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Digital Twins of Electromagnetic Propagation Environments for Live 5G networks—Part I: Channel Acquisition, EM Simulation and Verification

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Abstract—In this work, we address the key industry challenge of accurately capturing the propagation environment in live 5G commercial networks, which is essential for predicting radio device performance in realistic propagation conditions during the design phase. An advanced passive channel sounding system is designed to decode 5G downlink signals, such as the channel state information-reference signal (CSI-RS), and to resolve multipath parameters including delays, arrival angles, polarization, and complex amplitudes. To ensure measurement accuracy, the designed passive channel sounding system is rigorously calibrated and validated within a compact antenna test range (CATR) prior to field deployment. Furthermore, we propose a digital twin (DT) framework to create precise digital representations of electrical signals received on antennas of investigation through high-precision simulations, ensuring alignment with actual conditions among various locations and orientations for the antennas. The methodology begins with the precise digitization of 5G fading channel environments via the passive channel sounding process. Utilizing the acquired channel parameters and the complex radiation patterns of the targeted antennas, the DTs of the received electrical signals for the antennas can be computed. Field measurements, conducted using a standard dipole for electrical field scanning, validate the consistency between the DT predictions and measured results, thereby affirming the accuracy of both the passive channel sounding results and the proposed DT framework.

Index Terms—5G, Digital Twin, Channel Acquisition, Electrical Signal Simulation.

I. INTRODUCTION

The fifth generation (5G) wireless communication system promises significant advancements over its 4G predecessor, offering up to 1000 times the system capacity, 100 times the data rate, 3-5 times the spectral efficiency, and 10-100 times the energy efficiency [1], [2]. These improvements impose stringent demands on wireless device performance, particularly in base-band processing and radio frequency (RF) capabilities. The electromagnetic field environment in which wireless devices operate is crucial for communication performance [3]. It is necessary to evaluate device performance under various environments in the field before production. However, the field testing is costly and time-consuming [4], and the unpredictability of open-air testing environments further makes it unsuitable for testing purposes. Consequently, bringing the real-world propagation environment into the digital realm, i.e., the digital twin (DT) concept, has garnered significant interest from the industry. The target of digital twinning is to accurately capture and reproduce cellular network fading propagation environment in simulation systems, enabling troubleshooting, performance evaluation, and regression testing during the design phase. However, the primary challenge lies in the precise acquisition of real-world propagation channels in the live network.

Ray tracing (RT), based on ray optic theory, is a simulation method for predicting deterministic propagation channels. Initially used for network planning and coverage prediction [5], RT involves creating a detailed model of the scenario and predicting multipath component (MPC) parameters using known propagation mechanisms such as reflection, diffraction, and scattering [6]. RT can reduce the need for costly field channel measurements but its effectiveness is limited by input inaccuracies, such as three-dimensional (3-D) digital maps and material properties, which affect the accuracy of propagation environment predictions [7], [8]. The fidelity of RT is also constrained by the precise modeling of the aforementioned ray interaction mechanisms [9]. For example, many RT-based tools underestimate reflecting and scattering paths in rich scattering environments, particularly at low frequencies [10], [11].

Field channel measurement is a vital method for obtaining first-hand propagation environment data [12]. This process typically involves extracting the channel impulse response (CIR) from radio acquisition equipment and estimating MPC parameters with post-processing methods, such as the search-alternative generalized expectation-maximization (SAGE) algorithm [13]. There are mainly two categories of channel measurement frameworks, i.e., active sounding [14]-[17], which uses dedicated radio devices for transmission and reception, and passive sounding, which relies solely on a receiver to directly analyze downlink communication signals and concurrently determine propagation characteristics [18]. Active sounding, while widely used, may not accurately capture the propagation environment experienced by user equipment (UEs) in 5G commercial networks due to differences in...

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transmitter setups. Specifically, a self-defined transmitter in active sounding is generally different from a real 5G base station (BS) in terms of mounting locations, antenna array properties and beam management strategies.

Passive sounding, initially introduced for analyzing propagation characteristics in public in-service wireless communication systems such as universal mobile terrestrial system (UMTS) [19] and long-term evolution (LTE) [20], has been extended to 5G cellular networks [21] recently. This method provides an accurate representation of the electromagnetic environment encountered by wireless devices, facilitating the direct application of derived channel models for product performance evaluation and optimization [23]. However, the industrial foremost concern in adopting channel measurement results is their fidelity to real-world conditions. To our knowledge, the majority of the aforementioned studies have not fully addressed the need for a robust verification process to confirm the results against actual field conditions.

