5G Millimeter-Wave Channel Sounders, Measurements, and Models: Recent Developments and Future Challenges

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Millimeter wave (mmWave) communication is a key technology for fifth generation (5G) wireless communication systems due to its tremendous bandwidth available to support high data rate transmission. The authors investigate the recent developments and future challenges in 5G mmWave channel sounders, measurements, and models.

ABSTRACT

Millimeter wave (mmWave) communication is a key technology for fifth generation (5G) wireless communication systems due to its tremendous bandwidth available to support high data rate transmission. This article investigates the recent developments and future challenges in 5G mmWave channel sounders, measurements, and models. Various channel sounders are comprehensively classified and compared. Channel measurements in diverse indoor and outdoor scenarios for different mmWave bands are surveyed. Meanwhile, a comparison of multiple mmWave bands, validation of mmWave massive multiple-input multiple-output (MIMO) channel properties, and measurement and modeling of human blockage effects are shown. Different channel modeling approaches including deterministic, semi-deterministic, and stochastic modeling methods are summarized. Some future research directions are also given.

INTRODUCTION

The developments of wireless communications via traditional technologies seem to encounter bottleneck constraints due to limited bandwidths. The demands for high data rate transmission and high integrity services have grown rapidly in the coming fifth generation (5G) wireless communication systems. Millimeter wave (mmWave) communication is a promising key technology to meet 5G requirements.

MmWave communication has received increasing attention due to its tremendous bandwidth available to support Gigabits per second (Gb/s) data rate transmission in cellular (hotspot and small cell), wireless fronthaul/backhaul, indoor, device-to-device (D2D) communications, etc [1–3]. Early works concentrated on 60 GHz bands due to the huge unlicensed bandwidths. At least 5 GHz unlicensed bands are available globally at 60 GHz bands. In the USA, apart from the 57–64 GHz unlicensed bands, the 64–71 GHz bands were also authorized with unlicensed operations later by the Federal Communications Commission (FCC), for a total unlicensed bandwidth of 14 GHz (57–71 GHz). Meanwhile, the IEEE 802.15.3c and IEEE 802.11ad standards are completed, and IEEE 802.11ay is being developed for next generation wireless fidelity (WiFi) around 60 GHz bands. Other frequency bands that have been widely investigated include 11, 15, 28, 38, 45, and 73 GHz bands. Various standardization organizations, international projects, and research groups such as 5GCM, 3GPP, METIS, MiWEBA, mmMAGIC, and NYU WIRELESS have aimed to propose channel models for 6–100 GHz [1, 3]. In addition, the International Telecommunications Union (ITU) has identified different frequency bands in the range of 24.25–86 GHz as candidate frequencies for 5G at the World Radiocommunication Conference 2015 (WRC-15) [4]. Accordingly, there have been some preliminary works on investigating the propagation characteristics at the 26 GHz and 32 GHz bands [5, 6].

Furthermore, mmWave has very different channel propagation characteristics compared with sub-6 GHz bands, such as the high path loss (PL), high penetration loss, high directivity, high delay resolution, and human blockage. Due to the high PL, directional antennas will be used rather than omni-directional antennas. The high penetration loss constricts mmWave to be used in a relatively short distance. The high directivity makes beamforming a promising technology, which can overcome the high PL. Analog beamforming employs only one radio frequency (RF) chain for antenna arrays and only phases of the signal can be controlled. For digital beamforming, each antenna element is equipped with a RF chain and both the phase and amplitude of the signal can be controlled. The trade-off between cost and performance leads to hybrid beamforming. As the bandwidth is at the level of GHz, the delay resolution may be on the order of ns. Meanwhile, human movements will cause long fade durations with deep signal fades due to the use of directive antennas. Owing to the short wavelength, large antenna arrays with relatively small antenna form factors are possible, which makes massive multiple-input multiple-output (MIMO) communication favorable at mmWave bands. Additional propagation properties including spherical wavefront, non-stationarity in space-time-frequency domains, and cluster evolution, need to be carefully considered. All

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of these properties present huge challenges to mmWave channel sounders, measurements, and modeling for future 5G wireless communication systems.

Some earlier survey papers have focused on mmWave communication channels, for example, [3, 4], and [7]. An investigation of mmWave communications for future wireless systems was presented in [3], including recent channel measurement campaigns and modeling results. An extensive overview of mmWave propagation characterization and modeling was given in [4], and some channel sounding techniques and standardizations were mentioned. A summary of mmWave channel measurements conducted by NYU WIRELESS was given in [7] in 2015, as well as different directional and omni-directional PL models. However, none of the above survey papers have covered all the areas of mmWave channels, that is, classify existing channel sounders, summarize recent channel measurement campaigns, and discuss channel modeling approaches. Meanwhile, some recent advances have not been covered by previous surveys due to the fast developments of mmWave communications. For example, the comparison of multi-frequency mmWave bands, validation of MIMO properties, and big data enabled channel modeling were not discussed in previous works. Hence, the aim of this article is to provide a comprehensive overview of the state-of-the-art developments and future challenges in mmWave channel sounders, measurements, and models for 5G wireless communication systems.

