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Review of 5G Channel Models and Modelling of Indoor Path Loss at 32 GHz

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Abstract

The fifth generation (5G) mobile communication technology will be used in 2020s. One of the most important goals of 5G technologies is that it supports connectivity to anyone or anything at anytime, anywhere. For 5G systems, several technologies such as millimeter wave (mmWave) communications, massive Multiple Input Multiple Output (MIMO) communications, and vehicle to vehicle (V2V) communications are being investigated. These technologies bring with new propagation characteristics and certain requirements in the channel modelling stage. Channel modelling is indispensable because it provides information about system design, performance evaluation, efficiency and accuracy. For this reason, various channel modelling is urgently needed for 5G systems. In this study, we will first summarize the requirements for 5G channel modelling and then extensively examine the recent channel models. Eventually, a viewpoint will be provided for future research on channel models.

Keywords: 5G communication systems; Channel modelling requirements; Channel models; Beyond 5G communication systems

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Introduction

The fifth generation (5G) mobile communication technology supports people to access and share data with various scenarios, with very high speed and very low latency [1]. Compared to the current fourth generation (4G) technology, the system capacity is 1000 times, the data rate is 100 times, the energy efficiency is 10 to 100 times and the spectral efficiency is 3 to 5 times improved [2,3]. mmWave is one of the most significant and most promising technologies for 5G systems [4]. Different frequency bands from 24 GHz to 86 GHz in mmWave band are defined for 5G communication systems by International Telecommunication Union (ITU) in World Radio Communications Conference (WRC) in 2019 [5], in which 24.25-27.5 GHz and 31.8-33.4 GHz can be the primary choice for 5G wireless access. Until now there are some channel measurements and modelling work available at 24.25-27.5 GHz, however, there are not enough results at 31.8-33.4 GHz as far as we know which is why we concentrate on 32 GHz channel in this study. Millimeter wave communications can easily provide several gigabit data rates per second by the virtue of its huge bandwidth. If small cells with a radius of 100 to 200 m are utilized, mmWave communication can provide good performance without additional losses [6]. In order to tackle the high path loss, another method is beamforming that can be obtained using massive multiple input, multiple output (MIMO) technology. The working principle of MIMO technology is, an antenna array with high gain can transmit signals to desired directions or receive signals from the desired direction so that signals can transfer around obstacles and compensate for high path loss [7]. In addition, the massive MIMO provides better capacity and better reliability compared to MIMO [8,9]. It is predicted that 5G technologies will provide good performance both under various network structures and between various devices, for instance vehicle to vehicle or device to device (V2V/D2D) communications, moving networks or multihop networks. Moreover, 5G technologies should operate under a wide variety of scenarios, including rural, suburban, urban and indoor environments. The aforementioned technologies can be used to model channel in 5G mobile communications, but there are several requirements:

• Range of frequency: The new 5G channel model to be proposed should be able to operate in a wide frequency range from 500 MHz to 100 GHz. In terms of interoperability with other mobile communication generations (i.e., 3G, 4G), the channel model above 6 GHz should be able to work with the channel model below 6 GHz.

• Wide Bandwidths: The new 5G channel model to be designed should be able to support ultra-wide bandwidth from 250 MHz to 2 GHz.

• Wide variety of scenarios: The new 5G channel model to be offered should be able to bolster a wide variety of scenarios such as rural, suburban, urban and indoor environments.

• Three-Dimensional (3D) Modelling: A comprehensive 3D model should be produced including accurate and reliable 3D propagation modelling and 3D losses modelling in the new 5G channel model to be presented.

• D2D/V2V Scenarios: In these scenarios, both the transmitting antenna and the receiving antenna have small dimensions, so the antennas are subject to interaction with numerous scatterers. The most complex part in D2D or V2V channel models is that they are moving on both sides. The speeds of the two sides relative to each other and to be in different environments cause additional Doppler frequency shift and non-stationary channels [10,11]. Considering the above, it is seen that the D2D/V2V channels are very different from the cellular channels.

• Mobility: The new 5G channel model to be offered should be able to support the high-speed train scenario with a speed over 300 km/h. The channel model should be able to provide information about some of the characteristics of high-mobility channels, such as Doppler frequency and non-stationary.

Despite there are many studies on 5G channel modelling and measurement, there are almost no number surveys about 5G channel modelling and measurement. Moreover, most of the studies on 5G channel modelling and measurements have focused on specific subjects. For instance, mmWave communications [12], MIMO communications [13,14], and V2V communications [15-17]. In all the studies mentioned, there are deficient aspects related to 5G channel modelling. According to the results obtained from the literature review, there is a lack of survey study which includes 5G channel modelling, the channel models developed by various standardization organizations and channel modelling for beyond 5G systems. This paper aims to fill the gap in the literature. The following contributions are aimed with this study:

• The most important channel measurement models in the literature were examined in terms of applications, frequency bands and scenarios. New propagation mechanisms were considered and discussed.

• Various scenarios were presented for 5G channel models. Modelling structures were expressed and compared extensively for each scenario.

• In channel modelling, research directions for 5G and next generation mobile communication technologies were predicted.

The organization of the continuation of this study is as follows. In the second section, 5G channel models made by various standardization organizations are presented. In the third section, future research aspects of 5G and beyond 5G technologies are mentioned. Finally, in the fourth section, the results obtained are reported.