This paper introduces an advanced passive channel sounding system, designed to decode 5G downlink signals and to resolve multipath parameters. To ensure measurement accuracy, the designed passive channel sounding system is rigorously calibrated and validated within a compact antenna test range (CATR) system. Furthermore, we propose a DT framework designed to synchronize simulated outcomes with actual performance in 5G commercial networks, in terms of the electrical signals received by targeted antennas of test devices. These signals are cumulative electromagnetic responses from multiple rays striking the antennas, which are position-sensitive to the phase variations. A centimeter-level displacement can induce substantial variations in the synthesized electrical signal. Consequently, reproducing at the electrical signal level is a formidable endeavor, compounded by the challenges of accurately capturing the real-world fading environment and high-precision positioning control. The alignment of simulated and measured results inherently validates the accuracy of the derived multipath parameters. Main contributions of the work are as follows.

1) An advanced passive sounding system is developed to accurately extract the wireless channel propagation characteristics for 5G commercial networks by resolving downlink signals such as the synchronization signal block (SSB) and the channel state information reference signal (CSI-RS). With a large-scale omnidirectional antenna (ODA) array, this system exhibits an excellent ability to capture the multipath parameters including delays, arrival angles, polarization, and complex amplitudes. The accuracy of this sounding system has been validated within a CATR environment.

2) A DT framework for simulating antenna performance in real scenarios is first proposed in this paper, where the received electrical signals on the targeted antenna can be digitally reproduced. Moreover, higher-order performance metrics, e.g., multi-antenna correlation and throughput, can be derived directly from the calculated electrical signals.

3) Extensive experiments have been carried out across diverse scenarios to verify the feasibility of the proposed framework. These results demonstrate an excellent match between predictions and actual measurements, which is a significant progress beyond state of art works considering the challenging task of accurately monitoring electromagnetic conditions in 5G commercial networks.

The rest of the paper is organized as follows. In Section II, the DT framework is presented with a brief overview. In Section III, the passive channel sounding system is introduced. Besides, the calibration methods and verification results are described. Section IV presents the DT generation process in detail. In Section V, the verification experiments are conducted and the results are analysed. Finally, Section VI concludes this paper.

II. DIGITAL TWIN FRAMEWORK DESCRIPTION

The target of this framework is to accurately predict the antenna performance, in terms of its received electrical signals, under 5G commercial network fading conditions. It establishes a link between the virtual and physical realms, enabling the evaluation of antenna designs, in practical scenarios during the design phase.

The structure of the proposed framework is illustrated in Fig. 1. The generation of DTs for the received electrical signals necessitates two primary inputs: multipath parameters including propagation delays, impinging angles, polarization, and complex amplitudes, which are obtained by the channel acquisition in the 5G live network scenarios, and the complex radiation patterns of the antennas under investigation, which can be obtained from full-work EM simulation tools like CST [24] or HFSS [25], or direct measurement in the anechoic chamber with the over-the-air (OTA) testing systems [26]. A comprehensive explanation of the DT generation process is provided in Section IV. The outputs of the DT generation process are the calculated electrical signals received on the targeted antennas which are assumed to be placed within the propagation environment. The calculated electrical signals can be further used to determine other key performance metrics such as multi-antenna correlation, gain imbalance, and overall throughput.

To verify the reliability of DT predictions, on-site field measurements are conducted in the practical 5G networks. Subsequently, the calculated outcomes are compared with the
actual measurements to quantify the discrepancies between the prediction and reality. It is imperative for the multipath parameters and antenna patterns to be precise to achieve a high degree of alignment. Moreover, the DT generation process must be meticulously managed, given the highly position-sensitive nature of the complex electrical signals.

III. CHANNEL ACQUISITION IN 5G COMMERCIAL NETWORKS

A. The Channel Acquisition System

As depicted in Fig. 2, the channel acquisition system consists of two main components, i.e., a large-scale ODA array and a signal processing platform. Fig. 3 presents the main and top views of the ODA array, which comprises 80 dual-polarized antenna elements and is structured as six uniform circular arrays (UCAs). The base section of the ODA array consists of four horizontal rings with a radius of about 20 cm, each including 16 evenly-spaced antenna elements. The top section of the ODA array includes 8 antenna elements directed at $45^\circ$ in zenith and another 8 antenna elements at $0^\circ$ in zenith.

