50.00 | CI | 1.25 | — | 4.54 | — |
|       |     |   |            |       |       | FI | 65.84 | 1.13 | 4.94 | — |
|       |     |   |            |       |       | ABG | 30.51 | 1.32 | 4.81 | 2.25 |
| [59] | 39 | LOS | Indoor Office(Horn Antenna) | V-V | 1.00–50.00 | CI | 1.53 | — | 4.55 | — |
|       |     |   |            |       |       | FI | 62.19 | 1.61 | 4.54 | — |
|       |     |   |            |       |       | ABG | 30.51 | 1.32 | 4.81 | 2.25 |
| [59] | 26 | LOS | Indoor office(Omni Antenna) | V-V | 1.00–50.00 | CI | 1.34 | — | 4.49 | — |
|       |     |   |            |       |       | FI | 64.78 | 1.05 | 4.43 | — |
|       |     |   |            |       |       | ABG | 54.50 | 1.14 | 4.41 | 0.66 |
| [59] | 32 | LOS | Indoor office(Omni Antenna) | V-V | 1.00–50.00 | CI | 1.35 | — | 4.30 | — |
|       |     |   |            |       |       | FI | 63.50 | 1.29 | 4.30 | — |
|       |     |   |            |       |       | ABG | 54.50 | 1.14 | 4.41 | 0.66 |
| [59] | 39 | LOS | Indoor office(Omni Antenna) | V-V | 1.00–50.00 | CI | 1.14 | — | 4.25 | — |
|       |     |   |            |       |       | FI | 65.86 | 1.03 | 4.24 | — |
|       |     |   |            |       |       | ABG | 54.50 | 1.14 | 4.41 | 0.66 |
| [63] | 28 | LOS | Indoor Office | V-V | 4.10–21.30 | CI | 1.10 | — | 1.80 | — |
|       |     |   |            |       |       | FI | 1.20 | 60.40 | 1.80 | — |
| [63] | 73 | LOS | Indoor Office | V-V | 4.10–21.30 | CI | 1.30 | — | 2.40 | — |
|       |     |   |            |       |       | FI | 0.50 | 77.90 | 1.40 | — |
| [63] | 73.5 | LOS | Indoor Office | V-V | 4.10–21.30 | CI | 1.20 | — | 2.30 | — |
|       |     |   |            |       |       | ABG | 0.90 | 26.80 | 1.80 | 2.60 |

environment. The results suggest that an access point (AP) can be placed in the center of the network to reduce shadowing caused by the human impediments. It employs a high frequency for a problem that could have been solved with a frequency lower than 60 GHz. In [26], millimeter wave measurements were performed with the goal of determining the influence of atmospheric variables on transmission. The difference between the theoretical rain-induced signal attenuation and the practically recorded signal attenuation during rainfall was studied. The idea of rain forecasting and monitoring in real time was founded. As a result, the dynamic rain-aware link adaptation method was developed to allow the system to fit the modulation and coding scheme to rain intensity levels, resulting in improved performance of fixed modulation and coding schemes. The results demonstrate that the rain-induced signal is unpredictable in both practical and theoretical settings, ranging from 1.5 dB to 4.5 dB, due to attenuation caused by changes in weather conditions. This had the disadvantage of not allowing different linkages to be compared.

Gade et al. [27] discovered that on-chip wireless links function better than standard Networks –on-Chip (NoC) for millimeter wave systems. On-chip wireless channel characteristics, as well as antenna implementation with near field and multipath propagation effects, were used in the study. The near field/transition region, where the propagation in the on-chip wireless channel takes place, makes the channel more diﬃcult. It was also discovered that directional antennas are less impacted by the channel time dispersion, despite the fact that this is accompanied by higher losses, as compared to the omnidirectional antennas. The on-chip wireless channel provides the information on the characteristics of wireless communications and aids in the design of circuits for improving the performance.

The performance of millimeter waves for indoor communication at multiple bands between 28 GHz and 73 GHz was thoroughly examined for LOS and NLOS conditions considering the effects of various building and frequency sensitive materials. The link between separation distances and the duo of receive power and the delay spread was predicted to be inverse. By increasing the antenna's directivity, the separation distance can be increased. The system has also been able to solve the problem of bandwidth in electronic devices which is allowing the growth of the low-cost infrastructure for broadband mobile devices. The main limitation of this approach is that it tends to fail as separation distance and the communication capacity increase [28, 29, 30].

Chittimoju and Yalavarthi [31] provided a thorough assessment of millimeter wave communications, including some of the beneﬁts and uses. They demonstrated that millimeter wave encourages larger bandwidth while also increasing speed up to 10 Gbps. Some of the beneﬁts include the utilization of the compact components, less interference, and high security. The range is limited in the LoS, which is one of the uncovered key flaws. In [32], authors suggested a novel technique, termed as Q learn-based system, that incorporates edge computing function in an adjustable power and angle sub-6 GHz user equipment to tackle the capacity and efficiency problems in millimeter wave propagation. The end result shows that the user equipment using this scheme was able to achieve excellent energy efficiency which allows a very strong and steady transmission capacity. Further research by Maltsev et al. [33] focuses on the beneﬁts, drawbacks, and common applications of millimeter wave propagation for various 5G communication bands. Millimeter wave was determined to be critical in the deployment of 5G, and it is believed that signiﬁcant improvements in radio and network would be developed to aid in the deployment of the impending 6G.
Using ray tracing (RT) simulations and directed measurements, Fuschini et al. [34] investigated the narrowband and wideband properties of an in-room 70 GHz wireless channel. Reflection is the most pronounced mode of propagation, however, scattering is still present and appears more than when the frequencies are below 6 GHz. When comparing a more detailed environment to a less detailed environment, if both are exposed to the same sources of error, a faster rate of calculation was seen, but this did not translate to greater simulation accuracy. In [35], authors reviewed the results of measurements taken in two interior situations at a propagation frequency of 60 GHz. The response of three distinct types of antennas to different frequencies will aid in the prediction improvement and industry. Knowing full well that millimeter wave is still in the atmosphere, its expected to see more research on this topic.