The remainder of this article is organized as follows. The frequency and time domain channel sounders are compared in the following section. Different mmWave channel measurement campaigns are then summarized, as well as a comparison of multiple mmWave bands, validation of mmWave massive MIMO properties, and measurement and modeling of human blockage effects. Different channel modeling approaches are then summarized. Some future research directions are then given. Conclusions are drawn in the final section.

MMWAVE CHANNEL SOUNDERS

A channel sounder usually means a channel measurement system consisting of a transmitter (Tx), a receiver (Rx), and a fast data acquisition unit. As frequency increases, the equipment such as high performance signal generator, arbitrary waveform generator (AWG), and digitizer will be more expensive and difficult to design, as well as high quality power amplifier (PA) and low noise amplifier (LNA), high gain antennas, and low loss phase stable cables. Thus, the design of an mmWave channel sounder with large dynamic range, large bandwidth, fast measurement speed, long continuous record time, long measurable distance, and multiple channels, will be a challenging task.

Channel characteristics can be measured in either the time domain or frequency domain, generating the channel impulse response (CIR) or channel transfer function (CTF), respectively. Theoretically, the results are equivalent in both domains and can be transformed from one domain to the other by Fourier transform. However, in practice, the two measurement approaches are quite different.

FREQUENCY DOMAIN CHANNEL SOUNDERS

A frequency domain channel sounder typically uses chirp or multi-tone signals over a wide frequency range to sound the channel. This approach can be easily implemented based on a vector network analyzer (VNA), for example, channel measurements in [1, 8–10]. The VNA has flexible control to sweep frequency in a predefined large bandwidth with all the related hardware precisely synchronized. The measured S21 parameter denotes the CTF and can be transformed to CIR. As the Tx and Rx are physically in one unit, Tx and Rx antennas are connected to two ports of the VNA through a phase stable cable, which has high attenuation with increasing frequency and limits the measurable distance. Thus, this method is often confined to indoor channel measurements. Meanwhile, a snapshot of the channel takes a significant amount of time, depending on the measurement bandwidth, sweeping frequency points, and the intermediate frequency (IF) bandwidth. Hence, this method is usually limited to quasi-stationary environments. The variation and evolution of a dynamic channel cannot be measured.

There are some approaches to enlarge the dynamic range and measurable distance of the VNA-based channel sounder. Rather than using direct RF transmission, an additional up-converter and down-converter can be added at both ends to reduce the cable loss by transmitting a relatively low frequency local oscillator (LO) and IF signals [8]. Another approach is using additional signal generators to enlarge the Tx and Rx distance, such as in [8, 9]. The reference clock synchronization and frequency control between the signal generator and VNA can be achieved through rear panel cable connections. Moreover, additional electronic-to-optical (E/O) and optical-to-electronic (O/E) converters can be used, such as in [8]. The electric cable is then replaced by an optical fiber cable that can be as long as 200 m with low cable loss.

Meanwhile, there are also some custom-designed frequency domain channel sounders. In [11], a digital frequency sweep channel sounder was designed and used a chirp signal as a sounding signal. The channel sounder was used to measure a 2 × 2 MIMO channel. In [12], a channel sounder used an unmodulated multi-tone signal to measure a 24 × 24 MIMO channel. In [13], a channel sounder was designed and used a multi-tone sounding signal. Both Tx and Rx sides were equipped with 8 × 2 antenna arrays.

TIME DOMAIN CHANNEL SOUNDERS

Time domain channel sounders obtain CIRs by exciting the channel with short pulses or pseudo noise (PN) sequences at the Tx side and recording the received signal with a sampling oscilloscope at the Rx side, and then produce a time-dilated cross-correlation of the received and transmitted signals. Both PN and chirp sequences can achieve low peak to mean power ratios. Time domain channel sounders are usually implemented with more complicated custom-designed components or with commercial off-the-shelf (COTS) hardware. At the early stage, a swept time-delay cross-correlation (STDCC) sounder based on PN sequences is widely used. It is also

Additional propagation properties including spherical wavefront, non-stationarity in space-time-frequency domains, and cluster evolution, need to be carefully considered. All of these properties present huge challenges to mmWave channel sounders, measurements, and modeling for future 5G wireless communication systems.