Methodology

5G channel models of standardization organizations

In this section we will describe nine channel models. These channel models are; 3GPP [18], IEEE 802.11ay [19], COST 2100 [20,21], QuaDRiGa [22,23], MiWEBA [24,25], METIS [26], mmMAGIC [27], IMT-2020 [28] and the more general 5G channel model (MG5GCM) [29]. All other channel models except IEEE 802.11ay and MiWEBA channel models are accepted as Geometry Based Scotastic Models (GBSMs). The development of other channel models is based on WINNER II and the Spatial Channel Model (SCM). The Grid-Based GBSM (GGBSM) used in the mmMAGIC and 5GCMSIG channel models was first proposed in the METIS channel model. The GGBSM was developed to supply a spatially consistent and smooth time evolution simulations. The map-based approach, also known as deterministic channel modelling, was proposed by METIS. The map-based approach was improved basis on a 3D geometrical environment to supply realistic, reliable and accurate channel data. Combination of deterministic channel modelling and stochastic channel modelling, which is called hybrid channel modelling was first introduced by 3GPP and METIS, and then adopted by IMT-2020. The hybrid model has advantages such as providing a scalable and flexible simulation, ensuring a harmony between complexity and accuracy. In addition to the hybrid model, the IMT-2020 offers an extended module taking into account the Time-Spatial Propagation (TSP) model [30]. This proposed new method was used to obtain channel parameters by considering environment parameters such as building height, street width as an alternative to other channel models. In consideration of the quasi-optical properties of mmWave band, Quasi-Deterministic (Q-D) modelling method combining stochastic method and deterministic method was proposed by IEEE 802.11ay and MiWEBA. It was observed that the Q-D method exceeds the difficulties encountered in channel modelling for outdoor environment at 60 GHz band.

3GPP channel model: The 3GPP channel model has been updated several times, but the most up-to-date 3GPP channel model is the 3GPP TR38.901 [18], which is commonly used with a 3D wide range of additional modelling components.

Oxygen absorption between the 53 GHz and 67 GHz was modelled as a function of 3D distance between the transmitter and receiver, delay, central frequency by 3GPP. In the 3GPP channel model, intra-cluster powers and delays were unequally determined, moreover high spatial and temporal stability were achieved for large antenna arrays and large bandwidths. In order to have different angle, power and delay for each Multipath Component (MPC), the offset angles of the rays were randomly generated in the cluster. In addition, the number of rays in the cluster at a specified range were determined in light of a set of parameters; array size, intra-cluster delay propagation and intra-cluster angular propagation. Measurements in millimeter wave frequencies indicate that, the overlap of the Line of Sight (LoS) rays and the reflected rays from the ground induces an important fading effect. The rays reflected from the ground by the geometric method are modelled separately from the LoS components and the Non-Line of Sight (NLoS) components. The interaction of the waves having small wavelengths with the propagation environment indicates that the millimeter wave channels depend on the frequency [31]. Correlation modelling was supported in the 3GPP channel model, for multiple frequencies in the same scenario. In addition, parameters were modelled depending on the frequency, such as cluster power, angular propagation and delay propagation.

The 3GPP offered both a stochastic model and a map-based hybrid channel model. This map-based model is a combination of a deterministic component and a stochastic component. The deterministic component was constitute on a digital map by using the Ray Tracing (RT) method and taking into account effects of materials and environmental structures [26]. Stochastic component was improved from 3GPP stochastic modelling method. In the case of massive MIMO and large bandwidth, the entire bandwidth is divided into multiple sub-bands that are not more than the ratio of light speed to the maximum antenna aperture (c/D), and then sub-bands are modelled respectively one by one.

The channel model in a question, capable of simulating spherical waves in massive MIMO, non-stationary antenna array and dual mobility, also takes into account atmosphere attenuation, blockage effects and spatial consistency in mmWave bands. Furthermore, the parameterization study for four scenarios such as indoor office, rural macro cell (RMa), Urban Macro cell (UMa) and street canyon was completed.

IEEE 802.11ay channel model: The IEEE 802.11ad channel model [32], improved for the 60 GHz band (i.e. 57-68 band) was updated to become IEEE 802.11ay channel model [19]. The Quasi-Deterministic (Q-D) channel modelling approach used and developed in the MiWEBA model [24] has been adopted. F-rays, R-rays and D-rays form multipath of the IEEE 802.11ay channel model. F-rays originate from moving objects like vehicles and occur only for short periods of time relatively. F-rays were modelled in stochastic manner, but with a shorter existence time. Relatively poor rays resulting from reflections on objects (random or small) whose position is unpredictable are R-rays. R-rays also were modelled stochastic manner following specific distributions similar to F-rays. The arrival time of the R-rays follows a Poisson process, the phases were uniformly distributed, and the amplitudes were modelled as Rayleigh distribution [33]. As shown in **Figure 1** [19], such as rays reflected from the ground, LoS rays, and other rays reflected from important objects in the scenario relatively strong rays are D-rays. D-rays are modelled depending on the scenario.

