3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Millimeter-Wave Radar Measurement and Ray-Tracing Simulation for Urban Street Environment

Wenbin Li(1), Danping He*(1)(2), Ke Guan(1)(2), Xiangyu Shi(3), and Zhangdui Zhong(1)(4)
(1) State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing 100044, China
(2) Frontiers Science Center for Smart High-speed Railway System, Beijing 100044, China
(3) School of Computer and Information Technology, Beijing Jiaotong University, Beijing 100044, China
(4) Key Laboratory of Railway Industry of Broadband Mobile Information Communications, Beijing 100044, China

Abstract

Autonomous driving technology greatly contributes to the evolution of intelligent transportation systems (ITSs). As an important sensor, the millimeter-wave (mmWave) radar plays an irreplaceable role in the overall ITSs. In this paper, we use a mmWave automotive radar system to perform measurement in an urban street environment. The radar cross section of key targets is estimated from the measurements, and it is used to calibrate the electromagnetic parameters for the ray-tracing (RT) simulation. The calibrated simulation results are compared with simulation results in distance, angle, and velocity to verify the accuracy and reliability of the RT simulator. The presented method, process, and analysis in this work can be used for the understanding of mmWave radar channel and the design of autonomous driving technology.

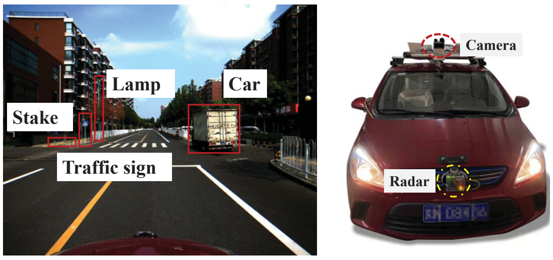
1 Introduction

With the innovation of technology, the automobile electronization has become a trend. Autonomous driving (AD) has been a key focus and hot spot of automotive research at this stage, and the realization of AD through perception systems can promote the development of intelligent transportation systems (ITSs) [1]. However, AD system are facing severe challenges in perceiving and understanding the environment due to heterogeneous backgrounds and the movement of complex targets. Driven by the Internet of Things (IoT), the Internet of Intelligent Vehicles (IoIV) has been seen as one of the most promising paradigms for achieving efficient ITS. At the same time, it is conceived as an intelligent paradigm equipped with a powerful multi-sensor platform, such as Light Detection and Ranging (LiDAR), millimeter-wave (mmWave) automotive radar, ultrasound, and cameras [2]. Among these exteroceptive sensors, mmWave radar has all-weather and all-time detection capabilities. It not only supports vehicles to obtain more information, but also promotes the innovation and progress of AD, which is an excellent prospect to enable technological improvement for the development of ITSs [3].

Autonomous vehicles and key technologies require extensive testing before they are officially commercialized. Traditional measurement methods no longer meet the ever-changing traffic scenarios. Therefore, there is an urgent need for a reliable AD simulation system which can reproduce all-weather, all-time, and all-scenario data to promote AD system tests breaking through the external limitations. Channel model is a fundamental component of AD simulation system. Deterministic channel modeling method, such as ray-tracing (RT) technology, can effectively describe the radio propagation in specified space. Scattering process as well as the model parameter are crucial for obtaining realistic results. For example, authors of [4] propose the directive scattering model. Authors of [5] propose to extracted the targets decomposed into scattering points through the measured data and RT simulation results. Meanwhile, authors in [6] and [7] use numerical methods to obtain the radar echo power pattern of the target and look up the table based on the angle information from the full physics simulation. Based on which, the works in [2] and [5] demonstrate the superiority and reliability of RT in mmWave automotive radar scenarios, which can fill the gap between measurement feasibility and test requirements.

