Map-based Millimeter-Wave Channel Models: An Overview, Guidelines, and Data

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Abstract—A wide range of available frequency bands is the promise of millimeter-wave (mm-Wave). For fifth generation (5G) communications, mm-Wave systems will service new applications such as enhanced mobile broadband, massive machine-type communication, and ultra-reliable low-latency communication service types. In order to establish mm-Wave systems, engineers should be able to model a mm-Wave channel. Researchers have tried to develop geometry-based stochastic channel models of mm-Wave radio links. The METIS group has presented a map-based channel model that is based on the ray-tracing algorithm; this model possesses a realistic channel in the given map to evaluate new technologies for 5G accurately. By now, map-based channel models have been widely discussed as a viable alternative to existing mm-Wave channels. This article presents an overview and an update of recent progress of mm-Wave channel models. We categorize map-based channel models and outline modeling guidelines for system-level evaluation including low-complexity modeling. Also, by utilizing map-based channel models, we put forward a concept of how to integrate a hardware and a software testbed/sounder. We next discuss some tips for designing a map-based channel model as well as some technical challenges to such designs. Lastly, we share the measurement data and the map-based channel parameters to the public.

Index Terms—Millimeter-wave, new radio, channel model, ray-tracing, system-level simulation, link-level simulation, and 5G.

I. INTRODUCTION

FUTURE fifth generation (5G) communication systems will include substantial types of service. These involve enhanced mobile broadband, massive machine-type communication (mMTC), and ultra-reliable low-latency communication. Researchers have discussed multiple applications of such service types and frequency bands for servicing them. Legacy radio communication systems have made tremendous use of sub-6 GHz bands due to the excellent radio propagation property. Thus, the lack of available sub-6GHz bands will give rise to various new applications made to operate in the millimeter-wave (mm-Wave) range. To establish mm-Wave communication systems, researchers should investigate appropriate mm-Wave channel models.

The sub-6 GHz channel models for system-level evaluation have focused on evaluating the performance of point-to-point

communications or multiple-input multiple-output (MIMO) systems with a small number of antennas (up to eight in LTE). These have been performed in the regular cell size of LTE and are based on a base station to a user equipment (BS-to-UE) link type. Recent mm-Wave channel models have not only included the inherent characteristics of the mm-Wave channel but added also channel properties for evaluating 5G communication technologies such as massive MIMO (M-MIMO) and hybrid beamforming [1]–[3]. These existing models have some limitations. For example, the channel model cannot support various modeling requirements for new applications of 5G [4]. Small cell technologies will become crucial, and many kinds of new applications' link types will vary, for example, device-to-device (D2D), vehicle-to-everything (V2X), air-to-everything (A2X). What needs to be investigated then is a new channel model, one that can possess realistic cell layouts and various modeling requirements for new applications.

In recent years, researchers have utilized ray-tracing (RT) not only to evaluate hardware (HW) testbeds but also to validate the theoretical performance of 5G vital technologies [5]–[9]. RT has the feasibility of modeling requirements and reasonable agreement with HW measurements [4], [9]–[12]. Designing map-based mm-Wave channel models that utilize RT have gathered momentum instead of the conventional geometry-based stochastic channel models (GSCMs) that only support particular modeling requirements. NYU WIRELESS developed the statistical spatial channel model (SSCM) by complementing HW channel measurements using RT [1]. The METIS group proposed a map-based channel model supporting various modeling requirements of 5G [2]. The 3GPP model adopted the hybrid of GSCM and map-based channels model [3], which was accepted to the ITU-R IMT-2020 evaluation report.