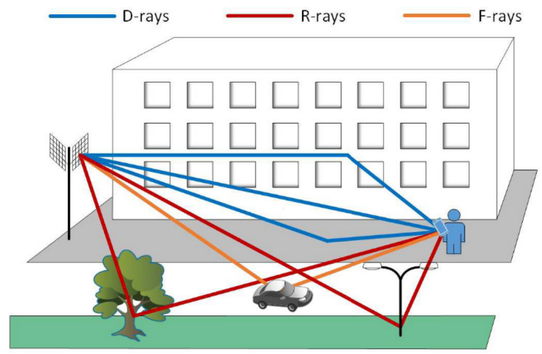

Figure 1: IEEE 802.11ay channel model F-rays, R-rays and D-rays.

The IEEE 802.11ad channel model, which focuses on indoor scenarios such as living room, cell environment and conference hall, is a Single Input Single Output (SISO) model. The IEEE 802.11ay channel model was obtained by adding MIMO usage to the IEEE 802.11ad channel model. Measurement results and RT simulations show that the model can be used more scenarios, such as open space and street canyon. In many outdoor scenarios, D-rays are composed of two components: the beam reflected from the ground and the LoS beam. In addition, the model cannot support high mobility and massive MIMO.

COST 2100 channel model: The COST 2100 channel model focusing on frequency bands below 6 GHz was improved in the light of the COST 259 [34] and the COST 273 channel models [35]. In the COST 2100 channel model, there are three types of clusters including twin clusters, single bounced clusters and local clusters as shown in **Figure 2** [20]. The Base Station (BS) and the Mobile Station (MS) must be defined in order to determine the locations of the twin clusters. The delay and angular parameters on both the BS and the MS side are required to determine the location of the single bounced clusters. Twin clusters and single bounced clusters are located far from the BS and MS. However local clusters are located around the BS or MS. It is assumed that all clusters in COST 2100 are shared by all links and distributed in fixed locations in the propagation environment. According to the cluster distributions and the geometry of their locations the parameters such as power, delay and angle were acquired. That is contrarily to the 3GPP/WINNER model, since clusters exist indirectly. The cluster parameters were designated indirectly according to clusters locations and propagation environment.

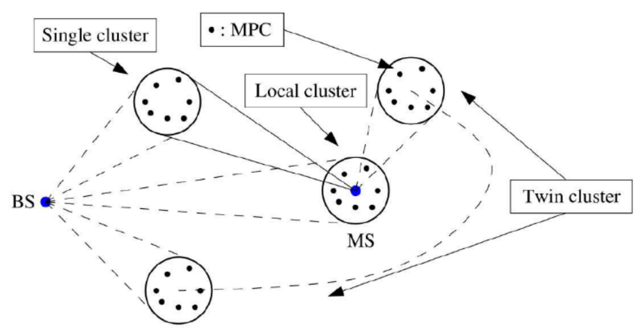

Figure 2: COST 2100 channel model three types of clusters.

The concept of Visibility Region (VR) in the COST 273 is also included in the COST 2100. The VRs were described with circular regions of the same size, equally distributed in the azimuth plane. VRs point out whether a cluster is visible by the MS. In other words, they indicate the extent to which a channel contributes to its realization and whether a cluster is active. Each VR corresponds to a certain cluster, and VRs may impose. The cluster corresponding to the MS changes as the mobile station enters and exits different visibility zones that are causing non-stationary channel simulations.

Receivers in closely configuration can see similar environments by taking advantage of certain locations of clusters. Therefore, the model is spatially consistent and able to be simulated in a realistic and natural way. The COST 2100 model is based on the fixed locations of the clusters in order to obtain the spherical wave fronts easily. It also promotes long time or long-distance simulations and smooth time evolution. The COST 2100 has a disadvantage that the propagation environments defined by the three types of clusters are complex, besides to the mentioned advantages. Furthermore, obtaining and verifying cluster properties through channel measurements leads to relatively difficulties. While propagation environments can be modelled in 3D, visibility zones cannot be modelled in 3D and are still modelled in 2 dimensions. These above-mentioned disadvantages restrain the use of the COST 2100 channel model.

QuaDRiGa: QuaDRiGa is a GBSM which was developed from the WINNER+ channel model and also supports many new features [22]. One of the innovations in the latest version of QuaDRiGa is the production process of the correlated Large-Scale Parameters (LSPs) and supports the frequency range of 0.45 to 100 GHz. In QuaDRiGa channel model, the correlated maps were produced with a 2D map was produced that includes all locations of the receivers. The 2D maps are filtered besides in vertical and horizontal directions, also in diagonal directions, in order to achieve a proper location evolution LSPs. This process was performed with two additional Finite Impulse Response (FIR) filters according to the correlation distance of the LSPs [22,23]. The model supports smooth time evolution by dividing the receiver trajectory into many parts for a long time or distance. A part is admitted to be a time interval, in which the wide-sense stationary is valid [36] and LSPs do not change significantly. A certain number of clusters were produced independently in each part and developed over time, according to geometric relationships. QuaDRiGa, utilizing superimposing regions, combines independent parts with long time sequence channel coefficients as shown in **Figure 3** [22]. This causes the old clusters to ramp-down and the new clusters ramp-up by following a sinus square function. When the MS moves with acceleration, the channel can be modelled by QuaDRiGa with improperly interpolating the channel coefficients. Moreover,

