28 GHz Channel Modeling
Using 3D Ray-Tracing in Urban Environments

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Abstract—In this paper, we analyze the radio channel characteristics at mmWave frequencies for 5G cellular communications in urban scenarios. 3D-ray tracing simulations in the downtown areas of Ottawa and Chicago are conducted in both the 2 GHz and 28 GHz bands. Each area has two different deployment scenarios, with different transmitter height and different density of buildings. Based on the observations of the ray-tracing experiments, important parameters of the radio channel model, such as path loss exponent, shadowing variance, delay spread and angle spread, are provided, forming the basis of a mmWave channel model. Based on the analysis and the 3GPP 3D-Spatial Channel Model (SCM) framework, we introduce a preliminary mmWave channel model at 28 GHz.

Index Terms—mmWave, 28GHz, ray-tracing, 3D-channel model.

I. INTRODUCTION

As one of the promising solutions for the next generation of wireless communications (5G), the use of enlarged system bandwidth in the millimeter wave (mmWave) frequency range is discussed [1]. The most fundamental question in mmWave cellular communication systems is the feasibility in outdoor environments, considering the much larger propagation loss compared to legacy cellular systems operating in the below 6 GHz band [1]. In [2], the channel characteristic of mmWave spectrum, based on field measurements, was analyzed at 28 GHz and 38 GHz in outdoor environments. Recently, [3], [4] conducted additional measurement campaigns in urban environment and proposed a mmWave channel model. As an alternative approach to analyze the mmWave channel characteristics and to fill up the gap in statistical description caused by the limited number of samples in measurement campaigns, ray-tracing can be considered since it provides good agreement with real measurement results [5], [6].

In this paper, we propose a mmWave channel model at 28 GHz based on ray-tracing in various urban scenarios. Thanks to available geometrical information, we model downtown areas of Ottawa and Chicago, and then perform 3D ray-tracing simulations at both 2 GHz and 28 GHz in those areas. First, we compare the pathloss propagation model from ray-tracing with a reference model used in standardization groups (such as 3GPP and ITU), and other measurement-based models [4]. Then, we provide modeling of other important channel parameters, such as shadowing variance, delay spread, angle spread, and elevation spread in both the 2 GHz and 28 GHz bands. We provide the channel modeling results which include crucial parameters and the 3D features, i.e., the elevation domain.

II. RAY-TRACING IN URBAN ENVIRONMENT

To model urban environments, 3D geographical building models are used for a ray-tracing approach. In this work, we modeled the city of Ottawa, Canada and the city of Chicago, IL, USA, especially the respective downtown areas. Note that in [7], the same 3D model and ray-tracing simulations are used for channel modeling in this paper.

In Fig. 1, the 3D modeled downtown of Chicago is shown. Two different environments are used for ray-tracing simulation: the northern-western area (Region 1) on the Chicago River as a sub-urban environment, and the Loop area (Region 2) with tall buildings as a dense-urban environment. The area of Region 1 (R1) has 194376 Rx samples within 1470m x 1280m with a resolution of 5m, and the area of Region 2 (R2) has 222170 Rx samples within 1570m x 1410m with the same resolution. A total 8 and 10 Tx locations are modeled in R1 and R2, respectively, where the locations are inferred from currently deployed cellular base-station locations. The receiver height is set to 1.5m above ground in both scenarios. At each receiver point, up to 40 rays are collected in descending order, and then a channel impulse response (CIR) including signal power, phase, propagation time, direction of departures and direction of arrivals (both azimuth and elevation) are
calculated. Note that the rays are traced up to 250 dB loss during the simulation.

For each of the various urban environments, two deployment scenarios are considered. To get mmWave channel statistics of general deployment scenarios, environment settings similar to Urban Macro (UMa) and the Urban Micro (UMi) models in ITU IMT-Advanced channel model [8] and 3GPP spatial channel model (SCM) [9] are used. In Ottawa Scenario 1 (S1), the transmitter is placed 5m above the rooftop like the UMa scenario. Scenario 2 (S2) in Ottawa follows the UMi model where the transmitter is installed at the corner of the building. The transmitter height is assumed to be 10m above ground. The receiver height is set to 1.5m above ground in both scenarios. In Chicago, R1 is considered as sub-urban area because the average building height in R1 is 31.4m and the Tx location is deployed in a range of 22m ~ 34m on rooftops. R2 is the center of the downtown area, where average building height is 56.9m, similar to dense-urban environment.

The Tx heights are in the range of 24m~91m. All the other conditions for the ray-tracing are identical to the simulation setup used in [7].

