

Editorial

Recent Advances in RF Propagation Modeling for 5G Systems

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Continuously increasing demand for higher data rates, larger network capacity, higher energy efficiency, and higher mobility has motivated research within fifth-generation (5G) communication systems modeling. 5G is generally agreed for a set of new requirements for wireless communications systems. These requirements will need to address several critical performance areas including cost constraints, traffic latency, reliability, security, availability, heterogeneous structure of networks, multicast/broadcast requirements, the requirement to serve a variety of different devices, and reduced energy consumption. Accurate 5G indoor and outdoor channel characterization and modeling are crucial for determining the system performance and thus for system and for 5G network realization. Namely, 5G radio frequency (RF) propagation is affected by various phenomena that more or less deteriorate the original transmitted signal arriving at the receiver (free-space propagation, object penetration, reflection, scattering, diffraction, and absorption caused by atmospheric gases, fog, and precipitation).

To generate reliable propagation models for 5G systems and further to determine standard performance measurements of 5G systems, corresponding path loss models must be built for link budget evaluation and signal strength prediction, with the inclusion of directional and beamforming antenna arrays and cochannel interference, while temporal dispersion caused by multipath propagation (impacting the timing, packet and frame sizes, and other air interface design parameters) should also be characterized. Therefore, general statistical models could not be sufficient in order to assess

the performance of system and specific models related to real-world reference scenarios with fine classification of terms will be required.

For the development of new 5G systems to operate in millimeter bands, there is a need for accurate propagation modeling at these bands. Exploitation of unused millimeter wave (mmWave) band spectrum (spectrum between 6 and 300 GHz) is an efficient solution for meeting the standards for 5G networks enormous data demand growth explosion. Measurements provided at 38 GHz (Base Station-to-Mobile Access Scenario [1] and Peer-to-Peer Scenario [2]), 60 GHz (Peer-to-Peer Scenario and Vehicular Scenario [3]), and 73 GHz [4] have clearly identified the existence of non-line-of-sight (NLOS) conditions. One of the most intensively used statistical models for characterizing the complex behavior and random nature of NLOS fading envelope is the Nakagami- m distribution. In [5–7] for the purpose of modeling observed 5G system propagation properties, the Nakagami- m parameter is directly computed from the measured data. Two most well-known procedures used for the estimation of the Nakagami- m fading parameter, m , are (1) maximum likelihood (ML) estimation and (2) moment-based estimation. However, it is known that sample moments are often subjected to the effects of outliers (even a small portion of extreme values, outliers, can affect the Gaussian parameters, especially the higher order moments). Moreover, occurrence of outliers is especially problematic when higher order sample moments are used for estimation, since estimation inaccuracy arises in such cases. Providing the best

moment-based estimator is still major issue that should be addressed.

Because of that, there is a need for developing a novel approach for NLOS channels parameter estimation based on performance measurements, which will enable us to estimate propagation parameters in real time and to avoid weaknesses of ML and moment-method estimation approaches.

Stochastic channel models for mmWave communications in both indoor and outdoor environments have been mostly characterized with a Rician distribution in line-of-sight (LOS) environments where a dominant path is present [8]. In [8] it has been shown that Ricean K -factor is ranging over a defined set of values for observed LOS and NLOS conditions in vertical-to-vertical (V-V) copolarized antenna scenario and corresponding set of values for observed LOS and NLOS conditions vertical-to-horizontal (V-H) cross-polarized antenna scenario. However, despite the fact shown in [8] that Rician distribution provides the best fit to the measurement data, results of [8] imply that conventional fading models fall short of accurate modeling of the random fluctuations of 5G wireless channel signal. In [9] it has been concluded that for accurate 5G systems channel modeling, proposed models should ensure that the channel LOS and NLOS conditions, the second-order statistics of the channel, and the channel realizations should change smoothly in the function of time, antenna position, and/or frequency. Therefore a need arises for novel characterization of propagation in LOS conditions, by observing Ricean K -factor as a random process.

In particular, the diversity of scenarios envisaged for the 5G applications at the mmWave band will certainly lead to a variety of propagation conditions. Currently, an enormous variety of waveforms are considered to be potential candidates for the 5G air interface. They include (i) single-carrier frequency division multiplexing (SC-FDMA), already used in 4G Long-Term Evolution (LTE) uplink, also called differently generalized discrete Fourier transforms- (GDFTs-) orthogonal frequency division multiplexing (OFDM) [10]; (ii) zero-tail (ZT) or unique-word (UW) DFT-spread-OFDM [11, 12], ultra-wideband- (UW-) OFDM, generalized frequency division multiplexing (GFDM) [13], and cyclic prefix- (CP-) OFDM (already used in the 4G LTE downlink); (iii) resource-block-filtered OFDM, filter-bank-multicarrier (FBMC), and universal filter multicarrier (UFMC). As it can be seen, the OFDM technique is omnipresent in the 5G waveform proposals. The OFDM technique shall certainly remain as the root framework for the new 5G waveform design, with some optimization to support the new 5G requirements [14, 15].