This article is motivated by the fact that researchers have been paying attention to designing a map-based mm-Wave channel model but still have a question – why should we utilize map-based channel models in the mm-Wave range instead of GSCM? The contributions of this work are as follows: i) an overview and an update of the recent progress of the mm-Wave channel models, ii) categorization of map-based channel models, iii) the presentation of how to integrate a HW and a software (SW) testbed/sounder with RT, iv) an offering of modeling guidelines for system-level evaluation including low-complexity modeling, and v) sharing the measurement database of the channel parameters for specific indoor- (Veritas C building in Yonsei University) and outdoor- (Gangnam Station in Seoul) regions to the public so that anyone can
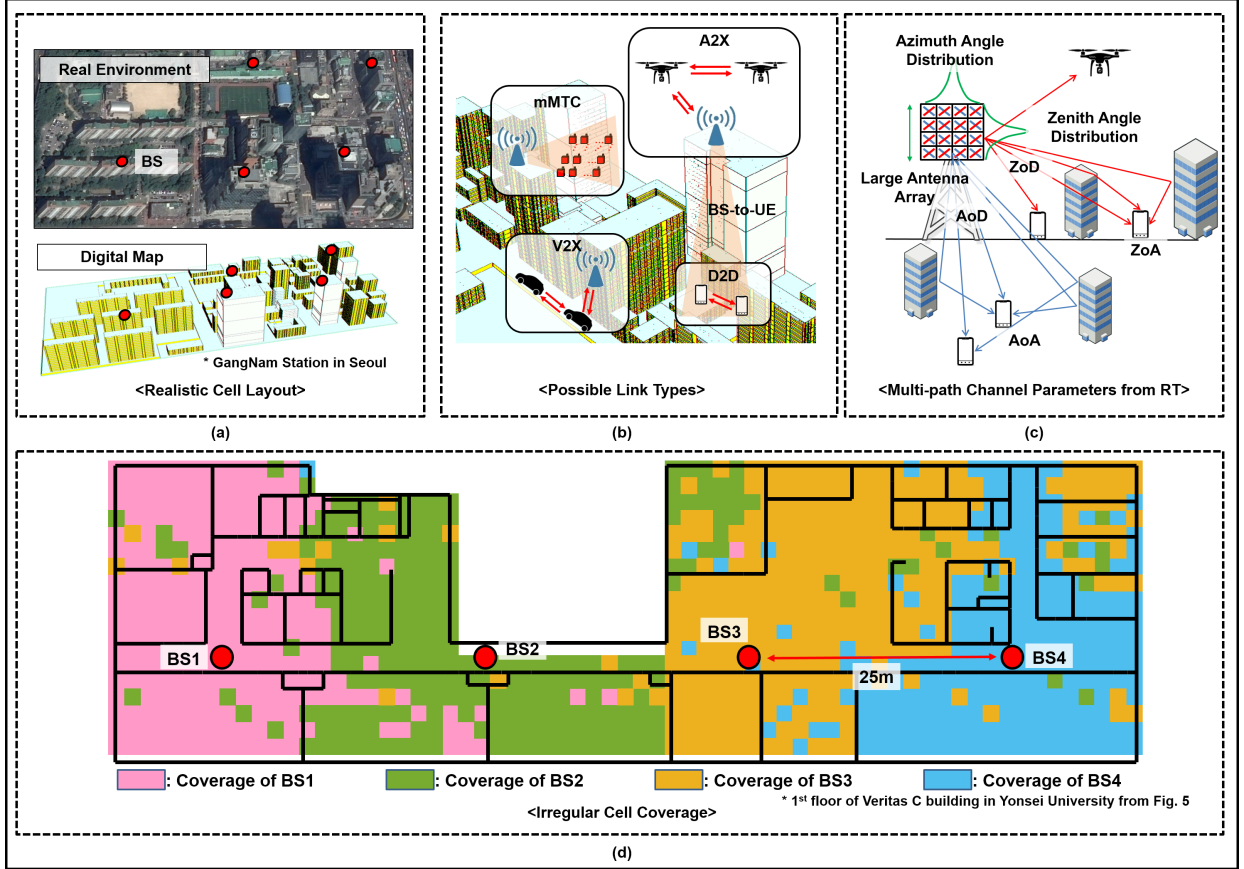
Fig. 1: An illustration of a map-based model and its characteristics: (a) a realistic cell layout in the digital map of GangNam Station, Seoul, South Korea; (b) possible link types; (c) the multipath channel parameters from RT; (d) irregular cell coverage based on a digital map shown in Fig. 5. In this illustration, WiSE, an RT software developed by Bell Labs [12], is used to show the digital map and predict coverage. The heights of the BSs and the UEs are, respectively, 3 m and 1 m with an isotropic antenna, and the center frequency is 28 GHz.

download and use for free.[1]

To the best of our knowledge, this is the first work that not only categorizes map-based channel models, but also shares the database of the map-based channel parameters. The categorization can ensure that each category can be efficiently utilized by concerning modeling approaches and requirements for various mm-Wave systems for 5G. Note, in this article, that we are not arguing the map-based mmWave channel model discussed is novel. Although most prior work on map-based channel models [2], [10], [11] focused on proposing RT algorithms, offering their specific procedure of the channel coefficients generation, and validating their model, some researchers might not be familiar with modeling the map-based channel. We expect that both the offered guidelines and the shared database encourage researchers to readily design a map-based channel model even without an RT software for evaluating theoretical technologies or HW testbeds for 5G.

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[1]These are available at http://www.cbchae.org/. We also present the demo video of our RT simulations in various scenarios including the digital map realization methods.

II. MODELING APPROACHES OF MM-WAVE CHANNELS

A. Characteristic of a mm-Wave Channel

Researchers have been attracted to a wide range of available frequency bands (6-100 GHz) in the mm-Wave ranges that promise higher data rates and the capacity to support various new applications for 5G. However, some inherent properties of mm-Wave propagation-links include high propagation-link loss by high path loss, high penetration loss, and blockages. Such properties lead to the received powers of radio signals being low. Consequently, engineers must try to achieve a higher propagation gain through technology, such as large array antenna systems. These systems can exploit the short wavelength of mm-Wave; in practice, such a system must have an array antenna of reasonable size. In this case, the spherical wave (no plane wave) assumption is plausible due to a large size of arrays regarding wavelength. Besides, if receivers (RXs) are located in a short distance away in a multi-user M-MIMO or an mMTC scenario, the correlations are very high between large-scale parameters (LSPs; e.g., path loss, delay spread (DS), angle spread (AS), the number of clusters and rays, etc.); that is, the channel is spatially consistent [4]. Considering these characteristics of the mm-Wave channel, the

additional features to the mm-Wave channel model can be summarized as follows:

- Channel parameters, such as LSPs and small-scale parameters (SSPs) (e.g., azimuth angle of departure (AoD), azimuth angle of arrival (AoA), zenith angle of departure (ZoD), zenith angle of arrival (ZoA), power delay profile (PDP), etc.), should be determined by considering various center frequencies of operating bands and frequency selectivity due to the broad system bandwidth.
- A channel model should take into account the high propagation-link loss. This modeling affects the received powers and the total number of clusters and rays, which are relatively smaller than those in the sub-6 GHz range.
- A channel model should consider spatial consistency by reflecting correlations of LSPs regarding distance among users and users' moving.
- In the large array antenna assumption, it is considered to model individual time of arrival and angle offsets for all rays per link between transmit and receive antennas. Besides, real beamforming patterns should be reflected in the model to evaluate beamforming technologies accurately.

