Deterministic Ray Tracing: A Promising Approach to THz Channel Modeling in 6G Deployment Scenarios

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In this work, the authors aim to address the opportunities and challenges with the deterministic ray tracing approach.

Abstract

Terahertz (THz) communication is considered to be a key enabling technology for 6G due to its abundant available spectrum resources. One prerequisite for implementing THz communication systems is to understand and model the THz radio channel in 6G deployment scenarios. However, new radio characteristics in THz bands (e.g., channel sparsity, near-field propagation, and large-scale antenna configuration) have brought new opportunities and challenges to channel modeling in terms of modeling complexity and accuracy. In this work, we aim to address these opportunities and challenges with the deterministic ray tracing (RT) approach. First, the propagation characteristics in THz bands are discussed. We elaborate on why deterministic RT can be a promising approach to model the propagation characteristics in THz bands for 6G. Second, an RT-based channel modeling approach is presented, which uses channel measurement data to calibrate simulation parameters. Third, the performance of the RT-based channel modeling approach is demonstrated through a comparison between simulations and channel measurements. The comparison results show that the RT-based channel modeling approach can well describe the propagation characteristics (i.e., the delay and spatial dispersion, channel sparsity, near-field propagation, and non-stationarity) with reduced simulation complexity in THz bands.

Introduction

Terahertz (THz) communication, which aims to use THz wave (0.1-10 THz) for wireless communications, has been considered the key enabling technology to meet the data rate demand in 6G due to its abundant available spectrum resources. THz communication is considered for various application scenarios, including short-range cellular communications and machine systems up to long-range point-to-point backhaul scenarios. Furthermore, THz communication is considered promising to be jointly exploited with other advanced technologies, such as multiple-input multiple-output (MIMO), sensing, and artificial intelligence [1].

Channel is the medium in which the radio wave propagates between the transmitter (Tx) and the receiver (Rx), and it determines the ultimate performance of the wireless communication system [2]. The objective of channel modeling is to build a mathematical representation of the physical propagation media. Also, channel modeling is essential for the design and performance evaluation of wireless communication systems [3]. Thus, understanding and modeling the channel is a prerequisite for implementing wireless communication systems [4]. Furthermore, the THz channel characteristics of the deployment scenario should be considered in the application. THz channels have experimentally shown directionality and can be characterized by a few dominant paths [5]. As a result, the propagation channel in THz bands will be highly sparse and specular. THz communication systems will rely mainly on the line-of-sight (LoS) path for long-range applications, while a few dominant paths (e.g., LoS and reflected paths) can be utilized for short-range applications. Importantly, due to the employment of large-scale antenna configuration (to combat severe propagation loss), the short-range deployment scenario, and short wavelength in THz bands, channel non-stationary is another aspect that should be considered in channel modeling. For example, antenna elements in massive MIMO systems might experience different channel statistics, which leads to spatial non-stationary channels [6].

Considering the channel characteristics and applications of THz communication systems, a ray tracing (RT)-based channel modeling approach may be more promising for 6G THz channel modeling. The sparsity characteristic of THz waves, the importance of dominant propagation paths, and their susceptibility to blockage lead to the need for site-specific channel modeling. First, RT, as the deterministic modeling approach based on electromagnetic (EM) field theory and geometrical optics, enables accurate modeling of the dominant paths of THz waves at specific sites. Also, the quasi-optical property of THz waves ensures the accuracy of the RT approach with high precision. Second, the need for accurate modeling of dominant paths can only effectively reduce the complexity of RT (in terms of database accuracy and interaction orders of propagation mechanisms). Third, for future data-driven research needs, RT simulations can provide the essential massive

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input data, which is not feasible with measurement data.

This article presents deterministic RT as a promising solution to channel modeling in THz bands. Two sets of indoor measurement campaigns in THz bands are conducted to calibrate and verify RT simulation results. Good agreement is achieved between the RT simulation and measurement results, which demonstrates the effectiveness of RT in THz bands for 6G.

Channel Characteristics and Applications of THz Communication Systems

Channel Characteristics in THz Bands

Radio channels in THz bands present many important and specific characteristics, which should be properly considered, as detailed below.

