ABSTRACT

This article first identifies requirements of 5G radio propagation models for relevant propagation scenarios and link types derived from the analysis of recently discussed 5G visions and respective 5G technology trends. A literature survey reveals that none of the state-of-the-art propagation models such as WINNER/IMT-Advanced, COST 2100, and IEEE 802.11 fully satisfies the model requirements without significant extensions, and therefore there is room for a new framework of propagation models. We then present a novel map-based propagation model that satisfies the model requirements, and also introduce new extensions to existing stochastic models. Several open issues are finally identified that require further studies in 5G propagation modeling.

INTRODUCTION

Recently, there have been various international activities to discuss what the next generation system, that is, fifth generation (5G), will be around 2020 and beyond (e.g., [1, 2]). It is generally predicted that areas of mobile services will be significantly expanded by a wide variety of use cases with challenging and diverse requirements in terms of data rate, number of connections, latency, and energy consumption, among other relevant metrics.

A 5G concept, along with relevant technology components, is being developed to address those future requirements (e.g., [1, 3]). These aspects are also translated to 5G propagation modeling requirements. To achieve higher data rates, radio frequencies above 6 GHz have been attracting attention as one of the promising solutions because of their potential to allow wider bandwidths than legacy radio systems operating below 6 GHz. In particular, ultra-dense networks (UDNs) using small cells can take advantage of the propagation properties of the high frequencies, showing higher path loss in the surrounding medium, while different link topologies like outdoor-to-indoor (O2I), and indoor-to-outdoor (I2O), might be possible. The link types include cellular access, point-to-point such as backhaul, and peer-to-peer links represented by D2D, MMC, and V2V communications.

5G PROPAGATION MODEL REQUIREMENTS

As discussed in the previous section, diverse use cases and requirements are foreseen for 5G, which lead to a wide range of relevant propagation scenarios and link types that have to be modeled. The propagation scenarios include environments such as dense urban, urban, indoor office, shopping mall, rural, highway, and stadium, while different link topologies like outdoor-to-outdoor (O2O), outdoor-to-indoor (O2I), and indoor-to-indoor (I2I) are possible. The link types include cellular access, point-to-point such as backhaul, and peer-to-peer links represented by D2D, MMC, and V2V communications.
The diverse propagation scenarios and link types set the following requirements of the 5G propagation models in addition to the challenges in their implementation in practice.

**Applicability to Dual-Mobility Channels**

Involvement of device mobility at two link ends as represented in D2D and V2V communications, which we call dual mobility in this article, incurs unique challenges in the propagation modeling (i.e., making the model spatially consistent). The multipath situation results in time-variant fading when a device moves over space as time elapses. The propagation model is spatially consistent if two closely located devices in space see similar radio channel profiles in the angular, delay, power, and polarization domains. The consistency therefore ensures that the channels evolve smoothly without discontinuities when devices move or turn around. The lack of spatial consistency potentially leads to significant errors in evaluating radio networks involving device mobility, including wrong handover decisions, unrealistic multihop scenarios, and so on.

Spatially consistent modeling is also crucial in MMC and cellular access links such as the UDN, as the density of links is expected to increase and the devices are spatially close to each other.

**Applicability to Frequency-Agile Channels**

Design of 5G cellular access links requires the propagation model to cover a wide frequency range from 0.5 to 100 GHz. This range is extremely wide compared to the spectrum discussed, for example, in 2G, 3G, and 4G. Although the propagation characteristics, especially diffraction, scattering, and penetration, show significant differences in attenuation at 100 GHz compared to those at 1 GHz, the propagation model should be consistent and applicable across the whole range.

**Applicability to Massive-Antenna Channels**

5G cellular communication systems aggressively exploit multiple antenna transmission techniques such as spatial multiplexing and spatial division multiple access. Many of these techniques, like M-MIMO and pencil beamforming, will utilize highly resolved spatial properties of the radio channel. Particularly for high carrier frequencies in the millimeter-wave (mmWave) range, narrow beams are required in order to compensate for the smaller omni-antenna aperture and also link blockage losses in diffraction at building corners and blocking by human bodies, moving objects, and vegetation. Furthermore, if the array antenna is large in respect to the wavelength, radio signals emanating from nearby wireless devices or scatterers cannot be approximated as plane waves, but have to be treated as spherical waves, which can possibly have an impact on beamforming methods. The knowledge of high-frequency radio channels along with the support of M-MIMO is very relevant in cellular UDNs.

