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Ray-tracing Assisted 3GPP Stochastic Channel Modeling for High-speed Railway Rural Scenario

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Abstract

In this paper, a ray-tracing (RT) assisted 3GPP stochastic channel modeling approach is proposed. Millimeter-wave (mmWave) channel of the high-speed railway (HSR) rural scenario is studied as an application example. The 3D environment model is constructed. With the linear deployment proposed by 3rd Generation Partnership Project (3GPP), RT simulations are then conducted at 25.25 GHz with 500 MHz bandwidth. The large- and small-scale channel parameters are extracted and modeled. Suggestions are provided to guide technology designs for similar scenarios. The proposed approach overcomes the challenges on mobile channel measurement and reduces the efforts on reconstructing 3D environment models for reliable RT simulation. The modeled parameters are successfully incorporated into a 3GPP-like stochastic channel generator, and the channels are generated efficiently to support technology evaluation and communication system design.

1 Introduction

Thorough understanding of the channel characteristics and accurate channel model are critical to support the design, simulation, and development of communication system technologies. The channel modeling approaches can be classified as stochastic and deterministic channel models. Spatial channel model (SCM), extended SCM (SCME) [2], Winner II (WIM2), Winner+ (WIM+), QuaDRiGa [7]) are typical 3GPP-like channel models with different features. The deterministic modeling approach are based on numerical approaches involving either solution of Maxwell's equations using full-wave simulation techniques, such as method of moment (MoM), finite-difference time domain (FDTD) [8], ray tracing (RT) [9], etc. Based on image theory, the RT methods can accurately describe multi-path effects for a given environment model and deployment configuration.

Compared to stochastic channel modeling, RT models have high computation complexity and can't be used when lacking detailed and reliable environment description databases [3]. Compared to RT, stochastic channel modeling requires a large amount of measurements in order to extract statistical features of the key channel parameters. High-speed scenario communications, mmWave and multiple-input multiple-output (MIMO) technologies are considered by fifth-generation (5G) communications. Thus, the channel models are required to feature with higher spatial resolution and time-varying properties. However, due to the constraints on measurement equipment, installations, and workforce, the measurement encounters challenges to efficiently fetch sufficient channel data for stochastic modeling. As an alternative, the academic research works in [6] combine constrained mmWave channel measurements with extensive RT simulations to explore angular domain channel characteristics. In [5], a map-based channel model is proposed by adding stochastic add-ons on top of the RT deterministic path search.

In order to efficiently support system design evaluation, the advantages of RT and stochastic channel model are combined in this work, and a ray-tracing assisted stochastic channel modeling approach is proposed. mmWave channel of the high-speed railway (HSR) rural scenario are studied. Large- and small-scale channel parameters are extracted and modeled. Suggestions are provided for HSR communication system design in the 5G mmWave band.

The remainder of this paper is organized as follows. Section II introduces the proposed RT assisted 3GPP stochastic channel modeling approach. Channel parameters are analyzed and modeled in Section III. Conclusions are drawn in Section IV.

2 Proposed approach

The work flow of the proposed RT assisted 3GPP stochastic channel modeling approach is shown in Fig. 1. The 3D environment model of the measured scenario is reconstructed for RT at first. Based on the channel measurements at a few snapshots with constrained deployments, the propagation environment model and involved material parameters are calibrated to improve the reliability of RT results. By varying the size and distribution of objects in the environment as well as the communication setups, intensive calibrated RT simulations can be conducted, and complete sets of channel parameters in time, spatial and frequency domains are