III. CHANNEL PARAMETER ANALYSIS

1) Propagation Analysis: Here we only present the propagation model at 28 GHz compared with the measurement-based NYU Campus model [4] in Fig. 2. In this paper, the simple analysis of propagation pathloss is described and more results and details can be found in [7], [10]. Following the approach of mmWave pathloss modeling in urban areas in [7], the pathloss is described by dual-slope models, which provides a better fit, i.e., lower root mean square error between simulation results and model. As described in [10], the dual-slope pathloss models both in Ottawa and Chicago agree well with the model based on measurement campaigns [4] in areas within 200m from the transmitter. Another comparison between 2 GHz and 28 GHz band concerns the shadowing factor (SF). The analysis of SF models are presented in [10], [11], and it is noted in this paper that while the standard deviation of the SF at 2 GHz is between 8 and 10 dB, the mmWave band exhibits severe shadowing with standard deviation 8~21 dB in the near region of the dual-slope and 15~30 dB in the far region for the second-slope model.

2) Analysis in Spatio-temporal Domain: The channel parameters in delay and angular domains are extracted. For the calculation of delay spread, the MPCs are cut out which power is 25 dB lower than the strongest MPC for each Tx-Rx combination. Interestingly, the statistics of delay and angle spreads at 28 GHz follow an exponential distribution, unlike the referenced models in the legacy bands below 6 GHz. To the best of our understanding, this is mainly caused by the propagation characteristic of the mmWave band, since only reflected and diffracted paths are observed without penetration through buildings. Furthermore, the reflection from far-away objects and the diffraction are attenuated more strongly at 28 GHz than at 2 GHz. The strong attenuation of these paths causes less heavy-tailed distribution of delay and angular spreads.

Comparing the results at 2 GHz with the channel model in [8], all mean values of the delay spread in the 2 GHz ray-tracing results are essentially between the values of the delay spread in the UMa scenario and the UMi scenario. The delay and azimuth angle spreads at 2 GHz are fitted to a log-normal distributed model like in [8], however, the channel model statistics in the 28 GHz band follow an exponential distribution. The values of delay spread in the 28 GHz band are smaller than the values of delay spread in the conventional cellular band. Besides the parameters on Table I, it is verified that the excess delays at both 28 GHz and 2 GHz are exponentially distributed, and azimuth angle of departure (AoD) and azimuth angle of arrival (AoA) follow a Laplacian distribution as expected.

Next, the K-Power-Means algorithm [12] is utilized for clustering of observed multipath components (MPCs). This algorithm is iterative and uses a distance metric based on the power-weighted multipath component distance (MCD). The algorithm minimizes the sum of MCDs from each data point in the cluster to the centroid of the cluster, which has the effect of minimizing cluster angular and delay spreads. Note that the delay scaling factor in MCD is set to 5 and the Kim-Park (KP) index proposed in [13] is used for determining the optimum number of clusters, following [14]. After the clustering, the results from the ray-tracing simulation are analyzed in the spatio-temporal domain, for parameters such as time of arrivals, angles at transmitter / receiver side, and the received powers. Based on the observed MPCs at each measurement point, inter-cluster and intra-cluster delay spreads and angle spreads are analyzed using the framework in [15]. The mean and standard deviation of all parameters at 2 GHz and 28 GHz are summarized in Table I and 28 GHz channel model parameters are shown in Table II. For the further modeling purpose, the parameters of the fitted distributions, such as (μ, σ) for the log-normal distribution and 1/λ for the exponential distribution, are also described.

In the extension to a 3D-channel model, i.e., including elevation angles, the elevation angle spread at Tx, which is also referred as zenith angle spread departure (ZSD) is analyzed and modeled as exponential distribution. Following the 3GPP...
3D-channel model [9], the statistics of elevation angle is observed as a function of distance between Tx and Rx. In Fig. 3(a), each ZSD is plotted as scatter point and the local mean and standard deviation of ZSD, which are plotted as red and magenta dotted line in Fig. 3(a) depend on distance. The mean and standard deviation of the ZSD is similarly modeled in [9] with breakpoint in single-slope, but we observe that the parameters are still a function of distance in the second slope after the breakpoint. Thus, the parameter \( \lambda \) is represented as dual-slope model. The zenith angle spread arrival (ZSA) follows the model in [9] and is well matched to a log-normal distribution.

The offsets of elevation angles, i.e., the local mean of elevation angles, zenith of departure (ZoD) and zenith of arrival (ZoA), are also modeled as a distance-dependent function as shown in Fig. 3(b). The offset of ZoD is well matched the the channel model in [8], however, the model of the offset of ZoA is proposed by following a power function, because the ZoA offset should be modeled as negative in the far region. In the area, LoS path from TX is hardly received with a positive offset, and most paths are coming from the ground-level. The proposed fitted models are plotted in Fig. 3(b). The parameters for elevation angle spread models and angle offset models are described in the later channel modeling section.