High Propagation Loss: The high propagation loss of the THz channel is introduced by high free-space path loss and non-negligible atmosphere molecular absorption. On one hand, the THz channel is known to have higher free-space propagation loss according to the Friis formula. To compensate for this high propagation loss and to consider the power limitations of current THz transceivers, high-gain directional antennas should be used at both Tx and Rx front-ends. On the other hand, the absorption of oxygen and water vapor is very common in atmospheric absorption in the THz channel, where the absorption of water vapor is dominant. Unlike lower-frequency bands, molecular absorption is a non-negligible factor and should be considered for long-range communication scenarios.

Sparsity: As experimentally demonstrated, the propagation channel becomes sparser and more specular as the frequency goes up. The THz propagation channels will be characterized only by a few dominant paths (e.g., LoS) and a few low-order reflection paths, due to high diffraction [7], penetration, and reflection losses of THz waves. Furthermore, due to the spatial filtering characteristics of highly directional antennas employed at both communication ends, the radio channels become sparser.

Near-Field and Spatial Non-Stationary: In massive MIMO systems, the far-field and spatial stationarity assumptions applied for traditional MIMO systems may be violated [8]. Due to the high frequency of THz waves and the small size of the antenna, a large number of antennas can be embedded in a few square millimeters. For example, graphene-based plasmonic nano-antenna arrays can achieve up to 1024 × 1024 MIMO [9]. And in the ultra-massive MIMO, Rayleigh distances can reach several hundred meters. It is generally agreed that the assumption of plane waves no longer holds when the propagation distance is less than the Rayleigh distance. As discussed, due to the high propagation loss, the communication range will be rather small, making the near-field (i.e., plane-wave model assumption becomes not valid) and spatial non-stationary (i.e., the spatial stationary assumption is violated) effects a pronounced problem in the THz bands. Therefore, it might become essential to model these effects in the THz channel modeling.

THz Channel Modeling

Channel modeling can be classified generally into deterministic and statistical approaches. The deterministic modeling approach is based on EM wave propagation theory, which in principle can match the site-specific measurement results. However, it typically requires a precise geometric database and EM information about the scenarios and suffers from computation complexity. RT is a representative site-specific deterministic modeling approach based on geometric optics. The empirical modeling approach has been widely adopted in the standards due to its simplicity. However, it is not site-specific, and it is not able to model channel near-field effects and spatial non-stationarity [6].

RT-based channel modeling has been extensively utilized in sub-6 GHz and mmWave bands. However, the channel modeling using the RT approach in the THz band is different from that in sub-6 GHz and mmWave bands. These differences bring new opportunities for RT-based channel modeling in THz bands:

1. For the inherent characteristics of RT, RT based on geometric optics can be explained by the high-frequency approximation of Maxwell's equations. Consequently, the quasi-optical characteristics make the RT results in the THz band more reliable and suitable than those in the sub-6 GHz band.
2. For THz channel characteristics, the high propagation loss and sparsity characteristics of the THz channel enhance the need for site-specific analysis, which can be well captured by RT simulation. Compared to sub-6 GHz, the propagation range of THz waves is shorter. RT only needs to be carried out over a limited distance. Moreover, considering the sparsity and specularity of the THz channel, RT simulation of the dominant paths, with limited propagation mechanism and reflection order, can be sufficiently accurate because RT simulation of the dominant paths does not require an accurate database of measurements [6]. In addition, the spatial filtering brought by the directional antennas at one or both communication ends makes the spatial channel more sparse. RT can easily characterize this sparse characteristic because it can simulate radio channels under any antenna configuration in principle.
3. Most THz applications are for high-rate transmission, which requires reliability and potentially real-time operation, such as autonomous driving. This increases the requirement for accurate beam alignment at Tx and Rx. RT can get more realistic and accurate channel information, and has the potential to achieve precise beam alignment. For MIMO systems with array configuration, non-planar wavefront issues in near-field scenarios need to be considered. In addition, for system applications, spatial multiplexing is often used in the sub-6 GHz band due to the abundance of paths, while weak paths need to be simulated for channel de-correlation. THz communication, on the other hand, only requires the dominant path, and beamforming generally requires steering