Ref.	Group	Hardware	Time/frequency domain	Waveform	Frequency and bandwidth (GHz)
[1, 9]	Shandong University, China	VNA + signal generator	Frequency domain	Chirp, sweep frequency	11, 16, 28, 38, and 60; 2/4
[2, 7]	NYU WIRELESS, USA	NI-based channel sounder	Time domain	PN, sliding/wideband correlation	28, 38, 60, and 73; 0.5/0.75/1
[5]	Beijing Jiaotong University, China	R & S signal generator and signal analyzer	Time domain	PN, wideband correlation	26; 0.2
[6]	North China Electric Power University, China	COTS Keysight channel sounder	Time domain	PN, wideband correlation	32; 1
[8]	Aalto University, Finland	VNA + signal generator + up/downconverter	Frequency domain	Chirp, sweep frequency	60; 4
[10]	Tongji University, China	VNA	Frequency domain	Chirp, sweep frequency	15; 4
[11]	Durham University, UK	Custom-designed channel sounder	Frequency domain	Chirp	60; 6
[12]	Tokyo Institute of Technology, Japan	Custom-designed channel sounder	Frequency domain	Multi-tone	11; 0.4
[13]	University of Southern California, USA	Custom-designed channel sounder	Frequency domain	Multi-tone	28; 0.4
[14]	Samsung, Korea	Custom-designed channel sounder	Time domain	PN, sliding correlation	28; 0.25
[15]	National Institute of Standards and Technology (NIST), USA	Custom-designed channel sounder	Time domain	PN, wideband correlation	83.5; 1

Table 1. A summary of mmWave channel sounders.

named a sliding correlation as it implements pulse compression based on the correlation principle. Two identical PN sequences with slightly different clock speeds are generated at the Tx and Rx sides. The received signal from the Tx (channel distorted PN sequence) is correlated with the PN sequence at the Rx, resulting in a time-dilated signal with a large processing gain that improves the signal-to-noise ratio (SNR). Channel sounders of NYU WIRELESS [7] and Samsung [14] are based on this technique. This method has the advantages of high bandwidth and efficient data compression to enable real-time recording and fast post-processing. Recently, some channel sounders based on direct correlation or wideband correlation have been developed, such as in [2, 5, 6, 15]. In [2], the developed channel sounder is mainly based on National Instruments (NI) hardware. It can switch between sliding correlation mode and wideband correlation mode. In [5], the channel sounder is based on a Rohde & Schwarz (R&S) signal generator and signal analyzer. In [6], the COTS channel sounder is based on Keysight hardware. Compared with sliding correlation, wideband correlation does not need a copy of the waveform and the received signals are directly sampled by a high-speed analog-to-digital converter (ADC).

The Tx and Rx sides of time domain channel sounders can be separated. Thus, time domain channel sounders are usually applied to outdoor channel measurements to gather a large number of samples quickly. However, the maximum signal bandwidth is constrained by instrument limitation, that is, the bandwidth or sampling speed of the available components. Rubidium clocks are usually used at both sides for time and frequency synchronization. Synchronization can also be achieved using alternative simple and low cost schemes such as cable connections.

To characterize the angular domain information, rotated directional antenna (RDA) and uniform virtual array (UVA) methods can be applied [9]. For the RDA-based method, a directional antenna is scanned in angular domains with a small angle rotation step. For a UVA-based method, an omni-directional antenna is shifted in the three-dimensional (3-D) space with a spacing step to form an antenna array. One of the disadvantages of the RDA and UVA methods is that the channel should be kept static during channel measurements. In addition, some channel sounders also have the ability to measure MIMO channels with real antenna arrays working in switch or in parallel [11, 12, 15].

A more detailed summary of channel sounders that have widely been used to conduct channel measurements in the literature is summarized in Table 1, considering the hardware, sounding method, waveform, frequency, and bandwidth. The measurement frequency varies from 11 GHz to 83.5 GHz, while the bandwidth varies from 0.2 GHz to 6 GHz. The advances of mmWave channel sounders mainly lie in high speed digitizers, directional antennas, and MIMO/beamforming antenna arrays. The measurable frequency bands, signal bandwidth, RF channels, system dynamic range, and measurement speed have largely been improved in recent channel sounder developments.