Therefore it is necessary to propose an efficient, simple, and general method to generate samples for general 5G channel and further to make use of this channel in order to assess the bit error rate performance of an OFDM system model.

Stochastic geometry has been a powerful technique to evaluate system performance in conventional cellular networks [16], which reveals the impacts of multiple system parameters such as base station density, transmit power, and path loss exponent on the performance parameters such as data rate or reliability. The key idea in [17] is to model

random obstacles (e.g., buildings) as rectangles with random sizes and orientations whose centers form a Poisson point process (PPP) in 2-dimensional space. However, instead of one-hop communication between the macro cell base station (MBS) and a single small cell base station (SBS) cluster, the 5G cellular networks may have multiple SBS clusters, which require multihop transmissions to improve the cell coverage. Considering the distance-dependence of the blockage effects (i.e., the likelihood of a blockage event increases as the distance increases) at mmWave, multihop communication can be an effective solution to build mmWave wireless backhaul systems. In this context, motivated by the limitation in [18], the single-hop wireless backhaul system from [18] can be extended to a multihop scenario with multiple SBS clusters. Multiple points-to-multiple-points (MBMs-to-MBMs) links could be also studied, instead of [18] single-point-to-multiple-points (MBS-to-SBSs) links. Therefore, with different distance statistics from [18], the intercluster SBS-to-SBS communication can benefit from higher order of spatial diversity compared to the MBS-to-SBS communication in [18].

From this point of view, the analysis of an optimal and suboptimal hop count to minimize the end-to-end outage performance between the MBS and the destination SBS cluster for a given end-to-end distance could be of interest, where the suboptimal hop count is based on only the per-hop outage performance.

Interference issues will become of crucial importance due to the coexistence of 5G devices, since a number of mmWave devices are expected to grow extensively in the near future [19]. In order to satisfy 5G quality-of-standard requirements and meet user mobility, due to the higher path loss at mmWave frequency range, multiple antenna arrays could be used in outdoor mmWave systems for providing an additional gain [20, 21]. The increasing growth of 5G devices number will prompt the study of array pattern nulling techniques. The objectives of design of the antenna arrays are to achieve a minimum side lobe level (SLL) and a narrow first null beam width (FNBW). Methods used for the antenna array synthesis can be classified into two categories: deterministic and stochastic. The biggest advantages of using stochastic methods are their ability in dealing with large number of optimization parameters and avoiding getting stuck in local minimum.

An interesting idea for 5G mmWave antenna array synthesis could be based on genetic algorithm for the synthesis of linear array with nonuniform interelement spacing in order to obtain the optimal position of the elements in order to obtain the minimum side lobe level and nulls in desired directions.

The use of mmWave bands for next-generation wireless systems could offer ultra-wideband spectrum availability and increased channel capacity. All these benefits come at the expense of potentially higher system complexity particularly in terms of radio frequency (RF) front end and antenna design. However, the recent advancements around mmWave wireless systems development have produced cost-effective solutions that can be leveraged to overcome these challenges. 60 GHz frequency band has its own standardized protocol,

that is, the Wireless Gigabit Alliance (WiGig) standard which is equivalent to IEEE 802.11ad [22]. A promising study would be the link budget estimation, performed based on WiGig/IEEE 802.11ad standard-defined modulation and coding scheme (MCS) modes and 60 GHz mmWave specific path loss and auxiliary attenuation factors. The considered systems parameters for this link budget estimation could be obtained from real-world hardware prototypes for next-generation mmWave mesh backhaul networks in industry.

Although multiple-input and multiple-output (MIMO) techniques have been widely employed in cellular and wireless local area network systems working at sub-6 GHz [23–25], the potential realizations of MIMO technique in mmWave band are not fully understood yet, considering the unique multipath propagation characteristics and the increased path loss over the lower frequency bands used in current 3G/4G wireless communication. Spatial multiplexing (SM) and beamforming (BF) are the two most commonly used approaches to realize a MIMO system. The multiplexing gain can be obtained by exploiting the spatial difference of the channel response in different transmit- (Tx-) receive (Rx) element pair. On the other hand, in the mmWave band, the propagation loss is higher compared to the lower frequencies; thus the high-gain antenna arrays are expected to compensate the increased path loss. Several researches have conducted analyses on the performance of SM and BF in the mmWave communications. The feasibility of indoor mmWave MIMO has been investigated by ray-tracing based channel modeling, by virtual antenna array based channel measurement [26, 27], and also by a 2×2 microstrip array in an underground mine environment [28]. The performance of a hybrid transmission combining BF and SM in mmWave communication is also analyzed based on a ray-tracing method in both LOS and multipath environment [29].