Further research work included compiling a broad analysis of 5G network approaches in millimeter wave wireless communication systems, as well as bringing together important millimeter wave propagation models from the past to the present. It also emphasizes the significance of developing diverse models based on RT and measurement procedures, not only for current use but also for future uses in academia and industry. Knowing full well that millimeter wave is still in the research era, notably in the application for 5G propagation [1], the data acquired on shadowing and path loss will aid in the predicted improvement. In [24], authors examine the main issues with millimeter wave propagation such as low beam width, high penetration loss, and strong route loss. It also discusses the differences between the analytical modeling and RT methods for channel modeling. After the measurement, data processing and analysis of the measurement results such as channel gain, scatterer identification, RMS delay spread and average power delay profile (APDP) were given. When taking measurements in varied settings, the usage of a MIMO channel with a wide frequency spectrum is essential.

The shooting and bouncing ray (SBR) method was validated by Wang et al. [36]. At a millimeter wave band frequency of 60 GHz and a decimeter band frequency of 2.4 GHz, the propagation parameters such as path loss, RMS delay spread and so on were given. The results demonstrate that millimeter waves have a lesser coverage area than the lower bands were scrutinized as propagation aspects.

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Table 5. Evaluation and observation of usage of various existing models for millimeter wave propagation.

| Reference | Frequency (GHz) | Environment | Model | Observation |
|-----------|-----------------|-------------|-------|-------------|
| [29]      | 28 and 73       | Indoor office | CI and FI | Simple CI models can be used in indoor wireless channels with the correctness even when using one or two functions that has a connection with the transmitted power. |
| [40]      | 28, 38 and 73   | Indoor and outdoor | CI | It only provides data for future research. |
| [41]      | 73.5            | Urban micro and macro cellular | CI and ABG | Simulation shows the accuracy of the CI model to be better than the ABG model as it offers a more stable and acceptable performance with greater level of accuracy. |
| [42]      | 2 to 73         | Urban microcell and macro cell | CI, CIIX and ABG | CI and CIF models show a better goodness of fit and more stable behavior of the components unlike the ABG. Inferring that CI is good for outdoor use. |
| [43]      | 1 to 100        | Indoor office and shopping mall | 3GPP | There is more dependency on the value of the frequency in the indoor environments as compared to the outdoor environments. |
| [49]      | 10, 20, and 26  | Indoor and outdoor | KED model | It shows that the KED model fits accurately with the indoor environment as well as rounded corners in outdoor scenarios. |
| [51]      | 40              | Indoor | CI and FI | Analysis of the CI and FI models shows that they have similar values for the PLE and slop line. |

Elmezghi et al. [18] reported propagation measurements at 14 GHz, 18 GHz, and 22 GHz frequency bands in an indoor environment. Two path loss prediction models and the analysis of communication scenarios for both NLOS and LOS were presented. The LOS analysis shows that the CI and FI models function nearly identically after execution at all frequencies. With the frequencies increasing along the LOS range, the PLE in the CI model rose tremendously. It rises from 1.37 to 1.66 for the 14 GHz and 22 GHz frequency bands, respectively, however, the LOS values do not match those of the FSPLE. Due to the environmental influences, it was discovered that path loss models exhibit symmetrical characteristics about 180° AoA. The models, on the other hand, perform better at 30°, 330°, and 180° AoA. The findings also demonstrated that CI and FI models may be employed reliably in both LOS and NLOS corridor scenarios. The main flaw that has to be addressed is the adoption of a higher-gain antenna to decrease extra route losses to the absolute minimum. In addition, as a follow-up to the above-mentioned result, the effect of transmitting antenna heights on these models’ parameters was studied in [19]. Elmezghi and Afullo [20] have recently updated this work, delivering an efficient improvement for both the CI and FI path loss models. The major findings show that for both LOS and NLOS communication scenarios, the modified models beat the standard models. Furthermore, the proposed models have substantially superior stability and sensitivity than standard models, especially in the NLOS condition. By combining these enhanced models with the LOS probability models described in [23], a generic and accurate model for indoor corridor environments may be obtained.

4. Path loss in mm wave propagation

Path loss is a phenomenon that occurs when a transmitting signal is attenuated as a function of the distance traveled as well as the propagation channel characteristics. It also refers to the loss or attenuation that a propagating electromagnetic signal (or wave) experiences as it travels from the transmitter to the receiver. As a result, the received power is lower than the broadcast power level. However, it is influenced by a number of elements, including antenna gains, operating frequency, transmitted power, and the distance between transmitter and receiver. The most common way to express path loss is in decibel (dB) [39]. Since, the distance between the transmitter and receiver is no longer linear, path loss in wireless propagation is mostly a function of a logarithm factor. The power density $P_D_{rad}$ of an isotropic antenna, with a transmitted power $P_t$ and power gain $G_t$, is given by Eq. (1) [40]:

$$P_D_{rad} = \frac{P_t G_t}{4 \pi R^2}$$  \hspace{1cm} (1)

The path gain $G_p(\lambda, d)$ is given by Eq. (2):

$$G_p(\lambda, d) = \left( \frac{\lambda}{4\pi d} \right)^2$$  \hspace{1cm} (2)

where $d, \lambda, c, f$ and $4\pi d^2$ are the sphere radius, the carrier wavelength, the speed of light in the vacuum, the carrier frequency, and the sphere area, respectively.

Table 6. Comparison of various propagation models in millimeter wave for the indoor office environments.