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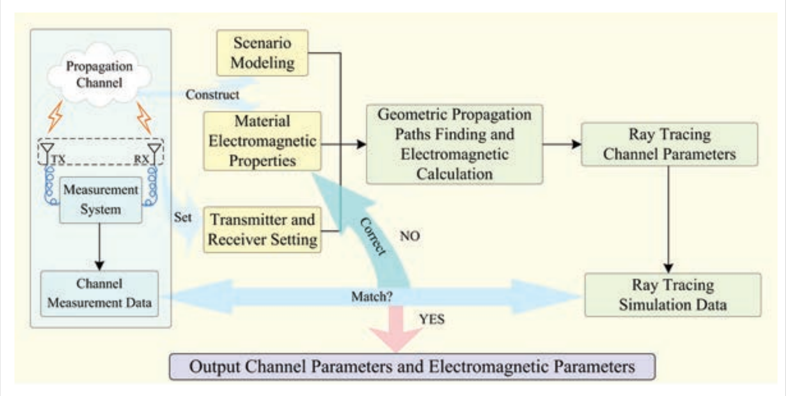

FIGURE 1. Flowchart of measurement-calibrated RT channel simulation.

to only one or two of the strongest paths. RT-assisted beamforming has been proposed to predict the dominant paths in real time by RT. Thus, multiple beams can be steered directly in the dominant directions, which avoids the time-consuming brute force beam search process. For joint communication and sensing modeling, we can have easy access to the digital map of the environment information required for RT. And in a data-driven network combined with artificial intelligence, we can easily generate a large set of RT channels, with scalable configuration. Thus, RT can provide sufficient data to implement new functions, such as predicting channels and exploring the relationship between THz channel parameters.

Challenges of THz Channel Modeling with RT

However, there are still some challenges to RT-based channel modeling in THz bands. Most notably, there is no complete EM property of the material in THz bands. Also, there is a lack of adequate measurements for validating and calibrating RT. For real-time applications, the RT channel model is difficult to implement.

Lack of Complete Knowledge of Material EM Properties: The lack of knowledge of EM properties in the THz band hinders the use of RT. Currently, there are two measurement approaches to address this challenge, with and without the material EM property measurement:

- Extensive material property measurement: Many groups have already measured the EM property of common building materials in the THz frequency band, such as [10]. This allows the measured EM parameters to be used directly in the RT. However, the measurement of the precise EM property is time-consuming. Only limited data in THz bands have been reported until now, which should be jointly addressed by the community.
- Calibration with measurement data: In case the measured material property is not available, RT calibration with measurement data (i.e., tuning material property in RT to obtain the best match with measurement data) is often used. Reference [11] proposed a broadband calibration algorithm based on simulated annealing. For example, [12, 13] calibrate RT using measurement data in indoor and kiosk scenarios, respectively, according to the algorithm of [11], and generate simulated channel data to obtain a stochastic model.

Inadequate Channel Measurement Data: Whether to verify or calibrate the RT-based channel models, there is still a lack of adequate and comprehensive channel measurement data. It is much more difficult to conduct a large-scale channel measurement campaign in the THz band than in the sub-6 GHz band. The main reason is that the THz measurement system is expensive. Moreover, there are almost no omnidirectional antennas in the THz band. The method of mechanically capturing multipath components (MPCs) information in all directions by rotational scanning of directional antennas is not only slow but also cannot obtain dynamic information in all directions.

Lack of Real-Time RT Implementation: The THz channel model supporting real time is promising for applications. THz waves are highly directional and easily blocked, so beam alignment and tracking are required for real-time applications in dynamic scenarios. However, real-time RT is mainly hampered by computational complexity. Dynamic RT allows the prediction of channels in coherent time to reduce the number of required RT runs. It is promising for obtaining instantaneous channel information. But the problem of estimating the correlation time is still not solved.

Measurement-Calibrated RT

To explore the performance of the deterministic RT in the THz band, this article uses measurements to calibrate the material EM properties in the corresponding scenario. The measurement-calibrated RT flow is shown in Fig. 1.