**Diversity to Accommodate Different Simulation Needs**

Finally, on a practical side, the wide range of propagation scenarios and link types sets a challenge of having a single scalable framework of the propagation model applicable to all the possible envisaged scenarios and link types. A model framework for long-range backhaul links may not be used to characterize indoor D2D channels. Furthermore, requirements of the model vary significantly for different link types. A massive sensor network in the form of D2D links may, for example, be based on very simple transceiver units with one antenna each that would not need an angular-dependent propagation model. On the contrary, when looking at cellular access links exploiting M-MIMO, the angular information is crucial, as described earlier. The more complex measurements imposed on the model, the more complex the implementation and computation. Therefore, it is important to use the right model framework that satisfies the model requirements with minimal complexity. It may be inevitable to have multiple propagation model frameworks with varying levels of requirements addressed, and hence varying complexity, to serve for different propagation scenarios and link types efficiently.

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**5G Propagation Modeling Approaches**

**Existing Models Compared to METIS Models**

This section reviews the existing models in the literature to see if the 5G propagation model requirements identified in the previous section are addressed.

**WINNER-Family Channel Models**

The family of geometry-based stochastic channel models (GSCM) includes WINNER [4], IMT-Advanced [5], and Third Generation Partnership Project (3GPP) stochastic channel model (SCM) and D2D model. Although they were originally designed for 2D propagation, further development has led to 3D extensions like WINNER+ [6], QuaDRiGa [7], and 3GPP-3D [8]. They are versatile models for frequencies below 6 GHz supported by a vast amount of channel measurement campaigns. System-level evaluations are supported by the so-called drop concept, which produces non-correlated channel realizations and also correlated large-scale parameters, like shadowing, and angular and delay spreads, for moving user terminals. Model parameters have been missing for frequencies higher than 6 GHz, which is a problem that is partially addressed by METIS 60 GHz measurements (e.g., [9]).

The GSCM framework has major challenges in satisfying the 5G propagation model requirements. For instance, the widely used WINNER-type channel models do not provide correlated channel realizations even if two user terminals are defined close to each other spatially, and hence, the spatial consistency is not supported. This exaggerates the performance of spatial techniques as in reality, the angular separability of the two links is limited because same clusters are visible to both links, resulting in the small-scale channel characteristics of those links being similar. Moreover, the WINNER family models lack realistic amplitude representation of highly resolved sub-paths, resulting in overestimated performance in the case of M-MIMO.

This is illustrated in Fig. 1, where the WINNER type of modeling is compared to a measured channel [10]. The singular value distribution of the WINNER modeling method results in a nearly ideal MIMO channel for the large antenna echo to the receiver.

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1 Clusters are defined as groups of radio wave scatterers producing multipath echoes to the receiver.
na array (an even distribution is optimal as the MIMO singular values correspond to the signal-to-noise ratio, SNR, values of the possible MIMO data transmission streams), whereas the measured channel performs much worse. In order to provide a solid basis for the optimization of M-MIMO transmission techniques for 5G, the corresponding channel modeling needs substantial improvement.

**COST 2100 Channel Model:** The COST 2100 channel model is better suited for spatially consistent modeling of propagation channels. In contrast to the earlier mentioned model family, the COST 2100 model defines clusters on a coordinate system of the environment simultaneously for all user terminals including those in proximity to each other. Each cluster has a visibility region stretching over a spatial area in the environment and determining whether a user terminal “sees” the cluster. Thus, closely located users experience similar propagation environments. Also, spherical waves and smooth time evolution of the channel are supported because of the coordinate-system-based cluster definition. Still, and similar to the WINNER family models, the COST 2100 model is not applicable to dual-mobility channels since it is designed for conditions where one link end, that is, a base station (BS), is fixed. Moreover, the COST 2100 model has only limited support for propagation scenarios and carrier frequencies below 6 GHz.

**IEEE802.11ad Channel Model:** The IEEE 802.11ad channel model, for very high data rate WLAN, was developed for frequencies around 60 GHz. The model supports spatio-temporal-polarimetric propagation characteristics of non-stationary channels. Line-of-sight, and first and second-order reflections are modeled based on accurate environment layouts. Intra-cluster properties associated with each reflection are characterized for 60 GHz and for three indoor scenarios only. The model has limited applicability to dual-mobility channel simulations since the cluster properties change significantly after major motion of WLAN devices. Moreover, cluster coordinates are not utilized, which prevents spherical wave modeling.

Table 1 summarizes the main features of a set of existing models and the two METIS model alternatives that are introduced in the next sections. The comparison reveals that none of the existing channel models fulfills all the listed features and hence satisfies the 5G model requirements.

**METIS Model (I): Map-Based Model**

As reviewed above, it is a considerable challenge to fulfill all the 5G requirements by extending the existing stochastic GSCM-family models with new features and parameters. Stochastic distributions of the necessary parameters (about 30 in [4], more than 40 in [10]) for all 5G frequency band and environment combinations must be determined such that the resulting model parameters would be consistent across frequency. In order to provide a reliable model parametrization of such a channel model, a large number of extensive channel measurements corresponding to all the modeled environments would be required, which might not be a viable way for-
ward. For this reason METIS provides an alternative modeling approach referred to as the “map-based” model [10].