Ref.	Frequency (GHz)	Bandwidth (GHz)	Scenario	Antenna configuration	Channel statistical properties
[12]	11	0.4	Indoor: room (18 x 10 x 3 m^3), hall (30 x 10 x 3 m^3), and museum (30 x 20 x 6.5 m^3)	Tx/Rx: dual-polarized 12-element circular arrays, 1.7 m height	PDP, DMC, XPR, eigenvalue
[1]	11/16/28/38	2/2/4/4	Indoor: office (7.2 x 7.2 x 3 m^3)	Tx: 2.6 m height, four locations, 10 dBi horn antenna, UVA; Rx: 1.45 m height, 3 dBi omni-directional antenna	PDP, PAP, RMS DS, RMS AS, channel capacity
[10]	15	4	Outdoor: building top	Tx: 0.6 m height, two locations, 4 dBi omni-directional antenna; Rx: 4 dBi omni-directional antenna, UVA	K-factor, RMS DS, RMS AS, number of clusters
[5]	26	0.2	Indoor: hall (20.1 x 20.2 x 4.5 m^3)	Tx: 2.5 m height, omni-directional antenna; Rx: 2 m height, omni-directional antenna, UVA	SF, PDP, RMS DS, coherence bandwidth
[7]	28/38/60/73	0.4/0.4/0.75 /0.4	Outdoor: campus, vehicular	Tx/Rx: horn antennas, RDA, various configurations	PL, outage probability, RMS DS
[13]	28	0.4	Outdoor: microcell	Tx: 7.5 m height, phase array; Rx: 1.8 m height, phase array	PL, RMS DS
[14]	28	0.25	Outdoor: urban street canyon	Tx: 15 m height, horn antenna; Rx: 1.5 m height, 48 locations, horn antenna, RDA	PL, RMS DS, RMS AS
[6]	32	1	Outdoor: campus	Tx: 6.1 m height, omni-directional antenna; Rx: 1.8 m height, horn antenna, RDA	PADP, PL, RMS DS, RMS AS, K-factor
[9]	60	2	Indoor: office (7.2 x 7.2 x 3 m^3)	Tx: 1.6 m height, 12 locations, 25 dBi horn antenna (RDA) or omni-directional antenna (UVA); Rx: 1.6 m height, horn antenna	PADP, PDP, PAP, RMS DS, RMS AS
[11]	60	6	Indoor: room; outdoor: street	Tx/Rx: 20.7 dBi horn antennas	PDP, PL, RMS DS, channel capacity
[15]	83.5	1	Indoor: laboratory (7 x 7 x 0.5 m^3)	Tx: 22.9 dBi horn antenna or 4 dBi reflector; Rx: octagonal waveguide antenna, switch	PADP, PDP, PL, Doppler shift

Table 2 . A summary of channel measurement campaigns.

MMWAVE CHANNEL MEASUREMENTS

MEASUREMENT SETUP

When planning for channel measurements, a set of predefined Tx and Rx antenna locations are chosen with different heights to imitate the base station and mobile station in different environments. Many mmWave indoor and outdoor measurements are conducted by using a high gain directional antenna due to the high PL. The measurement frequency, signal bandwidth, and antenna numbers at each side should also be carefully considered. The data obtained can be stored in a computer for post processing. Before the measurement, a back-to-back calibration should be conducted to calibrate the system response. In order to extract channel related parameters from the calibrated measurement data, including path amplitude, delay, and azimuth and elevation angles, parameter estimation algorithms like space-alternating generalized expectation-maximization (SAGE) are usually utilized.

MEASUREMENT RESULTS

Large-scale channel characteristics consist of PL and shadowing fading (SF) (usually characterized by PL exponent and SF standard deviation, respectively.) They are indispensable for efficient network deployment and optimization. Small-scale fading caused by multipath components (MPCs) causes rapid changes in signal strength over a small distance. It is crucial for physical layer (PHY) design in developing and testing different system schemes. This can be characterized by some important channel parameters in temporal and angular domains. The power delay profile (PDP), power angle profile (PAP), power angle delay profile (PADP), root mean square (RMS) delay spread (DS), angle of arrival (AoA), angle of departure (AoD), and RMS angle spread (AS) are among the most investigated ones.

Extensive channel measurements have been conducted at 11, 15, 16, 26, 28, 32, 38, 60, and 73 GHz bands in various indoor and outdoor environments. Table 2 summarizes some recent channel measurement results in the literature, including the frequency, bandwidth, scenario, antenna configuration, and channel statistical properties. The measured indoor scenarios include office, hall, museum, and laboratory, while the measured outdoor scenarios include UMi, UMa, RMa, open-square, street, campus, and building top. A detailed investigation of dense multipath component (DMC) and cross-polarization ratio (XPR) is given in [12]. MmWave mas-

