An SBR Based Ray Tracing Channel Modeling Method for THz and Massive MIMO Communications

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Abstract—Terahertz (THz) communication and the application of massive multiple-input multiple-output (MIMO) technology are significant for the sixth generation (6G) communication systems. In this paper, we employ the shooting and bouncing ray (SBR) method integrated with GPU acceleration technology to model THz and massive MIMO channel. The results of ray tracing (RT) simulation in this paper are in agreement with those produced by WI. Based on the Kirchhoff scattering effect on material surfaces and atmospheric absorption loss showing at THz frequency band, the modified propagation models of Fresnel reflection coefficients and free-space attenuation are consistent with the measured results. For massive MIMO, the channel capacity and the stochastic power distribution are analyzed. The results indicate the applicability of SBR method for building deterministic models of THz and massive MIMO channels with extensive functions and acceptable accuracy.

Index Terms—Ray tracing, SBR method, channel simulation, THz, massive MIMO

I. INTRODUCTION

The incoming 6G technology characterizes wider ranges of application scenarios, with transmission rates and communication quality rising significantly [1]–[4]. Thus, an accurate channels model incorporating new technologies like THz communication and massive MIMO is indispensable to meet the requirements in 6G design and deployment.

In [5], the RT based deterministic modeling was introduced as a perfect candidate for wireless prediction. The two most commonly adopted approaches for RT are the image method (IM) and the SBR method. The IM method can trace the ray with high efficiency while being time-consuming. By contrast, the SBR method can trace multiple rays simultaneously with width first search algorithm, therefore featuring lower computational complexity and better extensions [6]. These advantages make it more versatile and efficient in complex simulations.

In [7]–[10], THz and massive MIMO were proved to be prospective solutions to increase transmission rate. THz features ultra-high transmission rate with larger channel bandwidth [7]. In [8], the Kirchhoff scattering theory was introduced to model the diffusion of rays in THz band. In [9], attenuation and dispersion of atmosphere during the propagation of rays in THz channels were proved to be significant. Massive MIMO improved channel capacity and spectral efficiency, while it features the characteristics of near-field spherical wavefront when the distance between the transmitting and receiving antennas or a cluster are probably within the Rayleigh distance [10]. Under such circumstances, the simulation and calculation methods of MIMO channels need to be modified accordingly.

Recently, the most common approach to model high-frequency channels and massive MIMO channels is the geometry based stochastic model (GBSM), which is versatile but requires tremendous channel measurement is to validate, as well as being less accurate in specific scenarios than RT method [11]–[12]. WI, the most popular commercial RT software recently, is also limited in the simulation of high frequency channels and it only supports the frequency band between 50 MHz to 100 GHz. So in this paper the SBR method is adopted to perform THz and MIMO channel simulation, and the application of RT method in channel simulation can also be easily extended.

This paper focuses on the SBR based THz and massive MIMO channel modeling, and it innovatively combines THz correction with the SBR simulation structure, as well as verifying several important properties of massive MIMO with the SBR method. The atmospheric absorption and Kirchhoff scattering effect at THz band are considered and MIMO arrays are equipped at both transmitter and receiver sides. The simulation system is set up based on MATLAB and is to be extended into an integrated RT module for 6G channels in the future.

The rest of the paper is organized as follows. Section II
II. SBR BASED CHANNEL MODELING FOR THZ BAND

A. SBR method based forward RT and calculation

The SBR method is employed in the simulation, whose procedure consists of four steps, i.e., ray launching, ray tracing, ray reception, and ray calculation [5].

1) Ray launching: Previous works have demonstrated the effectiveness of icosahedron ray-sampling method, where an icosahedron is created to assist in the launch of rays. This method, illustrated in Fig. 1, characterizes the uniformity of launched rays’ distribution as well as provides significant topological information about different rays launched.

2) Ray tracing: In this step, each ray is tracked at the given propagation mechanisms (the permitted times of reflection, diffraction, scattering, etc.) according to Snell’s law and effective roughness (ER) theory as it propagates through geometric scenarios, and the different propagation mechanisms are illustrated vividly in Fig. 2. Simultaneously, the rays will experience various power losses during their propagation in the scenarios. At the same time, RT trees are established to store and arrange for the propagation of ray cones, and then pick out effective paths for the next step in II-A3.