B. Channel Modeling Approaches

In this section, we give channel modeling approaches concentrating on some popular mm-Wave channel models, such as the 3GPP model, the METIS model, and the SSCM. The SSCM is an extended model to the existing 3GPP sub-6 GHz model [13], as including the characteristics of the mm-Wave channel.

1) Geometry-based Stochastic Channel Models: GSCMs generate multi-path channel parameters that have statistical characteristics within target scenarios. The 3GPP model supports the following scenarios – an urban micro (UMi)-street canyon, a UMi-open square, an urban macro (UMa), and an indoor-office, an indoor shopping mall. The METIS model's scenario targets an outdoor square, an indoor cafeteria, and an indoor shopping mall. The SSCM enables channel modeling for UMi. Inter-site distance (ISD) for outdoor and indoor scenarios are respectively 200 m and 20 m for all models. To employ the mm-Wave characteristics mentioned above, GSCMs include the following approaches.

- The stochastic LSPs cover up to 100 GHz by fitting them regarding the center frequency from measurements.
- The 3GPP model applies outdoor-to-indoor (O2I) penetration loss, oxygen absorption loss regarding frequency, and blockage models to GSCM as considering the high propagation-link loss. Meanwhile, the SSCM gives the distribution of the number of clusters and rays reflecting the physical meaning of the high propagation-link loss.
- The 3GPP model supports spatial consistency by considering a correlation distance, which the users within have identical LSPs, with reflecting the trajectory of users and the transition of line-of-site (LOS)/non line-of-site (NLOS) state. Besides, the SSCM concerns an LSP correlation and a time-varying channel for modeling the spatial consistency.

- To support large array antenna and broad bandwidth, the independent ray parameters, such as angles, delays, and powers, are generated in the 3GPP model.

2) Map-based Channel Models and Categorization: Map-based channel models (a.k.a. site-specific propagation models) generate multi-path channel parameters by utilizing either mathematical descriptions or simulations of RT [2], [10], [11]. A customized three-dimensional digital map is used to organize a target network layout. We categorize map-based channel models from a modeling approach perspective.

Category I – Map-based Deterministic Channel Model: This model generates deterministic channel parameters at the particular transmitter (TX)/RX locations. This approach ensures that the channel is accurate for a given network layout. The channel represents only the characteristic of those locations for the given locations of random scatters and blockers. The METIS model includes this model.

Category II – Map-based Stochastic Channel Model: Stochastic LSPs are determined from channel measurements as many as possible in a target scenario and a given digital map. After fitting LSPs, this model generates multipath channel parameters in a way similar to that of a GSCM. For example, the channel model in [5] was based on this category and can be extended to the mm-Wave channel although the operating frequency was 5 GHz.

Category III – Map-based Hybrid Channel Model: This model is complementary to the other models or HW measurements. Various hybrid versions can be available. For example, the METIS and 3GPP models support the hybrid of a map-based deterministic channel model and a GSCM. The SSCM can be viewed as the hybrid of a map-based stochastic channel model and a GSCM.

3) Channel Models for Link-level Evaluation: The 3GPP model provides cluster delay lines (CDLs) and tapped delay lines (TDLs) for a link-level evaluation. In fact, these are not suitable for a mm-Wave channel model for the following reasons. A CDL represents only a single channel realization, so this is usually used to calibrate channel models. Meanwhile, a TDL does not employ the additional components for mm-Wave channel modeling in Section II-A.

The SSCM provides an alternative channel model for link-level evaluation. CDLs for the link-level evaluation are randomly generated. After defining the link for the particular TX-RX separation distance, their stochastic channel parameters are used to generate the channel parameters randomly. For a MIMO system, TDLs with the spatial correlation matrices are calculated from the CDLs. The limitation, however, is that it supports only UMi.

III. WHY SHOULD WE UTILIZE MAP-BASED CHANNEL MODELS IN THE MM-WAVE RANGE?

A. Various Modeling Requirements of Applications in the mm-Wave Range

Substantial types of applications will appear in 5G. Covering all modeling requirements for such applications is almost impossible with existing GSCMs, which still have insufficient channel measurement campaigns. In the map-based model, the

TABLE I: Comparison of a GSCM and a map-based channel model in the mm-Wave range.

Key Feature for mm-Wave Channels	GSCM	Map-based Channel Model
Frequency Range	Up to 100 GHz	Up to 100 GHz but Not Limited
Scenario	UMi (Street canyon, Open Square), UMa, Indoor (Office, Cafeteria, Shopping Mall)	Any Environment
Network Layout	Regular Layout (ISD: 50m (Indoor), 200m (Outdoor))	Irregular Layout
Support Large Array Antenna	O	O
Support Broad Bandwidth	O	O
Support Blockage	O	O
Support Spatial Consistency	O	O
Support Short-Range Link for New Applications (D2D, V2X, A2X, etc.)	Limited	O*
Modeling for Indoor Environment	O2I Penetration Loss	O2I and I2I Penetration Loss, Blockage Model at Middle of Path*
Support Dual-mobility and Blockers' mobility	Limited	O*
Support Indoor Mobility	X	O*
Support User-specific Channel Parameters	X	O*
Support Real Beamforming	Limited	O*
Support a HW Testbed Result	X	O*
Support a Channel Sounder	X	O*
Related Channel Model	3GPP, METIS, SSCM	Category I: METIS Category III: 3GPP, METIS, SSCM
*: Possible but have discussed yet in existing channel models.		

following modeling requirements can be handled and are not limited.