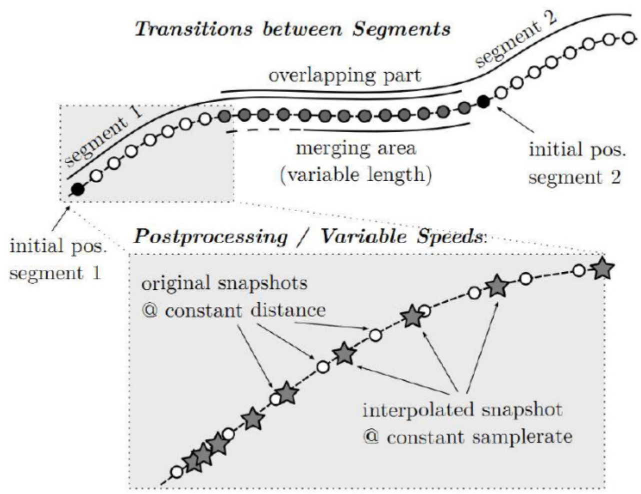

Figure 3: Achieving speed variations through interpolation and transition between segments.

Although QuaDRiGa current version cannot support scenarios where both the transmitter and the receiver are moving, it can support multi-hop networks, multi-cell, multi-user, massive MIMO antennas and 3D antenna modelling. Moreover, the model uses only the WINNER-like modelling structure. QuaDRiGa must achieve a reliable, scalable and flexible simulation and support more advanced channel properties, therefore it must take advantage of other modelling approach such as a map-based model.

MiWEBA channel model: 57 GHz and 66 GHz frequency range (i.e., 60 GHz band) is supported by MiWEBA channel model. In mmWave propagations, low-order reflection components and LoS components compose the majority of the receiving power that was observed through measurements [6,32,37,38]. Diffraction components power is relatively insignificant. In mmWave bands propagation channels demonstrate quasi-optical properties. Therefore a Q-D approach was utilized in MiWEBA channel model. The channel impulse response of the MiWEBA model is obtained by overlapping R-rays and D-rays as shown in **Figure 4** [24]. Reflected from objects such as lampposts, trees and cars weak rays are R-rays. These rays are obtained from the RT simulation results or channel measurement data, as random clusters with stated statistical parameters. D-Rays were modelled with a deterministic method according to the geometry of the environment and these rays compose most part of the received power.

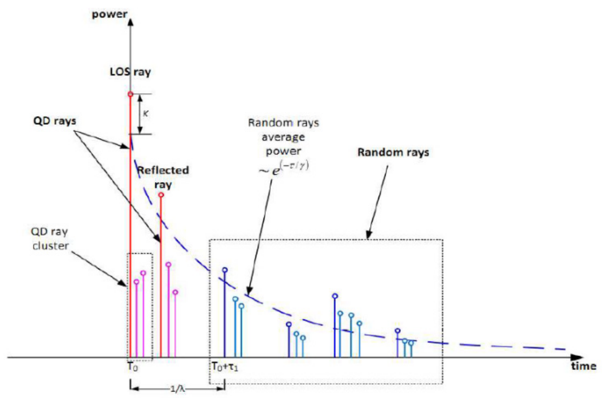

Figure 4: Channel impulse response in MiWEBA model.

Several new communication technologies, such as D2D communications, massive MIMO communications and beam forming are supported by MiWEBA channel model. Model also supports time evolution and evaluates the diffusion rate according to the specular reflection components. The first version of the model can be used for only three scenarios (D2D scenarios, backhaul and outdoor access) in the 60 GHz band. In MiWEBA channel model, dynamic modelling capability is still very restricted and D-Rays were acquired on a certain propagation environment using the RT method.

METIS channel model: In the METIS channel model, a stochastic model, a map-based model and a hybrid model [26] with their combination are used, to support scalable and flexible channel modelling. The stochastic model supports the frequency range of up to 70 GHz, the map-based model supports up to 100 GHz frequency range.

Based on random shadowing objects and using a simplified 3D geometric definition of a propagation environment and based on RT simulation were achieved map-based model. The model, considered propagation structures like blockage diffuse scattering, diffraction and specular reflection. In order to decrease complexity or to increase accuracy diffuse and specular components were taken into account or not. The map-based model meets most of the requirements of the 5G channel model. In addition, it is suitable for application of various 5G technologies such as beam forming, massive MIMO communications, mmWave communications, so it is a significant candidate as 5G channel model.

The METIS channel model uses the stochastic model that is a GBSM improved from the WINNER/3GPP model. In the D2D or V2V scenarios, a six-dimensional (6D) correlation map of LSPs is used when both the transmitter and the receiver are moving. This map creates spatially consistent LSPs [39,40] and leads to high computational complexity. A new approach was suggested including a sum of sinusoidals to produce spatially consistent large-scale parameters by METIS model, which provides more efficient memory utilization and computation than conventional methods. In the stochastic model shown in the **Figure 5** [26], an idea for spherical wavefront and time evolution was proposed. The clusters locations were kept constant according to parameters such as angles and delays. So, parameter deviations can be computed based on geometry.

