Comparative Analysis of Channel Models for mmWave Communications

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[1] ***Abstract*—In this report, the existing mmWave channel models proposed by 3GPP (according to TR 38.900 Release 14.2.0) and NYU are studied. The 3GPP model is a result of analysis of channel measurements above 6 GHz including certain parts borrowed from sub-6GHz band and the NYU model is derived from measurements made in specific scenarios for mmWave frequencies. These two models are investigated for four mmWave frequencies centred around 6, 30, 60 and 70 GHz in three different scenarios namely Urban Microcell, Urban Macrocell and Rural Macrocell under both Non Line of Sight (NLoS) and Line of Sight (LoS) conditions. The major differences in the two approaches are highlighted and metrics such as CDF of singular values of the channel and number of subpaths per cluster are compared by simulation studies.**

I. Introduction

Millimeter-Wave (mmWave) is a key technology that will play an important role in 5G wireless communication systems [1]. The small wavelengths at these frequencies make viable the accommodation of high number of antenna elements at the Base Station (BS) empowering massive MIMO systems. The combination of mmWave and massive MIMO will provide enough spatial diversity and beamforming gain to make up for the increase in path loss and absorption by atmospheric elements at such high frequencies. Therefore, in order to perform system and link level analysis at these frequencies, channel models that account for the unique characteristics of mmWave systems need to be developed and investigated.

A. Related Literature

There have been many attempts to model the mmWave channel in the past few years. METIS (Mobile and wireless communication Enablers for the Twenty-twenty Information Society) identified major 5G requirements and performed channel measurements between 2 GHz and 60 GHz. It proposed map based, stochastic and a hybrid model aimed at outdoor square and indoor specific scenarios [2]. MiWEBA (Millimetre-Wave Evolution for Backhaul and Access) proposed a Quasi-deterministic model solving challenges of shadowing, spatial consistency and polarization among others [3]. The ITU-R M channel models addressed the propagation and atmospheric loss at mmWave frequencies and proposed certain deployment scenarios focusing on dense urban environments [4]. QuaDRiGa (QUAsi Deterministic RadIo channel GenerAtor), developed at the Fraunhofer Heinrich Hertz Institute, is a fully fledged 3D Geometry based stochastic channel model and contains extensions to the WINNER channel models along with novel modelling approaches [5]. These projects are apart from the widely adopted 3GPP and the NYU models which will be discussed in detail in the coming sections.

The remaining report is organized as follows. In Section II, the details of the 3GPP Statistical Spatial Channel Model (SSCM) are elaborated. The NYU SSCM Channel Model is delineated in Section III. The evaluation of the two models is discussed in Section IV and is followed by concluding remarks in Section V.

II. 3GPP Channel Model

The 3GPP proposes two channel models in its TR 38.900 which is a study on channel models for frequency spectrum above 6GHz [6], namely the Clustered Delay Line (CDL) model and the Tapped Delay Line (TDL) model. The CDL model comprises of dividing the incoming rays into multiple Time Clusters (TC) with each cluster having a given number of rays and a specific mean angle and spread of arrival, both for azimuth and zenith. The TDL model on the other hand is characterized by taps over time, with each tap being associated with a certain power. Among the two, the CDL model does justice to the multipath nature of the channel and will be analyzed in this report.

A. Path Loss model:

The definitions of pathloss for each scenario is described in detail in section 7.4.1 of [6]. These expressions follow closely from the alpha-beta-gamma (ABG) path loss model and is given as in [7].

$$\begin{aligned}\mathbf{PL}_{ABG}(f_c, d_{3D})[dB] &= 10\alpha \log_{10}(d_{3D}) + \beta \\ &+10\gamma \log_{10}(f_c) + X_\sigma\end{aligned} \quad (1)$$

where α and γ are coefficients embodying the dependence of path loss on distance and frequency respectively, β is an optimized offset value for path loss in dB, f_c is the carrier frequency in GHz and X_σ is a zero mean Gaussian random variable with standard deviation σ in dB describing shadow fading (SF) over large distances. This is an omnidirectional path loss model and doesn't extend to directional scenarios. The directional model cannot be obtained by adding directional antenna gains into the omnidirectional model as not all multipaths contribute to the directional path loss [10].