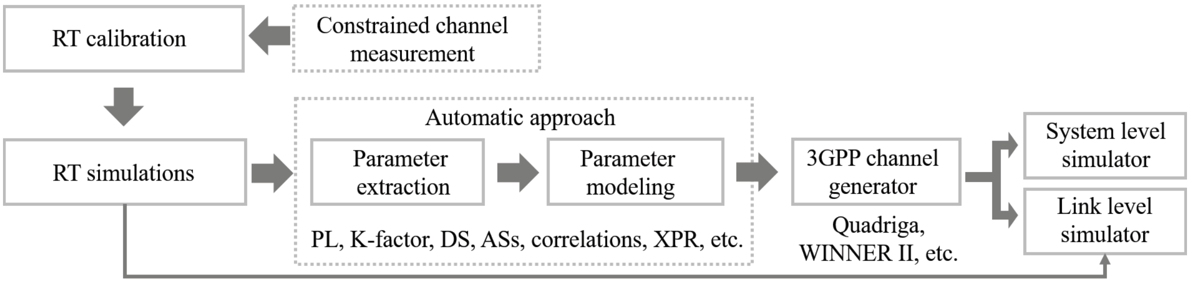


Figure 1. The work flow of the RT assisted 3GPP-like channel modeling and joint simulations with LLS and SLS

Table 1. Simulation parameters

Parameter	Value
Center frequency	25.25 GHz
Bandwidth	500 MHz
Sampling interval	0.1 m
Tx	5 m, omni-directional
Rx	3 m, omni-directional
Transmission power	0 dBm

intrinsically obtained. Therefore, the constrained channel measurements are compensated with sufficient information to fit parameters for the stochastic channel model. Once the parameter tables are provided to a 3GPP channel generator (WIM+, Quadriga, etc.), the channel impulse responses can be generated to support the link level simulation (LLS) and system level simulation (SLS).

3 mmWave channel modeling and analysis for HSR rural scenario

Fig. 2 shows 3D environment model of HSR rural scenario reconstructed based on Chinese HST specifications. Train, tracks and ground are typical objects. There are a few buildings along the traveling path, and both the distribution and the size of buildings may vary. The 3GPP high speed train mobile hotspot deployment is considered in this work. The simulation parameters are summarized in Table 1. The considered frequency band is 25.25 GHz with 500 MHz bandwidth. The Omni-directional antenna is used to generate pure propagation channel model. The transmitter (Tx) is placed 5 m far from the track, and a receiver (Rx) is placed in the front of the engine carriage. The heights of Tx and Rx are 5 m and 3 m, respectively. The traveling distance of the train is 1000 m. The RT and the the material electro-magnetic parameters are calibrated by using the methodology introduced in [4]. Direct path, up to 2nd order of reflection paths and diffuse scattering paths are considered in the simulation. The path loss coefficients, Rician-K factor, RMS delay spread, angular spreads and cross polarization ratio, etc. are the required key channel parameters and the fitting models can be found in 3GPP TR38901 [1]. As Quadriga can support mobile communication, it is used to regenerate the stochastic channel in this work.