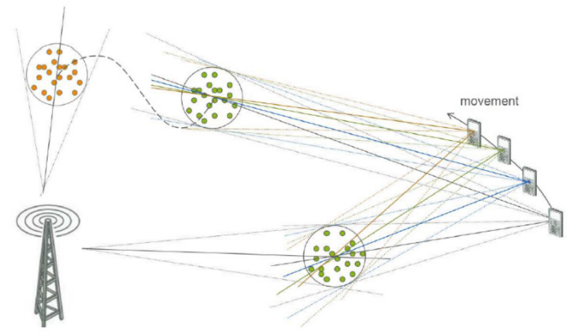

Figure 5: Deviation observed in the parameter due to a small movement of the receiver.

In the first METIS channel models [41], as well as the map-based model and stochastic model, grid-based GGBSM was offered for long time or distance simulations and spatial consistency was obtained. LSPs and Small-Scale Parameters (SSPs) in GGBSM were randomly generated for each predefined grid as shown in **Figure 6** [41], and were obtained on the basis of a 2D map covering all receiver locations in the GGBSM. The interpolation of the parameters in the four closest grids gives the parameters in the actual user locations. Deviations in LSPs and SSPs could be followed up depending on the geometry, and the locations of the clusters were specified by path angles and delays as shown in **Figure 5**.

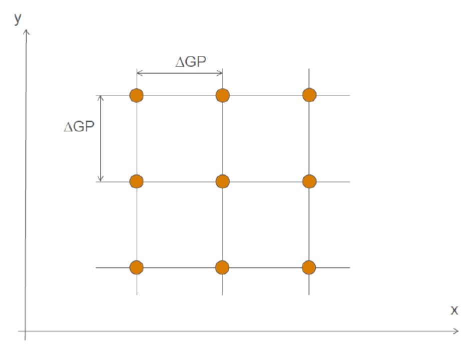

Figure 6: Grid points separated by ΔGP in the coordinate plane in the xy plane.

Scenarios such as V2V communications, D2D communications, shopping mall, indoor, urban micro cell (UMi) and dense UMa cell are supported by METIS channel model and it also supports scalable and flexible channel modelling. It is presumed that the map-based model is simpler than the stochastic model. Moreover map-based model is derived from a simplified 3D digital map that requires truing with measurements.

mmMAGIC channel: QuaDRiGa and the 3GPP (3GPP TR36.873) [42] 3D channel modelling approach was adopted by mmMAGIC channel model. Through the mmMAGIC channel model, measurements was performed in scenarios such as outdoor environment to indoor environment (O2I), open square in UMi, street canyon in UMi, airport and indoor office. In the mmMAGIC channel model, several new modelling methods were offered in order to operate in mmWave bands. LSPs were modelled, according to the measurement results, as frequency dependent. The rays and clusters were modelled according to extended Saleh-Valenzuela model [43], which defines both temporal and spatial domains and LSPs were also modelled according to measurement results as frequency dependent. Rays numbers and clusters numbers in a cluster are modelled random variables. Moreover, in the mmMAGIC channel model ground reflection and blockage effects are taken into account.

It is estimated that model compensates majority of the 5G channel modelling requirements. In addition model operates a great bandwidth 2 GHz and large frequency range between 6 GHz and 100 GHz. Scenarios are not supported yet where both the transmitter and the receiver are mobile. Despite the mmMAGIC channel model can cooperate with many advanced modelling components, how to decrease the complexity of the model and how to obtain a flexible combination of these modelling components must be handled.

IMT-2020 channel model: The IMT-2020 channel model (28) is a GBSM based on 3GPP TR36.873 channel model [42] and the IMT-Advanced channel model [44]. The model supports blockage modelling, large antenna array, spatial consistency, 3D propagation modelling and large bandwidth in great frequency range of up to 100 GHz. The IMT-2020 model was taken into account gas absorption for mmWave bands. Furthermore it also examined the effects of vegetation such as diffusely scattering caused by leaves and diffracted caused by tree canopy. A ground reflection model was presented in the IMT-2020 channel model similar to 3GPP TR38.901 and the frequency dependence of the channel was taken into account.

Two extended modules were offered that improve alternative approaches for producing channel parameters by IMT-2020 channel model. One of the extended modules operates below 6 GHz band and it was based on the TSP model used in the IMT-Advanced channel model. Environment-specific parameters like BS height, building height and street width were considered. The other one of the extended modules operates above 6 GHz band. It was improved based on the map-based hybrid model of the 3GPP that supports a flexible, realistic and accurate simulation utilizing a certain geometric environment. Simulations of both the transmitter and the receiver are mobile cannot be supported in the IMT-2020 channel model.

MG5GCM: Nowadays, the ability to perform specific characteristics of key 5G communication scenarios such as mmWave communications, V2V, high-speed train and massive MIMO, a non-stationary 3D more general 5G channel model was presented [29]. The presented model was improved according to the Saleh Valenzuela and WINNER II as illustrated in **Figure 7**. Birth-death processes are modelled as the appearance and disappearance of clusters on the time axis and array axis. In new composed clusters, angles, powers and delays are randomly produced according to specific distributions in each time instant. Based on their geometrical relations, the parameters were recreated for surviving clusters. In order to provide massive MIMO communications, the spherical wave front was computed based on the clusters physical location. Taking into account high spatial and temporal resolution needs of mmWave channel models, the rays numbers inside of clusters were modelled as Poisson distributed and the powers and delays of the rays inside of the clusters were modelled in an unevenly. Moreover, to provide V2V communications both on the transmitter and on the receiver side Doppler frequencies were considered.