The map-based model is based on simplified standard ray-tracing techniques with added important features and a coarse geometrical description of the environment. An example of such an environment description is the Madrid grid, depicted in Fig. 2 (also [11]), which has been specified for the METIS test cases. The map-based model inherently addresses all the critical 5G channel modeling challenges as it is based on physical principles using only a limited number of parameters corresponding to the relevant physical properties. In the following a brief overview of the METIS map-based channel model is provided. A detailed description including model parameters is provided in [10]. Notice that the model does not require specific optimization of parameters from measurements for all environment, frequency band, and deployment combinations.

**Model Specification:** A block diagram of the channel model is illustrated in Fig. 3 with numbered steps of the procedure to generate radio channel realizations. On a higher level the procedure is divided into four main operations: creation of the environment, determination of propagation pathways, determination of propagation channel matrices for path segments, and composition of the radio channel transfer function. In the following we describe the main operations briefly.

**Steps 1–4:** In the first four steps the 3D propagation environment is specified. The map contains coordinate points of wall corners (e.g., Point 1 in Fig. 2) where for simplicity walls are modeled as rectangular surfaces. Second, a set of random scattering/shadowing objects, representing humans, vehicles, and so on, is drawn on the map with a given scenario-dependent density. Third, rough surfaces (e.g., brick walls) are divided into tiles with certain tile center coordinate points, which act as point sources of diffuse scattering. In Step 4 transceiver locations or trajectories are defined. It is also possible to draw the transceiver locations randomly, which is analogous to drop simulations of GSCMs.

**Steps 5–6:** The next operation is to determine propagation pathways from the transmitter to the receiver. Coordinates of interaction points for parameter vectors are determined utilizing mathematical tools of analytical geometry. The principles of this part are simple and obvious to
the human eye, although writing an algorithmic description of the step is complicated.

Starting from the TX and RX locations (Fig. 2), all possible second nodes visible to the TX/RX node either with a line-of-sight (LOS) path or via a single specular reflection are identified. Possible second nodes are diffraction points like corners, scattering objects, or diffuse scattering point sources. Specular images are also considered as second nodes in this step. Then the coordinates and interaction types of interaction points (diffraction nodes and specular reflection points e.g., Points 1 and 2 in Fig. 2) are determined. Possible pathways are identified by checking whether any wall is blocking the direct or single order reflected paths. For specular image nodes, blocking also occurs if the path does not intersect the corresponding reflection surface. This procedure may be repeated to achieve any number of diffraction and specular reflection interactions. When repeated, the nodes of previous steps act as TX/RX of the first step.

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The map-based model provides two options for modeling of diffraction. The first option is based on the uniform theory of diffraction (UTD) and provides accurate modeling. A drawback of the UTD approach, however, is that it brings high complexity. For this reason a substantially simpler approach, based on the Berg recursive model [12], is provided as the baseline alternative. The Berg recursive model is semi-empirical and designed for signal strength prediction along streets in an urban environment. It is semi-empirical in the sense that it reflects physical propagation mechanisms without being strictly based on electromagnetics theory. It is based on the assumption that a street corner appears like a source of its own when a propagating radio wave turns around it. The corners of buildings and antennas represent nodes.

Step 12: The last operation is to compose the radio channel transfer functions by embedding antenna radiation patterns to shadowing losses (from Step 7) and composite propagation matrices. For a single path the complex gain is calculated as a product of the polarimetric antenna radiation pattern vectors, element-wise product of propagation matrices of each path segment of the path, and the total shadowing loss. The result contains all modeled antenna and propagation effects in the given environment for the specified RX and TX antenna locations.

Outdoor to Indoor and Indoor Modeling: For indoor propagation the same ray tracing technique as for outdoors is used with the exception that wall penetration is allowed. There are two complexity levels of determining the indoor penetration loss. For low complexity the loss is mod-

Figure 3. A block diagram of the METIS map-based model. Pol: polarization.
eled as a constant per unit indoor propagation length (typically in the range 0.3–1 dB/m). For higher complexity a specific loss is assigned to each penetrated indoor wall and/or floor.

For outdoor to indoor propagation a simplified principle is used. The reasoning for the simplification is to keep complexity as low as possible and avoid defining any detailed exterior wall structures such as windows. The model is divided into two cases depending on the level of available detail:
- There is no indoor layout.
- The indoor layout is specified.