The path loss expressions are a function of frequency of operation ($\mathbf{f}_c$), the 2 dimensional distance between Tx and Rx ($\mathbf{d}_{2D}$), the 3 dimensional distance between Tx and Rx ($\mathbf{d}_{3D}$), average building height ($\mathbf{h}$), average street width ($\mathbf{W}$), antenna height for Base Station ($\mathbf{h}_{BS}$) and the antenna height for User Terminal ($\mathbf{h}_{UT}$). The expressions are quite detailed and scenario specific.

B. Fast Fading model:

The fast fading model takes into account the generation of large scale parameters such as delay spread, angular spreads, Ricean K factor and shadow fading. These factors are scenario specific and mentioned in detail in Table 7.5-6 of [6]. The small scale parameters are also generated using the details given in Table 7.5-6. The delays $\tau_{\mathbf{n}}$ for each cluster $\mathbf{n}$ are generated using exponential delay distribution. The cluster powers $\mathbf{P}_n$ assume a single slope exponential power delay profile given by

$$\mathbf{P'}_n = exp(-\tau_{\mathbf{n}} \frac{\mathbf{r}_\tau - 1}{\mathbf{r}_\tau.\mathbf{DS}}).10^{\frac{-\mathbf{Z_n}}{10}} \tag{2}$$

where $\mathbf{P'}_n$ are the cluster powers before normalization (have to be normalized to be equal to the total received power), τ_n are the cluster delays, $\mathbf{r}_\tau$ is the delay distribution proportionality factor, $\mathbf{DS}$ is the delay spread and $\mathbf{Z_n} \sim \mathcal{N}(0, \sigma^2)$ is the per cluster shadowing term in [dB].

In the case of LoS Condition, an additional specular component is added to the first cluster with power given by

$$\mathbf{P}_{1LOS} = \frac{\mathbf{K_R}}{\mathbf{K_R} + 1} \tag{3}$$

where $\mathbf{K_R}$ is the Ricean K-factor.

The generation of azimuth angles of arrival ($\mathbf{AOA}$) assumes that the power angular spectrum in azimuth is a wrapped Gaussian. Therefore, the $\mathbf{AOA}$ are determined by applying the inverse Gaussian function with input parameters $\mathbf{P_n}$ and azimuth angle spread $\mathbf{ASA}$. The generation of zenith angle of arrival ($\mathbf{ZOA}$) assumes that the power angular spectrum in zenith dimension is Laplacian. Therefore, the $\mathbf{ZOA}$ are determined by applying the inverse Laplacian function with input parameters $\mathbf{P_n}$ and zenith angle spread $\mathbf{ZSA}$. A similar procedure is followed for the generation of azimuth and zenith angles of departure ($\mathbf{AOD}$ and $\mathbf{ZOD}$) [6]. This essentially means that the delay and the angle are characterized by a joint distribution.

III. NYU Channel Model

The NYU channel model [11] retains most of the functionalities of the 3GPP model but deviates in some aspects. The NYU model replaces the ABG pathloss model with a simpler Close-In free space reference distance (CI) path loss model. It also replaces the concept of Time Clusters (TC) with the concept of Time Cluster and Spatial Lobe (TCSL) where TC's comprise of multipath components arriving/departing at similar times from potentially different directions and SL's comprise of multipaths arriving/departing in a specific direction over some duration of time [10]. This,the NYU model claims, is a result of channel measurements made at mmWave frequencies as elaborated in [8], [9].