Short-Range Communication Links: Figure 1 illustrates a map-based model and its characteristics. In 5G, the cell sizes are likely to shrink for high network density. In a practical small cell topography, the coverages of each cell vary due to the assorted shapes and heights of surrounding structures. Thus, the level of the intercell interference will be dependent on the real geometry while that in a GSCM is mainly dependent on the distance between the BS and the UE because of a regular cell layout. Besides, new mm-Wave applications of D2D, V2X, and A2X will have a short-range communication link. The shorter the link is, the more the map-based models can depict the channel characteristics influenced by surrounding topography.

Realistic Indoor Environments: If RXs are located in indoors, penetration loss by both external walls and internal walls will be considered for more accurate modeling. The 3GPP model considers only external walls, although many scenarios support indoor users (e.g., 80 percent users in outdoor scenarios), and one of the essential characteristics of a mm-Wave channel is penetration loss. In indoor-to-indoor (I2I) paths, since similar heights of TXs and RXs result in blockers at the middle of the paths, this should also be applied.

Various Mobility Types: The new applications of mm-Wave systems will have various mobility types. Not only dual-mobility of such applications but the mobility of blockers should also be considered to ensure that channel modeling is accurate. Notably, in the case of indoor D2D type communications, researchers should consider devices' moving from room to room or from floor to floor.[2]

User-specific Channel Parameters: In GSCM, LSPs per cell are randomly generated from the same distribution regardless of cell topography; meanwhile, SSPs per user are generated from cell-specific LSPs regardless of users' locations. These would yield an unsure performance evaluation for cell- or user-specific technologies; for example, a dynamic cyclic prefix (CP) that can reduce CP overhead according to users' delay [5]. Besides, the real beamforming pattern should be applied to channel parameters. Such technologies can be evaluated by measuring SSPs regarding users' location and applying the per-user beamforming pattern.

B. Consistent Link-level Evaluation for the Target Scenario

Recent mm-Wave technologies have emerged within various scenarios; some technologies can enhance system performance by utilizing the characteristics of a mm-Wave channel. To prevent either over- or under-estimated link-level evaluation, researchers are required to use an appropriate channel model that well possesses the scenario of their technologies. For example, Fig. 2d shows the probability mass function (PMF) of the number of the clusters and rays. Three scenarios– a practical indoor scenario (many blockers in the building), an indoor scenario with no blockers, and an indoor scenario with five blockers around the RX (similar to the 3GPP blockage model), are considered in the indoor digital map. It shows that the PMFs of the number of the clusters among three indoor scenarios have a similar trend, and the number of clusters can be smaller than that of a UMi scenario derived from

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[2]The channel models for V2V and D2D are the study item of the 3GPP model [3].
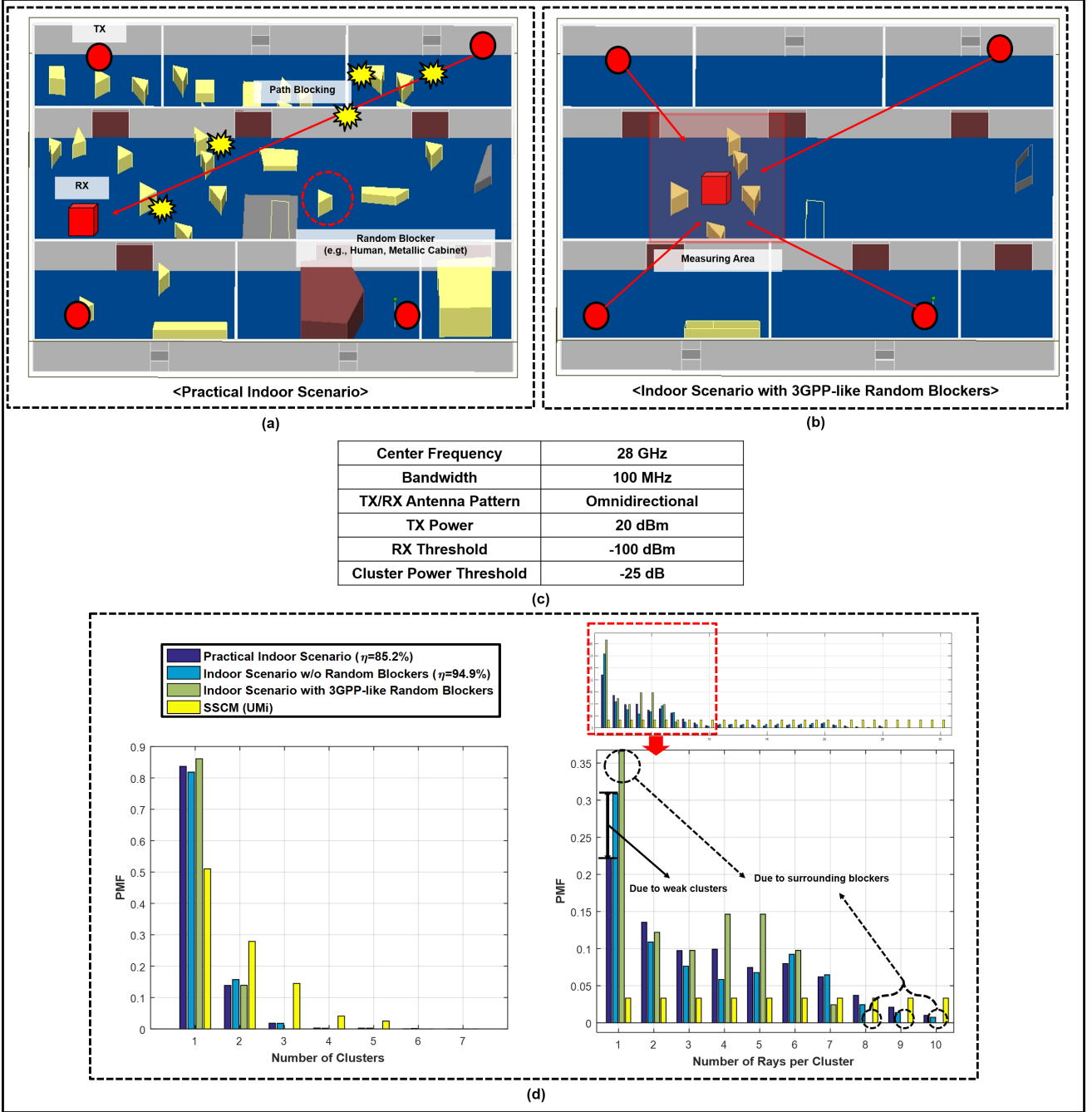
Fig. 2: Channel parameter modeling using map-based channels: (a) the digital map for a practical indoor scenario where the RXs are uniformly distributed in a building; (b) an indoor scenario with 3GPP-like random blockers where channel parameters are measured in the shaded area; (c) simulation parameters; and (d) simulation results. In this illustration, we use Wireless InSite, the RT software developed by Remcom.