### IV. MMWAVE CHANNEL MODELING

In this section, the ray-tracing-based mmWave channel models in various scenarios (UMi, UMa, dense-urban, and sub-urban) are proposed. The channel modeling procedures are basically following the ITU channel model [8] and 3GPPP 3D-channel model [9], to which some modifications from the observation in the previous section are suggested.

#### A. Generation of Channel Parameters

In this section, the channel generation methodology is presented based on the obtained parameters in the previous section. After applying the pathloss model described in Section III-I, N clusters, path delays, path AoD/AoA and ZoD/ZoA are generated. Then, with the generated spatio-temporal channel parameters of clusters and paths, one can compute the channel coefficients for each cluster and each receiver and transmitter element pair, \( H_{n,s,n}(t) \) which is defined in [9]. The generation procedures of each channel parameter are described later in this section, and the channel large-scale parameters are randomly generated according to the distribution and parameters summarized in Table I.

For the accurate channel model, the number of clusters \( N \) should be generated as a realization of a random variable following a Poisson distribution. However, due to the complexity of the channel model and the difficulty of deriving all conditional probabilities of relevant channel parameters, we instead use a fixed number of paths, \( N = 6 \), for simplified channel modeling. Also, due to the limited number of rays (25 in Ottawa or 40 in Chicago) of the ray-tracing result, the subpath number is also fixed for modeling purpose because each cluster does not have enough subpaths. The number of subpath is set to 20 in the 3GPPP 3D-channel model and ITU channel model in legacy bands, however, the number of subpath is smaller in the mmWave band according to the ray-tracing observation. The number of subpath \( M \) is thus fixed to 10 in our model.

#### Path delays: The delay spread \( \sigma_r \) is modeled as an exponential random variable with \( \lambda \) in Table I. Then, the \( n \)-th cluster delay is generated via an auxiliary realization of exponential random variable as [8] \( \tau_{n}^{(r)} = -r_{\text{aux}} \sigma_r \ln(X_n) \) where \( r_{\text{aux}} \) is the delay distribution proportionality factor, \( X_n \sim U(0,1) \), and the cluster index \( n = 1, \cdots, N \). The cluster delay \( \tau_n \) is then calculated by normalization and descending sorting, \( \tau_n = \text{sort}(\tau_n^{(r)} - \min(\tau_n^{(r)})) \). The subpath delays \( \tau_{n,m} \) are calculated by adding the intra-cluster delay offset. Even though the intra-cluster delay spread is obtained from the ray-tracing results, we simply added the fixed delay offset, similarly to ITU model. The delays of the subpaths are grouped and defined by

\[
\begin{align*}
\tau_{n,m} &= \tau_n + 0 \text{ [ns]}, \quad m = 1, 2, 3, 4, 10 \\
\tau_{n,m} &= \tau_n + 5 \text{ [ns]}, \quad m = 5, 6, 9 \\
\tau_{n,m} &= \tau_n + 10 \text{ [ns]}, \quad m = 7, 8
\end{align*}
\]
### Table I: Ray-Tracing Results - Modeling Parameters

<table>
<thead>
<tr>
<th>Channel Environment</th>
<th>Ottawa S1 (Urban)</th>
<th>Ottawa S2 (Urban)</th>
<th>Chicago R1 (Sub-urban)</th>
<th>Chicago R2 (Dense Urban)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 GHz</td>
<td>28 GHz</td>
<td>2 GHz</td>
<td>28 GHz</td>
</tr>
<tr>
<td></td>
<td>(265.7, 178.5)</td>
<td>(217.3, 224.2)</td>
<td>(109, 145.3)</td>
<td>(337.5, 265.6)</td>
</tr>
<tr>
<td>RMS Delay Spread</td>
<td>Fitted Model</td>
<td>Log-Normal [-6.69, 0.37]</td>
<td>Log-Normal [-6.91, 0.40]</td>
<td>Log-Normal [-6.47, 0.35]</td>
</tr>
<tr>
<td></td>
<td>Azimuth AoD Spread (ASD)</td>
<td>Exponential [1/λ = 266.5 m]</td>
<td>Exponential [1/λ = 117.8 m]</td>
<td>Exponential [1/λ = 36.3 m]</td>
</tr>
<tr>
<td></td>
<td>Fitted Model</td>
<td>Log-Normal [-1.15, 0.42]</td>
<td>Log-Normal [-1.97, 0.47]</td>
<td>Log-Normal [-1.62, 0.37]</td>
</tr>
<tr>
<td></td>
<td>Elevation AoD Spread (ZSD)</td>
<td>Exponential [1/λ = 0.6575]</td>
<td>Exponential [1/λ = 1.614]</td>
<td>Exponential [1/λ = 1.87]</td>
</tr>
</tbody>
</table>