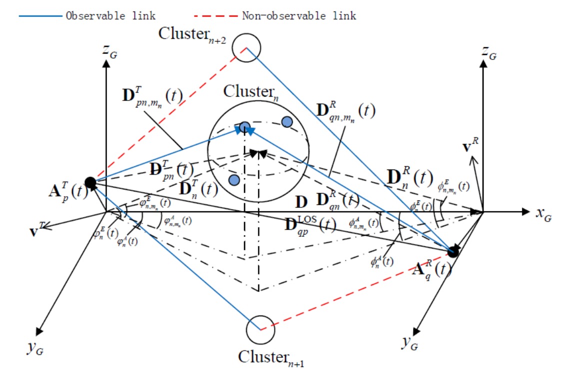

Figure 7: A non-stationary 3D general 5G GBSM.

In the MG5GCM channel model, a number of channel modelling technologies such as intracluster delay propagation, spherical wave front, and array-time evolution were combined. Majority of 5G channel modelling necessities can be met and also can be reduced computational complexity by model. By adjusting the parameters correctly, the model is not only reduced to a variety of simplified channel models but can also be adapted to various communication scenarios. Nevertheless, the MG5GCM was focused on omitted large-scale fading and small-scale fading. In addition the model parameters should be subtracted from the future channel measurements for different scenarios.

Comparison of 5G channel models: Several 5G channel models such as 3GPP (TR38.901), QuaDRiGa, METIS, mmMAGIC, 5GCMSIG, IMT-2020 and MG5GCM utilized WINNER-like framework. According to 5G channel modelling requirements, additional modelling components were added to these models. 3GPP (TR38.901), METIS and IMT-2020 channel models used the map-based hybrid channel model, in order to obtain a reliable, scalable and flexible simulation. In IEEE 802.11ay and MiWEBA channel model, combining a deterministic model which is based on (Q-D) method and a stochastic method is used. Many of 5G channel models promote a large range of frequencies from 0.45 GHz to 100 GHz. Exceptionally the IEEE 802.11ay and MiWEBA channel model were focused on only on the 60 GHz band. In order to model for mmWave channel, 3GPP TR38.901, IEEE 802.11ay, MiWEBA, mmMAGIC and IMT-2020 channel model can be used. These models are map-based channel models that take into account the effects of blockage and gas absorption, and have accurate and realistic determinations on propagation in mmWave bands. In addition, the MG5GCM bolsters the most demanding four scenarios of 5G communication systems such as mmWave communications, high-speed train communications, V2V communications and massive MIMO communications. As shown in **Table 1** an extensive comparison of 5G channel models was performed.

Table 1: 5G channel models comparison.

Characteristic	3GPP	IEEE 802.11ay	COST 2100	QuaDRiGa	MiWEBA	METIS		mmMAGIC	IMT-2020	MG5GM
Range of frequency (GHz)	0.5-100	57-68	<6	0.45-100	57-66	up to 100	up to 70	6-100	0.5-100	-
Bandwidth	10% of the center frequency	2.64 GHz	-	1 GHz	2.16 GHz	10% of the center frequency	100 MHz (<6GH), 1 GHz at 60 GHz	100 MHz (<6 GHz), 10% of the center frequency (>6 GHz)	7:00 p.m.	-
Support mmWave	ok	ok	none	ok	ok	ok	partly	ok	ok	ok
Method of modeling	GBSM, map-based hybrid model	Q-D based model	GBSM	GBSM	Q-D based model	map-based	stochastic	GBSM, GGBSM	GBSM, TSP, map-based hybrid model	GBSM
Modeling of blockage	ok	ok	none	none	ok	ok	none	ok	ok	none
Gas absorption	ok	ok	none	none	ok	ok	none	ok	ok	none
High mobility	limited	none	ok	ok	none	none	limited	ok	limited	ok
Dynamic modeling	ok	limited	ok	ok	limited	ok	none	ok	ok	ok
Support dual-mobility	none	ok	none	none	ok	ok	limited	none	none	ok
Spatial consistency	ok	none	ok	ok	ok	ok	shadow fading only	ok	ok	none
Support spherical waves	none	none	none	ok	ok	ok	none	ok	none	ok

-: No information was found in the relevant papers.

Results and Discussion

Simulations of large-scale path loss model at 32 GHz in indoor office

In this section, we present an explanation of the path loss model and scenario discussed in the simulation campaign. We utilized Wireless Insite software from REMCOM Inc. for the simulation campaign. Wireless InSite software can simulate complex urban, indoor and rural environments using the ray tracing method and provides efficient and accurate predictions of electromagnetic propagation and communication channel characteristics.

Simulation software: Simulations were performed *via* Wireless Insite 3.3.0.3 software. In the simulation environment, the waveform was selected as sinusoid with center frequency 32 GHz, bandwidth 1 GHz and phase angle 0˚. On the transmitter side, omnidirectional antenna with a gain of 20 dBi, VSWR value 1, E-plane half-power beamwidth of 45˚ and input power of 25 dBm was used. On the receiver side, broadband directional pyramidal horn antenna was used with a gain of 18.5 dBi, VSWR value 1, and 3 dB beamwidth of 10˚ in azimuth and 11˚ elevation. The antennas on both the transmitter side and the receiver side were vertically polarized. The continuous wave was transmitted from the transmitter and the received power was recorded on the receiving side. Shooting-and-Bouncing-Rays (SBR) method was chosen as the ray tracing method and full 3-D model was chosen as the propagation model in the simulation environment. **Table 2** show the parameters used in the simulation environment.