Figs. 4(a) and 4(b) depict the measured radiation patterns of the antenna element for vertical and horizontal polarization, respectively. Note that the antenna patterns for different antenna elements will be different due to different coupling from surroundings. The beam pattern of this ODA array is illustrated in Fig. 4(c), where the excitation of antenna elements is designed to form a beam at $0^\circ$ in azimuth and $90^\circ$ in zenith. The 3-dB beam-width of single element is approximately $70^\circ$ at 2.4 GHz, while the beam pattern of ODA array has a 3-dB beam-width of about $25^\circ$ at the same frequency. The scanning range of the ODA array covers $[0^\circ, 360^\circ]$ in azimuth and $[0^\circ, 150^\circ]$ in zenith. The array operates within the frequency range of 2.4 GHz to 3.7 GHz, encompassing the primary commercial 5G bands, i.e., N41 and N78.

The schematic diagram of the channel acquisition system is detailed in Fig. 5. The 80-element ODA array captures electromagnetic signals emitted by 5G BSs and converts them into RF signals. To reduce complexity and cost, a 160-in/2-out RF switch array is implemented to manage the reception of signals from all 80 elements, based on a time division multiplexing (TDM) strategy. Consequently, this channel acquisition system is only suitable for analysing static or quasi-static scenarios, which means that the propagation environment should be unchanged during measurements. The system is capable of handling two types of 5G signals in live networks: SSB and CSI-RS. From our field test results, these signals are predominantly transmitted at a periodicity of 20 ms. Thus, a complete measurement snapshot take a total of $160 \div 2 \times 20\text{ms} = 1.6\text{s}$.
at least. The key parameters of the acquisition system are summarized in Table I.

<table>
<thead>
<tr>
<th>Key</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omnidirectional antenna array</td>
<td>80 dual-polarized elements with 160 antenna ports</td>
</tr>
<tr>
<td>Frequency range</td>
<td>2.4 – 3.7 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>122.88 MHz</td>
</tr>
<tr>
<td>Low-noise amplifier gain range</td>
<td>90 dB</td>
</tr>
<tr>
<td>Signals to analysis</td>
<td>CSI-RS/SSB</td>
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</tbody>
</table>

**TABLE I**

**SOME KEY PARAMETERS OF THE CHANNEL ACQUISITION SYSTEM.**

Fig. 6. The multipath propagation model.

at least. The key parameters of the acquisition system are summarized in Table I.

B. Channel Impulse Response Received by the Channel Acquisition System

Fig. 6 depicts a typical complete propagation channel from a BS to a UE with multiple impinging rays. Due to the passive sounding mechanism, only the fading characteristics on the receiver side can be detected. Therefore, the CIR perceived by the acquisition system \( h(\tau, \theta, \phi) \) can be expressed as a sum of all rays arriving at the acquisition location as

\[
h(\tau, \theta, \phi) = \sum_{l=1}^{L} \bar{E}_l \cdot \delta(\tau - \tau_l) \delta(\theta - \theta_l) \delta(\phi - \phi_l),
\]

where \( \tau_l, \theta_l, \phi_l \) correspond to the delay, azimuth angle of arrival (AOA), and zenith angle of arrival (ZoA) for the \( l \)th ray, respectively, and \( \bar{E}_l \) represents the complex field vector associated with each ray. As the channel parameter of a single channel snapshot is investigated, the Doppler is ignored.

C. Signal Models and Multipath Parameter Estimation Algorithm

The SAGE algorithm, widely used in the literature as high-resolution parameter estimation algorithm [13], is utilized to estimate the multipath parameters in this paper. Moreover, we use the notations \( \beta_{hl} \) and \( \beta_{vl} \) to denote the complex amplitude in horizontal and vertical polarization, respectively. Thus, the channel parameters for the \( l \)th ray, as resolved by the acquisition system, are represented by the vector \( \chi_l^T = (\tau_l, \theta_l, \phi_l, \beta_{hl}, \beta_{vl}) \). Assume that the receiver is equipped with an antenna array comprising \( M \) elements. Thus, the EM complex responses of the array in the direction \( [\theta_l, \phi_l] \) for both polarization can be written as

\[
\alpha^p(\theta_l, \phi_l) = [\alpha_{hl}^p(\theta_l, \phi_l), \alpha_{vl}^p(\theta_l, \phi_l), ..., \alpha_{MK}^p(\theta_l, \phi_l)]^T,
\]