3) Ray reception: Effective paths selected in the last step in II-A2 are tested to determine whether the wavefront intersects the receiving antenna. Reception spheres in Fig. 3 are used to model this process where the radius of spheres is determined by the distance between the signal transmitter and receiver, representing the cross section of ray cones. If a center ray intersects the receiver sphere, this ray cone will contribute to the total electric field of the receiver.

4) Ray calculation: With Maxwell equations in time-harmonic electromagnetic fields, the electric field $\mathbf{E}_r_{\theta,\varphi,i}$ of the $i$-th received ray is calculated according to the propagation record of it, which can be demonstrated by [3]

$$\mathbf{E}_r_{\theta,\varphi,i} = \left[ \prod_j \mathbf{R}_{\theta,\varphi,j} \right] \cdot \left[ \prod_k \mathbf{S}_{\theta,\varphi,k} \right] \cdot \left[ \prod_l \mathbf{D}_{\theta,\varphi,l} \right] \cdot \mathbf{A}_{d_i} \cdot \mathbf{E}_{\theta,\varphi,1}$$

In massive MIMO channel, electric fields need to be combined coherently with phase. The total electric field $\mathbf{E}_r_{\theta,\varphi}$ received at one certain receiving point is accumulated by $\mathbf{E}_r_{\theta,\varphi,i}$ according to the linear nature of Maxwell equations, which can be calculated as

$$(\mathbf{E}_r)_{\theta,\varphi} = \left| \sum_{n=1}^{N_p} \mathbf{E}_r_{\theta,\varphi,n} \right|$$

where $N_p$ is the number of multipath components (MPCs).
The total power at the receiving point is derived from the power density of the electromagnetic field, and it can be calculated as
\[ P = \frac{\lambda^2 \beta}{8\pi\eta_0} (Er)^2_{\theta, \phi} \] (3)
where \( \lambda \) represents the wavelength, \( \eta_0 \) is the free space impedance, and \( \beta \) is the quality factor, which denotes the overlap of the frequency spectrum of the transmitted waveform and the spectrum of the frequency sensitivity of the receiver.

The channel impulse response (CIR) can describe a channel, which is
\[ h(\tau) = \sum_{n=1}^{N_p} A_n \delta(\tau - \tau_n) e^{-j\psi_n} \] (4)
where \( \delta() \) is the Dirac function, \( A_n, \tau_n, \) and \( \psi_n \) denote the amplitude, delay, and phase of the \( n \)-th path, respectively.

The multipath richness of a communication channel can be illustrated by the root mean square (RMS) delay spread, which can be calculated as
\[ \tau_{RMS} = \sqrt{\frac{\sum_{n=1}^{N_p} P_n \tau_n^2 - \left( \sum_{n=1}^{N_p} P_n \tau_n \right)^2}{\sum_{n=1}^{N_p} P_n}} \] (5)
where \( \tau_n \) denotes the delay of the \( n \)-th path, \( N_p \) is the total number of effective paths and \( P_n \) is square of the amplitude of the \( n \)-th path.

B. Characteristics of wireless channels at THz band

1) The Kirchhoff scattering theory: Wavelength at THz frequencies is at the order of millimeters or below, thus the roughness of materials cannot be neglected. In such environments, diffuse scattering can result in severe power loss in specular reflection directions. The Rayleigh roughness factor [10] from Kirchhoff scattering theory is introduced as
\[ \rho = e^{-\frac{\sigma}{\lambda}} \] (6)
where \( g \) is calculated by
\[ g = \left( \frac{4\pi \cdot \sigma \cdot \cos \theta_i}{\lambda} \right)^2 \] (7)
where \( \sigma \) represents the roughness of materials, \( \theta_i \) is the incident angle. Then the modified reflection coefficient can be demonstrated as
\[ r_{TE/TM} = \rho \cdot r_{TE/TM} \] (8)
where \( r_{TE/TM} \) stands for the original Fresnel reflection coefficients under TE/TM polarization, while \( r_{TE/TM} \) for the modified ones at THz band.