For RT simulation, first, the environment is modeled according to the measurement scenario, and the Tx and Rx coordinates are set. Next, the geometric paths are determined generally based on geometric optics theory and coherent bypass theory. Then EM calculations are performed to obtain information such as power gain, delay, and angle for each path (i.e., the RT channel parameters). The RT channel parameters are processed to obtain the required channel information, which is represented as RT simulation data in Fig. 1. In this work, the commercial RT tool Wireless InSite is adopted for the RT simulation.

The calibration process is shown in Fig. 1. We tune the material EM properties in RT simulation to reach the best agreement in terms of power and delay for the dominant propagation paths. In the beginning, the RT simulation outputs the results corresponding to the initial EM parameters, which are compared to the measurement data. If the results of power and delay parameters for the dominant paths match (with an objective to minimize the root mean square error), the simulation results are output. If the results do not match, the relative permittivity and conductivity of the materials are updated, and the simulation results are output again. This operation is repeated until the best agreement between the simulation and measurement results is achieved.

Results and Analysis

In this section, the performance of the measurement-calibrated RT is analyzed based on two sets of indoor measurement campaigns in THz bands.

Parameter	Empty room scenario	Spacious hall scenario
Frequency (GHz)	100	300
Bandwidth (GHz)	6	2
Transmitted power (dBm)	0	5
Measurement description	Virtual array (Aperture = 1 m)	Horn antenna rotation
TX antenna type (gain, HPBW)	Omnidirection (4.5 dBi, —)	Horn antenna (26 dBi,8°)
TX rotation	Fixed	[−90:4:90]
RX antenna type (gain, HPBW)	Omnidirection (4.5 dBi, —)	Horn antenna (26 dBi,8°)
RX rotation	[−180:0.5:180] (virtual array)	[−180:4:180]
TX-RX distance (m)	6.5	4.2
Antenna height (m)	1.25	1.25

TABLE 1. Measurement setup.

Channel measurements are performed based on a vector network analyzer measurement system at Aalborg University, Denmark [14]. In addition, the 300 GHz system also utilizes the radio-over-fiber technique to extend the measurement distance. The measurement setting parameters are shown in Table 1. The measurements were conducted in two indoor typical scenarios: the empty room and the spacious hall. Also, channel characteristics among the two scenarios are different, and they are intentionally selected to demonstrate the accuracy of RT simulation in different deployment scenarios. The obtained parameters of several dominant paths are shown in Table 2 for measurement and RT comparison. Note that the gain in the spacious hall scenario is calculated with the antenna gain included.

Scenario	Path index	Parameter	Measurement	RT	Difference
Empty room*	1	Delay (ns)	20.3	20.2	0.1
		Path gain (dB)	-86.9	-87.1	0.2
	2	Delay (ns)	23.7	23.7	0
		Path gain (dB)	−87.5	−87.2	−0.3
	3	Delay (ns)	27.2	27.2	0
		Path gain (dB)	−91.3	−91.2	−0.1
Spacious hall	1	AOA (deg)	−38.0	−36.3	−1.7
		AOD (deg)	−36.0	−36.3	0.3
		Delay (ns)	14.0	14.1	−0.1
		Path gain (dB)	−44.5	−44.5	0
	2	AOA (deg)	−56.0	−54.3	−1.7
		AOD (deg)	82.0	82.4	−0.4
		Delay (ns)	24.0	24.4	−0.4
		Path gain (dB)	−57.9	−57.6	-0.3
	3	AOA (deg)	−104.0	−102.2	−1.8
		AOD (deg)	22.0	23.5	−1.5
		Delay (ns)	31.5	30.8	0.7
		Path gain (dB)	−65.4	−64.7	−0.7
*: Note that the path parameters of this scenario are obtained with one element of the virtual large-scale array as the reference.					

TABLE 2. Parameters of measurement and RT paths.