with \( p \in \{h, v\} \) indicating horizontal (h) or vertical (v) polarization. The contribution of the \( l \)th path to the frequency-domain channel response at subcarrier frequency \( f_k \) for the antenna array \( H_l(f_k; \chi_l) \) can be formulated as

\[
H_l(f_k; \chi_l) = \sum_{p=\{h,v\}}^{M} \beta_{hl}^p \alpha_p^p(\theta_l, \phi_l) e^{-j2\pi f_k \tau_l},
\]

where \( k \) is the subcarrier index with \( k = 1, 2, ..., K \).

By aggregating the contributions from all the \( L \) rays, the complete observable channel response at subcarrier frequency \( f_k \) across the array can be written as

\[
H(f_k) = \sum_{l=1}^{L} H_l(f_k; \chi_l) + \sqrt{\frac{N_0}{2}} N_k,
\]

where \( N_k \) denotes the Gaussian noise vector at the \( k \)th subcarrier, and \( N_0 \) represents the noise power.

By introducing the expectation-maximization concept [28], the SAGE algorithm is capable of solving the multipath parameters iteratively. The estimated multipath parameter \( \chi_l' = [\tau_l', \theta_l', \phi_l', \beta_{hl}^{v'}, \beta_{vl}^{v'}] \) by SAGE algorithm can be obtained as

\[
(\tau_l') = \arg \max_{\tau_l} \sum_{k=1}^{K} e^{j2\pi f_k \tau_l} H(f_k)
\]

\[
(\theta_l', \phi_l') = \arg \max_{\theta_l, \phi_l} (Q^H D^{-1} Q)
\]

\[
(\beta_{hl}^{v'}, \beta_{vl}^{v'}) = \frac{1}{MK} (D^{-1} Q),
\]

where

\[
Q = \begin{bmatrix} \alpha^v(\theta_l, \phi_l) & \alpha^h(\theta_l, \phi_l) \\ \alpha^h(\theta_l, \phi_l) & \alpha^v(\theta_l, \phi_l) \end{bmatrix} \sum_{k=1}^{K} e^{j2\pi f_k \tau_l'} H(f_k)
\]

\[
D = \begin{bmatrix} \alpha^v(\theta_l, \phi_l) & \alpha^v(\theta_l, \phi_l) & \alpha^v(\theta_l, \phi_l) & \alpha^h(\theta_l, \phi_l) \\ \alpha^h(\theta_l, \phi_l) & \alpha^h(\theta_l, \phi_l) & \alpha^h(\theta_l, \phi_l) & \alpha^h(\theta_l, \phi_l) \end{bmatrix}.
\]

D. Self-Calibration Procedures

To ensure the accuracy of channel acquisition, the system has undergone comprehensive calibration across multiple dimensions, including the wide-band frequency responses of RF channels, clock drift, antenna patterns, and phase center alignment. To maintain brevity, an overview of the self-calibration workflow is presented.

The initial step involves calibrating the RF channel responses, which include the entire system chain: RF switches, filters, low noise amplifiers, programmable attenuators, mixers, and analog-to-digital converters. This step aims to record the inhomogeneity among RF channels caused by the imperfections of hardware components and compensate these differences in post processing.
Subsequently, clock drift calibration is addressed. The reference clock of BS, which typically is sourced from GPS, and the reference clock of the acquisition system, which is provided by an internal rubidium clock, operate independently, resulting in a phase shift during the measurement process. This phase shift will significantly distort the TDM-based channel sounding mechanism, as it introduces unexpected phase deviations in the results for each antenna element. Therefore, it is imperative to measure, monitor, and calibrate out the clock drift in the acquisition process.

Third, accurately identifying the phase center of the 3-D antenna pattern of the ODA array is critical, as all derived multipath parameters, particularly the phase of each path, are estimated relative to this reference point. The rays’ phase properties play a pivotal role on the calculation of the electrical signal. A detailed explanation of this process will be provided in Section IV.

E. Accuracy Verification for the Channel Acquisition System in CATR

To verify the accuracy of passive channel sounder and parameter estimator, the acquisition system is initially assessed within a controlled and known laboratory setting, i.e., the CATR system as shown in Fig. 7.