**Path powers**: Cluster powers are modeled as exponential distribution, and the cluster powers are related to the exponentially distributed cluster delays. Determine first

\[ P'_n = \exp \left( -\frac{\tau_n}{\tau_{rns}} \right) \cdot 10^{\frac{P_0}{10}} \]

where \( Z_n \sim N(0, \xi) \) is the inter-cluster shadowing factor in [dB]. Then, the cluster power of each channel realization is normalized, and expressed as

\[ P_n = \frac{P'_n}{\sum_{n=1}^{N} P'_n}. \]

**Path angles**: The spatial characteristic of departure and arrival azimuth angle is modeled as Gaussian distribution. First, we describe the AoD and all processes can be applied to the AoA in the same manner. The model of the angle distribution is well matched only when the cluster size is enough for the angles to be randomly distributed. Assuming the AoD is a Gaussian distributed random variable, AoD for \( n \)-th cluster is generated by \( \phi_{n, AoD} = X_n \varphi_n + Y_n + \phi_{LoS,AoD} \) where \( \phi_{LoS,AoD} \) is the LoS direction in azimuth between Tx and Rx, and

\[ \varphi_n = \frac{2\sigma_{ASD} \sqrt{\ln \left( \frac{P_n}{\text{max}(P_n)} \right)}}{1.4C} \]

where \( X_n \in \{1, -1\} \) is a uniformly distributed random variable, constant \( C \) is a scaling factor related to total number of clusters (note that \( C \) is scaled to 0.9 in this model with fixed \( N = 6 \)), and \( Y_n \sim N(0, \sigma_{ASD}/7) \) is another random variable. Finally, the subpath angles are calculated with a random intra-cluster offset angles \( \alpha_m \), which is given by

\[ \phi_{n, m, AoD} = \phi_{n, AoD} + \alpha_m \]

where \( \alpha_m \) is a Laplacian random variable with zero mean and standard deviation referred as intra-cluster ASD.

The ZoD and ZOA angles are generated as Laplacian random variables. The angle ZoD is generated similarly to azimuth angles and is defined as \( \theta_{n, ZoD} = X_n \theta_n + Y_n + \theta_{LoS,ZoD} + \mu_{ZoD,ZoD} \) where \( \theta_{LoS,ZoD} \) is the LoS direction in zenith between Tx and Rx, and

\[ \theta_n = \frac{\sigma_{ZoD} \ln \left( \frac{P_n}{\text{max}(P_n)} \right)}{C} \]

where a scaling factor \( C \) is set to 0.98. The ZSD \( \sigma_{ZoD} \) is an exponential random variable characterized by \( \lambda_{ZoD} \), which is a function of distance given by

\[ 1/\lambda_{ZoD}(d_{2D}) = \max(\alpha_1 d_{2D} + \beta_1, \alpha_2 d_{2D} + \beta_2) \]

where \( d_{2D} \) is the 2D distance between Tx and Rx and \( \alpha, \beta \) is taken from Table II. The offset of ZoD is modeled by

\[ \mu_{ZoD,ZoD}(d_{2D}) = -10(\alpha_2 d_{2D} \log_{10}(\max(b_{ZoD}, d_{2D}))) + \epsilon_{ZoD} \]

and the parameters are summarized in Table II. Then, the subpath angles are calculated with a random intra-cluster offset angles \( \alpha_m \), which is given by

\[ \theta_{n, m, ZoD} = \theta_{n, ZoD} + \alpha_m \]

where \( \alpha_m \) is a Laplacian random variable with zero mean and standard deviation referred as intra-cluster ZSD. In the same manner, the ZOA angle is generated by following [9] and the ZSA is modeled as dual-slope given by

\[ \mu_{ZoA,ZoA}(d_{2D}) = a_{ZoA} \left( d_{2D}^b \right) + c_{ZoA} \]

The SCM-like channel model based on ray-tracing results can be calculated with path delays, powers, and angles we described in this section. All channel model parameters that are separately analyzed in this work are summarized in Table I and II.

### References

[9]
In this paper, we proposed a 28 GHz channel model for two common deployment scenarios and different urban environments based on 3D ray-tracing simulations. The mmWave channel models in two different urban environments in two cities are parametrized in accordance with the SCM-like channel modeling approach. We compare the channel model output with ray-tracing simulations and some measurement-based pathloss models. The resulting channel model, while preliminary and subject to further improvements, can serve to assess the feasibility of mmWave communications in urban environments. For future works, a scattering and blockage model at mmWave frequencies will be considered.

REFERENCES