| Reference | Frequency (GHz) | Environment | Scenario | Models | Result | Observation |
|-----------|-----------------|-------------|----------|--------|--------|-------------|
| [47]      | 6.5, 10.5, 11.5, 19, 28 and 38 | Indoor | NLOS and LOS | Frequency attenuation model CIIX, ABG and ABGX | The results indicate that the value of the path loss exponents for the models adopted is lesser compared to the value when the model is in a free space, which is applicable for all the frequencies. The values were within 0.1–1.4. | This new proposed model shows its simplicity; lesser path loss exponent and has a good RMS delay spread and dispersion factor value. |
| [48]      | 4.5, 28 and 38  | Indoor office | NLOS and LOS | New improved model | It shows that there is a better result of path loss when modelled with one parameter. | The result should be modelled with more than one parameter to actually know the stability at multiple frequencies. |
| [55]      | Varying frequency | Indoor and outdoor | NLOS and LOS | A scheme that adopte mode assignment by reuse | It uses D2D communication with a good values of SINR. | The major advantage of this model is that it helps in a situation where there is problem of path loss attenuation in both indoor and outdoor environment. |
| [57]      | Varying frequency | Indoor | LOS and NLOS | Indoor localization approach | There is a major improvement in the environment at different distances when compared to the existing schemes. | It only considers the distance and path loss. Frequency is another major factor that needs to be considered. |
| [64]      | Varying frequencies | Indoor short office range | NLOS and LOS | Empirical path loss models | It shows appreciable varying values of path loss at different frequencies which also shows less complexity. | There is a need to test this novel prediction path loss, model in a commercial environment where more obstructions will take place. |
In the free space, the fall of signal strength is proportional to the square of the distance, also power path loss within a distance in meters is also proportional to $d^2$. In radio propagation, path loss is usually expressed with the channel attenuation which is the path gain inverse. The expression for the path loss ($L_p$) in decibel form is given in Eq. (3):

$$L_p = L_0 + 20\log_{10}(d)$$  \hspace{1cm} (3)

Where $L_0$ is the path loss in the first distance in meters and it is given by:

$$L_0 = 20\log_{10}\left(\frac{4\pi}{\lambda}\right)$$  \hspace{1cm} (4)

Eq. (4) implies that the coefficient of path loss in free space is characterized by a component $L_0$ that is fixed and its rate goes up as there is increase in the frequency and also another component causing attenuation of 20 dB/decade of the distance [39, 40].

### 4.1. Path loss propagation models

In the last 20 years, there has been substantial research into various propagation channels that could be used for interior channels. While some have concentrated on both outdoor and indoor office environments, others have moved their focus to exclusively indoor office environments [41, 42, 43, 44, 45, 46, 47]. Wang et al. proposed a model descriptions using probability distributions and their reliance on the parameters in his research on an empirical path-loss model for wireless channels in indoor short-range office environment. The model was able to depict appreciable variable values of route loss at different frequencies, while also resulting in a simpler model that simplifies radio propagation in difficult situations. However, because this study was conducted in an office setting, it is necessary to evaluate this unique prediction path loss model in a commercial setting with more obstacles [41].

Further study has revealed that most propagation models that work at frequencies less than 6 GHz are inapplicable when considering route loss models for millimeter wave frequency bands which are generally above 6 GHz. Majed et al. presented channel models that can operate in interior circumstances at frequency ranges of 4.5 GHz, 28 GHz, and 38 GHz in order to find a solution. Both LOS and NLOS measurements were taken in an inside office environment, with the transmitting and receiving antennas set at a distance of 23 m. The goal of the research was to compare the new large-scale generic path loss models with the existing path loss models for omnidirectional and directional as well as multi-frequency and single-frequency. The results of the investigation show that when the large scale path loss model is modeled with one parameter path loss exponent (PLE) and related to the transmitted power, it tends to perform better [48]. Shadowing and attenuation, which were explored in [49], are another set of properties common to an indoor environment. Wireless open access research platform (WARP) equipment was used to model route loss and shadowing. As a result, the propagation path loss value is in line with those measured in the literature, with an exponent of 4 and a standard variation of 6.4 dB.

In millimeter wave propagation, the direct exchange of information between two near distance devices in the absence of a base station, known as device to device (D2D) communication, has various advantages such as energy efficiency, better data throughput and shorter latency [50, 51]. The effect of path loss on D2D communication is unique and unequalled. Modeling a method that will result in a significant reduction in attenuation is required. In [48], a strategy was developed that uses mode assignment by reuse, cellular modulo dedication based on a tradeoff of path loss attenuation and D2D user range. This scheme's analysis is compared with the other existing schemes such as the alternate offer bargaining game (AOBG) theory based algorithm and the heuristic algorithm. The main benefit of the proposed approach is that D2D users' SINR threshold is supported to a certain extent. The practicality of this technology is demonstrated by the fact that it is extremely useful in circumstances where path loss attenuation is a concern in both indoor and outdoor contexts. Another measurement work was conducted in two different locations in the United States of America (USA) by MacCartney Jr et al. to check the path loss models for 5G millimeter wave propagation channels in Urban Microcells using the best of sliding correlator channel sounder at 28 GHz and 38 GHz. Using directional antennas of varied heights as well as the gains, this experiment investigates multiple microcellular conditions. The linear regression fits were used to create the path loss models. The path loss spanned a distance that is dependent on the power received, according to the measurements. When compared to the existing path loss models, the suggested model performs better in terms of lowering shadow factors by several decibels and provides a better fit to empirical data while permitting only a minor path loss [52].

Naruke et al. proposed an indoor localization method based on path loss – distance relationship using handset sensor data. The range between the Bluetooth Low Energy (BLE) transmitter and the smartphone was computed using this proposed model, which first used the relationship between distance and path loss, and then used the Pedestrian Dead-Reckoning (PDR) fix on the mobile phone's accelerometer. When the proposed scheme is compared with the existing schemes, the results reveal a significant improvement in the distance error [53].

Al-Saman et al. conducted a comprehensive assessment for millimeter wave propagation models as well as measurements in indoor environments. Time dispersion and path loss were identified to be the key indoor wireless channels in terms of millimeter wave propagation. Although the path loss coefficient increases as the frequency increases, the exponent is only affected by the structure and kind of environment, not by the frequency [29]. Considering the various research articles in the frequency range of 28 GHz–100 GHz, the overall observation is that the CI and FI models are the best for both LOS and NLOS channel propagation in millimeter wave bands especially in an interior environment. This achievement in the deployment of millimeter wave propagation for both 5G and 6G networks with negligible propagation loss [54] is an important advance forward. There is a general classification of models that require minimal site or path details and count hindrances or obstructions as a component of the distance dependent loss, whereas site-specific models assess the loss due to each hindrance separately. These models are taken into account by placing the measured variables into a generic phrase. There are four major path loss propagation models, CI, FI, CIF, and ABG, which are frequently used: two of them are single frequency models, while the other two are multi-frequency models [55, 56, 57, 58, 59].

