

SURVEY, TAXONOMY, AND UNIFICATION OF STANDARD MMWAVE CHANNEL MODELS FOR WPAN, WLAN, AND CELLULAR SYSTEMS IN 6G

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ABSTRACT

This study aims to provide a unified view of the various standard millimeter-wave (mmWave) channel modeling frameworks for mmWave wireless deployments in sixth generation (6G) wireless networks, focusing on wireless personal area networks (WPAN), wireless local area networks (WLAN), and cellular networks (CN). The 6G era will witness the emergence of security-sensitive, more mission-critical, and data-intensive applications, wherein massive amount of data will be exchanged while satisfying the stringent requirements for latency, reliability, trustworthiness, and data rate. Thus, mmWave connectivity has been considered and would result in the co-existence of decentralized networks and centralized CNs, eventually blurring the distinction between WPANs, WLANs, and CNs. Motivated by this futuristic vision, we first reviewed the present status of the standard channel models for WPAN, WLAN, and CNs to understand the common characteristics of mmWave channel models therein. We show that despite their differences in sight-specificity levels and employed mathematical functions, all standard channel models target the generation of a commonly structured channel impulse response comprising eight shared components. Furthermore, based on the affinity, we propose a research direction to develop unified mmWave channel generation for WPAN, WLAN, and CN, where channel simulations for the three scenarios can be conducted in an identical framework. Our experimental results shed light on the feasibility of the proposed research direction and highlight the challenges and opportunities.

INTRODUCTION

Fueled by the standardization of fifth-generation (5G) networks, millimeter wave (mmWave) communications have attracted considerable attention owing to the availability of enormous bandwidths. The support provided for different service types in 5G, typified by enhanced mobile broadband, massive machine-type communication, and ultra-reliable low-latency communications, has led to the emergence of more data-intensive, mission-critical, and security-sensitive applications. Therefore, the current usage of sub-6 GHz bands will inevitably result in a severe shortage of radio frequency

resources. Thus, exploiting the mmWave bands is crucial for supporting these emerging applications in next-generation communication systems.

The primary characteristic of futuristic communication systems is that the network operation is not limited to base station (BS)-station (STA) communication, as in current cellular networks (CNs). Rather, as proven by the emergence of private 5G or sidelink communication, local or personal communications unconnected with a BS are envisioned to co-exist to meet the above service types. In this context, owing to their shorter range, mmWave frequencies are also likely to support local or personal communications. Hence, in futuristic networks, the joint deployment of mmWave CNs, wireless personal area networks (WPANs), and wireless local area networks (WLANs) is expected.

Thus, there is a need to develop a unified view of the standard mmWave channel models for WPANs, WLANs, and CNs to understand their common modeling characteristics. To date, research on mmWave channel modeling for WPANs, WLANs, and CNs has been conducted by separate standardization and academic communities. However, regardless of the separate communities and differences in the models, there should be several affinities among them because they target the same frequency band, ranging from approximately 28 to 90 GHz. In this article, we aim to highlight this affinity to gain an in-depth understanding of modeling mmWave channels by surveying the present status of the mmWave channel models.

Moreover, based on these affinities, we propose an approach for developing a unified mmWave channel generation framework. For futuristic networks with high co-existence of WPANs, WLANs, and CNs, the channel simulation should be completed with an identical framework with slight scenario-specific modifications (e.g., parameters or distribution functions), and not by drastically switching the channel generation frameworks. The proposed approach contributes to reaching this goal, enabling the simplest channel simulation framework, even under a complicated co-existence scenario. As an exemplary study, we examined whether the 3GPP statistical channel model (SCM) can be a unified channel

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generation framework by investigating the feasibility of the 3GPP SCM, originating from CNs, generating channels in a WPAN scenario. Based on this attempt, we discussed the challenges and opportunities for implementing the unified framework, shedding light on the process for realizing our goal of simplifying channel simulations.

The scope of this study is within WPAN, WLAN, and CN scenarios, among which we focus on the channel that can be regarded as the sum of multiple plane waves arriving with different delay and angular characteristics. To this end, we focus on the scenarios where the main attribution of the multi-path waves is the reflection from objects far from a transmitter and receiver enough to maintain the far-field assumption (e.g., indoor walls/ceilings or building walls outside). Even with such shared characteristics, the standard channel models have been developed differently. This study aims to shed light on this difference; hence, other scenarios that do not hold these assumptions are beyond the scope of this study.

STANDARD MMWAVE CHANNEL MODELS AND USE CASES

First, we briefly introduce channel models standardized or made by a large-scale project, focusing on their use cases and scenarios. Note that our survey is oriented toward simulating channels for link-level or system-level simulations. Hence, measurement campaigns (e.g., [1] and [2]) before the first standardization of mmWave communication systems, i.e., IEEE 802.15.3c, are not included.

MMWAVE WPAN—IEEE 802.15.3c MODEL

The fastest channel model for mmWave systems was the IEEE 802.15.3c model [3]. Standardization efforts were spent on establishing a physical (PHY) layer and medium access control (MAC) layer protocols for indoor WPAN networks operated at 60 GHz bands. The use cases were represented by:

1. “Sync and go,” i.e., Kiosk downloading
2. “Computer peripherals,” replacement of wired connections among computer peripherals, and
3. Video streaming.

The targeted communication range was several meters [4]. The first open-source 60 GHz channel model simulator for link-level simulation was developed by MATLAB in the standard [5].