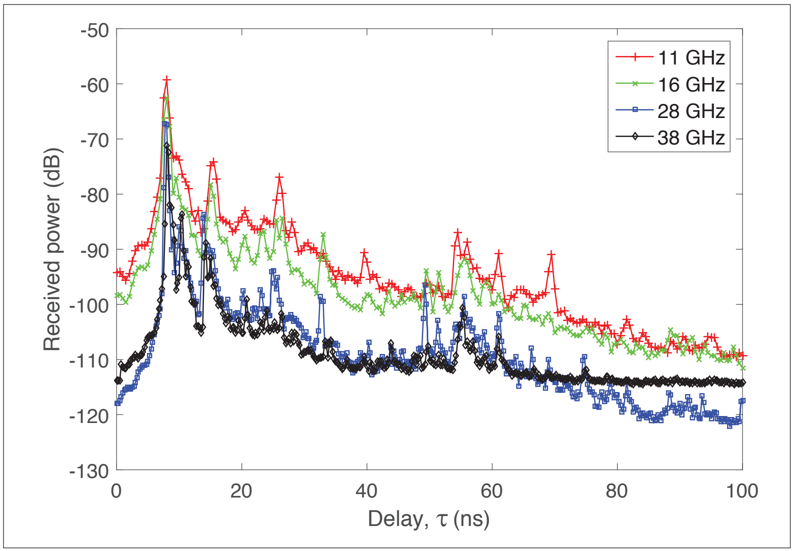

Figure 1. Comparison of APDPs at multiple mmWave bands.

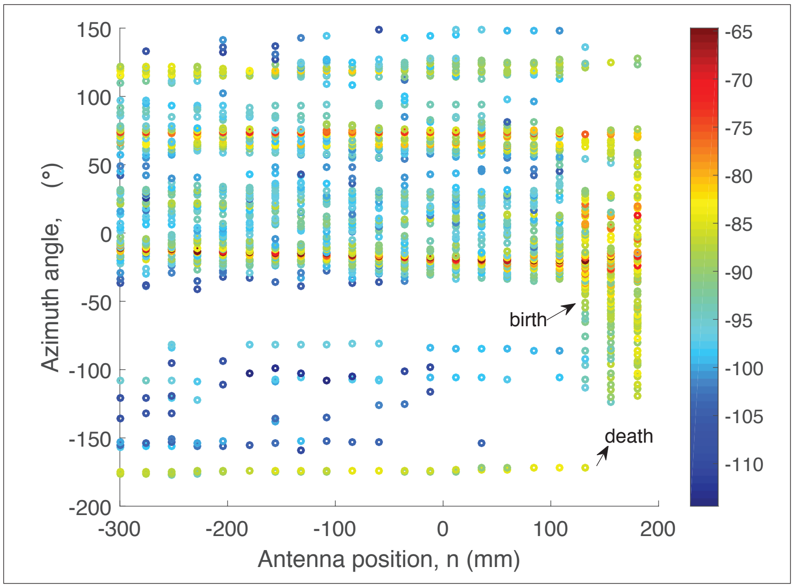

Figure 2. PAP variations over the array at 16 GHz band [1].

sive MIMO properties are studied in [1, 5, 10]. Doppler shift is shown in [15] in a time-varying environment.

Meanwhile, there have been various theoretical works on mmWave channel sparsity, diversity, multiplexing, shadowing correlation, and so on. Some general conclusions can be drawn about mmWave channels based on experimental and theoretical works. MmWave shows sparsity in space and arrives in clusters. MmWave is also sensitive to the environments and shows non-stationarity. The RMS DS is usually smaller for indoor scenarios than that of outdoor scenarios. Large diversity and multiplexing gains can be achieved via massive MIMO antenna arrays.

In addition, we have taken multiple mmWave massive MIMO channel measurements and human blockage measurements. Three specific aspects will be investigated here, including a comparison of multiple mmWave bands, validation of mmWave massive MIMO properties, and measurement and modeling of human blockage effects.

Multi-Frequency Comparison: As many channel measurements were conducted with different configurations, it is hard to fairly compare propagation characteristics of different mmWave bands. Thus, it is desirable to compare different mmWave bands with the same configurations [1]. We conducted channel measurements in an office environment at multiple mmWave bands. Figure 1 shows the comparison of average PDP (APDP) at 11, 16, 28, and 38 GHz bands [1]. As frequency increases, both the powers of the line-of-sight (LOS) path and reflected paths decrease due to free space path loss in the first meter, multiple-reflections, penetration, and so on. For the four mmWave bands, most paths arrive with similar delays and angles. The RMS DS and ASs have no clear tendency with frequency. The power level and power decay rate are the main differences between different mmWave bands.

Massive MIMO Properties Validation: The combination of mmWave with massive MIMO can enormously improve wireless access and throughput. A mmWave massive MIMO system can have a relatively small antenna form factor and benefits from large available signal bandwidth. We conducted channel measurements in the same indoor office environment by using the UVA method. The Rx omni-directional antenna was placed on the positioner and controlled to scan to form a large horizontal virtual array. Figure 2 shows the PAP variations over the array at 16 GHz band [1]. The azimuth angles of MPCs drift over the array, which shows that MPCs arrive with spherical wavefront rather than plane wavefront. Meanwhile, some MPCs were not observed all over the array, illustrating the cluster birth-death and non-stationary properties. These mmWave massive MIMO properties need to be further studied.