Empty Room Scenario

This set of measurement campaigns was conducted at 100 GHz with a bandwidth of 6 GHz. The Tx uses a vertically polarized omnidirectional antenna while the Rx uses a virtual uniform circular array (UCA) antenna with a radius of 0.5 m and 2400 elements. With this UCA antenna, accurate parameters of MPCs (e.g., the path gain, delay, and angle) can be extracted from measurement data through parametric estimation [15]. The gain of the Tx and Rx antennas is 4.5 dBi. The UCA position is referred to by the center of the UCA; then the distance between Tx and Rx is 6.5 m. The height of both Tx and Rx is 1.25 m. During measurement, a metal plate stands near the Rx, as shown in Fig. 2a.

Figure 2b shows the ray trajectories diagrams of the dominant path. The trajectory color changes in the order of red-orange-yellow-green indicating that the received power decreases sequentially. It can be seen that the dominant paths come from first-order reflection and second-order reflection paths. The received power of the paths generally decreases as the reflection order increases, as expected. Furthermore, the measurement power delay profile across elements of UCA results is shown in Fig. 2c. We can see that the power and delay of MPCs vary with the element, exhibiting a non-stationary characteristic in the spatial domain. The non-stationary characteristics of the path with high delay are more obvious, as shown by the expansion of the range of power values and the increase of the curvature of the delay-element curve. It indicates that the spatial non-stationary characteristics of higher-order reflection paths may be more obvious. Figure 2d shows the RT results with measurement-based calibration. The trajectory of MPCs across the array elements is almost the same between the RT results and the measurement results. In particular, three strong MPCs are marked in numbers. Good agreement is achieved among the measurement and RT simulated paths in terms of power, angle, and delay. As shown in Table 2, the delay differences between the three dominant paths are 0.1 ns. The power differences are within ±0.3 dB. Note that the standard geometry-based stochastic channel modeling approaches would fail to model such near-field and spatial non-stationarity effects.

Spacious Hall Scenario

This set of measurement campaigns was conducted in a spacious hall scenario at 300 GHz. The measurement bandwidth is set to 2 GHz. In the measurement campaign, Tx and Rx use horn antennas with horizontal half-power beam width (HPBW) of 8° and a gain of 26 dBi. Tx and Rx are rotated horizontally by 180° and 360° in steps of 4°, respectively. The measurement results are stitched to the rotation results. The distance between Tx and Rx is 4.2 m. The height of both Tx and Rx is 1.25 m.