The CATR system provides a controlled environment by generating a single horizontally-impinged plane wave with vertical polarization on the test area. The antenna array of acquisition system is mounted on a turntable, which is capable of full 360° rotation at horizontal plane with high precision. Through rotation of the turntable, single-ray environments for various azimuth angles can be constructed. During the test, the angles of turntable are sequentially set to \{0°, 30°, ..., 330°\}, to simulate diverse incidence directions.

The testing system diagrams within the CATR system are presented in Fig. 8. Two parallel tests are conducted using this system: the first test employs our acquisition system with a 5G BS simulator as the signal source, while the second test, serving as a benchmark, uses a vector network analyzer (VNA) to capture the channel response. By performing the SAGE algorithm, the estimated AoA, ZoA, power, and polarization can be calculated for these two setups, which are illustrated in Fig 9(a), Fig 9(b), Fig 9(c), and Fig 9(d), respectively.

As depicted in Fig. 9(a), the estimated AoAs of both setups closely match the ideal results with a maximum deviation of 1°, where the ideal results are related to the rotating angle settings of the turntable. Fig. 9(b) presents that the ZoA values for both setups exhibit slight fluctuations around 90°, with a maximum deviation of 1 degree, where the 90° corresponds to the horizontal direction. Fig. 9(c) illustrates the normalized power values for the rays in both setups, which have a similar variation pattern with a maximum deviation of ±0.8 dB across different azimuth angles. Lastly, the polarization results are shown in Fig. 9(d), where the measured polarization angles for both setups are consistently close to 0°, regardless of the turntable’s angles. The 0° reading corresponds to vertical polarization, which is the targeted polarization state of the impinging ray configured in the CATR environment. The above results indicate the estimation results of the acquisition system have the same level of accuracy as the VNA-based system. In addition, the estimated results of AoA, ZoA, normalized power, and polarization are close to the real values, which reveals a high estimation accuracy of our acquisition system.
IV. DIGITAL TWIN GENERATION

In this section, the detailed procedure for DT generation is presented, where the direct outputs are the calculated electrical signals received on the target antennas in the 5G commercial propagation environment. For comparison, the antennas are assumed to be positioned at a specific location $D_0$ in the 5G commercial network, coinciding with the site where channel acquisition is actually performed.

A. Basic Principle to Calculate Electrical Signals on Antennas

Assume $L$ rays are collected at a specific location $D_0$, where the $l$th ray is characterized by delay $\tau_l$, AoA $\phi_l$, amplitude $\alpha^h_l$ and phase $\omega^h_l$ at horizontal polarization, and amplitude $\alpha^v_l$ and phase $\omega^v_l$ at vertical polarization. It is noted that $\beta^h_l = \alpha^h_l \exp(j\omega^h_l)$ and $\beta^v_l = \alpha^v_l \exp(j\omega^v_l)$ represent the complex amplitudes in different polarization. Assume a target antenna, whose $\theta$-polarized and $\phi$-polarized 3-D complex patterns denote as $F_\theta(\theta, \phi)$ and $F_\phi(\theta, \phi)$, is precisely placed at $D_0$. Then, the received electrical signal $E$ on the target antenna can be expressed as a sum of contributions from all $L$ rays as

$$E = \sum_{l=1}^{L} \left[ \begin{array}{c} \alpha^h_l \cdot \exp(j\omega^h_l) \\ \alpha^v_l \cdot \exp(j\omega^v_l) \end{array} \right]^T \left[ \begin{array}{c} F_\theta(\theta_l, \phi_l) \\ F_\phi(\theta_l, \phi_l) \end{array} \right].$$

(9)

It can be seen that the phase and amplitude of each signal path directly impact the calculation result, especially for those signals with significant power. Thus, the accurate phase tracking of all received signal paths is necessary for digital twinning at EM level.

B. Phase Center Determination and Phase Compensation for Location Offset

The phase values of the estimated rays, and the phase response of the antenna are actually defined relatively to their respective reference points, i.e., the phase centers. In fact, the phase center is a user-defined geometric point which could be located at any positions. However, for the facilitation of analysis, the phase center is usually considered to be the physical center of an antenna array, or around the central region [24]. In this paper, careful determination of two phase centers is required: one for the channel acquisition system and another for radio devices, such as smartphones. It is noted that Eq. (9) holds only when the two phase centers coincide. Otherwise, the phase values of multipath signals must be compensated according to the shift in the locations of the two phase centers.