A. Path Loss model:

The CI model using a 1 m close-in free space reference distance can be expressed as

$$\begin{aligned}\mathbf{PL}_{CI}(f_c, d_{3D})[dB] &= FSPL(f_c, 1m)[dB] \\ &+ 10\eta \log_{10}(d_{3D}) + AT[dB] + X_\sigma\end{aligned} \tag{4}$$

where $FSPL(f_c, 1m)$ denotes the free space path loss in dB at a 1 m 3D T-R separation distance at the carrier frequency f_c in GHz, η denotes the path loss exponent (PLE), AT is the attenuation term induced by the atmosphere and X_σ is a zero mean Gaussian random variable with a standard deviation σ in dB.

The NYU model also notes that the directional path loss will be equal to the transmit power plus the Tx and Rx antenna gains, minus the directional received power [11]. Due to the spatial filtering of many multipath components the directional pathloss will always be greater than the omnidirectional one. Therefore in order to calculate directional path loss, Half Power Beam Widths (HPBW) are set at both Tx and Rx and the process is repeated by changing the direction of the beam [9].

B. Fast Fading model:

The NYU model has a fixed inter-cluster void interval that represents the minimum propagation time delay between objects. This departs from the joint distribution method used in 3GPP and resorts to a time-partitioning methodology. It is worthy of a mention that the number of time clusters, the number of subpaths per cluster and the number of spatial lobes follow certain distributions and can vary in each channel realization supporting the observed channel measurement data [9].

The TC powers are generated using an exponential function over time delay as in 3GPP. The power of subpath m (SP) within cluster n are given as

$$\mathbf{\Pi'}_{m,n} = \bar{\mathbf{\Pi}}_{\mathbf{0}} e^{\frac{-\rho_{\mathbf{m,n}}}{\gamma}} 10^{\frac{\mathbf{U_{m,n}}}{10}} \tag{5}$$

where $\mathbf{\Pi'}_{m,n}$ are the SP powers before normalization (have to be normalized to be equal to the total cluster power), $\bar{\Pi}_0$ is the average power in the first received intra-cluster SP, $\rho_{\mathbf{m,n}}$ are the intracluster SP excess delays, γ is the SP decay time constant and $U_{m,n} \sim \mathcal{N}(0, \sigma^2)$ in dB.

The mean $\mathbf{AOD}$ and $\mathbf{AOA}$ angles for the spatial lobes are generated using an uniform distribution between a particular $\theta_{\mathbf{min}}$ and $\theta_{\mathbf{max}}$. The mean $\mathbf{ZOA}$ and $\mathbf{ZOD}$ angles for the spatial lobes are generated using a normal distribution with a particular mean μ and variance σ. Then each multipath component is assigned a unique spatial departure and arrival lobe according to a uniform distribution in addition to a random offset (Laplacian for $\mathbf{AOA}$ and Gaussian for the rest) within the SL [8].

IV. EVALUATION

Three scenarios namely the Urban Microcell - Street Canyon (UMi-SC), Urban Macrocell (UMa) and Rural Macrocell (RMa) are considered for evaluation. One micro site with 3 sectors is used and this is realized by modelling the radiation pattern of each antenna element according to the table 7.3-1 in [6]. The cell size is Characterized by the Inter Site Distance (ISD) and is equal to $ISD/3$ [14]. ISD values of 200 m and 500 m are used for Microcell and Macrocell respectively [13].

The channel model full calibration specifications are mentioned in section 7.8-2 of [6]. At BS and UT 64 and 2 antennas are used respectively. 10 users are dropped uniformly within the cell and for each user 200 independent channel realizations are considered for averaging.

A. 3GPP:

The channel profiles for NLoS and LoS cases are mentioned in Table 7.7.1 of [6], which is used to simulate behaviour in these environments. The total number of Time Clusters (TC) and the number of rays in each cluster considered varies depending on the scenario and the condition (LoS,NLoS) chosen. These values remain relatively same across scenarios but only change significantly with the operating condition. This model is valid from 6 to 100GHz, except for the RMa scenario for which its valid only for 6GHz. The mobility of the UT is taken to be 3km/h [6].