2) The attenuation and dispersion of atmosphere: At THz band, the molecular absorption effect of water vapor and oxygen is non-negligible. Thus, we adopt an algorithm to calculate atmospheric attenuation and dispersion. The specific atmospheric attenuation is given by [11]
\[ \gamma = \gamma_o + \gamma_w = 0.1820 f (N'_o(f) + N'_w(f)) \text{(dB/km)} \] (9)
where \( \gamma_o \) and \( \gamma_w \) are the specific attenuation of dry air and water vapor, respectively. \( f \) denotes the frequency. \( N'_o(f) \) is the imaginary part of complex refractive index for oxygen and water vapor.

The specific atmospheric dispersion is given by
\[ \varphi = \varphi_o + \varphi_w = -1.2008 f (N'_o(f) + N'_w(f)) \text{ (°/km)} \] (10)
where \( \varphi_o \) and \( \varphi_w \) stand for specific phase dispersion of them. \( N'_o(f) \) is the real part of complex refractive index for oxygen and water vapor.

C. The characteristics of wireless channels in massive MIMO scenarios

At the working frequency band of RT method, the size of antenna can normally be ignored compared to the scenario. The antenna matrix of MIMO system constructed in uniform planar array (UPA) or uniform linear array (ULA) can be simplified as a series of points, denoted as [10]
\[ T_x = [T_1, T_2, \ldots, T_N] \] (11)
\[ R_x = [R_1, R_2, \ldots, R_N] \] (12)
where \( T_i(i = 1, \ldots, N_t) \) and \( R_j(j = 1, \ldots, N_r) \) are the transmitting and receiving points in the MIMO arrays.

The channel matrix \( H_{N_t \times N_r} \) is commonly employed to describe MIMO channels, and it can be
\[ H_{N_t \times N_r} = \begin{pmatrix} h_{11} & h_{12} & \ldots & h_{1N_r} \\ h_{21} & h_{22} & \ldots & h_{2N_r} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_t,1} & h_{N_t,2} & \ldots & h_{N_t,N_r} \end{pmatrix} \] (13)
where \( h_{qp}(q = 1, \ldots, N_r, p = 1, \ldots, N_t) \) denotes the CIR for transmit antenna \( p \) and receive antenna \( q \) and can be calculated as
\[ h_{qp} = \sqrt{(P_{qp})} e^{j\theta_{qp}} \] (14)
where \( P_{qp} \) is the received power of antenna \( R_q \) from transmitting antenna \( T_p \), and \( \theta_{qp} \) denotes the phase component of \( P_{qp} \).

The channel capacity \( C(SNR) \), which is applied to illustrate the maximum transmission rate of the channel. It is denoted as
\[ C(SNR) = \log_2 \left| I_n + \frac{SNR}{N_t} W \right| \text{ bits/Hz} \] (15)
where \( SNR \) denotes the average signal-to-noise ratio, \( H^T \) stands for the Hermitian transpose of \( H \) and \( I_n \) is the identity matrix.
III. SIMULATION SYSTEM SETUP

A. Model preparation for simulation

Our simulation system supports 3 dimension (3-D) scenarios in the formats of JSON (JavaScript Object Notation), STL (stereolithography) and XML (Extensible Markup Language). The office scenario for this paper is modeled with sketchup 2021. The specific room dimensions are 7.2 × 7.2 × 3 m³. On one side of the wall it is equipped with two glass windows, which cover almost the entire wall on the other side. The rest of the walls are covered with wallpaper. The floor and ceiling is made of gypsum. The transmitting and receiving point are set at (1.46, 2.42, 2.41) and (5.2, 5.2, 1.5), respectively. The room is presented in Fig. 4.

B. Software architecture and workflow

Constructed in MATLAB, our simulation system consists of five main modules, i.e., antenna, geometry, ray tracing, paths, and output module, which correspond to different functions. The algorithms of channel modeling presented in Section II are neatly embedded in this system to meet the requirements in simulation performance. The workflow of system is vividly illustrated in Fig. 5.

C. Simulation acceleration based on parallel computation

The intersection determination process in ray tracing in the second step in II-A2 is extremely time-consuming, thus we employ parallel computation in our system for acceleration. Graphic processing unit (GPU) computation is especially suitable for RT acceleration with massive MIMO arrays [13]. We implement kernel functions to achieve parallel computation, encapsulating compute unified device architecture (CUDA) C++ programs for GPU as a library to be called in MATLAB.