MMWAVE WLAN—IEEE 802.11ad AND 11ay MODELS

The standardization efforts of mmWave WPAN were followed by the standardization of mmWave wireless local area networks (WLAN). The two standardizations, IEEE 802.11ad and IEEE 802.11ay emerged subsequently and are detailed as follows:

IEEE 802.11ad Model. First, the IEEE 802.11ad model [6] was established during 2009–2010. The use cases in the IEEE 802.11ad standard are almost identical to the current indoor LAN systems, i.e., they provide a connection between an access point and STAs. The usage scenarios were office cubicles, conference rooms, and living rooms; therefore, the targeted communication range was approximately 10 m.

IEEE 802.11ay Model. IEEE 802.11ad was followed by IEEE 802.11ay TG [7], which extends

the usage environment to indoor open public areas, open outdoors, and street canyons; namely, the targeted communication range is expanded up to several hundreds of meters. This is because the IEEE 802.11ay usage model includes backhaul/fronthaul and mobile hotspots. In addition to the scenario extension, the key distinction from the IEEE 802.11ad model is the employment of a quasi-deterministic model and the support of multiple input and multiple output. More precisely, IEEE 802.11ay recommends generating clusters using ray-tracing simulations, without performing statistical modeling. Hence, the preparation of ray-tracing simulations is required to perform link/system-level simulations.

MMWAVE CELLULAR NETWORKS—NYUSIM, MMAGIC, MIWEBA, AND 3GPP 38.901 MODELS

Parallel channel measurement and modeling campaigns emerged for mmWave CNs, among which we introduced the channel models standardized or established by large-scale projects: the NYUSIM model [8, 9], mmMAGIC model [10], MiWEBA model [11], and 3GPP 38.901 model [12]. The common and basic use cases of these channel models are urban macro (UMa), urban micro (UMi), and indoor scenarios. The UMa scenario targets long-range connectivity between a BS and STAs with an inter-site distance (ISD) ranging from 500 m to several kilometers, whereas the UMi scenario targets the ISD in the order of tens or hundreds of meters.

NYUSIM Model. The NYUSIM model includes UMi, UMa, and indoor scenarios, supporting a frequency band ranging from 500 MHz to 150 GHz. As for the indoor scenario, the model is based on measurement campaigns conducted in an office located at New York University [13]; hence, the indoor scenario is also referred to as an “indoor hotspot for offices (InH).” Additionally, a rural macrocell scenario (RMa), referred to as a macrocell scenario with fewer reflecting/shadowing buildings, is also supported.

mmMAGIC/Quadrige Model. The mmMAGIC model includes UMi and indoor scenarios in detail, with a frequency range of 6 to 86 GHz. The UMa scenarios are not included because the usage of mmWave communication is envisioned to have shorter-range connectivity [10]. The UMi scenario is subdivided into “street canyon” and “open square,” while the indoor scenario is subdivided into “office,” “shopping mall,” and “airport.” Moreover, semi-outdoor environments are included by considering outdoor-to-indoor (O2I), stadium, and station railway platform scenarios. Note that in terms of the initial CIR generation mechanism without terminal mobility for mmWave bands, the Quadrige model [13] follows the mmMAGIC model; hence, we discuss the two models together in the following analysis.

MiWEBA Model. The MiWEBA model includes UMi-like scenarios and indoor scenarios as “access scenarios,” mainly supporting the 60 GHz bands. More specifically, as UMi-like scenarios, the model involves open-area scenarios, exemplified by university campuses and street canyons. The MiWEBA project raised hotel lobbies as an exemplary indoor scenario. Moreover, backhaul/fronthaul scenarios were also included by considering situations similar to the above

To this end, we focus on the scenarios where the main attribution of the multi-path waves is the reflection from objects far from a transmitter and receiver enough to maintain the far-field assumption (e.g., indoor walls/ceilings or building walls outside).