The MATLAB implementation of the 3GPP channel model [15] was extended by me to support high bandwidth and large antenna array simulations by implementing the changes mentioned in Section 7.6.2 of [6]. To support high bandwidth the channel response is modified as per Equation 7.6-3 in [6]. To support large antenna arrays the mean angles and angle spreads are scaled as per Table 7.5-6 in [6]. The **DS** is scaled for each scenario and frequency as given in Table I.

TABLE I: Parameter table

Scenario	Parameter	6G	30G	60G	70G
UMi-Sc	Tx Power (dBm)	44	35	35	35
	DS NLoS (ns)	93	66	55	53
	DS LoS (ns)	45	32	27	26
UMa	Tx Power (dBm)	49	35	35	35
	DS NLoS (ns)	363	266	228	221
	DS LoS (ns)	93	80	75	74
RMa	Tx Power (dBm)	49	35	35	35
	DS NLoS (ns)	37	-	-	-
	DS LoS (ns)	32	-	-	-

B. NYU:

All the scenarios (even RMa) are valid from 500MHz to 100GHz. The values of PLE (η) and shadow fading standard deviation for LoS and NLoS condition for each scenario are given in [8], [9], [7], [16]. The number of TC's, subpaths per TC and number of SL's (departure and arrival) are not fixed but follow certain distributions and can vary with each channel realization as mentioned in Table 2 of [8] and in [17]. The delay spread values at different frequencies are modelled by different exponential distributions unlike the fixed values in 3GPP [9]. The large scale parameters for urban scenarios are given in [9] and rural scenario are given in [19]. The small scale parameters are mentioned in [18].

The channel simulator doesn't take into account the mobility of the user (although a way to simulate this is mentioned [8], as the source code is unavailable, changes cannot be made to the channel model). The auto correlation of individual multipaths is modelled using an exponential function over antenna separation distance. The MIMO simulations are enabled by using Tx and Rx spatial correlation matrices. The auto correlation of the number of TC's and SL's of closely spaced locations is also modelled [8]. High bandwidth extension of channel response is implemented by me according to equation 4 in [11].

C. Comparison:

1) Path Loss: It can be seen from Figure 1 that the 3GPP Path Loss increases with frequency.

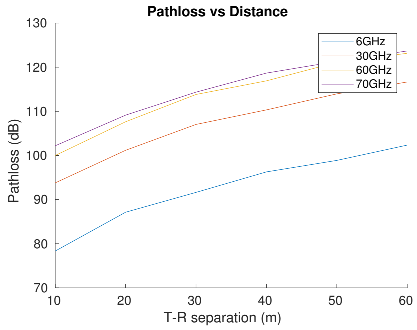

Fig. 1: 3GPP Path Loss (UMi-Sc NLoS)

The NYU omnidirectional and directional Path Loss at 70GHz is shown in Figure 2.

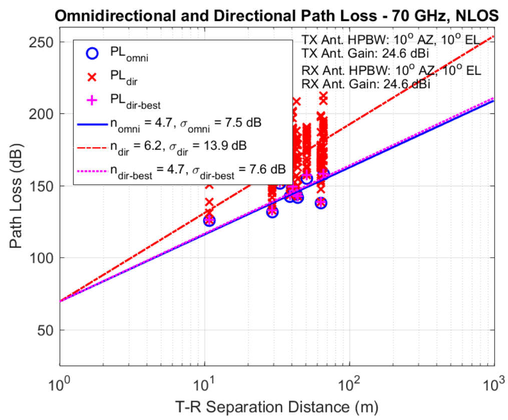

Fig. 2: NYU Path Loss (UMi-Sc NLoS)

The Path Loss trend for 3GPP is given in Equation 6 and an exact opposite trend is observed for NYU.

$$\mathbf{UMi - Sc < UMa < RMa} \tag{6}$$

The NYU Path Loss model offers directional insights, uses fewer parameters and offers an intuitive explanation for path loss.