Human Blockage Measurements and Modeling: Human blockage will degrade the received signal strength and have great impact on channel quality. Human blockage effects were measured in [2] at 73 GHz bands. The METIS knife-edge diffraction (KED) model was applied to model the human blockage loss. Here, we conducted human blockage measurements at 32 GHz bands similar to [2]. The Tx and Rx were equipped with 20 dBi horn antennas. Figure 3a shows the measured CIR when the person walked along the perpendicular direction of the Tx-Rx connecting line. The relative received power means that the maximum received power of paths is set to 0 dB. Not only the LOS path was heavily blocked when the person was between the Tx and Rx antennas, but also some reflected paths were blocked. In Fig. 3b, the measured and modeled human blockage losses are shown. The METIS KED, Kirchhoff KED, and geometrical theory of diffraction (GTD) models were applied to model the loss. In addition, the Gaussian model was applied to fit the loss. The maximum loss can be 15–20 dB, which will degrade the quality of the communication channel, except that the GTD model over-estimates the loss, while other models fit the measurement data very well.

MMWAVE CHANNEL MODELS

Channel modeling is an abstraction of the real wireless channel and based on experimental channel measurements. It can be done in a deterministic manner in a site-specific environment and

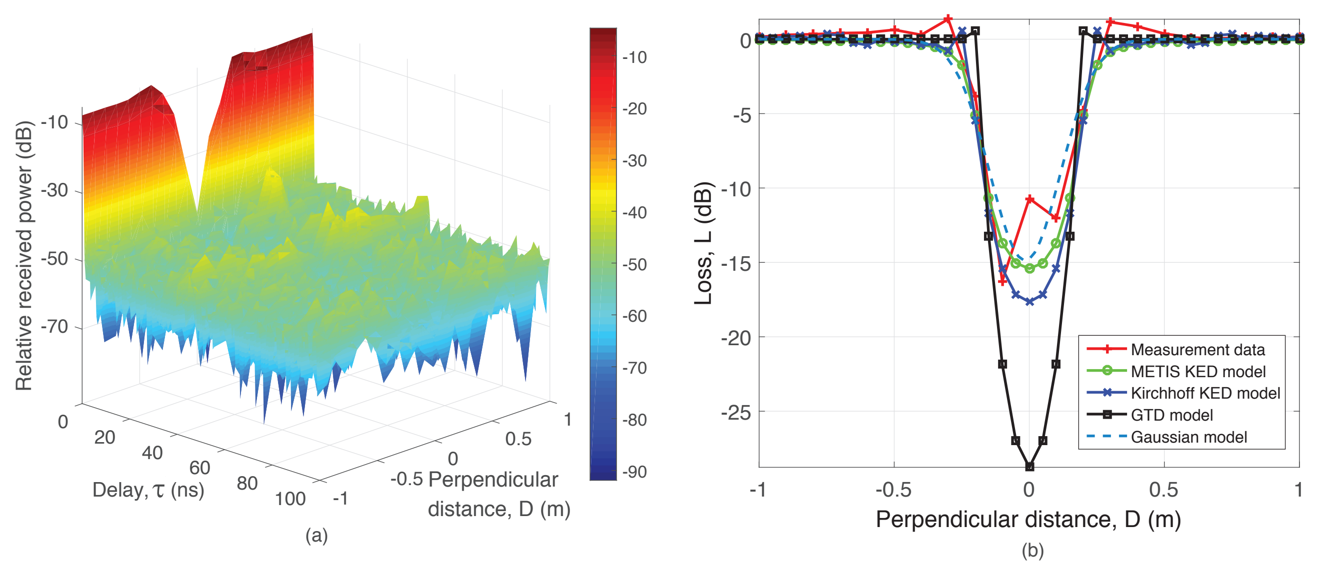

Figure 3. a) Measured CIR with human blockage; b) measured and modeled loss caused by human blockage.

validated by comparing detailed path parameters with channel measurements, or in a stochastic manner to model general environments and validated by comparing channel statistical properties with channel measurements. Channel models can shed light on complex radio wave propagation mechanisms and allow system performance evaluation. Typically, channel models highly depend on carrier frequency, bandwidth, environment layout, and system under consideration.

MmWave is more susceptible to the propagation environment and hence, propagation mechanisms related to frequency should be taken into consideration. Parameters related to penetration, reflection, diffraction, diffuse scattering, and others should be considered as frequency-dependent and carefully investigated. In the following, modeling approaches including ray tracing, map-based, point cloud, quasi-deterministic (Q-D), Saleh-Valenzuela (SV), propagation graph, and geometry based stochastic model (GBSM), are summarized in Table 3 and classified into deterministic, semi-deterministic, and stochastic channel models.