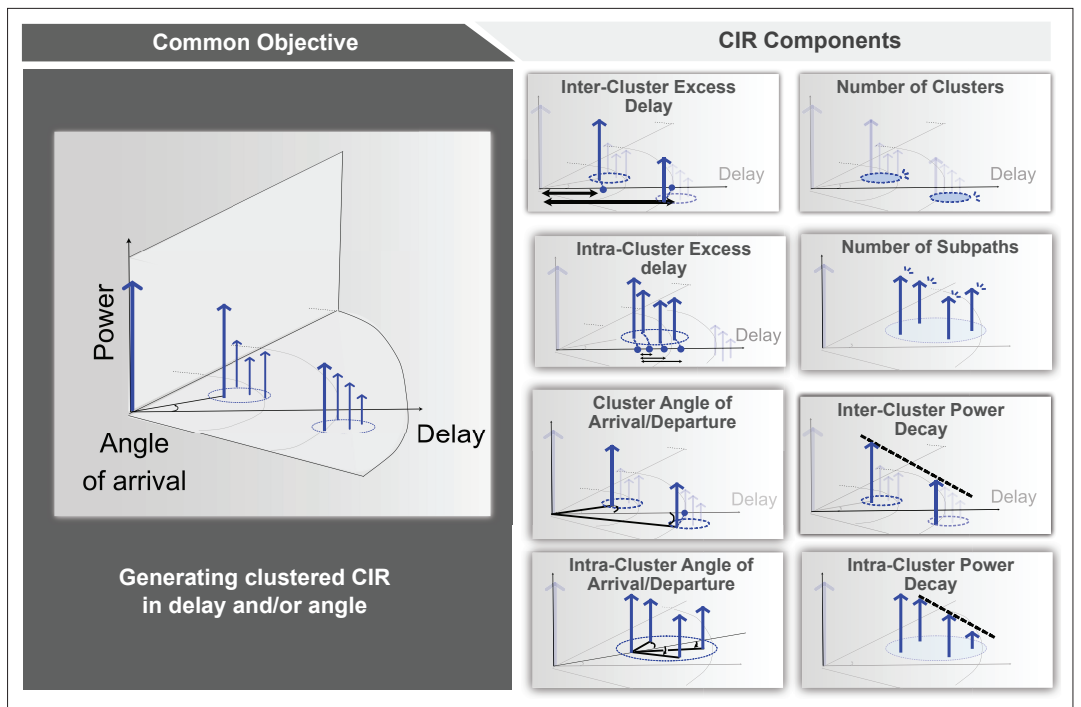


FIGURE 1. Generated CIR components commonly found in all mmWave channel models. Note that as an angular information, we only depict AOA for the ease of visual inspection, whereas our analysis is general for elevation angle of arrival, azimuth angle of departure, and elevation angle of departure.

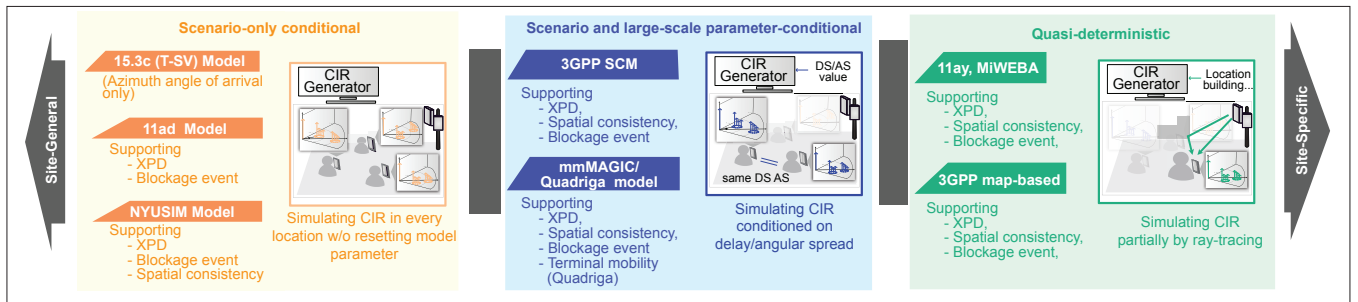


FIGURE 2. Model taxonomy according to site-specificity levels.

cited UMi-like scenarios. Note that, similar to the IEEE 802.11ay model, the MiWEBA model is not fully stochastic; namely, it employs a quasi-deterministic model, which is elaborated on in the subsequent section.

3GPP Channel Model in TR 38.901. The 3GPP model is established in the technical report (TR) 38.901 [12] based on worldwide measurement campaigns in the frequency range from 0.5 GHz up to 100 GHz. This report includes the following two models: SCM and map-based channel model. The former model generates the channel statistically, and at the time of writing, concrete parameter sets were reported for the UMa, UMi street canyon, indoor office, indoor factory, and RMa scenarios. Contrary, the latter model is a hybrid model of the SCM and ray-tracing. Hereinafter, we refer to these models as the 3GPP SCM and 3GPP map-based model, respectively.

TAXONOMICAL ANALYSIS ON STATISTICAL MMWAVE CHANNEL MODEL

In this section, we provide a taxonomical analysis of the standard channel models introduced above, focusing on the generative procedure of channel

impulse responses (CIRs). Here, we focused on the most essential and common aspects of the above channel models, i.e., generating static CIRs clustered in a delay and/or an angular domain (Fig. 1). As shown in Fig. 1, we focus on the mathematical models and generative procedure of the following components:

1. Inter-cluster excess delay
2. Intra-cluster excess delay
3. Cluster angle-of-departure/arrival
4. Intra-cluster angle-of-departure/arrival
5. Number of clusters
6. Number of subpaths
7. Inter-cluster power decay
8. Intra-cluster power decay.

Notably, several models include more advanced characteristics, such as spatial consistency, polarization characteristics, and human blockage effects, which enhance accuracy by adding them to the above eight components. However, our focus is on clarifying the differences and affinities in the characteristics of mmWave PHY/MAC simulations. Hence, we limit the discussion to the generation of the above cited eight components of CIRs, with the additional features presented in Fig. 2 with no discussion.

TAXONOMY ACCORDING TO SITE-SPECIFICITY LEVELS

As summarized in Fig. 2, we first present the model taxonomy according to the site-specificity levels. This analysis focuses on how the mathematical distribution functions representing the aforementioned eight components (hereinafter referred to as CIR components) are conditioned by scenarios, node locations, and/or other peripheral staff, such as walls and buildings.

Category 1: Scenario-only Conditional. The first category is “scenario-only conditional,” implying that the distributions for generating the CIR components are conditioned based only on scenarios. Therefore, the generated samples for the CIR components are regarded as realizations of various node locations in a given scenario. This is considered the most site-general model because the generated CIR components are not conditioned on specific node locations in a given scenario, but oriented to emulate CIRs in various locations.

Among the channel models, the IEEE 802.15.3c, IEEE 802.11ad, and NYUSIM models fall into this category. For the IEEE 802.15.3c channel model, the scenario-wise parameters to generate the CIR components (e.g., the arrival rate of inter- and intra-cluster rays and dispersion of the azimuth angle of arrival (AAoA) in intra-cluster rays) can be found in [3]. For the IEEE 802.11ad channel model, the distributions of CIR components dependent on scenarios found by extensive ray-tracing simulations were reported in [6]. For the NYUSIM model, the basic parameter set was reported in [13] for an indoor office and in [9] for a UMi scenario in New York City.