As illustrated in Fig. 10, assume a scenario where the phase center of the acquisition system is located at $d_0 = [x_0, y_0, z_0]$, and the phase center of the smartphone is located at $d_1 = [x_1, y_1, z_1]$. Then the location offset is denoted as $\Delta d = d_0 - d_1$. Additionally, the unit directional vector [29] of the $l$th ray can be written as

$$\rho_l = \begin{pmatrix} \sin\phi_l \cos\theta_l \\ \sin\phi_l \sin\theta_l \\ \cos\theta_l \end{pmatrix}.$$

(10)

Based on $\Delta d$ and $\rho_l$, the phase value of each path can be compensated as

$$\bar{\omega}^h_l = \omega^h_l - 2\pi \frac{\Delta d \cdot \rho_l}{\lambda},$$

(11)

$$\bar{\omega}^v_l = \omega^v_l - 2\pi \frac{\Delta d \cdot \rho_l}{\lambda},$$

(12)

where $\lambda$ is the wavelength of the center frequency.

C. Phase Compensation for delays

The specific signals to analyse are 5G downlink signals including SSB and non-zero power CSI-RS. Typically, these signals are not located at the center of the frequency band. Therefore, an extra phase is introduced when using the SAGE algorithm to resolve the time delays of the multipaths in Eq. (9). Hence, the phase value of the $l$th ray needs to further be compensated as

$$\bar{\omega}^h_l = \omega^h_l - 2\pi \tau_l \left( \frac{1}{K} \sum_{k=1}^{K} f_k \right),$$

(13)

$$\bar{\omega}^v_l = \omega^v_l - 2\pi \tau_l \left( \frac{1}{K} \sum_{k=1}^{K} f_k \right),$$

(14)

D. Generation of the Digital Mirror and Applications

Assume that there are $U$ antennas on a target device, and $F_{\theta,u}(\theta, \phi)$ and $F_{\phi,u}(\theta, \phi)$ denote the $\theta$-polarized and $\phi$-polarized 3-D complex patterns for the $u$th antenna, respectively. The DT of the received electrical signal for the $u$th antenna with the updated phase values, can be expressed as

$$E_u = \sum_{l=1}^{L} \left[ \begin{array}{c} \alpha^h_l \cdot \exp(j\omega^h_l) \\ \alpha^v_l \cdot \exp(j\omega^v_l) \end{array} \right]^T \left[ \begin{array}{c} F_{\theta,u}(\theta_l, \phi_l) \\ F_{\phi,u}(\theta_l, \phi_l) \end{array} \right].$$

(15)

More analysis can be proceed based on the DT, and some exemplary metrics of the industrial concerns are listed as follows.
1) **MIMO Matrix:** Taking the CSI-RS as an example, assume that there are total $N$ CSI-RS ports in a configured CSI-RS resource [31]. For each CSI-RS port, we can calculate the DT using Eq. (15) for each antenna. Denote the DT for the $u$th antenna and the $n$th CSI-RS port as $E_{u,n}$, then the MIMO matrix can be expressed as

$$H = \begin{bmatrix}
E_{1,1}, & E_{1,2}, & \ldots, & E_{1,N} \\
E_{2,1}, & E_{2,2}, & \ldots, & E_{2,N} \\
\vdots, & \vdots, & \ddots, & \vdots \\
E_{U,1}, & E_{U,2}, & \ldots, & E_{U,N}
\end{bmatrix}. \quad (16)$$

Based on Eq. (16), theoretical channel capacity can be directly derived. Moreover, the impact of different antenna designs can be quantitatively evaluated by introducing actual radiation patterns of antennas of interest into Eq. (15).

2) **Multiple Antenna Correlation:** The correlation of multiple antennas has a direct impact on channel capacity, which is one of key performance indicators for multi-antenna designs in industry. The correlation value $\eta_{u_1,u_2}$ for the $u_1$th and $u_2$th antenna, which is determined by both the propagation environment and the antenna radiation pattern, can be calculated as

$$\eta_{u_1,u_2} = \frac{\sum_{t=1}^{T} E_{u_1}(t) \cdot E_{u_2}(t)}{\sqrt{\sum_{t=1}^{T} |E_{u_1}(t)|^2 \cdot \sum_{t=1}^{T} |E_{u_2}(t)|^2}}, \quad (17)$$

where $E_{u_1}(t)$ and $E_{u_2}(t)$ denote the electrical signals received on antenna $u_1$ and $u_2$ at the time snapshot $t$, respectively, with the range $t = 1, 2, \ldots, T$.