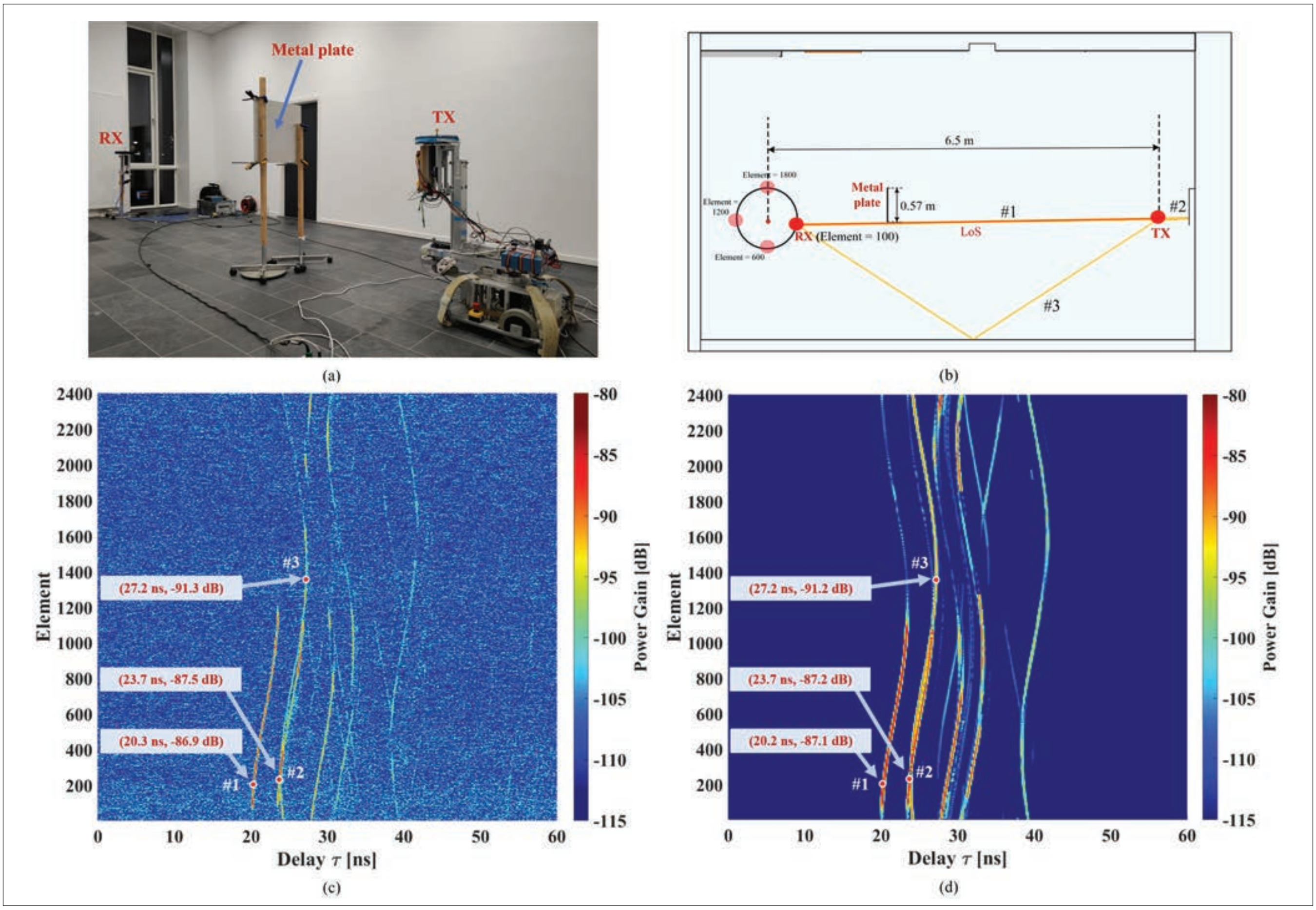

FIGURE 2. Empty room scenario: a) Rx view in the empty room scenario; b) ray trajectories; c) power-delay-element measurement result; d) power-delay-element simulation result.

Figure 3b shows the ray trajectories, and it can be seen that the five dominant paths come from the LoS path and the reflection paths of the adjacent columns. Figure 3c shows the measurement power angle profile, in which five dominant paths are also marked in numbers. Furthermore, the delay of five dominant paths is plotted to do the comparison. Figure 3d shows the results of RT simulations for the five dominant paths. By comparing Fig. 3c with Fig. 3d, it can be seen that MPCs have good agreement in both the spatial and the delay domains between the measurement and RT results. For example, the differences between the measurements and RT simulations for the delay of the five paths are within ±2 ns. From Table 2, the maximum differences of angle of arrival (AoA), angle of departure (AoD), delay, and power gain of the dominant paths are −1.8°, −1.5°, 0.7 ns, and -0.7 dB respectively, while the minimum differences come from path 1, up to -1.7°, 0.3°, −0.1 ns, and 0 dB, respectively.

Conclusions

In this work, we present that deterministic RT modeling is a promising approach for THz channel modeling. To support this viewpoint, we first introduce propagation characteristics in THz bands, such as high propagation loss, sparsity, near-field, and spatial non-stationarity need to be properly considered in the channel modeling. Then we expound that these propagation characteristics and the requirements of 6G applications for site-specific channel models bring opportunities and challenges to RT-based channel modeling. On one hand, characteristics of RT, THz channel characteristics, and THz applications make RT become more applicable in THz channel modeling compared to channel modeling in low-frequency bands. On the other hand, RT meets challenges in three aspects: material EM properties, channel measurements, and real-time implementation.