It could be of interest to provide the measurement-based channel capacity comparison between SM and BF under realistic antenna arrays, with the same Tx power, the same array position, and the same propagation condition. In particular, a SM system could be analyzed and divided into 4 subarrays, each one of them consisting of 4 elements, corresponding to a 4×4 MIMO system, while in the BF system, the antenna array could be constructed by the whole 16 elements, which corresponds to a single-input and single-output (SISO) system but with a larger array gain than that of the SM system.

The introduction of MIMO and receiver diversity wireless devices provides large gains in the throughput performance. These gains are highly dependent on the performance of the receiving-antenna system and the receiving algorithm [30]. The devices can change the behavior of the antenna systems, for example, by using beamforming mechanisms, and also can adapt software algorithms to suit the environment they are currently used in. Wireless equipment manufacturers as well as network providers are pushing to have performance tests of the hand-held devices. Network providers expect to recommend the user equipment (UE) with the best performance to their customers; manufacturers wish to be able to compare the quality of their own UE to the one of the competitors. These comparisons should include

the effect of the antenna systems, the analog frontends, digital receiving algorithms, and baseband processing. One of the methods proposed by 3GPP, yet very promising one, is the decomposition method (DM). Over-the-air (OTA) throughput tests of wireless MIMO devices are an important tool for network operators and manufacturers. The UE is placed in an anechoic chamber and a random fading process is emulated by a base station emulator (BSE). The antenna characteristic of the UE is taken into account by sampling the sphere around the UE with the BSE test antenna at a large number of positions. For low-variance throughput results, long measurement intervals over many fading realizations are required, leading to long and expensive measurement periods in an anechoic chamber. Analyzing the possibilities of speeding up OTA testing through upgrading methods for DM analysis could be interesting task in performing throughput testing of wireless MIMO devices.

Attenuation by a human body and trees and penetration losses of material at the ITU proposed frequency bands [31], 24.25–27.5 and 37–40.5 GHz, are important issues for future 5G wireless access systems. In [31] the attenuation by a human body and trees and penetration loss of different materials with 1 GHz bandwidth were measured with a time domain channel sounder at 26 and 39 GHz, respectively. As far as we know, there are no measurements and modeling work reported in open literature on human blockage, attenuation by trees, and penetration loss of different materials at 24.25–27.5 and 37–40.5 GHz frequency bands. The prediction of attenuation by a human body and trees and the penetration losses in this work are important and necessary for future mmWave wireless communication systems deployment. By considering a human body as an infinite absorbing screen, two knife-edge (KE) models were used to predict the attenuation by a person in a frequency range from 4 to 10 GHz in [32]. In addition to regarding a human body as an absorbing screen, a cylindrical model by uniform theory of diffraction (UTD) was also applied to predict human body attenuation. Measurements in [33, 34] were performed at 10 GHz which showed a strong correlation between a human body and a perfect conducting cylinder. Previous works about penetration losses of material in mmWave bands were focused on 28 GHz and 60 GHz. In [35], signals through a hollow plasterboard wall resulted in a penetration loss ranging between 5.4 dB and 8.1 dB. In [36], the measured penetration losses are 2 dB, 9 dB, and 35.5 dB at 60 GHz through a glass door, a plasterboard wall with metallic studs, and a wall with a metal-backed blackboard, respectively. For this reason, it would be of interest to carry out measurements of the attenuation at 26 and 39 GHz by a human body and trees as well as penetration losses for material with a person lateral crossing the transceiver connection line and to use KE and UTD methods to predict its attenuation. Also it would be of interest to measure the attenuation by willow trees at 26 GHz and then to compare with ITU-R P-833-8 model and modify the model at 26 GHz. An interesting investigation would also be carrying out measurements of the penetration loss for different materials as well, for example, transparent glass with different thickness, frosted glass, and wood with plastic clad.

5G wireless communication networks are expected to fulfill the demand for higher data rates, lower latency, and/or massive connectivity of a growing number of users/devices exploiting a variety of wireless applications. This envisioned rapid increase in the use of wireless services would lead the wireless research community to start looking at new technologies to address problems related to the RF propagation modeling. This includes the development of models for new concepts such as massive MIMO systems to improve the spectral efficiency at the link and network layers and developing novel propagation models for characterizing communication in particular in the upper mmWave.

Generally, we need to continue to progress in our research for appropriate 5G radio propagation models, which can adequately and faithfully model mmWave communication properties much more than what has been done at the moment. The progress reported in this Special Edition is just a small step in achieving this goal in the future.

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