Category 2: Scenario and Large-Scale Parameter-Conditional. The second category is “scenario and large-scale parameter-conditional,” implying that the generated CIR components are conditioned not only by scenarios but also by location-specific factors represented by large-scale parameters (LSPs). More specifically, the generators of the inter-cluster and intra-cluster delays are conditioned on the delay spreads (DS) and intra-cluster DS, respectively, whereas those of both the inter-cluster and intra-cluster angles of arrival/departure are conditioned on the angular spread (AS) and intra-cluster AS, respectively. Moreover, both inter-cluster and intra-cluster power decays depend on DS and intra-cluster DS, respectively.

Accordingly, the channel generation procedure for the models in this category employs a two-step procedure. First, the LSPs are sampled according to scenario-specific distributions (e.g., DS is typically sampled from a log-normal distribution with scenario-specific parameters). Subsequently, given the LSPs, CIR components were sampled. Hence, the generated CIR components are specific to the scenarios and node locations specified by the LSPs. We can consider this model as a more site-specific model than scenario-only conditional models.

Among the channel models, the 3GPP SCM and mmMAGIC models fall into this category. For the 3GPP SCM, scenario-dependent parameters of log-normal distributions generating the DSs and ASs are reported in [12] for the UMi-street canyon, UMa, RMa, indoor-office, and indoor factory scenarios. For the mmMAGIC model, the same type of parameters was reported in [10] for the

UMi outdoor, indoor office, and airport scenarios. For both models, the generation procedures for the CIR components, given the DS/AS, are described in the corresponding reports.

Category 3: Quasi-deterministic. The third category is “quasi-deterministic,” implying that the generative procedure of partial CIR components relies on ray-tracing simulations. Namely, the generation of CIR components is conditioned on scenarios, node locations, and surrounding objects, such as buildings, walls, and blockage objects. In contrast to the above categories, the quasi-deterministic model is cast as the most site-specific model because the pre-determined condition for CIR generation is the most detailed, i.e., the quasi-deterministic model is oriented to generate CIRs with a specific spot in pre-determined environments.

Among the channel models, the MiWEBA, IEEE 802.11ay, and 3GPP map-based models belong to this category. The two former models recommend generating the inter-cluster delay and cluster angles of arrival/departure using ray-tracing simulations, whereas the intra-cluster excess delay and intra-cluster angles of arrival/departure are generated in the same manner as the scenario-conditional models. The CIR generated by the former procedure is named “D-ray,” while that generated by the latter is named “R-ray.” The 3GPP map-based model merges the rays generated by ray-tracing and those generated by the 3GPP SCM under the LSPs found from ray-tracing. These models can be applied to broader scenarios (e.g., device-to-device or vehicle-to-vehicle scenarios) to generate extract CIRs in a given scenario as long as detailed information on the environments surrounding the nodes is set in the simulator.

DIFFERENCE IN USED MATHEMATICAL FUNCTIONS FOR CHANNEL COMPONENTS

Second, we summarize the differences in the mathematical distribution functions that generate the eight CIR components. Figure 3 illustrates this difference, which is discussed as follows.

Inter-cluster Excess Delay. Inter-cluster excess delay is generated by the following four methods: Poisson arrival, order statistics of an exponential distribution, order statistics of a piecewise-linear distribution, and ray-tracing simulation. The IEEE 802.15.3c employs Poisson arrival, the 3GPP SCM, and mmMAGIC model employ the order statistics of an exponential distribution, IEEE 802.11ad employs a piecewise-linear distribution, and IEEE 802.11ay and MiWEBA models employ a ray-tracing simulation. Exceptionally, the NYUSIM model does not explicitly generate an inter-cluster excess delay and generates a delay separation between adjacent clusters with the order statistics of an exponential distribution.

Intra-cluster Excess Delay. Intra-cluster excess delay is generated by the following three methods: Poisson arrival, order statistics of uniform distribution, and order statistics of an exponential distribution. The IEEE 802.15.3c, IEEE 802.11ad, and IEEE 802.11ay/MiWEBA models employ a Poisson arrival, the 3GPP SCM employs the order statistics of a uniform distribution, and the mmMAGIC model employs the order statistics of an exponential distribution. The NYUSIM model does not employ any order statistics and generates the intra-cluster excess delay as

The two former models recommend generating the inter-cluster delay and cluster angles of arrival/departure using ray-tracing simulations, whereas the intra-cluster excess delay and intra-cluster angles of arrival/departure are generated in the same manner as the scenario-conditional models.