To further demonstrate our viewpoint about RT, the RT-based channel modeling methodology is introduced, and its performance is investigated. By comparing measurements and simulations in two indoor typical scenarios (i.e., the empty room and the spacious hall), we find that good agreement is achieved between the measurement and RT simulation. However, in order to obtain a more accurate measurement-calibrated RT channel model, more measurements are still needed to calibrate EM properties of materials accurately in RT simulation, and more detailed scenario database description is required in RT. There is a trade-off between RT simulation accuracy and complexity, and the goal is to achieve reasonably good accuracy with minimal simulation complexity (e.g., as done in the METIS work for 5G). In this work, we have achieved excellent agreement between RT simulation and measurement for the dominant propagation paths with simple database and EM property description, which clearly demonstrates the potential of RT simulation for accurate THz channel modeling.

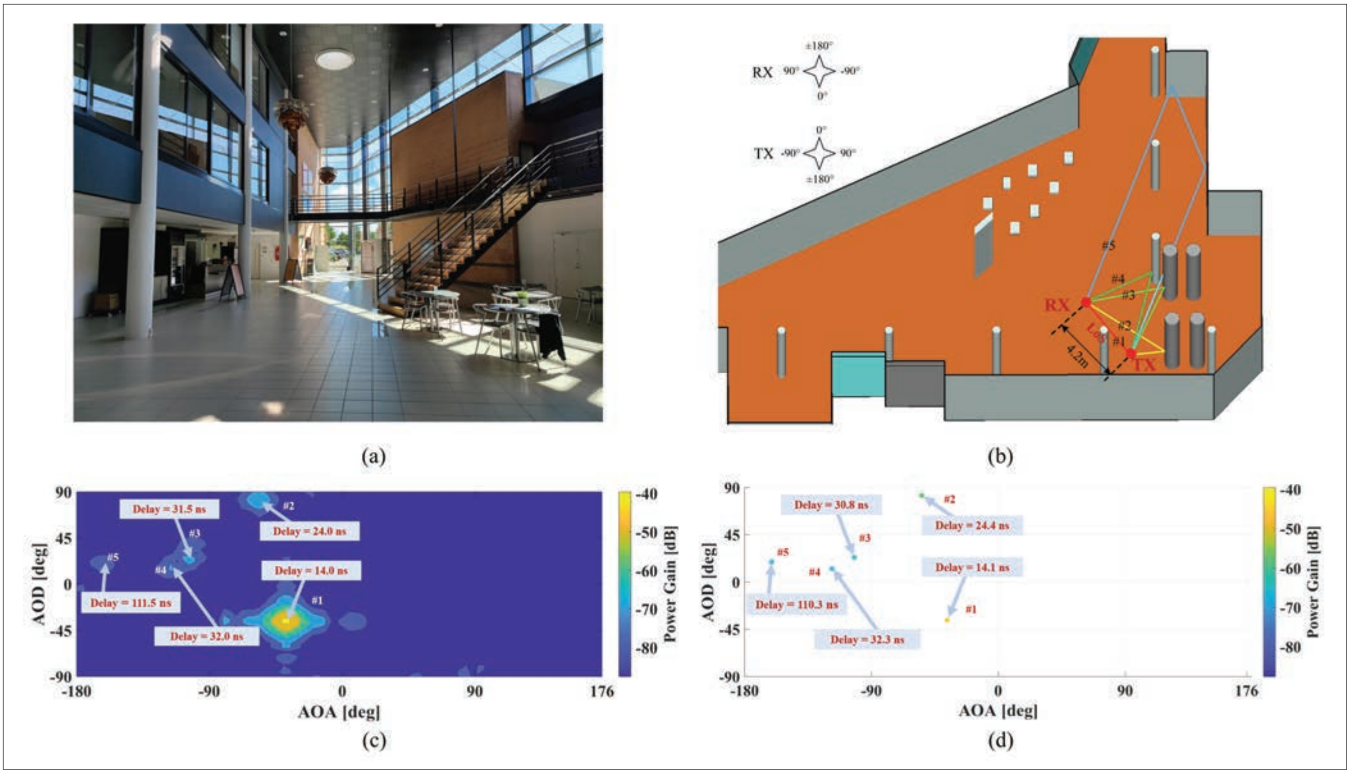

FIGURE 3. Spacious hall scenario: a) photograph in the hall scenario; b) ray trajectories; c) power-AoA-AoD measurement result; d) power-AoD-AoA simulation result.

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