3) **Gain Imbalance:** The gain imbalance factor [32], can be utilized to reflect the impact of different antenna designs on the link quality for the deployment scenarios. Based on Eq. (15), the gain imbalance factor $\epsilon_{u_1,u_2}$ for antennas $u_1$ and $u_2$, with $u_1, u_2 \in \{1, 2, \ldots, U\}$ can be expressed as

$$\epsilon_{u_1,u_2} = 10 \log_{10} \left( \frac{|E_{u_2}|^2}{|E_{u_1}|} \right), \quad (18)$$

where $|\cdot|$ is absolute value function.

V. **MEASUREMENT VALIDATION**

In order to examine the accuracy of the proposed DT framework, we have conducted a series of experimental measurements both in the field and in the laboratory. The measured results are compared with the simulated results generated by the DT framework. As depicted in Fig. 1, the initial step involved executing a channel acquisition process to capture the site-specific channel parameters, which served as inputs for the DT generation process. Concurrently, a probe antenna is employed for direct power scanning within the area of the channel acquisition. It is noted that the captured 5G signal for power scanning, is the SSB-demodulation reference signal (DMRS), the power of which is also known as the reference signal received power (RSRP). Subsequently, the DTs of the received electrical signals on the probe antenna are calculated and their accuracy is evaluated with the field scanning.

The power scanning locations are depicted in Fig. 11, which are uniformly distributed on a horizontal circle. A turntable is utilized to ensure the positioning accuracy, covering the angle range from $0^\circ$ to $360^\circ$ degrees with the accuracy within 0.1°. In addition, a dedicated RF interface panel is used to ensure the precise configuration of the scanning radius, with several RF ports pre-installed on the panel corresponding to radius of 0 cm, 5 cm, and 10 cm, respectively. A dipole serves as the probe antenna, as its received signal can indicate the electrical strength of vertical polarization as depicted in Fig. 11. Assume there are $S$ sampling points, then the normalized power values obtained by the direct power scanning are denoted as $p = [p_1, p_2, \ldots, p_S]$ with unit in dB. Correspondingly, the calculated values from the DT platform based on Eq. (15) are denoted as $q = [q_1, q_2, \ldots, q_S]$ with unit in dB. The quality factor of accuracy is defined as the root mean square error (RMSE) of the two sets of power values as

$$\delta = \sqrt{\frac{\sum_{s=1}^{S} |p_s - q_s|^2}{S}}. \quad (19)$$

The validation experiment is first carried out in the laboratory, i.e., a controlled environment in an anechoic chamber with two horn antennas, capable of emulating a two-ray propagation environment. Subsequently, a series of validation experiments are carried out in 5G commercial networks, whose propagation environments are more sophisticated and uncontrollable. It is important to note that in both controlled and uncontrolled test scenarios, the channel propagation parameters remain unknown, necessitating the execution of a channel acquisition procedure to capture these parameters.

A. **Validations in the Controlled Two-Ray Environment**

The controlled two-ray environment is illustrated in Fig. 12, where two horn antennas of vertical polarization are used to transmitting signals from a 5G BS simulator. Fig. 13 presents...
the testing setups for the channel acquisition procedure (left) and the power scanning procedure (right), respectively. The absolute radio frequency channel number (ARFCN) of SSB is 504990, corresponding to 2524.95 MHz [31].

Given the dimension of a 5G smartphone is generally less than 20 cm, the radius of the power scanning circle is set as $r = 10$ cm. Besides, the height of the scanning circle is set as the same level as the phase center of the acquisition system, denoting as $\Delta h = 0$ cm. The validation results are shown in Fig. 14. It can be observed that the normalized measured power values coincides well with that of the DTs for different scanning angles. Besides, the RMSE of these two set of values are 2.6 dB according to Eq. (19). The deviation in results near the $100^\circ$ turntable angle may be attributed to the channel acquisition system’s inability to accurately detect multipath signals below -25 dB, as well as minor changes in the EM environments under the two configurations as depicted in Fig. 13.