With GPU acceleration, we can reduce the time consumption of massive MIMO simulations by 61.9%.

IV. RESULTS AND ANALYSIS

A. SBR ray tracing and calculation

As is introduced above, our RT simulation supports line-of-sight (LoS) propagation as well as reflection, diffraction, and scattering, and some RT simulation results are shown in Fig. 6. This system also supports simulating frequencies lower than THz band. In order to make comparison with the commercial software WI, the simulations of PDP, AoA, and AoA with forth order reflection were carried out at the frequency of 2.4 GHz, so that they can be supported by both systems. With careful comparisons, we found out that fine agreements have been reached within 5.2% error in Fig. 7. The calculated results of channel characteristics under 2.4 GHz with forth order diffraction are listed in Table I.

Such results are of great value for the design of actual communication systems. The path loss helps design channels with less energy loss, while the level of channel transmission rate can be estimated from the simulated channel capacity. RMS delay spread helps analyze whether the waveform expansion will cause inter-code crosstalk and evaluate its communication quality. The AoA and AoD can guide the beam assignment design of antenna, which is meaningful for the deployment of communication channel.

| Parameter                        | Value       |
|----------------------------------|-------------|
| Pass loss (dB)                   | 83.18       |
| Channel capacity (bpe/Hz)        | 52.516      |
| RMS delay spread (ns)            | 52.21       |
| Mean angle of departure(AoD) (°) | (35.72, -16.90) |
| Mean angle of arrival(AoA) (°)   | (37.91, 15.83) |
Fig. 7. Comparison between results simulated by this system and those by WI respectively, (a) PDP, (b) AoD, and (c) AoA.

B. THz band simulations

1) Atmospheric attenuation and dispersion simulations: The simulation for Atmospheric attenuation and dispersion is demonstrated graphically in Fig. 8, in which the results is in good consistency with the results in ITU-R documents [9]. At higher frequencies, the molecular absorption of water vapor is dominant in atmospheric interference, which grows stronger with increasing humidity. It is easy to figure out that each curve has absorption peaks at several specific signal frequencies, thus it is necessary to avoid these frequencies when actually deploying THz channels so that power wastage can be well mitigated.

2) The Kirchhoff scattering based reflection modification: Comparison has been made between simulation and measurement for modified reflection coefficients of the wallpaper sample in the scenario. Good agreements are found in Fig. 9 with errors generally lower than 6.5% in reflection coefficients simulations for TE and TM polarized waves at the frequency of 350 GHz.

C. Massive MIMO simulations

The simulation results of channel capacity for massive MIMO system are shown in Fig. 10. This pattern indicates the changing trend of channel capacity, which increases rapidly...
as the scales of antenna arrays in MIMO systems grow. The result illustrates the improvement of MIMO channel capacity, demonstrating the inherent advantage of massive MIMO in terms of transmission rate improvement.

The power under different antenna ports combined with phase is illustrated in Fig. 11, where the power of received signals in MIMO array demonstrates spatial non-stationarity in distribution. This trend is in comply with the non-stationary characteristics of MIMO channels, which is caused by the shelter of LoS path between the receive point and one certain antenna. The shadow fading caused by determined scatterer in the scenario and the multipath effect collectively result in this pattern with a zig-zag like line.

V. CONCLUSIONS

In this paper, we have employed SBR method to model 6G THz and massive MIMO channels in a complex indoor scenario. Simulations have been carried out with our proposed RT system and the results have been verified by commercial RT software WI. We have modified the calculation method of Fresnel reflection coefficient according to Kirchhoff scattering theory and the simulation results have been proved consistent with experimental data in literatures. The atmospheric absorption effect has also been considered to exemplify the frequency selective fading effect at THz band. MIMO simulation module has also been integrated in the system to analyze the capacity improvement and spatial non-stationarity brought by MIMO.

Moreover, GPU parallel computation has been employed to accelerate MIMO simulations so that more than half of the time consumption can be saved. The results of our work have indicated that RT method is suitable for MIMO and THz channel model.

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