Table 2: Channel parameters in the simulation environment.

Parameter	Configuration	Units
Center frequency	32	GHz
Bandwidth	1	GHz
Transmission signal	Continuous wave	-
Transmitter and receiver antenna	Omnidirectional and directional horn antenna	-
Transmitter antenna power	25	dBm
Transmitter antenna height	2.3	m
Receiver antenna height	1.6	m
Transmitter and receiver antenna polarization	Vertical	-

Simulation scenario: We performed simulation campaigns in the indoor office on 4th floor of the Engineering Faculty building, University of Karabuk, Turkey. The simulation environment was a well-known indoor office, floor and walls made of concrete, glass windows, wooden furniture's and doors. The transmitter antenna was mounted 2.3 meters above the ground as in characteristic indoor hotspots, and the receiver antenna was mounted 1.6 meters as in characteristic handsets. In the office, the transmitter antenna was fixed, the receiving antenna was positioned in 6 different locations for simulations both LoS and NLoS. The directional horn antenna on the receiver side was rotated in 10˚ steps over the azimuth plane. Both omnidirectional antenna and pyramidal horn antenna were vertically polarized in all simulation tests.

The separation distance between the transmitter and receiver varied from 1 m to 4 m. The simulations were carried out with 1 m steps from 1 m to 4 m under LoS conditions and at 1.8 m and 3.64 m under NLoS conditions. The simulations were performed indoor office that is in the 4.88 m long, 2.80 in wide and 3.30 m high indoor office. The transmitter (yellow box) and receiver positions (red boxes) and the office plan are seen in **Figure 8**. In each of transmitter and receiver combinations, the receiver was rotated over azimuth plane with 10˚ steps, elevation plane kept constant at 0˚. 36 different angles of arrival were obtained at each receiver position with rotating 10˚ steps over 360˚ azimuth plane. The transmitter antenna kept constant at 0˚ in both azimuth and elevation plane.

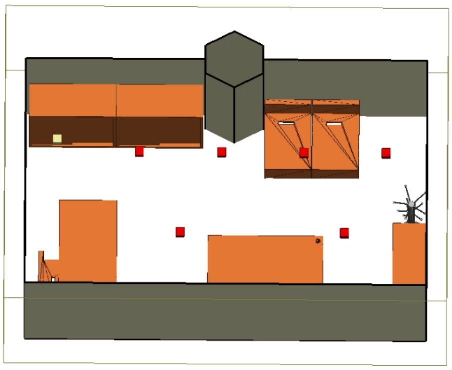

Figure 8: Top view of indoor office.

We processed the received power for each receiver locations *via* the simulation software. The path loss was estimated through the conversion of the power received at each point.

Analysis of large-scale path loss model: The attenuation of the signals propagating in any environment over the distance is estimated by large-scale path loss models. They are important to design more accurate, reliable and efficient next-generation communication systems. Estimating the dominant propagation mechanisms in the indoor office environment is significant in modelling the path loss for 5G communications. In this study, large-scale path loss was modelled in office environments and compared with other 5G channel models in office environments.

Path loss value in free space is calculated with the following equation:

$$FSPL=20\log_{10}(d)+20\log_{10}(f)+20\log_{10}(4\pi/c)-G_t-G_r \qquad (1)$$

where d is the separation distance between transmitter and receiver, f is the carrier frequency, c is the speed of light, G_t is the gain of the transmitter and G_r is the gain of the receiver.

In this study, the model known as close-in (CI) was used to improve the path loss model. The reference distance in free space is accepted as 1 meter and the path loss intercept in CI model is calculated as follows:

$$PL_{CI}=20\log_{10}(4\pi f/c)+10n\log_{10}(d/d_0)+X_\sigma^{CI} \qquad (2)$$

where f is the carrier frequency, c is the speed of light, n is the path loss exponent, d is the separation distance between transmitter and receiver in 3D space, d_0 is the reference distance in free space and X_σ^CI is a random variable with zero mean Gaussian random variable with a standard deviation σ in dB. The path loss exponent (n) is determined using the minimum square error method. Measurement environment is shown in **Figure 9**.

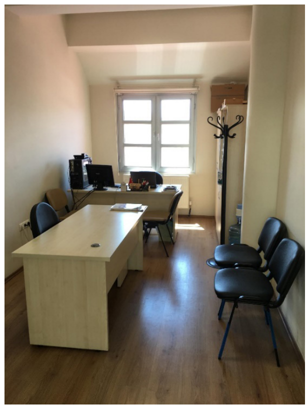

Figure 9: Measurement environment.

In the simulations, the horn antenna at the receiver side is rotated by 10˚ angular steps over the entire azimuth plane while the elevation angle is 0˚. Thus, the directional path loss model is improved which is very useful for the beam forming technique in future millimeter wave communication systems. The directional path loss for the LoS and NLoS simulation scenarios using the CI method expressed in (1) is shown in **Figure 10**. The dashed blue line represents the path loss according to the CI method in the case of LoS, and the blue line represents the path loss according to the CI method in the case of NLoS in **Figure 10**. The 36 black marks in each column are 36 path loss values from 36 azimuth angles while the elevation angle is 0˚. The parameters of the path loss model are listed in **Table 3**.