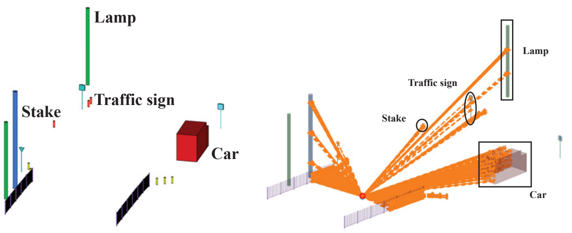
In this paper, mmWave radar measurement and RT channel simulation are performed for urban street environment. The key targets are extracted from the measurement data. The material electromagnetic (EM) parameters of the targets are tuned using the RT simulator in a three-dimensional (3D) scenario model with accurate target locations. It is observed that static targets at both sides of the road have large impact on the measurements. Based on the calibrated EM parameters, the range-rower profile, range-angle profile and range-Doppler profile are obtained. By analyzing the three profiles, it is verified that the RT simulator can characterize the mmWave radar channel. Finally, the follow-up research directions and goals are scheduled.

The rest of this paper is organized as follows. Section 2 describes the mmWave automotive radar measurement campaign and system deployment. The comparison and verification between RT simulation and measurement are analyzed in Section 3. Conclusions are drawn in Section 4.



(a) Frame 16 **(b)** Radar car

Figure 1. (a)Snapshot at Frame 16; (b) measurement configuration



(a) **(b)**

Figure 2. (a) SketchUp 3D scenario model; (b) RT simulation MPCs at Frame 16

Table 1. Radar system parameters

Parameter	Value	Parameter	Value
Frame time (ms)	100	Start frequency (GHz)	77.00
Idle time (μs)	2	ADC valid start time (μs)	3.9
ADC sampling time (μs)	22.319	ADC sampling rate (KHz)	11201
Ramp end time (μs)	27.22	Frequency slope ($MHz/\mu s$)	8.4
Sample per chirp	250	Bandwidth (MHz)	187.48
Chirp cycle time (μs)	29.22	Chirp loop per frame	41

2 Measurement Campaign

The measurements were conducted in Malianwa South Road, Haidian District, Beijing, a typical urban street scenario. The radar car measures along the specified direction and obtains the raw radar measurement data. The snapshot of the measurement scenario at Frame 16 is shown in Fig. 1a. As can be seen, the main objects in the urban street are cars, traffic signs, road stakes, and street lamps. The hardware system of mmWave radar is mainly composed of two parts: the evaluation module and the data acquisition module. The evaluation module adopts AWR1843, and the data acquisition module adopts DCA1000EVM, both of which are developed by TI. The platform is installed on a radar car equipped with laser and camera systems as shown Fig. 1b. The measurement system also recorded the real-time scenario and laser point cloud data to provide accurate position for subsequent processing. The system parameters of the mmWave radar such as start frequency, frame time, and frequency slope are configured before measurement, and are detailed in Table 1.

3 RT Simulation and Result Analysis

The RT simulator (CloudRT, http://raytracer.cloud) proposed in [8] realizes high-precision deterministic channel model, and outputs detailed channel information to provide support for subsequent analysis. Table 2 summarizes the simulation configurations in detail. Fig. 2a is the reconstructed 3D model of the urban street scenario. In the mmWave automotive radar system, the scattering model is very important. The single-lobe directive scattering model is used in this simulation, which is expressed as follow:

$$E_s^2 = \frac{G_{sys-sim}}{r_i^2 r_s^2} S^2 \Gamma^2 \frac{dS \cos\theta_i}{F_{\alpha_R}} \left(\frac{1+\cos\Psi_R}{2}\right)^{\alpha_R} \tag{1}$$

where $G_{sys-sim}$ is the simulation system parameter, which is dependent on the antenna gain (Fig. 3) and transmission power. Γ is the reflectance by Fresnel equations [9]. S is the scattering gain with the value of [0,1], α_R is the effective smoothness with the value of $[0,+\infty]$. S and α_R are the material parameters to be calibrated and significantly influence the accuracy of the simulation results.