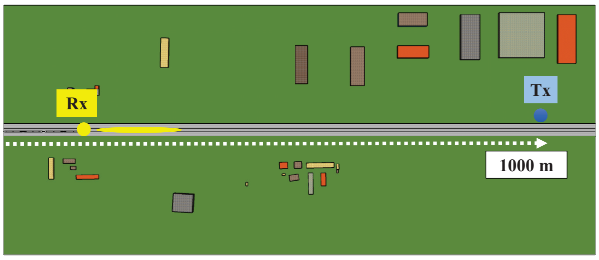


Figure 2. Environment model of rural scenario

Table 2. Extracted parameters of PL, SD and KF

Extracted parameters of PL

A	B	σ [dB]	λ_{SF} [m]	SF_c [dB]	N_c
19.64	61.29	6.33	5.00	5.38	11

Extracted parameters of DS

μ_{DS} [dB s]	σ_{DS} [dB s]	λ_{DS} [m]	r_{DS}
-7.78	0.44	19.00	0.56

Extracted parameters of KF

μ_{KF} [dB]	σ_{KF} [dB]	λ_{KF} [m]
13.02	9.70	26.00

3.1 Path loss

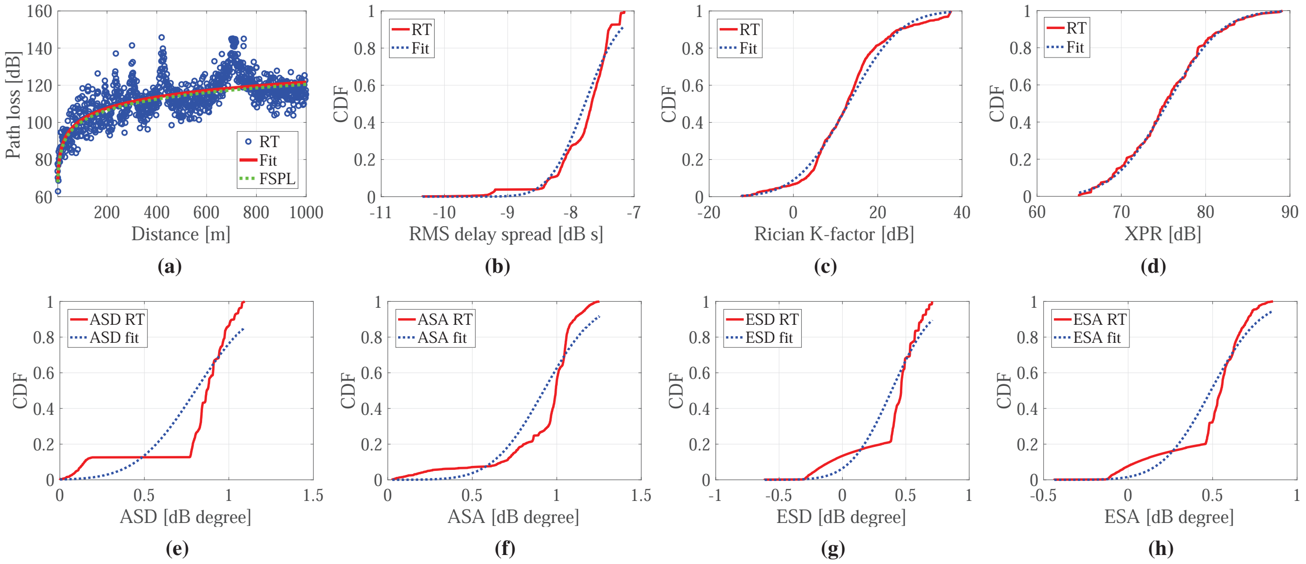
The path loss PL is fitted by the 'A-B' model:

$$PL = A\log10(d) + B + X_{\sigma_{SF}} \tag{1}$$

where d is the distance between Tx and Rx, A is the slope, B is the interception, and $X_{\sigma_{SF}}$ is the shadow fading (SF) expressed as a Gaussian distribution function with a standard deviation σ_{SF}. Fig. 3(a) compares the PL of RT, the fitted model and the free-space path loss (FSPL). The parameters are summarized in Table 2. The fitted A and B are close to FSPL ($A = 20$ and $B = 60.49$). σ_{SF} is 6.33 dB and the correlated distances λ_{SF} is 5.00 m. Similar as 3GPP TR38.901, the number of clusters N_c in this scenario is 11. The per cluster SF SF_c=5.38 dB, which is slightly less than the overall SF.

3.2 Delay spread and Rician K-factor

Fig. 3(b) and Fig. 3(c) show the CDFs of the root-mean-square (RMS) delay spread (DS) and Rician K-factor (KF),



(a) (b) (c) (d)

(e) (f) (g) (h)

Figure 3. Extracted parameters and fitting results

respectively. They can be fitted by log-normal distribution function. The mean value of DS μ_{DS}=-7.78 dB s (16.60 ns). The standard deviation is 0.44 dB s. Less than 10% of the KFs are smaller than 0, the mean KF μ_{KF}=13.02 dB, and the maximum value reaches 40 dB. Thus, compared to the other multi-path components (MPCs), the direct path significantly dominates the power contribution. The correlated distances λ_{DS}=19.00 m and λ_{KF}=26.00 m.

3.3 Angular domain

The RMS angular spreads (AS) are shown in Fig. 3(e)-Fig. 3(h). The fitting parameters are listed in Table 3. ASA, ASD, ESA, ESD are the angular spreads of the azimuth angle of arrival, the azimuth angle of departure, the elevation angle of arrival and elevation angle of departure, respectively.

As the horizontal diversity of the surrounding objects is larger than the vertical diversity, the mean values, standard deviations and per cluster mean values of the ASs in the elevation domain are smaller than that in the azimuth domain. The correlated distances of all the ASs are larger than SF, DS and KF. λ_{SF} is the smallest among all the parameters.