DETERMINISTIC CHANNEL MODEL

Ray Tracing Model: Ray tracing is a deterministic simulation approach due to its ability to provide a deterministic characterization of multipath channels. It is based on geometry optics (GO), GTD, and uniform theory of diffraction (UTD), which can approximate and simplify high frequency electromagnetic propagations. GO is used to calculate the direct, reflection, and refraction paths, while GTD and UTD are used to calculate the diffraction paths. Image-based and shooting and bouncing ray (SBR) are two widely used methods to find pathways from the Tx side to the Rx side. For each path, the complex amplitude, delay, and departure and arrival angles are obtained. The accuracy of ray tracing vastly depends on detailed descriptions of the environment, including physical structures of objects and their electromagnetic parameters. A more accurate description of the environment leads to higher complexity.

Map-Based Model: The map-based channel model is proposed by METIS [3]. It is based on ray tracing using a simplified 3-D geometric description of the environment and thus inherently accounts for significant propagation mechanisms like specular reflection, diffraction, scattering, and blocking. The model provides accurate and realistic spatial channel properties and is suitable for evaluating massive MIMO and beamforming, and also for realistic PL modeling in the case of D2D and vehicle-to-vehicle (V2V). At first, a map is defined and random objects are drawn. Then point sources for diffuse scattering and Tx/Rx locations are defined. Pathways are then determined with path lengths and arrival/departure angles. Shadowing loss, LOS, reflection, diffraction, and scattering are considered to compose the CIR.

Model	Deterministic/ stochastic	Example	Scenario	Features
Ray tracing	Deterministic	IEEE 802.11ad	Indoor/outdoor	Site specific and high complexity
Map-based	Deterministic	METIS	Indoor/outdoor	Support massive MIMO and beamforming
Point cloud	Deterministic	–	Indoor	Characterize the environment with higher precision
Q-D	Deterministic + stochastic	MiWEBA and IEEE 802.11ay	Outdoor	Support non-stationary environments
SV	Stochastic	IEEE 802.15.3c and IEEE 802.11ad	Indoor	Clustering MPCs in delay and angle domains
Propagation graph	Deterministic/ stochastic	–	Indoor	Predict PDP transition from specular to diffuse
GBSM	Stochastic	NYU WIRELESS, 3GPP TR 38.901, METIS, and mmMAGIC	Indoor/outdoor	Characterize 3-D and non-stationary properties

Table 3. A summary of channel modeling approaches.

For 5G wireless communication systems, there are some challenging scenarios, including massive MIMO, V2V, high speed train (HST), and so on. These challenging scenarios have not been fully measured and analyzed. More mmWave channel measurements in these challenging scenarios is indispensable for mmWave propagation channel characteristics.

Point Cloud Model: The point cloud model is a prediction tool similar to ray tracing to characterize the environment with higher precision [8]. Well known methods like laser scanning can be applied to obtain the point cloud environment data with finer object structures. However, point cloud data cannot be used directly in ray tracing tools because no surface representation is available. At first, cloud points are filtered and neighboring points are found, then normals and plane depth are found to form local surfaces. Propagation mechanisms including LOS path, specular paths, and diffuse paths are considered. MPC parameters including amplitudes, delays, and angles are calculated. At last, PDP is calculated from combined paths with bandwidth limitation.

Semi-Deterministic Channel Model

Q-D Model: A new Q-D modeling approach is proposed for mmWave channels in non-stationary environments and adopted by MiWEBA and IEEE 802.11ay. This method is based on measurement results and ray tracing simulations. The rays with different activity percentages are defined as deterministic rays (D-rays), random rays (R-rays), and flashing rays (F-rays), respectively. It models D-rays in deterministic and R/F-rays in stochastic. It also adopts the IEEE 802.11ad model for PDP modeling. Such a hybrid approach does not require a detailed scenario description such as ray tracing and is much more accurate than pure statistical approaches. The modeled channel includes power, delay, arrival and departure angles, and polarization matrix of rays.

Stochastic Channel Model

SV-Based Mode: The SV model has been widely used to model CIR in indoor environments [9]. The original SV model assumes that rays arrive in clusters in the delay domain, where delays follow a Poisson distribution and inter-arrival times follow an exponential distribution. The CIRs are described by parameters including cluster power decay rate, ray power decay rate, cluster arrival rate, and ray arrival rate. The SV model is then modified and extended to the angle domain and adopted by IEEE 802.15.3c and IEEE 802.11ad [9]. In IEEE 802.11ad channel model, the SV model is modified with both pre-cursor and post-cursor decay rates in each cluster.