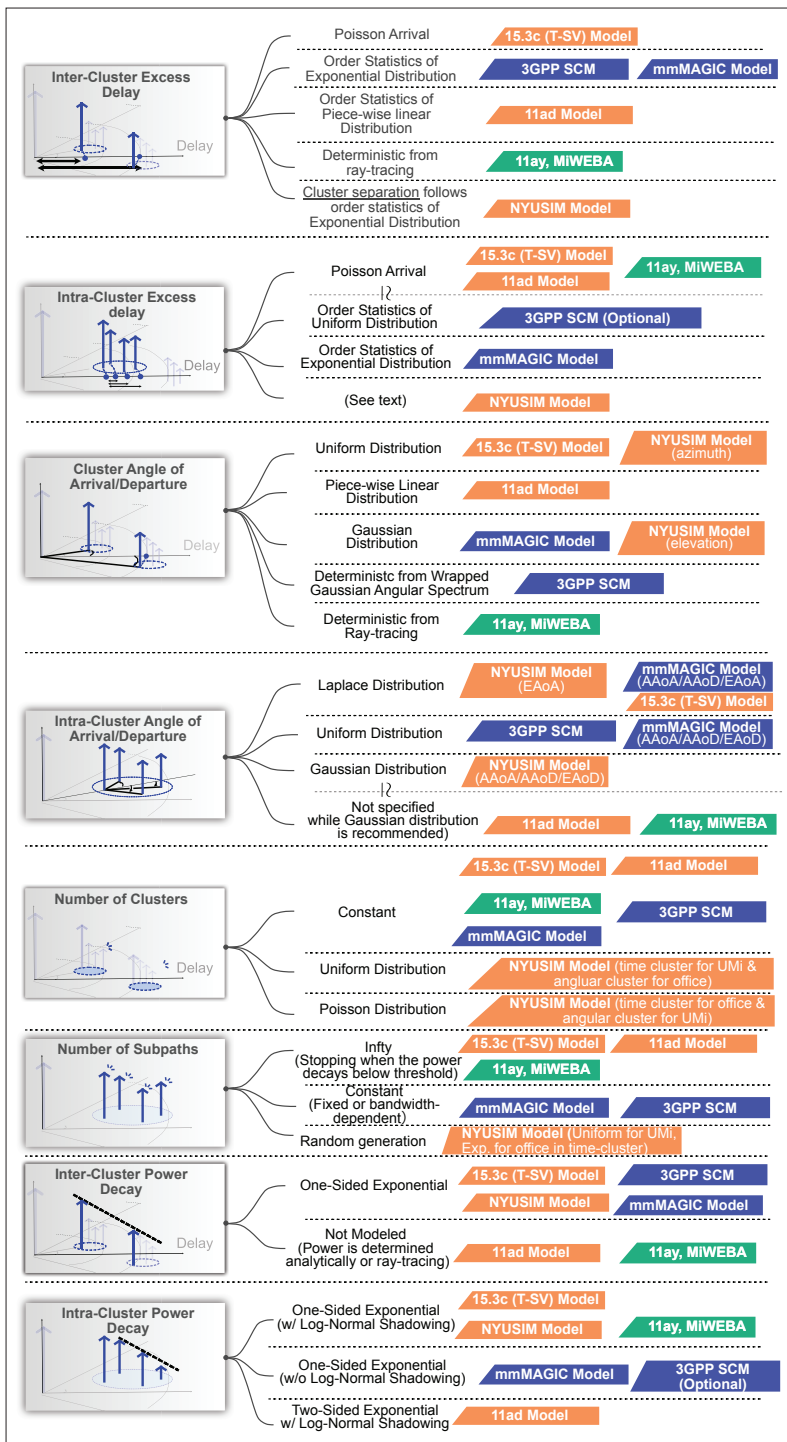


FIGURE 3. Difference in generation of CIR components among standard mmWave channel models.

$(1/B)^{1+X}$, $(2/B)^{1+X}$, ..., $((M - 1)/B)^{1+X}$, where B is the bandwidth, M is the number of subpaths in each cluster, and X is a random variable following a uniform distribution.

Cluster Angle of Arrival/Departure. The cluster angles of arrival and departure are generated by the following methods: sampling from uniform, Gaussian, or piecewise linear distributions, or performing a ray-tracing simulation. The IEEE 802.15.3c model samples them from a uniform distribution, the IEEE 802.11ad samples them from a piecewise linear distribution, and the IEEE 802.11ay and MiWEBA models derive them with

a ray-tracing simulation. The mmMAGIC model samples them from Gaussian distributions and scales them to ensure consistency with AS. The NYUSIM model separately samples the azimuth and elevation domain information from the uniform and Gaussian distributions, respectively. Exceptionally, the 3GPP SCM deterministically gives the cluster angles of arrival and departure, such that the resultant angular spectrum forms a wrapped Gaussian function consistent with the AS sampled in the LSP generation step.

Intra-cluster Angle of Arrival/Departure. The intra-cluster angles of arrival and departure are generated by the following four types of methods: determining from the Laplace distribution, uniform distribution, or Gaussian distribution. The IEEE 802.15.3c and mmMAGIC models sample them from a Laplace distribution, the 3GPP SCM samples them from a uniform distribution, and the NYUSIM model samples AAoA, the azimuth angle of departure (AAoD), and elevation angle of departure (EAoD) from a Gaussian distribution. Note that for elevation angle of arrival (EAoA), the NYUSIM model samples it from a Laplace distribution. The IEEE 802.11ad and IEEE 802.11ay models do not specify the generation procedure, whereas sampling from a Gaussian distribution with zero mean and a standard deviation of 5° is recommended.

Number of Clusters. The number of generated clusters is given by either a constant value or sample of a Poisson distribution. The 3GPP SCM, mmMAGIC, and IEEE 802.15.3c models employ constant values ranging from 2 to 20. IEEE 802.11ad and 11ay determine the number of clusters based on the number of reflections in the ray tracing simulation. In the NYUSIM model, the cluster is doubly defined for the delay time (a.k.a. time cluster) and angular information (a.k.a. spatial lobe), where the number of clusters in the delay domain is sampled from a Poisson distribution for an indoor office scenario [13], and a uniform distribution for an outdoor UMi-like scenario [9]. The number of clusters in an angular domain was sampled from a Poisson distribution for an outdoor UMi-like scenario and a uniform distribution for an indoor office scenario.