the distribution in [1]. In the practical case, the coverage (η) shrinks, and some weak clusters consisting of one ray vanish due to many blockers. The maximum number of rays per cluster decreases when deploying 3GPP-like blockers. These are related to the rank of the channel, which affects not only the MIMO performance but also the accuracy of channel estimation algorithms that utilize the sparsity of the channel. Thus, a reliable channel model for the target scenario is necessary to keep the consistency of link-level evaluation [11].

The other issue is that of a link-level evaluation of a HW testbed. We can reconfirm the result of the HW testbed by link-level evaluation in the map-based model that describes the test site of the HW testbed. Besides, the map-based model facilitates system-level evaluation of a HW testbed, which we will discuss in Section IV.

IV. INTEGRATION OF A HW AND A SW TESTBED/SOUNDER

A. System-level Evaluation of a HW Testbed Based on a Map-based Channel Model

In trying to develop novel mm-Wave technologies, both their theoretical model and algorithm implementation have been jointly evaluated through a SW testbed at the link- to system-level in various scenarios and environments. Notwithstanding the versatility of a SW testbed, it is crucial to prototype a HW testbed before implementing technologies in the real world. The SW testbed has limitations, such as being unable to reflect well HW impairments. System-level evaluation using a HW testbed is, however, laborious, so a HW testbed usually assesses a technology at the link-level. System-level evaluation is desirable due to the complex radio-links of the mmWave system supporting complicated scenarios for various applications. If system-level evaluation using a HW testbed is practically feasible, it will promote furthering a mm-Wave system.

One option to do system-level evaluations using a HW testbed is to integrate HW testbed with a map-based SW testbed. As reflecting a link-level evaluation result of a HW testbed into that of a SW testbed (i.e., calibration), the system-level evaluation can be conducted in the digital map consisting of the test site. We leave some related work that utilized integrated testbeds based on their HW testbed's results.

- The authors in [6] evaluated the system-level performance of the demonstrated real-time hybrid beamforming HW testbed for small cell environments by using a map-based channel model. The authors in [7] compared the proposed non-linear self-interference cancellation with the existing cancellations in a full-duplex system considering D2D interference links and a polarized channel by utilizing the integration of their HW and SW testbeds. Although their research was conducted in the sub- 6 GHz, it can be extended to the mm-Wave range.
- The authors in [8] fabricated an RF lens that operated on 77 GHz and measured its HW performance. Then, they evaluated an RF lens-embedded massive MIMO system at the system level by combining HW measurements and their proposed algorithm with a map-based channel.

B. A Channel Sounder based on a Map-based Channel Model

Another use of integration based on a map-based channel model is to allow it to play the role of a SW channel sounder by utilizing measurements of a real-world channel sounder. This concept enables measuring channel characteristics and assessing theoretical technologies, and includes the existing mm-Wave channel model:

- The authors in [10] and [11] proposed map-based deterministic channel models and showed the reasonable agreement with the HW measurements. They presented realistic indoor digital maps that possess specific material information of walls including specialized environments (e.g., an indoor of the aircraft). These could be extended to suit any digital map and any mm-Wave channel.

- The authors of the SSCM utilized a map-based hybrid channel model by using RT results to complement the HW channel sounder. RT recreated the absolute propagation time of arrivals from BS-to-UE and retrieved AoA distribution for the validity of the model.
- The authors in [14] measured LSPs and SSPs by using a 60 GHz channel sounder. They calibrated the map-based channel, as well as evaluated theoretical beamforming technologies in a digital map.