Fig. 4 illustrates the calibration process of the EM parameters. The 3D scenario model, simulation configuration, and initialized EM parameters are embedded into the RT simulator. The obtained simulation results are compared

Table 2. RT simulation configurations

Configuration	Details	
Frequency	77 GHz	
Bandwidth	2 GHz	
Tx	Transmitted Power	0 dBm
	Antenna Type	Horizontal beam width is approximately 90 degrees, Vertical beam width is approximately 15 degrees.
	Antenna pattern	Shown in Fig. 3
Rx	Antenna Type	Same as Tx
	Location	Shown in Fig. 3
Propagation	Scattering	Directive scattering model [4]

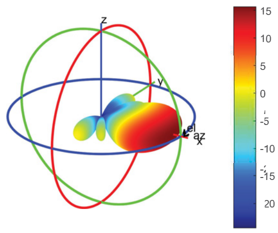


Figure 3. Antenna pattern

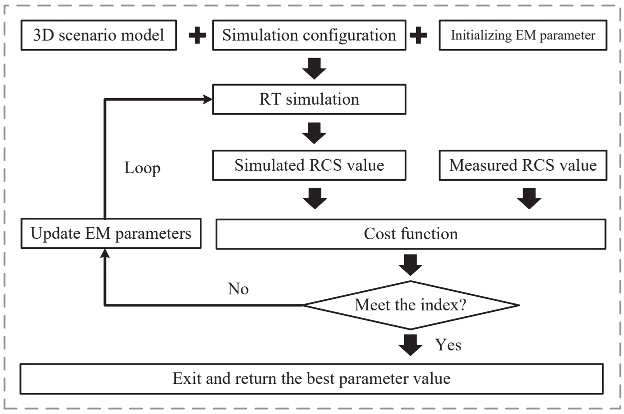


Figure 4. Parameter estimation diagram.

Table 3. EM parameters of key targets

Target	Initialized			Estimated		
	ε_{rel}	S	α_R	ε_{rel}	S	α_R
Car	1+100j	0.02	5	1+16.38j	0.0118	1.7328
Metal stakes	1+100j	0.02	5	1+99.17j	0.3284	14.1748
Traffic signs	1+100j	0.02	5	1+98.88j	0.0737	3.0000
Lamps	1+100j	0.02	5	1+91.50j	0.1177	1.0000

Table 4. Error statistics

Metric	Initialized		Estimated	
	ME [dB]	RMSE [dB]	ME [dB]	RMSE [dB]
RCS	0.54	11.54	0.02	5.41
Power	0.39	11.54	0.13	5.41

with the measured data and evaluated according to the cost function. The cost function is defined as the root-mean-square error (RMSE) between the simulated RCSs (σ_{RCSs}) and the measured RCSm (σ_{RCSm}) of all frames, which calculated as follow:

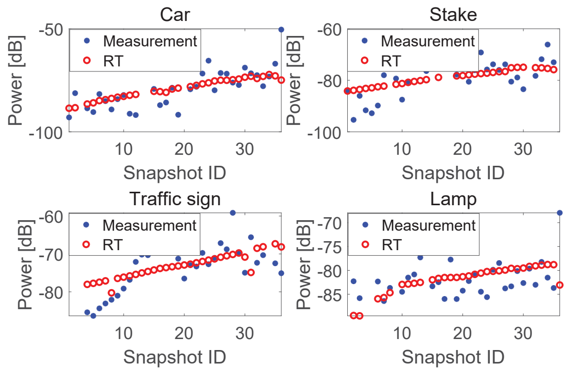
$$Cost = RMS(\sigma_{RCSs} - \sigma_{RCSm}) \tag{2}$$

The simulated echo power P_{rs} is obtained by the coherent superposition of MPCs energies, as follow:

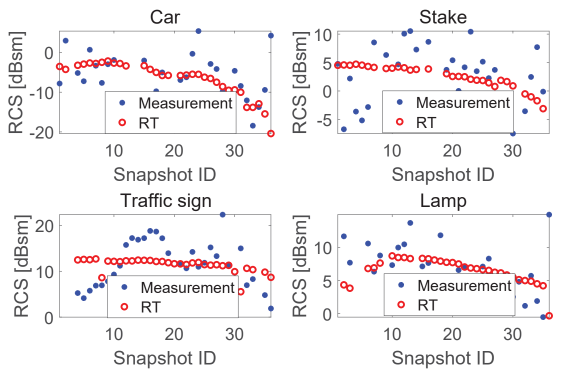
$$P_{rs}[mW] = \left(\sum_{i=1}^{k} a_i\right)^2, \forall \left|\frac{\tau_i}{2} - \frac{R_{obj}}{c}\right| < \frac{\Delta\tau}{2} \tag{3}$$

where a_i and τ_i are the amplitude and time delay of the electric field of the i-th ray, c is the speed of light and $\Delta\tau/2$ is the maximum allowable deviation range of simulated echo time delay. If the result of the cost function calculation does not reach the expected result, continue to update the EM parameters of the material and return to the RT simulation until the calibration of the EM parameters is completed. The estimated EM parameters are summarized in Table 3. The simulated RCSs and echo power are compared with the measurement in Fig. 5a and Fig. 5b. As summarized in Table 4, the mean error (ME) of both RCS and power of each object is less than 1 dB while the RMSE is around 5 dB, which indicates a good match between the simulation and measurement.

To verify the reliability of the calibrated EM parameters and the usability of the RT simulator, the simulation data are implemented the same processing as measurement data. Fig. 2 shows the traced rays of Frame 16. The results are comprehensively compared and verified to the 3D information (range-power profile, range-angle profile, and range-Doppler profile) of the mmWave radar channel simulation and the actual measurement. Fig. 6 shows the trajectory and power information of different targets in the range-power profile measured and simulated. The blue dotted line represents the trajectory of the target. Fig. 6b proves that RT simulation can restore the measured radar echo and position to a greater extent. The entire scenario extracts

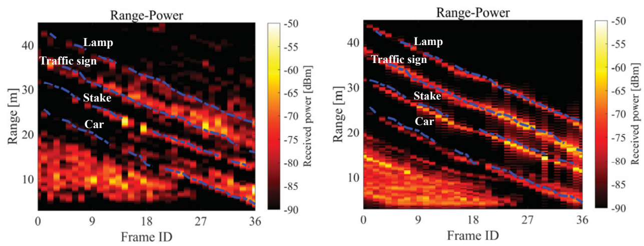


(a) Comparison of echo power



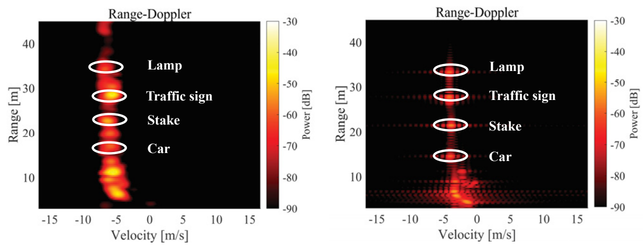
(b) Comparison of RCS

Figure 5. Comparison of calibration results



(a) Measurement **(b)** Simulation

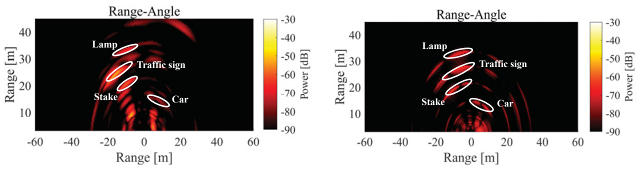
Figure 6. Rang-Power profile



(a) Measurement **(b)** Simulation

Figure 7. Range-Doppler profile

the trajectories of four objects. We select the universal moment, Frame 16, for quantitative analysis. At Frame 16, therein the first object appears at 15.47 m with echo power of -87.05 dB, which corresponds to the roadside car. The