Number of Subpaths. The number of generated inter-cluster sub-paths is predetermined as either a constant value, a random sample from a discrete uniform distribution, or infinite values. The 3GPP SCM and mmMAGIC model fix the number of subpaths as a constant value, where the former model defines the value from the bandwidth-dependent formula found in clause 7.6.2.2 in [12], whereas the mmMAGIC model provides this value from a scenario-wise parameter table. The NYUSIM model mainly samples this number from a discrete uniform distribution. The IEEE 802.15.3c, 11ad, and 11ay models provide this value as an infinite value because the arrival of subpaths is modeled as Poisson arrival. Therefore, the generated subpaths with power below the threshold are removed.

Inter-cluster Power Decay. The inter-cluster power decay is modeled as a one-sided exponential decay model for a cluster excess delay or is determined by ray-tracing simulations. The IEEE 802.15.3c, mmMAGIC, and NYUSIM models and 3GPP SCM employ a one-sided exponential model, whereas the IEEE 802.11ad and IEEE 802.11ay models employ ray tracing simulations.

Intra-cluster Power Decay. The inter-cluster power decay is modeled as either a one- or two-sided exponential decay model. All models except the IEEE 802.11ad model employ a one-sided exponential model, whereas the IEEE 802.11ad model employs a two-sided model. Note that in the 3GPP SCM, the power decay is determined not only by delay values but also by intra-cluster angles of arrival and departure for the subpaths. Moreover, these two models do not include intra-cluster shadowing, meaning that the random dispersion in the powers of the intra-cluster subpaths was not modeled.

SUMMARY OF SURVEY AND PROPOSAL FOR UNIFIED CHANNEL GENERATION FRAMEWORK

SUMMARY OF SURVEY

The standard channel models possess differences in terms of both site-specificity levels and use mathematical functions to generate CIR. However, despite these differences, the aforementioned channel models generate a commonly structured CIR. Each model is a cluster-based channel model that aims to model inter-cluster and intra-cluster characteristics for both delay and angular domains. In particular, among the eight CIR components, the intra-cluster excess delay and intra-cluster power decay are specific for characterizing mmWave communications because the intra-cluster subpath can be resolved owing to the large bandwidth, which was not found in the channel model in lower frequency bands. This affinity provides us with a unified view of the separated and diversified mmWave channel models.

Given this affinity, the following question remains whether we need such various mmWave channel generation frameworks. Especially, in the current situation, when one aims to perform channel simulations for the high-coexistence of WPANs, WLAN, and CNs, channel generation methods must be drastically switched to fit each scenario. This requires extensive efforts and cumbersome procedures, pushing back the research developments in futuristic mmWave networks. This issue motivated us to propose a research direction for unifying various standard channel models, as discussed next.

PROPOSED RESEARCH DIRECTION TOWARD UNIFIED CHANNEL GENERATION FRAMEWORK

One possible research direction is to develop a unified framework that generates the eight CIR components for either WPAN, WLAN, or CN in an identical framework by changing only the parameters or mathematical functions for switching scenarios when required. One insight from this survey is the dearth of proof that the surveyed channel-generation framework cannot be applied to other scenarios. Namely, every model can be a unified framework that can be applied to not only the originally targeted scenarios but also other scenarios, as long as the validity of the mathematical functions and their parameters are extensively confirmed. Hence, investigating the applicability of one model to other scenarios and reporting required amendments is one research direction.

Indeed, as proven by the emergence of the quasi-deterministic model, a channel genera-

tion framework to test systems may rely more on ray-tracing in the future. Nonetheless, statistical channel models serve as a language to describe the overall channel characteristics to draw a design guideline for the systems, where a unified statistical channel model should be still developed. In the next section, we discuss the challenges and opportunities for this vision by investigating whether the 3GPP SCM can be a unified statistical channel-generation framework.

CHALLENGES AND OPPORTUNITIES FOR UNIFIED CHANNEL MODELING APPROACH

As an example, we investigated whether the 3GPP SCM, which originates from CNs, can generate the CIRs also for a WPAN scenario [15]. Among WPAN scenarios, we take a desktop scenario as an example, which was actually investigated in the IEEE 802.15.3c standardization, to bridge the 3GPP SCM and IEEE 802.15.3c model. Moreover, to this end, we only consider the AAoA as angular information because the IEEE 802.15.3c model only considered the AAoA. Note that as shown in Fig. 4, the “desktop” scenario is more similar to device-to-device communication in a conference room rather than personal desktops, where the source of the multi-path is the reflection from the walls majorly located far-field from the receiver. Hence, the assumption for plane waves in Sec. I still holds. In Fig. 4a, we pick up a key result from [15] to draw insights for unified channel modeling with extracted parameters compatible with the 3GPP SCM in Table 1. The results in Fig. 4a yield the following two key insights, which showcase the challenges and opportunities shown in the right and left parts of the figure, respectively. As a reference, we also generated the CIR with the IEEE 802.15.3c model originating from WPANs, which exhibits agreement with the real CIR data. However, this model is not consistent with other models, particularly the current standard 3GPP SCM, which is cast as the “Problem” in this figure.