In both cases the paths are determined assuming that the building where the user is located does not exist. In other words, the exterior walls are fully transparent in the outdoor-to-indoor direction in the phase of determining propagation paths. When the paths have been identified the building is reintroduced, and the corresponding attenuations for each path due to exterior wall penetration and indoor penetration, as specified above, are determined. To keep the model simple, paths diffraeted by, for example, window frames are neglected.

**Validation by Measurements:** Comparisons with measurement data are crucial to provide validation and reliability of any model. The METIS map-based model has been compared to selected measurement data for this purpose. One example is D2D propagation, which is simulated with the layout of Fig. 5 (left). For this scenario the modeling of scattering and blocking by objects has been successfully validated using two sets of measurement data. The Doppler characteristics, caused by objects along the route of the UE in an urban street, are validated by measurements in [13]. Path loss and shadowing characteristics of the LOS links are shown in Fig. 5 (right) for both the simulation scenario and corresponding measurements in the city of Oulu, which were conducted by University of Oulu and are reported in [10, 14]. The antenna heights are 2.5 and 1.6 m at the different link ends. The frequency is 5.25 GHz. In the model all random objects have the same height of 1.5 m. Thus, no object is fully blocking the direct path. In the measurement higher vehicles were occasionally present, which might have temporarily obstructed the LOS. The spike in measurement results at 40 m is caused by a double-decker bus which blocks the LOS. For this scenario the agreement between mea-
What is important is to validate each model component corresponding to each specific physical propagation mechanism. This validation was only partly performed within the framework of the METIS project. However, it is straightforward to utilize publicly available measurement results to complete the validation of the METIS map-based model.

**METIS Channel Model (II): Stochastic Model Extension**

As detailed previously in this article, the stochastic model refers to models based on the GSCM approach, in which scenario-specific parameter distributions are extracted from channel measurements. Model parameter extraction for new scenarios (e.g., moving networks, stadium, UDN, and new frequencies above 6 GHz) is a crucial aspect of fulfilling the requirements of the channel model for 5G simulations. Thus, the METIS stochastic model extension especially focuses on modeling three-dimensional spatial channels in urban microcellular environments, dense urban small cell scenarios, and short-range indoor and outdoor 60 GHz channels (e.g., [9, 10, 15, 16]).

The extension includes the following [10] (also see Table 1):

- New frequency agile path loss model for UMi street canyon scenarios covering a frequency from 0.8 to 60.4 GHz
- Model parametrization at 60 GHz in shopping mall [9] and open square scenarios
- Generation of large-scale parameters based on the sum-of-sinusoids method in order to support spatial consistency in the case of moving transmitters and receivers
- Direct sampling of the Laplacian shaped angular spectrum in order to support very large array antennas
- Explicit placing of scattering clusters between TX and RX locations in order to allow for spherical wave modeling to be used

Each of these features was established and supported based on the evidence obtained through extensive channel measurements; the details of the measurements and evidence can be found in [10].

**SUMMARY AND FUTURE WORK**

This article introduces a new set of 5G propagation models that are applicable to propagation scenarios and link types derived from recent discussions on 5G visions and respective 5G technology trends. Through the literature survey it is concluded that none of the existing channel models is fully applicable to 5G link design and that consequently new channel models are needed.

We present a new map-based model that accounts for all the requirements of 5G propagation model. A brief overview of the new extensions for stochastic models is also provided.

As future work, the model should be validated and reinforced for an even wider range of frequency bands, environments, and network deployment scenarios. Industrial environments for MMC are one of the important scenarios that have been scarcely covered. The literature survey indicated that radio channel measurement results between 6 and 60, and above 70 GHz are far from comprehensive in general. Additionally, most channel sounding has been performed at a single frequency band at different measurement sites. Open questions still remain on a frequency dependent model of diffuse scattering, material absorption, cluster properties, and so on. Finally, it is also intriguing to consider a hybrid approach of the map-based and stochastic models to take advantage of the strength of both models. For example, detailed behaviors of channels (e.g., polarization) are modeled in a physically meaningful manner in the map-based model, but without much comparison with measurements. The stochastic model, on the other hand, is based fully on empirical analysis, while its physical basis is justified only intuitively. One of the possible hybrid approaches of these two models is to add measurement evidence into the physically sound map-based model.

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**REFERENCES**


**ADDITIONAL READING**


**BIOGRAPHIES**

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Katsutoshi Kusume received his M.Sc. and Dr.-Ing. degrees from Munich University of Technology in 2001 and 2010, respectively. In 2002 he joined DoCoMo Euro-Labs and is currently manager of the Wireless Research Group. He led the work package in the METIS project on scenarios/requirements, channel modeling, and testbed from 2013 to 2015. He received the Best Paper Award at IEEE GLOBECOM ‘09. His research interests include multiple antennas, iterative processing, and waveform designs.

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