The usage of models in propagation path loss can be used to reflect the effects of path loss on the signal at the receiving end on a wide scale. It is a useful tool for calculating signal attenuation and declining as it travels from the transmitter to the receiver, taking into account propagation distance and other factors. The models differ in that some specify the topographical profile for easy signal analysis, while others just use the carrier frequency and distance to determine their target [60, 61]. The CI, CIF, and ABG path loss models are stochastic in nature. These models capture the phenomenon of large-scale propagation over a given distance and can work at all appropriate frequencies in the given environment. The CI and CIF models are found to be equivalent to the standard forms of 3GPP path loss models i.e. the FI and ABG models. Only the floating constant and the free space constant, which are dependent on propagation frequency and observance of the free space reference distance of 1 m, are relevant in this case [62, 63, 64, 65, 66].

#### 4.1.1. CI free space path loss model

This is a model whose basic premise is based on the anchor point and is dependent on the frequency in free space. The model parameter includes the free space path loss (FSSP), which is also dependent on the carrier propagating signal frequency ($f$ in GHz). The distance between the transmitter and receiver ($d$ in meters) as well as a specified reference distance ($d_r$) are both crucial. Another CI model parameter, PLE ($n$) [60, 66, 67, 68], is determined in dB. The path loss for CI model ($PL_{CI}(d)$) is given by Eq. (5):
where $d_0 = 1 \text{ m}$.

Where $X_{\text{CI}}^{\text{FI}}$ and $\sigma$ are zero mean gaussian random variable and the standard deviation in dB, respectively. The FSPL (in dB) is given by Eq. (6):

$$FSPL(f, d_0)[\text{dB}] = 10\log_{10}\left(\frac{4\pi d_0}{\lambda}\right)^2$$

(6)

### 4.1.3. $\text{ABG}$ path loss model

Another type of multi-frequency model approach is the Alpha-Beta-Gamma (ABG) model. The reference distance and the reference frequency of the ABG model are 1 m and 1 GHz, respectively. The path loss dependency on distance coefficient and the path loss dependency on the frequency coefficient are $\alpha$ and $\gamma$, respectively. The offset path loss, the distance between transmitter and receiver, and the carrier frequency are $\beta$, $d$, and $f$, respectively [66, 67]. Eq. (8) gives the expression for the path loss (in dB) for the ABG model.

$$P_L^{\text{ABG}}(f, d)[\text{dB}] = \alpha 10 \log\left(\frac{d}{d_0}\right) + \beta + 10 \gamma \log\left(\frac{f}{1\text{GHz}}\right) + X_{\text{ABG}}^{\text{FS}}$$

(8)

When $d_0 = 1 \text{ m}$. The ABG path loss model for $d_0 = 1 \text{ m}$ is given in Eq. (9).

$$P_L^{\text{ABG}}(f, d)[\text{dB}] = \alpha 10 \log(d) + \beta + 10 \gamma \log(f) + X_{\text{ABG}}^{\text{FS}}$$

(9)

5. Accuracy and viability of propagation models for indoor and outdoor environments

The accuracy and feasibility of various models are highly dependent on the propagation scenario and the frequency spectrum that is taken into account. Various proposed models by the researchers have a unique application that has a long way to go in terms of distance and frequency of application in order to improve delay time output and PLE performance. An experiment on ultra-wideband propagation was carried out at New York University in a typical indoor office environment [67]. The results of the experiment were used to calculate the statistics of large-scale route loss for current and future applications. The measurements were conducted in an enclosed structure with LOS and NLOS conditions using directional horn antennas at 28 and 73 GHz. During the investigation, it was discovered that basic CI and FI models may accurately represent large scale path loss (with distance and frequency) in millimeter wave indoor wireless channels while only employing one or two functions that are related to the transmitted power [39].

Maccarthey et al. presented some omnidirectional propagation data recorded at frequencies of 28 GHz, 38 GHz, and 73 GHz in New York Downtown city to validate the accuracy and validity of the CI path loss model. The paper’s main goal is to give data for wave propagation research and comparison when working on similar measurements [40].

Sun et al. used two primary large scale route loss models in their work on propagation path loss models, CI and ABG, for 5G urban micro and macro-cellular scenarios. Data was collected from around 20 measurement operations with frequency bands spanning from 2 GHz to 73.5 GHz over a distance of 5 m–1429 m. According to the examination of the results, the simulation accuracy of the CI model is superior to the ABG model [63]. The former provides more consistent and acceptable performance across all frequencies and distance ranges investigated during the trial, whereas the latter does not. To reach a higher level of accuracy, only minor changes to the CI model, which is user-friendly over a wide frequency range, are required [69, 70, 71, 72].

The ABG model was compared to the three most common large scale path loss models i.e. close in free reference distance model (CI), close in path model with frequency-weighted path loss exponent (CIF), and ABG in a range of data sets with distances ranging from 4 m to 1238 m and frequencies ranging from 2 GHz to 73 GHz. Urban microcells, shopping malls, and an indoor office environment were the scenarios [63]. The CI (two parameters considered) and the CIF (three parameters considered) models have better goodness of fit and more stable behavior of the components, whereas the ABG model (four parameters considered) under predicts and over predicts path losses when it is close to the transmitter and when it is far from the transmitter, respectively. This discovery remains true across all distances and frequencies studied. The CI model was shown to be suitable for the outdoor application, whilst the CIF model was found to be the best for indoor modeling [42, 73].

Haneda et al. used both present and past measurements on channel propagation in the frequency band up to 100 GHz in their work on indoor 5G 3GPP-like channel models for office and shopping mall environments. It was discovered that there is an increase in penetration loss as a result of increase in frequency changes the material properties. According to the UMI and Uma models [43], the indoor channels have a higher dependency on the frequency as compared to the outdoor channels.

Measurements were performed at 28 GHz and 38 GHz in three cities: New York, Austin, and Texas, as part of an empirically-based large scale propagation route loss model for 5G cellular network planning in millimeter wave band. In the course of performing path loss simulations with a random selection of antenna pointing angles, it was discovered that when the best direction of the antenna is pointed at both the mobile and the base station, there is a significant increase in the portion of coverage. This reduces the interference and the number of 5G base stations [45]. The analysis of Rural Macrocell path loss models for millimeter wave wireless communications, which is part of a larger research project, provides a full understanding of the current 3GPP, RMA LOS, and NLOS path loss models in the frequency range of 0.5 GHz–100 GHz. In a rural location with good weather, directional antennas were used for a real-time measurement campaign employing the CI and CHI model components. The finding brings into question the use of current 3GPP RMa path loss models for frequencies above 6 GHz. The observed data verifies the CHI model’s correctness, dependability, and frequency dependency even beyond the first meter of propagation distance [45].