Challenges. First, the 3GPP SCM cannot be applied straightforwardly to channel generation in a WPAN scenario, even after setting the derived scenario-specific parameters in Table 1. More concretely, the CIR generated from the 3GPP SCM does not match the real CIR in terms of AAoA and power characteristics. This is shown on the right-hand side of Fig. 4a. The characteristics of the real CIR can be summarized as follows:

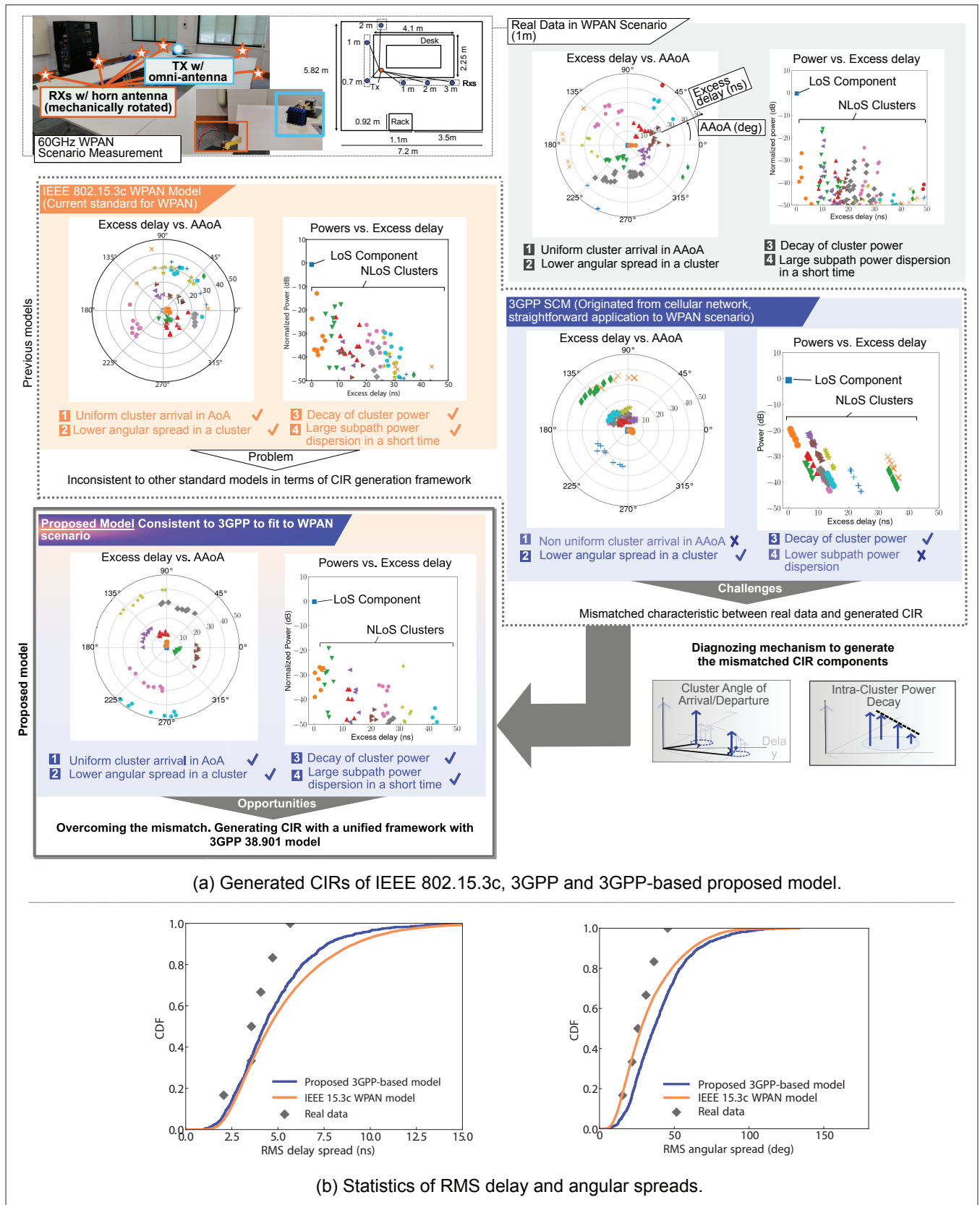
1. Uniform cluster arrival in AAoA
 2. Lower angular spread in cluster subpaths,
 3. Decay of cluster power with respect to excess delay
 4. Large subpath power dispersion in a short time.
- However, compared to the measured CIR, the generated CIR lacks the second and fourth characteristics; namely, the cluster is not uniformly distributed in the AAoA domain, and the power of subpaths is not dispersed. The first mismatch is attributed to the wrapped Gaussian distribution model for cluster AAoA, whereas the second mismatch is attributed to the lack of a power dispersion model in intra-cluster subpath powers.

Opportunities. Second, by diagnosing the CIR components exhibiting a mismatch from the real data, we can modify the 3GPP SCM to fit the WPAN scenario, which results in the proposed

The standard channel models possess differences in terms of both site-specificity levels and use mathematical functions to generate CIR.

model, as shown in the bottom-left part of Fig. 4a. In the proposed model, the cluster AOA is generated by a uniform distribution and not by a wrapped Gaussian model in [12]. Moreover, the

random dispersion was introduced in intra-cluster power decay as “intra-cluster shadowing” with a standard deviation of 6.81 dB, which was found by linear regression. As a result, as shown in Fig.



(a) Generated CIRs of IEEE 802.15.3c, 3GPP and 3GPP-based proposed model.

(b) Statistics of RMS delay and angular spreads.