V. MODELING GUIDELINES FOR SYSTEM-LEVEL EVALUATION

A. Guideline for Map-based Channel Model

Map-based deterministic Channel Model: Figure 3 illustrates block diagrams of map-based channel modeling processes. We first outline a guideline for a map-based deterministic channel model with dropping TX/RX and random objects.

- *System Setup:* In the first step, the digital map is realized; it represents the area and scenario for the target application and its adopted technologies. In the second step, the system parameters of the target application's TX/RX are set up. The antenna pattern of TX/RX and their array configurations including array types, the center frequency, the system bandwidth, the link types, and duplex mode are determined.
- *Network Layout:* First, TX/RX and random objects are dropped in the digital map. At the next snapshot, their locations move according to their mobility and trajectory. Note that random scatters and blockers are moving; this is in contrast to GSCM in which their impact is involved in the stochastic parameters. When considering the V2X scenario, it is needed for the accurate channel model to reflect the mobility and trajectory of surround vehicles that are blockers. In the last step, a beamforming pattern and allocated resource for each TX and RX per dropping are applied.
- *RT Simulation:* In this stage, channel parameters are predicted through an RT simulation. From this, it may be recognized whether a pair of TX and RX is LOS state or not as well as whether TX and RX are located in outdoors. An RT simulator also measures path loss, SSPs, and so on. In broad bandwidth modeling, this stage proceeds for each frequency bin (e.g., bins of the subcarrier). In large array modeling, each array is positioned at the actual coordinates in the digital map, and then beamforming pattern is applied.
- *Generate Channel Coefficient:* Channel coefficients are generated by utilizing channel parameters applying the clustered channel model equation (e.g., the equations in [1], [3], [11]).

Map-based Stochastic Channel Model: After the system setup stage, the map-based stochastic channel modeling proceeds as follows:

- *Predetermine Stochastic Parameters:* The stochastic channel parameters of the target scenario is predetermined from the database of the measurements (i.e., the snapshots for the given system setup of the map-based
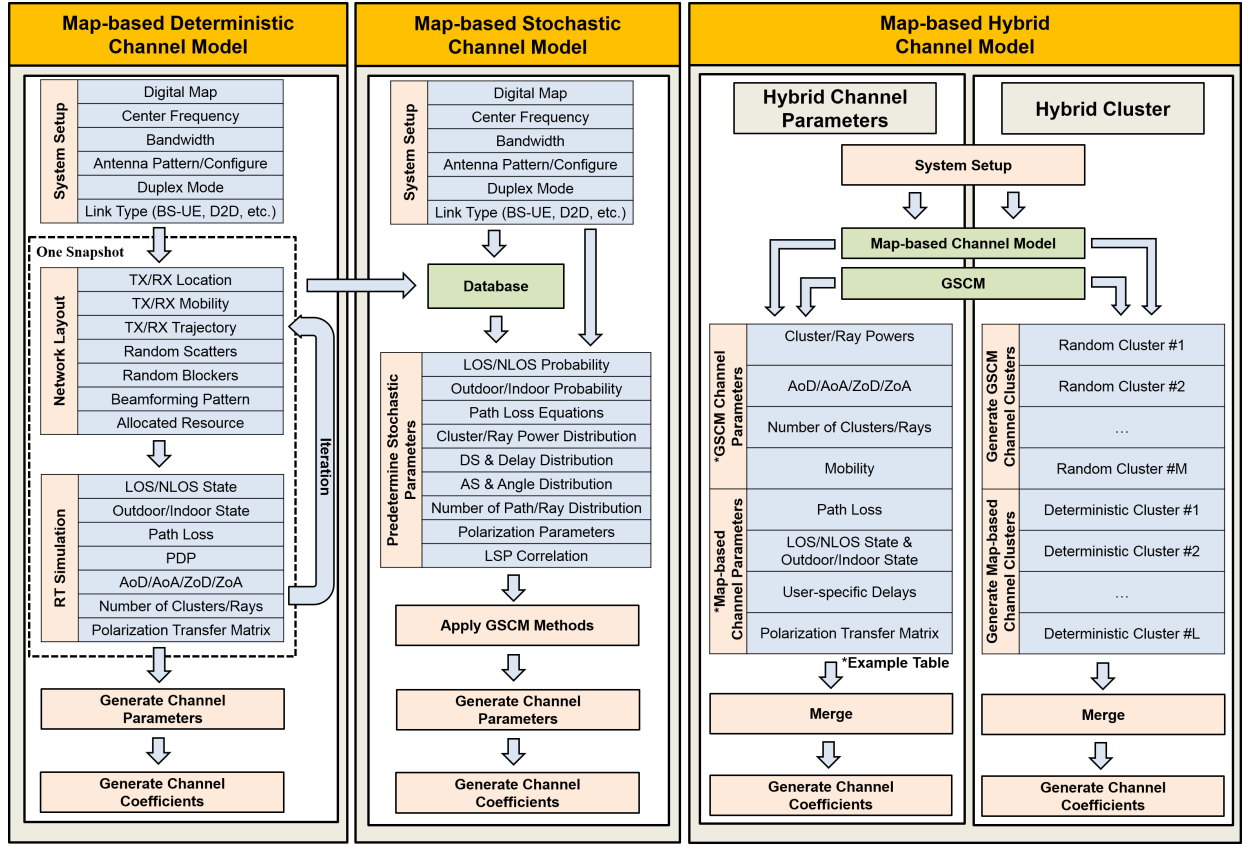
Fig. 3: Block diagrams of map-based channel models. Total number of random clusters and deterministic clusters are denoted by M and L in this illustration.

deterministic model). This model is similar to modeling GSCM in which the LSP is predetermined by collecting a number of the real-world measurements. For example, DS, delay distribution, and cluster/ray distribution are adjusted from multiple snapshots of PDP [5], otherwise AS and angle distribution are calculated from those of PDP and AoD/AoA/ZoD/ZoA.