The characteristics of propagation channels in the frequency bands of 6.5 GHz, 10.5 GHz, 15 GHz, 19 GHz, 28 GHz, and 38 GHz in an indoor scenario were investigated further with a measurement campaign spanning 4,000 power delay profiles using a horn directional antenna as a receiver and an omnidirectional antenna in the transmitting section. The frequency attenuation model, which considers both the distance and the frequency, has been presented as a novel path loss model. This also aids in the estimation of the XPD component of close in reference distance using XPD (CI) and ABG with XPD (ABG) path loss models, which do not require the use of the minimal mean square error approach. The RMS delay spread and dispersion factor values of this model illustrate its simplicity, lower path loss exponents, and good RMS delay spread and dispersion factor values [46].

Al-Samman et al. examined the features of millimeter wave 5G channels in order to figure out the components of path loss and time dispersion in an outdoor situation in their work on path loss and RMS delay spread model for 5G channel at 19 GHz [47]. When using the
horn-horn as well as the horn-omni antennas in a line of sight condition, the path loss model generated from the observed data shows a drop in the PLE, which is due to the summing up of the multipath component parameters in the LOS environment. However, the values of the PLE and free space path loss in the two situations are identical in the NLOS scenario. The results of this experiment show that when using horn-horn and horn-omni antenna applications in both LOS and NLOS situations, the mean values of the delay spread drop dramatically, indicating that the influence of delay spread on the directional horn antenna at the transmitting side is minimal [47].

The FI model and the CI model were used to conduct measurement campaigns in an indoor environment in both LOS and NLOS cellular systems at a frequency of 40 GHz in order to access the functionality of 5G wireless propagation and the route loss exponent at this frequency band. The two models are compared to the ones used during the measuring campaign. The results of this experiment reveal that the CI and FI models have similar values for the PLE and slope line in both the LOS and NLOS. This is strong evidence that the CI and FI models are the best large-scale path loss models for indoor application in a 5G propagation system at the 40 GHz frequency band [48]. Work was done on the 10 GHz, 20 GHz, and 26 GHz frequency bands in the measurement of diffraction as well as the prediction models of signal strengths in environments with corners, irregular objects, and pillars in both indoor and outdoor scenarios using a continuous wave channel sounder with similar antenna pairs that are a directional horn type at the receiving and transmitter sections [49].

Khatun et al. took the research on the comparison of the path loss model in both outdoor and interior environments in both LOS and NLOS scenarios to the next level. They carried out their survey at the Boise Airport and Boise State University [50]. At a frequency band of 60 GHz, a detailed research was carried out using the techniques of CI reference and FI path loss models with a high gain directional antenna. Although there was a correlation between the final result and the measurement campaign results [50], stochastically and statistically analyzing it revealed that the weather condition at the Boise airport was responsible for the higher value of PLE associated with the outdoor scenario when compared to the indoor scenarios.

Due to the obvious signal propagation disparity, the majority of the propagation models now in use for any frequency band below 6 GHz are not acceptable for path loss modeling of millimeter wave propagation, and of course any frequency band above 6 GHz. The measurement was performed in an indoor situation in the frequency bands of 4.5 GHz, 28 GHz, and 38 GHz for LOS and NLOS in order to construct a model that can sufficiently work in these bands together [48]. The research was carried out at Universiti Teknologi Malaysia (UTM Malaysia). In directional and Omni directional antenna applications, path loss analysis of single and multi-frequency signals was performed. It was deduced that modeling path loss on a large scale with respect to distance over distance is easier to do using a less complex model approach with the adoption of only one PLE parameter (n) that is dependent on the transmitted power, rather than using a model that is not transmitted power dependent and may require more parameters, making the modeling complex [48].

Another indoor laboratory measurement scenario was carried out for LOS and NLOS propagation at a frequency of 2.4 GHz, and a route loss with spatial variability was proposed. This proposed model was built on the foundation of FI and log-distance models. It uses a combination of coherent and non-coherent power gains to reduce the percentage path loss exponent or the cumulative distribution function (CDF). As a result, the average route loss value in four coherent signals for a LOS scenario decreases path loss by 89.4 percent, compared to the strategy of employing the NCC scenario, which reduces path loss by only 55.98 percent [52]. The characteristics of millimeter-wave channels in the Urban Microcell Environment were discussed in [40]. In the transmitter and reception sections; a vertically polarized omnidirectional antenna is used based on the SBR Method. The performance of the SBR technique was further validated by analyzing the LOS and NLOS in the vertical and horizontal directions and justifying the performance with both measured and simulated data. As a result, certain characteristics of millimeter wave channel in UMi provide a good background for propagation, but only in outdoor circumstances.

Furthermore, Wang et al. studied the 60 GHz millimeter-wave propagation characteristics in indoor environment. Efforts were made to thoroughly examine the workability and performance of the SBR/IM method on the basis of accuracy, reliability, and ease of use, as well as a simulation of the important components of channel propagation such as RMS delay spread and path loss. At a frequency of 60 GHz, the RMS delay spread has a very low value and a rise in the coherent bandwidth, but there is a tendency for anti-interference at 2.4 GHz [36]. In the empirical research of millimeter wave in an indoor context, the dual slope model was used. The measurement was performed in a completely blocked location to a location with deep fading, and the performance was compared to the single slope path loss model, which is the most prevalent in both LOS and NLOS scenarios utilizing omni directional antennas. The results reveal that the suggested dual slope model fits the values of the measurement campaigns fairly well, but with certain shadow variables [53].