FIGURE 4. Characteristics of real CIR and generated CIR from 3GPP SCM-based model for WPAN scenario: a) visualization of generated CIR in different models. Different markers and colors indicate that the subpaths are categorized in different clusters; b) RMS delay and angular spreads in CIRs generated by IEEE 802.15.3c and proposed 3GPP SCM-based models.

4a, the generated CIR exhibits the above four characteristics of the real CIR. Moreover, in Fig. 4b, we show the cumulative distribution function (CDF) of the root-mean-squared (RMS) DS and AS in the CIRs generated by the IEEE 802.15.3c and proposed 3GPP SCM-based model. The RMS DS in the proposed 3GPP SCM-based model distributes lower than those in the IEEE 802.15.3c model, while the trend of the RMS AS is the opposite. These trends are residual differences between the above two models and are attributed to the joint difference in the generation mechanisms of remaining CIR components. Nonetheless, both models are not highly contradictory to the real data, suggesting that the 3GPP SCM can fundamentally generate a CIR for WPAN scenarios. A summary of the proposed channel generation flow of the 3GPP SCM for the WPAN scenario is shown in Fig. 5.

CONCLUSIONS

This study surveyed the current status of standard mmWave channel models developed by several standardizations and academic communities for CNs, WLANs, and WPANs. We highlighted the difference between these channel models in terms of site-specificity levels and the mathematical functions used to generate the CIR. Nonetheless, we also showed that these models targeted the generation of commonly structured CIR, leading to the possibility that one model originating from one scenario can be a unified framework that generates channels for other scenarios. We believe that this unification is of more importance because there will be a growing demand to evaluate more complex networks with the co-existence of mmWave CNs, WPAN, and WLANs.

Moreover, a unified mmWave channel model is paramount in preparation for channel modeling in the terahertz (THz) band. An initial THz channel model was established in the IEEE 802.15.3d TG for scenarios of mainly proximity communications where the cluster delay, cluster AoA/

AoD, power of each cluster, and the number of clusters are modeled. This model lacks the consideration on intra-cluster parameters that does not fit the scenarios surveyed in this study. Thus, how to design a standard THz model for WPAN, WLAN, and CNs is now an open question, which is deferred as our future work.

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Parameters	Value
Mean of delay spread $\log_{10}(DS/s)$	-8.42
Standard deviation of delay spread $\log_{10}(DS/s)$	0.136
Mean of AAoA spread $\log_{10}(ASA/deg)$	1.44
Standard deviation of AAoA spread $\log_{10}(ASA/deg)$	0.152
Mean of K factor	8.60 dB
Standard deviation of K factor	3.40 dB
Intra-cluster delay spread	1.87 ns
Intra-cluster angular spread	14.8 degree
Delay scaling factor	2.65
Per-cluster shadowing standard deviation	7.97 dB
Cross correlation between DS vs. ASA	0.936
Cross correlation between DS vs. K factor	-0.948
Cross correlation between ASA vs. K factor	-0.937
Intra-cluster shadowing standard deviation (Parameter added for WPAN scenario)	6.81 dB

Note: A threshold of -50 dB from the maximum peak is applied for extracting multipath components.

TABLE 1. Extracted parameters for 3GPP SCM in WPAN desktop scenario [15].

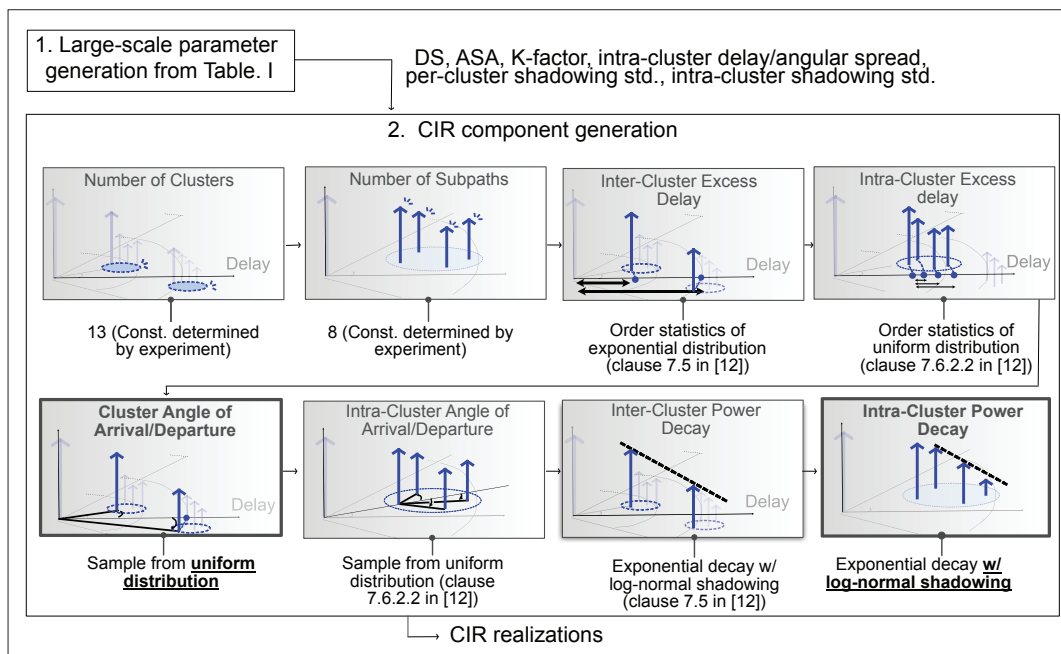


FIGURE 5. Proposed flow for CIR generation consistent to 3GPP SCM for WPAN scenario.

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