- *Apply GSCM Methods:* Channel coefficients can be calculated by applying the GSCM methods from these stochastic parameters.

Map-based Hybrid Channel Model: We present guidelines for three types of map-based hybrid channel models.

- *Hybrid Clusters:* The conventional hybrid model is the 3GPP model that deals with channel parameters from the digital map as deterministic clusters' parameters and those from GSCM as random clusters' parameters. These clusters are treated as independent clusters but merged by putting weight to each of them.
- *Hybrid Channel Parameters:* The other method is that each channel parameter is independently generated from each other channel model so as to supplement its shortcomings. In the hybrid of the map-based model and GSCM, for example, the user-specific channel parameters can be determined from the map-based channel model since GSCM do not support this.
- *Hybrid of a Map-based Model and a HW Measurement:* In this case, the generated channel parameters from

the map-based model are combined into the channel coefficient with the calibration factors, as mentioned in Section IV.

B. Guidelines for Low Complexity Map-based Deterministic Channel Model

The higher accuracy the map-based deterministic model has, the higher its complexity gets. Each snapshot represents the deterministic channel for a given TX/RX location while that from GSCM is not dependent on the TX/RX location.[3] Random objects should be dropped to prevent the channel coefficient from fixing for the given TX/RX location, which requires additional snapshots, so the complexity increases. Figure 4 illustrates block diagrams of low complexity map-based deterministic channel models; the details are given below:

Database of Deterministic Channel Snapshots: A channel snapshot for given TX/RX information (e.g., locations, mobility, trajectory) can be picked out from the database since a snapshot of the map-based deterministic model represents a channel of the specific pairs of TX and RX regarding locations of random objects for a given system setup. This method not only maintains the accuracy of the map-based deterministic model but also reduces, to a tremendous degree,

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[3]These mean that there is a trade-off between being a deterministic channel and characterizing spatial consistency.
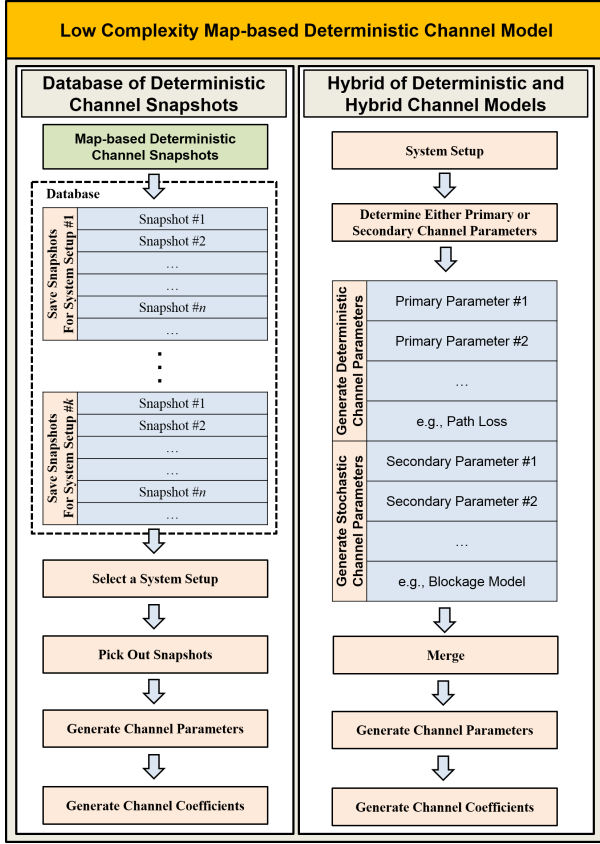
Fig. 4: Block diagrams of low complexity map-based deterministic channel models. In this illustration, the indexes of the system setup and the snapshot are denoted by k and n.

the complexity of the channel generation (i.e., it only needs a picking-out-algorithm). Note that the database, however, is necessary to determine stochastic channel parameters for either map-based stochastic modeling or a channel measurement campaign using a SW channel sounder.

Hybrid of Deterministic and Stochastic Channel Models: Another complexity reduction method is combining with a map-based stochastic model that has equal complexity with GSCM while this hybrid model still represents the characteristic of the digital map. In the first step, the parameters are determined that will be either primary channel parameters that contribute more to the performance of the target scenario or secondary channel parameters that contribute less to the performance or yield high complexity, is determined. In the second step, primary channel parameters are generated from a map-based deterministic model while the others are produced from a map-based stochastic model. Finally, the primary and secondary channel parameters are combined. For example, for the realistic multi-cell layout, a primary channel parameter will be path loss. On the other hand, to reduce the complexity of allocating random blockers in the digital map, the blockage model, which is defined in stochastic models, can be applied.

C. Some Tips for More Precise Evaluation

Digital Map Realization for Realistic Environment: One of the significant virtues of the map-based model is modeling a realistic digital map [10]. Nevertheless, previous work in the mm-Wave range has considered simple digital maps, such as few square-shaped buildings that consist only of concrete external walls without internal walls for either an outdoor-to-outdoor or V2X scenario; and a part of building with few rooms for an I2I scenario [4], [9]. In this regard, we present methods for the practical digital map realization.