1) Vertical Movement: In this part, we move the power scanning circle upwards or downwards by a small increment to further verify the predictions of the DT framework. The main characteristics of the propagation environment in new locations of power scanning, such as AoAs and ZoAs, is assumed to be unchanged, therefore the channel acquisition procedure is not needed. The radius of the scanning circle is maintained as $r = 10$ cm, with the height adjusted to $\Delta h = 7.5$ cm for the upward movement and $\Delta h = -10$ cm for the downward movement. The power scanning results are
Fig. 17. Power scanning results of the measurement and the digital twin after horizontal movement in x-axis by $\Delta x = 10$ cm in the two-ray environment.

Fig. 19. Power scanning results of the measurement and the digital twin in a corridor scenario under the 5G commercial network.

Fig. 20. The tested outdoor environment in the live 5G network, and the power-angular distribution of the estimated multipaths.

presented in Fig. 15 and Fig. 16, respectively. The measured lines coincides well with the corresponding digital mirror lines, where the RMSEs are 1.6 dB and 0.97 dB for the upward and the downward scenarios, respectively.

2) Horizontal Movement: By adjusting the power scanning area in the direction of x-axis by $\Delta x = 10$ cm, the comparison of direct measurement and the simulation results are shown in Fig. 17. It can be seen that a good consistency between the measured and the simulated results is achieved.

The experiments conducted in the controlled two-ray environment present a satisfactory alignment between simulation and measurement results at the EM level, which demonstrates the feasibility of our proposed DT framework. Then the experiments are extended to uncontrolled 5G commercial network scenarios, encompassing both indoor and outdoor environments.

B. Validations in the Field

It is crucial to verify the feasibility of the DT framework in 5G commercial networks, where the live environment represents the realistic application scenario for diverse wireless communication devices. However, the EM environment in the live network is more sophisticated and uncontrollable, containing unexpected multiple propagation effects, including reflection, diffraction scattering, and etc.

1) Indoor Scenarios: As depicted in Fig. 18, the validation procedure is conducted in an indoor corridor environment, situated on the fourth floor of Building B at the China Academy of Information and Communications Technology (CAICT) in Beijing, China. The network operator is China Mobile Communications Corporation (CMCC), where the frequency band is N41 with SSB ARFCN configured as 504990. A 5G indoor BS is mounted under the ceiling, and its position is identified by the yellow circle in Fig. 18. The propagation environment is first captured by the channel acquisition system, and the power-angular distribution of estimated multipaths is illustrated in Fig. 18. In addition, the power scanning locations is marked out by the red dashed line with $r = 10$ cm and $\Delta h = 0$ cm, where a dipole is used as the probe antenna.

The measured and the simulated curves of the receiving power are shown in Fig. 19. It can be seen that the two curves coincide with each other for most scanning positions, with the maximum deviation of 3 dB occurring at around 250°. The RMSE of these two curves is 1.32 dB.

2) Outdoor Scenarios: The outdoor scenario in urban street is selected to further examine the accuracy of the proposed DT framework. The propagation environment and the power-angular distribution of estimated multipath are illustrated in Fig. 20. The tested environment is a non line-of-sight scenario, whose multipaths mainly come from the reflections on the surrounding buildings, cars, and trees.

The measured and simulated results are shown in Fig.
21. It can be seen that these two curves coincide well with each other with the RMSE value of 4.48 dB. Moreover, the severe deviations usually occur at the points with relative field strength less than $-20$ dB, which might be attributed to the multipaths with weak power, e.g., less than $-20$ dB.

With the above experiments, it can be concluded that the alignment of the measured results and the DT predictions has been achieved in the scenarios of investigation.

VI. CONCLUSION

This paper proposes a high-accuracy digital twin implementation method that enables a precise alignment between real-world electromagnetic fields and their digital twin counterparts. This method comprises two primary steps. Firstly, digitizing the real-world environment with the channel acquisition system to obtain the key channel parameters including delays, AoAs, ZoAs, polarization, and complex amplitudes. Second, the digitization process continues based on the target antenna radiation pattern and the digital twinning techniques. Extensive experiments, conducted both in the laboratory and in the field, have been used to compare the electromagnetic fields of the real-world and the digital twin platforms, indicating that a good alignment has been achieved. The proposed framework has great potential to build a robust foundation for the usage of digital twin methods in the industry. For example, extensive representative deployment scenarios can be measured with the proposed passive channel sounder and we can then construct a scenario library, which could be used to quickly predict the performance of antennas or receivers under real deployment scenarios. Optimization tasks can be efficiently executed in the virtual software platform in the design phase, which is anticipated to significantly enhance optimization efficiency and mitigate design risks, potentially leading to new technological innovations in the product development process.

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