2) Omnidirectional PDP: The 3GPP model has a fixed value of **DS** for all the users for a given scenario, LoS/NLoS condition and frequency whereas the NYU model has varied **DS** for users, following an exponential distribution. As the PDP for different users can not be shown here due to constraint of space, all the figures can be found at [20].

3) Departure and Arrival angles: For 3GPP, due to large number of subpaths, only the mean of the subpaths in a time cluster is plotted in Figure 3 (UMi-Sc NLoS 6 GHz). Every user has the same number of subpaths in 3GPP. The $ZOA \in (0, 180)$ degrees.

For NYU the number of TC's, subpaths and SL's have common distributions across different frequencies, conditions and scenarios, only differing in their mean and variance [8]. As seen in Figure 4 (UMi-Sc NLoS 6 GHz), the number of SP's in NYU is much lesser when compared to 3GPP, supported by measurements [9]. The $ZOA \in (0, 90)$ degrees. The graphs for different scenarios can be found at [20].

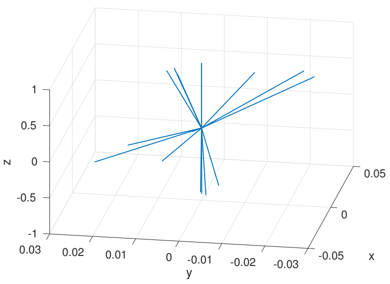

Fig. 3: 3GPP 3D plot of Arrival

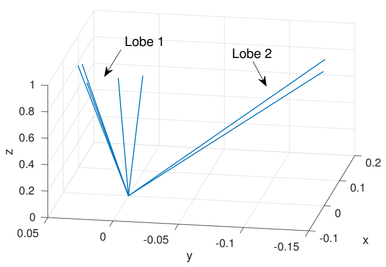

Fig. 4: NYU 3D plot of Arrival

4) Singular values of the channel: The Figure 5 (UMi-Sc NLoS 70GHz) is the CDF of the singular values (S1,S2) averaged over all the users for the sub carriers and it shows that the larger singular value in the NYU model is much higher in magnitude when compared to the larger singular value in the 3GPP model. Also, the gap between the smaller and larger singular value is greater in the NYU model compared to the 3GPP model. The NYU model gives stronger dominant singular values and 3GPP gives closer singular modes with weaker powers. Therefore the channel generated by NYU model is sparser compared to its 3GPP counterpart leading the 3GPP model to have a higher rank channel matrix (lower condition number) compared to the NYU model which predicts lower MIMO diversity.

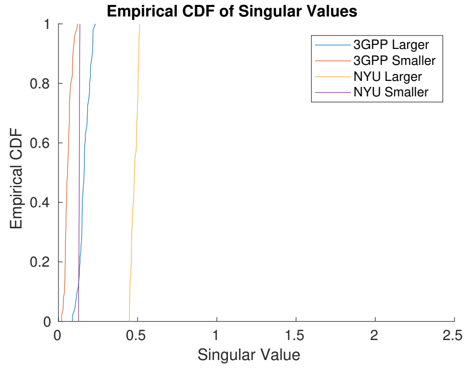

Fig. 5: CDF of the singular values for UMi-Sc

Figure 6 plots the Larger singular value of NYU model for UMi-Sc NLoS scenario. It can be seen from Figure 6 that the the singular values decrease with frequency due to attenuation.

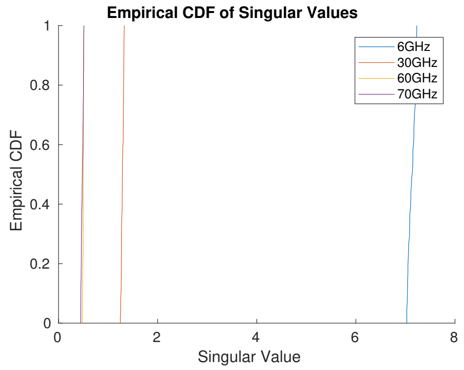

Fig. 6: CDF of singular values (NYU) for different frequencies

Figure 7 shows that the singular values are stronger for the LOS condition when compared to the NLOS condition of the same scenario (UMi-Sc 70GHz), for both the models. This is expected, because of the additional stronger LOS component.