Table 3. Extracted parameters of the path loss model

	μ [dB °]	σ [dB °]	λ [m]	Per cluster [°]
ASD	0.80	0.28	27.00	10.28
ASA	0.92	0.24	29.00	10.26
ESD	0.39	0.25	29.00	6.08
ESA	0.49	0.22	30.00	6.58

3.4 Cross correlation of key parameters

The cross correlation of two variables is a measure of their linear dependence. The cross correlation of the aforementioned parameters are computed according to Pearson correlation coefficient with a crossing threshold 0.9, and Table 4 summarizes the values. As can be seen, the ASs are strongly correlated with each other, while the remaining parameters are less correlated.

Table 4. Cross correlation of the parameters

	DS	KF	SF	ASD	ASA	ESD	ESA
DS	1	-0.35	-0.17	0.19	0.30	-0.17	-0.21
KF		1	0.06	-0.53	-0.52	-0.19	0.08
SF			1	-0.07	-0.05	-0.02	-0.04
ASD				1	0.96	0.85	0.78
ASA					1	0.74	0.67
ESD						1	0.98
ESA							1

3.5 Polarization

The cross-polarization ratio (XPR) is expressed as:

$$XPR = 20log_{10}(\frac{E_{co}}{E_{cross}})$$

It refers to the field transmitted and received with the same antenna polarization (E_{co}) relative to the field transmitted and received with different antenna polarizations E_{cross}. The fields are computed from the channel impulse responses, and are fitted as log-normal distribution (Fig.3(d)). The mean XPR μ_{XPR} is 75 dB, the standard deviation σ_{XPR} is 3.23 dB. The minimum XPR value is far greater than 0, indicating that the de-polarization is trivial and co-polarized antenna configuration is sufficient.

3.6 Implementing the channel model

With all the provided parameters, the 3GPP-like Quadriga channel generator is used to realize stochastic channels for the target scenario. Fig.4 shows the regenerated power delay profile (PDP) of a single run, the evolution of MPCs

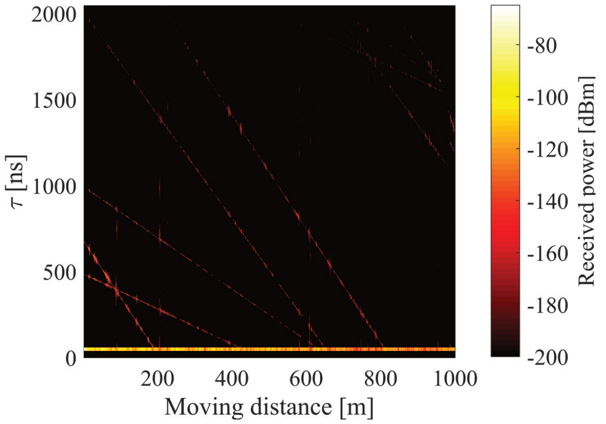


Figure 4. Regenerated PDP by implementing extracted parameter table to Quadriga chennel generator

are smooth. At different runs of the same Tx-Rx locations, the random seeds are different and the stochastic channel generator is able to realize different channels. Thus, without reconstructing diverse 3D environment models for RT simulation and without conducting comprehensive channel measurements, the proposed methodology is able to efficiently and reliably support technology evaluation.

4 Conclusion

In this paper, an RT assisted 3GPP stochastic channel modeling approach is proposed. The mmWave channel of HSR rural scenario is analyzed and modeled based on the proposed approach. Based on previous developed RT calibration methodology and material parameters, the RT is able to generate accurate and reliable simulation results with detailed ray information. The path loss, RMS delay spread, Rician K-factor, 3D angular spreads and polarization are extracted and modeled. According to the observed correlation distances of the parameters, the SF varies faster than others, while the variations of the angular spreads are much slower. The XPR is far greater than 0. Therefore, the performance of the system can be good with only co-polarized antennas. The extracted parameters are successfully incorporated to Quadriga channel generator to realized stochastic channels. With the proposed approach, the challenges brought by channel measurements and RT simulations are overcome. The researchers and engineers can efficiently realize practical stochastic channels to evaluate technology and the performance of designed communication systems.

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