Schlichter et al. in [66], authors provided a stretching out tool box of stochastic geometry based model and proof of the theorem that yields the expression of the functional of the result in their work on interference functional in Poisson networks. This finding was put to use in wireless networks. Also, authors computed the joint outage probability of some transmissions, which would be utilized as a template for any path loss models. The efforts of numerous international groups to model channels for both licensed and unlicensed applications are described here, along with early results and key concepts of 5G networks that were presented in [67, 68]. Over the frequency range of 0.5–100 GHz, various standardization bodies’ simulations of various propagation parameters and channel models, including line-of-sight (LOS) probabilities, large-scale path loss, and building penetration loss, are compared. Yang and associates developed a geometry-based multipath model to characterize the rapidly changing properties of high-speed trains communicating in the millimeter wave frequency region. A validated RT simulator was used to create this model [69]. Because each dominant multipath lifetime has a defined geometry factor, which is drawn out inside separate local Wide-Sense Stationary (WSS) regions and monitored to determine its “birth and death” positions, the dominant multipath component in this approach. By comparing the Doppler and delay spreads of the channel being modeled with the channel of the simulated RT, the model's notion is proven. In a comparable model, the overall result of this work provides a good channel model for the overall design procedures. However, when utilizing the large antenna arrays to increase power gain, one of the primary issues in millimeter wave propagation is the beam direction of the domain angles of both transmitting and receiving antennas. The codebook design was a two-step process that used sub-array and deactivation approaches to solve the problem. The BMW-SS codebook was found to have the advantages of flatter and more active beams, resulting in improved power system performance and models [70, 71, 72].

Wu et al. [73] used a rotated directional antenna (RDA) method in conjunction with the uniform virtual array (UVA) method to analyze the three-dimensional channel of the frequency band, which takes into account both the azimuth and co-elevation domains for modeling of mm Wave channel for indoor office situations at a frequency band of 60 GHz. Using the UVA on SAGE algorithm as well as the K-means algorithm, the results for both LOS and NLOS in roughly 6 instances were analyzed. Despite being located in a limited direction distance, the angles of departure of the azimuth differ. This is strongly linked to the height difference of the antennas. It was also revealed that in either the cluster or global level, the faster rate of spread of the angle of azimuth is on the high side when compared to the elevation angle. In the mm wave band, Qu and Zhe [74] proposed a design technique for a high-gain wide-angle antenna. It utilized a novel gradient-index (GRIN) lens and a phase array antenna (PAA) coupled to a high-directivity aperture coupled microstrip
antenna (ACMA). Particle swarm optimization (PSO) was first employed in conjunction with a quasi-two-dimensional (2-D) model, and excitation coefficients for beam steering were later derived using the PSO algorithm. Although the antenna is to be manufactured using three-dimensional (3-D) printing, measurements conducted using the antenna demonstrate a good agreement with the simulated findings. The research in [75] revealed the introduction of the eventual deployment of E-band spectrum for broadband propagation. The capacity to minimize interference among neighboring broadband BSs and a visible overlap of their coverage areas were identified to be the key advantages of E-band that necessitate its wide implementation in broadband. The main disadvantage of this strategy is its inability to guarantee good network coverage, especially when some mobile users do not have access to LOS links in the BSs closest to them. This research also suggests the solution to this problem by deploying a hybrid EMB and 4G system in order to provide a decent balance of data and coverage.

In their work channel estimation and hybrid beam forming for reconfigurable intelligent surfaces assisted THz communications, Qin et al. proposed a three-phase approach to bringing about distinct groups of measurements employing a cooperative channel method via beam training. A pair of innovative codebooks were also created to make the 3-tree search necessary in the beam generating procedure as simple as possible. A tree dictionary (TD) technique was combined with a phase shifter deactivation (PSD) approach in the application of wide-beam designs in the codebook. A twin closed form propagation technique was also developed to improve the overall efficiency of the spectrum, despite its modest complexity [76].

The analysis of these path loss models reveals that there is a need to develop a model that is an improvement over the basic models, such as CI, FI, and ABG, that is simple but performs better in terms of path loss of the transmitted signal from the transmitter to the receiver as shown in Table 1 and Table 2. The CI free space reference model and the FI path loss models were found to be the best appropriate path loss models for indoor millimeter wave propagation in both LOS and NLOS scenarios in the study. Future research will concentrate on how to improve the appropriate model with the best line of fit and the simplest application for path loss model estimation in both LOS and NLOS scenarios in an indoor environment.

6. Findings on path loss propagation in different antenna polarizations using the CI, FI, and ABG models

Observations in [18, 20], as shown in Table 3 and Table 4, demonstrate that the PLE increases in a logarithmic fashion, when the frequency of operations increases. Because of diffractions, reflections, and wave guiding, constructive interference occurs at the receiving end. In a LOS indoor setting, the PLE for the CI path loss model at 14 GHz, 18 GHz, and 22 GHz is less than the theoretical free space path loss exponent FSPLE of 2. At frequencies 14 GHz, 18 GHz, and 22 GHz, the values of the floating intercept parameter are 55.44, 57.45, and 61.03, respectively, which are almost identical to the predicted PLE in the FI path loss model. When compared to the LOS, high values of path loss are observed in the NLOS environment. It is also worth noting that the maximum PLE is recorded in the 18 GHz frequency as opposed to 14 GHz and 22 GHz frequencies, indicating that reflections off the building's structural routes are more problematic at 18 GHz.

The parameters tested in [46] were in the frequency ranges of 6.5 GHz, 10.5 GHz, 15 GHz, 19 GHz, 28 GHz, and 38 GHz, with two antenna configurations of cross polarization (V–H) and co-polarization (V–V). The PLE value for the frequency bands under consideration with the two antenna configurations i.e. V–V (1, 1.1, 1.4, 6.0, 0.9, and 0.8) and V–H (1.3, 1, 2, 1.9, 1, 4, 1, 8, and 1.1) for 6.5 GHz, 10.5 GHz, 15 GHz, 19 GHz, 28 GHz, and 38 GHz correspondingly is less than the theoretical standard value of 2. This demonstrates that the MPCs of the internal corridor's walls combine to generate a waveguide. The values of α, deviate from the space path loss for the V–V polarization in the case of the FI path loss model parameters, showing that this channel has not been physically described properly by the FI. The V–V measurement and the combined polarization measurements of both the V–H and V–V have identical values in the ABG multi-frequency path loss model. In [47], the research indicates that the PLE obtained in the NLOS environment for the CI path loss is higher than the FSPLE, indicating that the received signals are produced by diffraction and reflection processes. In the LOS, the PLE (n) values are less than the FSPLE (2). The received power will go off at a distance rate of 18 dB and 29 dB per decade for LOS and NLOS environments, respectively. For the FI path loss model, the same result is obtained for the PLE in both the NLOS and LOS settings. These are summarized in Table 3 and Table 4.