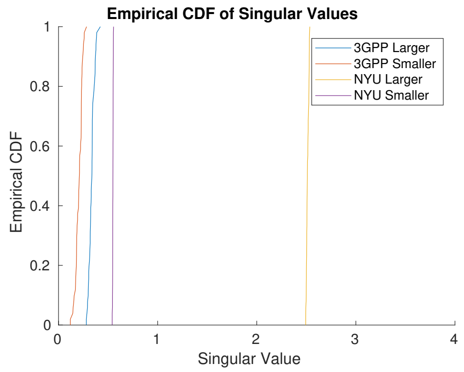

Fig. 7: CDF of singular values for NYU and 3GPP

Figure 8 shows the CDF of singular values for UMa NLoS (70GHz) scenario. The NYU singular values have lot less variability compared to the 3GPP model. Also, the dominance of NYU is not clearly seen in this scenario. Figure 8 shows the RMa NLoS scenario (6GHz) and NYU singular values dominate in this scenario. This can also be explained by the reversal of the Path Loss trend in Equation 6.

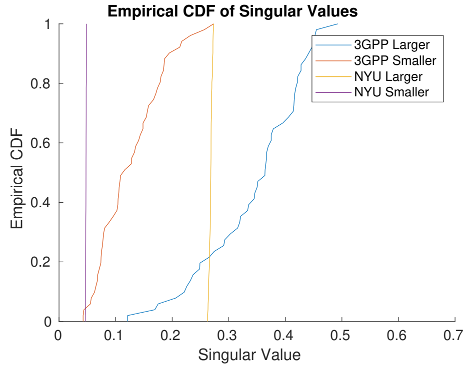

Fig. 8: CDF of singular values for UMa

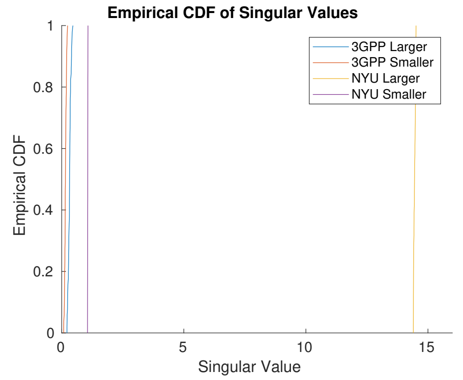

Fig. 9: CDF of singular values for RMa

V. Conclusion

Based on the study conducted, some notes for researchers who want to simulate mmWave channels are mentioned below:

- The 3GPP channel model is very comprehensive in its approach and gives elaborate details of how to calibrate the results, add additional components like blockage, oxygen absorption, spatial consistency for position and mobility, extend to large bandwidth and large antenna arrays and conduct multi-frequency simulations. All this data is present in one document [6] with an occasional citation to other specifications and reports unlike the NYU model without a comprehensive report.
- With Mathworks releasing the 3GPP model along with the 5G library, changes can be made to the model as per requirements. The NYU model on the other hand does not allow for changes as the MATLAB source code is not released yet (although a ns-3 version is available at [21]).
- The NYU model largely derives from the 3GPP model, but has some changes like shifting from the ABG pathloss model to the CI reference distance model for convenience and uniformity, using distributions instead of constant values for parameters like number of TC's, subpaths and Delay Spread.
- The NYU model introduces a new concept of Spatial Lobes to support new measurement data [9] and reduces the number of subpaths to support sparsity in the mmWave scattering channel.
- NYUSIM does not allow for the time variation of the channel in its simulator, which is unrealistic for 5G wireless channels.
- Decrease in order of 10 in simulation time is seen for NYU compared to 3GPP.

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