Propagation Graph Model: The propagation graph channel model can predict the exponentially decaying PDP which exhibits a transition from specular to diffuse components [1]. Thus, it is suitable for the modeling of mmWave channels. The propagation graph model is based on graph theory. A propagation graph is a pair of disjoint sets of edges and vertices. Txs, Rxs, and scatterers are represented by vertices, and the propagation conditions between the vertices are represented by edges with probability values. After the generation of a signal flow graph from the Tx side to the Rx side, the frequency-dependent CTF can be obtained and transformed to CIR. The angle information can also be obtained from the geometry distributions of Txs, Rxs, and scatterers.

GBSM: GBSMs have been widely used for channel modeling in various scenarios including mmWave bands [1]. GBSMs can be classified as regular-shaped (RS) GBSMs and irregular-shaped (IS) GBSMs. RS GBSMs assume effective scatterers to be located on regular shapes such as one-ring, two-ring, ellipses, cylinders, and so on. For IS GBSMs, irregular shapes of effective scatterer locations are assumed.

The standard WINNER II channel model and 3GPP spatial channel model (SCM) are IS GBSMs. First, the scenario, network layout, and antenna parameters are set. The LOS/Non-LOS (NLOS) condition is then assigned according to the LOS probability model and the PL is calculated according to the PL model. Correlated large-scale parameters (LSPs) including RMS DS, azimuth angle spread of arrival (ASA), azimuth angle spread of departure (ASD), zenith angle spread of arrival (ZSA), zenith angle spread of departure (ZSD), K-factor, and SF are then generated. Small-scale parameters including delays, cluster powers, arrival and departure angles, and XPR are then generated and randomly coupled. Lastly, initial phases are randomly assigned and channel coefficients are obtained. The values of the channel model parameters table are extracted from a large amount of channel measurements. Some works have tried to extend the WINNER/3GPP-style model to mmWave bands, such as the proposed channel model in [14]. Meanwhile, the NYU WIRELESS model, 3GPP TR 38.901 model, and METIS stochastic model are based on GBSMs. Furthermore, the quasi deterministic radio channel generator (QuaDRiGa) open source channel model, which was extended from the WINNER channel model and developed by Fraunhofer HHI, was adopted by mmMAGIC. Recent work in [6] verified the QuaDRiGa model by using 32 GHz channel measurements.

For RS GBSM, rays are classified as LOS component, single-bounce component, and double-bounce component according to the geometry relationships. The multi-bounce component can be abstracted as a virtual link between a twin-cluster consisting of the first bounce cluster and last bounce cluster at the Tx side and the Rx side, respectively. The ray powers and delays are generated similar to the standardized WINNER II model. Angles are often assumed to be von Mises distributed. Distance vectors are then obtained based on the geometry relationships. Important properties like 3-D and non-stationary can be characterized based on this modeling approach.

Future Research Directions

High Performance Channel Sounder Design: Though many mmWave channel sounders have been built to conduct channel measurement campaigns, no COTS or custom-designed channel sounders can fully satisfy the measurement requirements of 5G wireless communication systems. The design of a high performance channel sounder is very important to measure mmWave channels with high system dynamic range, large bandwidths (high delay resolution), fast measurement speed, and so on.

Channel Measurements in Challenging Scenarios: For 5G wireless communication systems, there are some challenging scenarios, including massive MIMO, V2V, high speed train (HST), and so on. These challenging scenarios have not been fully measured and analyzed. More mmWave channel measurements in these challenging scenarios is indispensable for mmWave propagation channel characteristics.

Big Data Enabled Channel Modeling: The increasing number of smart phones, new scenarios, huge frequency bands, massive antennas, and numerous cells will generate massive datasets and bring 5G wireless communications to the era of big data. Channel measurements will generate large amounts of datasets. Big data analytical tools, especially machine learning algorithms like artificial neural network (ANN), convolutional neural network (CNN), support vector machine (SVM), and relevance vector machine (RVM), can be utilized to process the big measurement datasets and learn the wireless channel structure. Based on channel measurements and big data analytical tools, a unified channel model for 5G wireless communication systems may be possible.

CONCLUSIONS

This article has provided a comprehensive investigation of recent developments and future challenges in mmWave channel sounders, measurements, and models for 5G wireless communication systems. Frequency and time domain channel sounders have been compared. Channel measurements in various indoor and outdoor scenarios for multiple mmWave bands have been investigated. Comparison of multiple mmWave bands, validation of massive MIMO properties, and measurement and modeling of human blockage effects have been shown. Different channel modeling approaches including deterministic, semi-deterministic, and stochastic modeling methods have been compared and summarized. Some future research directions have also been discussed.

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