The path loss model in [46] uses the CI model for directed and omnidirectional paths in the LOS and NLOS settings at frequency ranges of 4.5, 28, and 38 GHz. The antenna's polarizations were (V–V) and (V–V) (V–H). The PLE values determined from (V–V) polarization in the LOS are 0.7, 0.92, and 2.229 at frequencies of 4.5, 28, and 38 GHz, respectively. Because their PLE was significantly less than the FSPLE of 2 in the V–V antenna polarization, the effect of constructive interference was more noticeable at 4.5 GHz and 28 GHz frequencies. In the V–H polarization, on the other hand, the PLE values obtained are higher than those obtained in the V–V polarization. There is strong evidence of depolarization in the PLE values for both LOS and NLOS settings in the NLOS environment at frequencies of 28 GHz and 38 GHz. The result of the FI path loss model in the LOS was compared to the theoretical FSPLE values of 45.5 dB, 61.4 dB, and 64 dB, as well as the FI path loss model values of 41.4 dB, 60.1 dB, and 82.5 dB in the V–V polarization at 1 m reference distance for the frequencies 4.5 GHz, 28 GHz, and 38 GHz, respectively. In the theoretical FSPLE, the V-Omni path loss LOS values are 45.5 dB, 61.4 dB, and 64 dB, whereas the FI path loss values are 71.09 dB, 68.23 dB, and 83.79 dB. The NLOS scenario demonstrates that the FI values are independent of frequency. Although, it demonstrates that the FI path loss model is highly sensitive. Only two antenna polarizations, V–V and V-Omni, are present in the ABG path loss model. When compared with the LOS scenario, the α in the NLOS case study has a greater value.

Results in the LOS scenario for the frequencies 26 GHz, 32 GHz, and 39 GHz in [59] show that horn antenna configurations create higher path loss values when compared to the omnidirectional antenna configurations. Despite the fact that none of the path loss values were close to the theoretical FSPLE value of 2, the influence of reflections in the walls and structures of the buildings, which function as a wave guide in the signal propagation, was confirmed in Table 3 and Table 4.

In [63], the LOS PLE demonstrates that their CI path loss models have values of 1.1 at 28 GHz and 1.3 at 73 GHz, implying that there is constructive interference, as seen in practically all other indoor millimeter wave propagation measurements, which is caused by diffractions, reflections, and wave guiding. It has a PLE of 2.7 at 28 GHz and 3.2 at 73 GHz in the NLOS environment, showing considerable attenuation at 73 GHz, although there is a reduction of attenuation in the FI model for both LOS and NLOS circumstances. The CI model's simplicity and correctness were further validated by the fact that just one parameter is necessary. The analysis and observation of various existing models for millimeter wave for the indoor office environments are presented in Table 5 and Table 6. This further collaborates with the simplicity of the CI and FI models, but the CI model provides better accuracy.

7. Conclusion

This paper compares millimeter waves propagation observations in the outdoor, indoor office, and corridor for various frequencies to single frequency route loss models from CI and FI, as well as the multi-frequency path loss model from ABG. Because the CI and FI route loss models are simple, they function similarly practically for all the examined frequency bands. Their PLE values are in line with the measured values for the LOS environment. In a similar vein, the NLOS performance is not awful; nevertheless, a higher gain antenna should be used to
compensate for the significant path loss. Almost all of the models PLE values are less than the FSPLE of 2, owing to the multipath components being added together as a result of reflections and wave guiding along the walls of the interior environment, whether it's an office or a corridor. In the LOS context, the conventional 1 m reference distance also allows for simple calculations, a better degree of precision, and good prediction of measured Path loss. The sole need for this to work in an NLOS environment is that there are no barriers in the first meter of propagation. According to the multi-frequency ABG route loss model, the value of the frequency slope value (β) at all frequency bands in both LOS and NLOS environments does not convert to a realistic amount of attenuation as frequency increases. Although all three models perform well, the model with the smallest amount of parameters is the best to utilize for simplicity and convenience of use. This is shown in Table 5 and Table 6. The theory and performance of various route loss models, including ABG, CI, and FI, as well as some other modified models derived from the three fundamental path loss models: ABG, CI, and FI for 5G networks have been presented in detail. The study looked at measurement situations in both LOS and NLOS for both indoor and outdoor environments at the frequencies of 0.5 GHz, 2 GHz, 2.4 GHz, 6.5 GHz, 10 GHz, 10.5 GHz, 15 GHz, 14 GHz, 18 GHz, 19 GHz, 20 GHz, 22 GHz, 26 GHz, 28 GHz, 38 GHz, 40 GHz, 60 GHz, and 73 GHz. To illustrate the process, the results of each article were quickly described in each instance. Despite the fact that some studies employ identical frequencies but distinct path loss models, others use a modified version of the path loss models used in previous research but with better performance and simplicity than before. It was revealed that increasing the frequency does not result in an increase in the path loss exponent, but rather has an effect on the environment. The study concluded that the CI free space reference models and the FI path loss models are the most appropriate path loss models for indoor millimeter wave propagation in both LOS and NLOS scenarios. However, since each indoor environment investigated in the papers are made of different building designs, researchers in future work should develop the improved models for both CI and FI path loss models with better performance in path loss exponent, shadow fading and other path loss parameters for the specific building designs in the propagation of millimeter wave for 5G networks in an enclosed environment.