The digital map, in general, is composed of sets of co-ordinates points of wall corners and material information (e.g., relative permittivity, conductivity, etc.) of walls that is frequency-dependent and listed in [15]. One simple method of the digital map realization is obtaining 2D coordinates points of wall corners from a ground plan or a floor plan and then inputting the height and the material information of walls. Components of the digital map should be matched to the RT simulator's format.

Figure 5 illustrates the realization method of the indoor digital map in our previous work [6]–[8]. Using a graphics tool, we drew traced pictures over the real floor plans of the building. The 2D coordinate points of wall corners were acquired from the traced pictures by using a customized source code, and the other information was also inputted. The outdoor digital map in Fig. 1 was realized in a similar way which can additionally support both O2I and V2X scenarios by modeling interiors of buildings and roads between buildings. On top of that, there are many other methods of the digital map realization (e.g., by utilizing CAD [10], [12] or Google SketchUp [9]).

Realistic Polarized Channel: Modeling a realistic polarized channel has become crucial for future MIMO technologies. Conventional channel models have used a polarization transfer matrix representing a polarized channel. This matrix is denoted by field patterns of each copolarization (e.g., either vertical or horizontal polarization) and stochastic cross-polarization-ratio (XPR) for describing each polarization power. In contrast, cross-polarization antenna patterns, which can be measured in an anechoic chamber, can be applied to the matrix instead of using XPR in a map-based channel model [7]. Besides, as the map-based model can exploit specific behaviors of the polarization, this ensures the polarized channel model is realistic [4].

VI. Research Challenges

Map-based Channel for Link-level Evaluation: Notwithstanding our focus on outlining guidelines for map-based channel models for every category, researchers should pursue work on a convenient link-level map-based channel. For example, we can model a TDL with spatial correlation matrices that calculated from a CDL of a map-based mm-Wave channel model. Such a TDL model, however, would need adaptive LSP-scaling methods and additional tabulating methods. What also remains to be investigated is an SSCM-like map-based link-level channel model as a research challenge.

Channel Measurement Campaign: As mentioned in Section IV, we can conduct a channel measurement campaign by using the map-based channels. Notably, a vehicular channel sounder for V2X and an airborne channel sounder for A2X
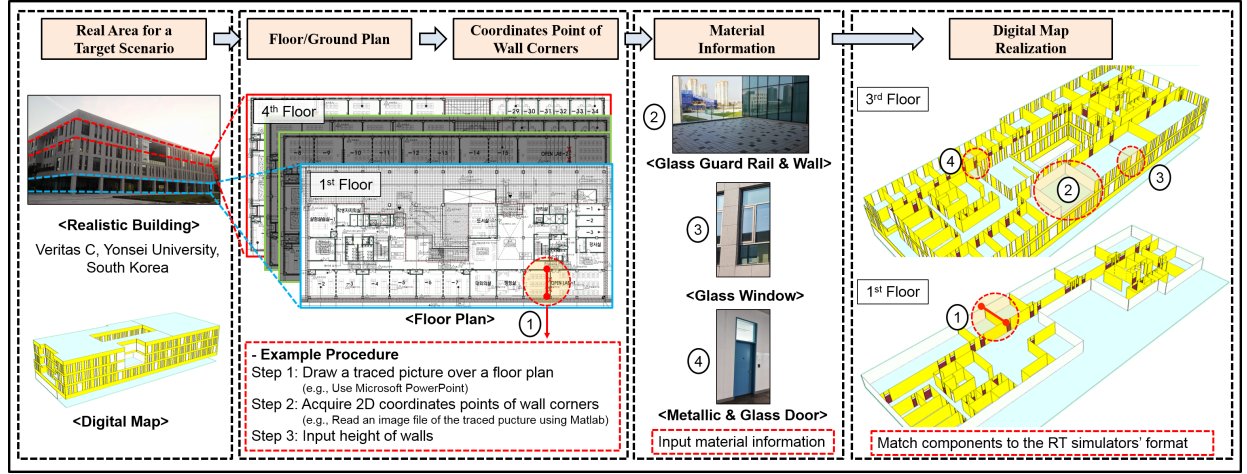
Fig. 5: The realization method of the digital map. In this illustration, the specific procedure of modeling of the building, Veritas C, Yonsei University, South Korea, is shown.

should be developed; the measurement procedure for such scenarios would be complicated. Thus, it would be efficient to perform a channel measurement campaign through a map-based channel model before firmly establishing a HW-based measurement procedure. In addition to that, the channel measurement can be accurately conducted with the aid of the map-based channel models for point-to-point communications such as wireless backhauls, one of the application candidates in the mm-Wave range.

VII. CONCLUSION

This article has given an overview and an update of recent progress of the modeling approaches for existing mm-Wave GSCMs and map-based mm-Wave channel models. We have also categorized map-based channel models as the map-based deterministic model, the map-based stochastic model, and the map-based hybrid model. The map-based models should be utilized to consider the various modeling requirements of applications in the mm-Wave range that are the short-range communications link, realistic indoor environments, various mobility types, and user-specific channel parameters. The map-based model could support a HW measurement validation at both the link level and system level so that it could be treated as a supplementary SW testbed/sounder. Also, we have outlined modeling guidelines for system-level evaluations including low complexity modeling. Finally, we share the measurement database of the channel parameters for two scenarios (indoor and outdoor) to the public. Our future work will consist of designing map-based V2X and A2X mm-Wave channel models.

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