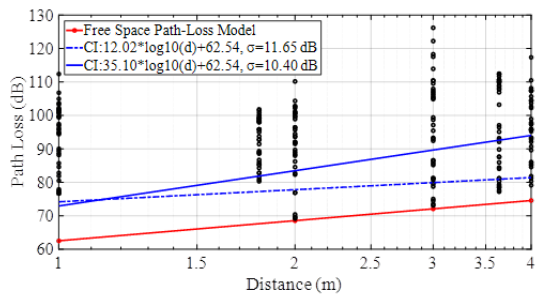

Figure 10: Path loss model for both LoS and NLoS environment.

Table 3: Comparison of the parameters in this study and open literature.

Frequency (GHz)	32 GHz*		32 GHz in mmMAGIC**		32 GHz in 3GPP TR 38.901***	
	LoS	NLoS	LoS	NLoS	LoS	NLoS
Path loss exponent	1.2	3.51	1.38	3.69	1.73	3.83
Intercept	62.54	62.54	33.6	15.2	32.4	17.3
σ	11.65	10.4	1.18	8.03	3	8.03

The obtained path loss exponents are in good agreement with the channel models such as 3GPP and mmMAGIC in the open literature. The obtained parameters of intercept and are different from 3GPP and mmMAGIC channel models, due to the channel models use ABG path loss model and we use CI path loss model.

Future research aspects for 5G and beyond 5G channel modelling

Still there are many disputes about the characteristics of future channel models, except for the topics mentioned above. In future, due to improving channel models, researches will concentrate on that are working together with other modelling methods, covering extremely large frequency bands, focusing on new scenarios and more efficient. In order to model the channel in the future, attractive bands will be Terahertz (THz) communication and visible light communications, the attractive environments will be the human body, underwater, underground and tunnel.

THz communication channel modelling: In the electromagnetic spectrum, taking part between the mmWave and infrared wave, electromagnetic waves ranging from 300 GHz to 10000 GHz, are called THz waves. The THz band is considered a virgin field that has not been exploited before [45]. Due to the advancement of semiconductor device technology and the high data rate required by the end user, the attention to THz communication technologies is rapidly growth. The THz communication is predicted to support high data rates of up to 100 Gbps with its great bandwidth [46]. The signals propagated in the THz band, owing to their high frequencies can face with much greater atmospheric attenuation and free space path loss than the signals propagated in lower frequency bands [47]. Hence, THz systems will highly likely be used together with beam steering techniques in indoor scenarios. The number of developed THz channel models is very low, and THz channel modelling is still in the initial phase. A GBSM proposed to evaluate the performance of the THz channels at system level and to explore their physical properties [48]. A THz channel multi-ray model offered by means of RT methods considering the components of diffracted, scattered, reflected and LoS [49]. It is estimated that more THz channel models will be developed and will be useful.

Visible light communication channel modelling: The visible light band is considered another virgin field that has not been exploited before. The visible light spectrum is taking part between 430 THz and 790 THz [50]. This range can be detected by the human eye. Light Emitting Diode (LED) can be used as a transmitter in visible light communication, thus providing both communication and illumination at the same time. Visible light communication, which has many attractive characteristics, can be a promising solution considering the spectrum shortage in microwave bands. Compared to microwave channels, visible light communication channels can demonstrate different features such as high security, economical, energy saving and environmentally friendly [2,51]. So far, few visible light communication channel models have been improved. Developed deterministic models according to the RT method proposed for visible light communications channels [52,53]. Both the geometry-based single-bounced channel model and the geometry-based multi-bounced channel model are offered for visible light communication channels [54,55]. However, a single-ring model is basis on the geometry-based single-bounced channel model, and an ellipse model or two-ring model is basis on the geometry-based multi-bounced channel model. Three-order reflections were taken into account in the geometry-based multi-bounced channel model. A group of researchers was proposed a model of path loss channel for the visible light communication in the underground mine scenario [56]. A detailed review of the channel modelling and measurements in optical wireless communication systems was conducted. It is estimated that more visible light communication channel models will be developed and will be useful.

Conclusion

In this study, an extensive survey of important issues presents in 5G channel modelling and future research aspects beyond 5G. 5G channel modelling requirements have been investigated. The channel models developed by various standardization organizations for the scenarios that are expected to be used in 5G technology such as mmWave communication, V2V communication and massive MIMO communication have been examined and debated. The channel models covering 5G scenarios are compared. Additionally the path loss is modelled in an indoor office environment for 5G communication in the millimeter waveband. The obtained path loss model is compared with the other path loss models in the open literature. Future research aspects for 5G systems and beyond 5G systems have been summarized. 5G channel models must be simulated through wireless propagation channels, in various scenarios, in various network topologies and in a wide range of frequencies. In 5G systems, hybrid channel model method or multiple channel modelling method should be used rather than only one modelling method. Thus, the challenges faced in 5G systems can be overcome and a good balance can be obtained between the complexity and the accuracy of the model.

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