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References
[1] T.S. Rappaport, Y. Xing, G.R. MacCartney Jr., A.F. Molsich, E. Mellios, J. Zhang, Overview of millimeter wave communications for fifth-generation (5G) wireless

networks with a focus on propagation models, IEEE Trans. Antenn. Propag. 65 (12) (2017) 6213–6230.
[2] S. Salo, E. V Degli, F. Fuschini, D. Dupleich, R. Müller, R.S. Thomas, K. Haneda, G. Molina, Jose-Maria, G.J. Pasqual, D. P Galliot, M. Nekovee, S. Hur, R. Müller, Millimeter-wave propagation characterization and modelling for 5G systems, IEEE Antenn. Propag. Mag. 58 (6) (2016) 115–127.
[3] http://www.eng.iu.edu/~dbh/mmwave.htm, Retrieved 10th August 2021.
[4] J. Caruso, Copper 10 Gigabit Ethernet NICs Unveiled, Network World, 2007.
[5] K.C. Huang, Z. Wang, Millimeter Wave Communication Systems, Institute of Electrical and Electronics Engineers, John Wiley & Sons, Inc., Piscataway, New Jersey, 2011.
[6] W.J. Way, Spectrally efficient parallel PHY for 100GbE MAN and WAN, IEEE Commun. Mag. 45 (12) (2007) 72–79.
[7] K.C. Huang, Z.C. Wang, Millimeter-wave circular polarized beam-steering antenna array for gigabit wireless communications, IEEE Trans. Antenn. Propag. 54 (2) (2006) 743–746.
[8] R.C. Qiu, H. Liu, X. Shen, Ultra-wideband for multiple access communications, IEEE Commun. Mag. 43 (2) (Feb. 2005) 80–87.
[9] N.O. Oyie, T.J.O. Afullo, Measurement and analysis of large scale path loss model at 14 and 22 GHz indoor corridor, IEEE Access 4 (2016).
[10] N.A. Muhammad, P. Wang, Y. Li, B. Vucetic, Analytical model for outdoor millimeter wave channels using geometry-based stochastic approach, IEEE Trans. Veh. Technol. 66 (2) (2017) 912–926.
[11] M.R. Aldeeni, Y. Liu, M.K. Samimi, S. Sun, S. Rangan, T.S. Rappoport, E. Erkip, Millimeter Wave Channel modeling and cellular capacity evaluation, IEEE J. Sel. Area. Commun. 32 (6) (2014) 1164–1179.
[12] M. Leci, P. Testolina, M. Giordani, M. Polese, T. Ropitaust, C. Gentile, Simplified Ray Tracing for the Millimeter Wave Channel: A Performance Evaluation, A publication of National Institute of Technology (NIST), Information Theory and Applications Workshop (ITA), Gaithersburg, Feb. 2020.
[13] https://micro.magnet.fsu.edu/primer/lightandcolor/elecmagintro.html/retrieved 1st August 2022, 9.05 am.
[14] M.K. Elmezughi, T.J. Afullo, Evaluation of Line-Of-Sight Probability Models for future mobile networks in enclosed indoor environments, IEEE Access 9 (2021) 110332.
[15] M.K. Elmezughi, T.J. Afullo, Investigation of Antenna Heights for 5G Networks—with a focus on propagation models, IEEE Trans. Antenn. Propag. 65 (12) (2017) 6213–6230.
[16] A.F. Molisch, Wireless Communications, second ed., John Wiley & Sons, Ltd, 2011.
[17] M.K. Elmezughi, T.J. Afullo, N.O. Oyie, Measurement and analysis of path loss models for future mobile networks in enclosed indoor environments, IEEE Access 9 (2021) 110332–110345.
[18] M.K. Elmezughi, T.J. Afullo, Performance of Line-Of-Sight Probability Models for Enclosed Indoor Environments at 14 to 22 GHz, in: in: icABC2020 Conf., IEEE, 2020, pp. 1–7.
[19] M.K. Elmezughi, T.J. Afullo, An efficient approach of improving path loss models for future mobile networks in enclosed indoor environments, IEEE Access 9 (2021) 110332–110345.
[20] M.E. Hajj, G. Zaharia, G.E. Zein, H. Farhat, S. Sadek, Millimeter wave propagation measurements and predictions in the VHF and UHF bands, Heliyon (2021) e07298.
[21] C. Seker, M.T. Guenes, H. Aman, Millimeter-wave propagation modeling and characterization at 32 GHz in indoor office for 5G networks, Int. J. RF Microw. Computer-Aided Eng. 30 (12) (2020), e22455.
[22] L. Zhijian, D. Xiaojing, C. Hsiao-Hwa, B. Ai, C. Zhifeng, D. Wu, Modeling and Measurements for 5G Mobile Networks, 2018 arXiv:1804.02027v1.
[23] M.E. Hajj, G. Zaharia, G.E. Zein, H. Farhat, S. Sadek, Millimeter wave propagation measurements at 60 GHz in indoor environments, in: 2019 International Symposium on Signals, Circuits and Systems (ISSCS), 2019, pp. 1–4.
[24] C. Han, S. Duan, Impact of Atmospheric Parameters on the Propagated Signal Power of Millimeter-Wave Bands Based on Real Measurement Data, IEEE Access (2019).
[25] S.H. Gade, S.S. Ram, S. Deb, Millimeter wave wireless interconnects in deep submicron chips: challenges and opportunities, Integration 64 (2019) 127–136.
[26] M.M. Abdulwahid, O.A.S. Al-Ani, M.F. Mosleh, R.A. Abd-Alhameed, Investigation of Millimeter-Wave Indoor Propagation at Different Frequencies, in: 4th Scientific International Conference Najaf (SICN), 2019, pp. 25–30.
[27] A.M. Al-Sammam, M. H Azmi, Y.A. Al-Gumaei, T. Al-Hadhrami, T.Abd. Rahman, Y. Fazea, A. Al-Mqashidi, Millimeter wave propagation measurements and characteristics for 5G system, Appl. Sci. 10 (1) (2020) 335.
[28] J. Xiao, C. Zhao, X. Feng, X. Dong, J. Zuo, J. Ming, Y. Zhou, Review on the millimeter-wave generation techniques based on photon assisted for the RoF network system, Adv. Condens. Matter Phys. 10 (2020) 1–14.
[29] G. Chittimoju, U.D. Yalavarthi, A comprehensive review on millimeter waves applications and antennas, J. Phys. Conf. Ser. 1804 (1) (2021), 012205.
[30] J. Gui, X. Dai, X. Deng, Stabilizing transmission capacity in millimeter wave links by Q-learning-based scheme, Hindawi, Mobile Inf. Syst. 2020 (2020).