(a) Measurement **(b)** Simulation

Figure 8. Range-Angle profile

target object at 22.50 m is a metal road stake, which has a power of -74.25 dB. The third one is a traffic sign, which has a distance of 27.42 m and a power of 67.54 dB. The last target object at 34.10 m is a lamp, which has a power of -82.47 dB. In Fig. 7a therein the white circle appears at 15-35 m with a velocity of -5 m/s, representing the roadside stationary object. This is because the targets studied in the current scenario are stationary and the radar vehicle is moving at a certain speed, Thus the speed of the static targets is negative. It can be seen that at the same distance in Fig. 8a, the scattered energy obtained from the range-power profile does not all come from the grasped targets, while other objects next to it also produce some scattered energy. This means that the calibration based on the range-power profile, the calibration is biased larger than the actual result. It attributes all the scattered energy generated by other ignored targets to the grasped target.

4 Conclusion

In this paper, the mmWave automotive radar is used to measure channel in a typical urban street scenario. The EM parameters of RT model are calibrated, and simulation results are validated and analyzed. The range-power profile, range-angle profile, and range-Doppler profile are presented, and quantitative analysis is performed. It is found that the RT simulation results can estimate the position and velocity of the targets accurately. The current work calibrates the EM parameters based on range-power domain, which can lead to local optimum by interference among objects with some range. In the future, range-angle and range-Doppler profiles will be considered to calibrate the EM parameters and reach global optimum.

5 Acknowledgements

This work is supported by Key-Area Research and Development Program of Guangdong Province, China, under Grant 2019B010157001, National Key R&D Program of China under Grant 2020YFB1806604, NSFC under Grant 61901029, and Beijing Natural Science Foundation L212029.

References

[1] E. Yurtsever, J. Lambert, A. Carballo, and K. Takeda, "A survey of autonomous driving: Common practices and emerging technologies," *IEEE Access*, vol. 8, pp. 58 443–58 469, 2020.

[2] L. Zhu, D. He, B. Ai, Z. Zhong, F. Zhu, and Z. Wang, "Measurement and ray-tracing simulation for millimeter-wave automotive radar," in *2021 IEEE 4th International Conference on Electronic Information and Communication Technology (ICEICT)*, 2021, pp. 582–587.

[3] X. Cheng, D. Duan, L. Yang, and N. Zheng, "Cooperative intelligence for autonomous driving," *ZTE Communications*, vol. 17, no. 2, pp. 44–50, 2019.

[4] V. Degli-Esposti, F. Fuschini, E. M. Vitucci, and G. Falciasecca, "Measurement and modelling of scattering from buildings," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 1, pp. 143–153, 2007.

[5] K. Schuler, D. Becker, and W. Wiesbeck, "Extraction of virtual scattering centers of vehicles by ray-tracing simulations," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 11, pp. 3543–3551, 2008.

[6] U. Chipengo, "Full physics simulation study of guardrail radar-returns for 77 GHz automotive radar systems," *IEEE Access*, vol. 6, pp. 70 053–70 060, 2018.

[7] A. P. Sligar, "Machine learning-based radar perception for autonomous vehicles using full physics simulation," *IEEE Access*, vol. 8, pp. 51 470–51 476, 2020.

[8] D. He, B. Ai, K. Guan, L. Wang, Z. Zhong, and T. KÃijrner, "The design and applications of high-performance ray-tracing simulation platform for 5G and beyond wireless communications: A tutorial," *IEEE Communications Surveys Tutorials*, vol. 21, no. 1, pp. 10–27, 2019.

[9] E. Hecht, *Optics, 5e*. Pearson Education India, 2002.