

Holographic RIS-Aided Wideband Communication With Beam-Squint Mitigation

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Abstract—Reconfigurable intelligent surface (RIS) is a key potential technology for the sixth generation wireless communication. The deployment of RIS in wideband communication systems can effectively mitigate severe path loss and against the blockage of line-of-sight path, which can improve transmission gain and enhance communication quality. However, with the increase of RIS array and bandwidth, beam-squint effect will occur and seriously damage the performance of communication systems. In this paper, we first establish a holographic RIS-aided wideband communication system model from the perspective of the electromagnetic wave propagation theory. Then, we analyze the holographic RIS electromagnetic characteristics under the beam-squint effect. Further, we derive the angle spread range, 3dB beam bandwidth, and beam coverage range to analyze the regularities of beam offset. Besides, we propose a new codebook design scheme to address the impact of the beam-squint effect. Finally, we introduce the true-time-delay (TTD) lines into the holographic RIS structure to mitigate the beam-squint effect. The simulation results reveal the influence of the beam-squint, and also verify the mitigation effect of TTD lines on the beam-squint effect.

Index Terms—Reconfigurable intelligent surface (RIS), holographic, beam-squint, electromagnetic characteristic analysis, true-time-delay (TTD) line.

I. INTRODUCTION

RECONFIGURABLE intelligent surface (RIS) is considered a promising technology in the sixth generation wireless communication networks due to its ability of flexibly modifications the wireless propagation environment [1].

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Specifically, RIS consists of numerous low-power consumption and low-complexity hardware elements, which can adjust the phase and polarization of the electromagnetic waves, thereby enhancing the transmission gain [2]. To satisfy the high data rate and rich available bandwidth, mmWave/Terahertz communication has attracted extensive research [3], [4], [5]. Due to the small size of wideband mmWave/Terahertz electronic components, RIS is easier to implement in the wideband system. According to the electromagnetic propagation theory, wideband signal propagation mainly relies on line-of-sight (LoS) path and faces significant path loss, which can cause serious degradation in communication performance. The integration of RIS in the wideband system has been proposed as a promising solution to prevent the blockage of LoS path, compensate for path loss, and enhance communication quality [6].

Some researchers have commenced the application of RIS for wideband communication systems [7], [8], [9], [10], [11]. In [7], Zhang and Dai jointly designed the precoding at base station (BS) and RIS to maximize the network capacity in a wideband RIS-aided cell-free network. In [8], Lin et al. proposed an adaptive transmission protocol to execute channel estimation and passive beamforming simultaneously for the wideband RIS-assisted OFDM system. In [9], He et al. designed a delay matching based scheme to decouple the multi-RIS design to reduce overhead and limit feedback. In [10], He et al. proposed a channel estimation method via atomic norm minimization and exploited the prior information of objects to improve the estimation accuracy. In [11], He et al. utilized a majorization-minimization-based iterative approach to optimize the RIS passive beamforming.

However, as the size of the RIS array and the transmission bandwidth increase, the delay difference among array elements can not be ignored. The beam-squint effect will occur, which directs the beam in different directions on different subcarriers, leading the communication performance degradation [12], [13], [14]. Recently, some works have considered the beam-squint effect in RIS-aided wideband systems [15], [16], [17], [18], [19], [20]. In [15], Sun et al. modeled the beam-squint effect of RIS and utilized true-time-delay (TTD) lines to mitigate the impact of the beam-squint effect on system performance. In [16], Chen et al. proposed an optimized design for RIS beamforming in LoS and NLoS communication under the beam-squint effect. In [17], Yuan et al. designed two neural networks to calculate the BS hybrid precoding and RIS beamforming, respectively. In [18], Ma et al. proposed a two-stage orthogonal matching pursuit algorithm to estimate the RIS cascaded channel under the beam-squint

effect. In [19], Gao et al. proposed the virtual sub-array based and TTD based wideband hybrid beamforming approaches to eliminate the impact of beam squint. In [20], Chen et al. exploited the full channel state information to design hybrid transmit precoding, which projected all frequencies to the central frequency and constructed the common analog hybrid precoding matrix.

In above works, the authors modeled RIS as a phase shift diagonal matrix. The RIS cascaded channel model is a cascaded form of transmitter-RIS channel, RIS phase shift diagonal matrix, and RIS-receiver channel. Although the model is intuitive and facilitates straightforward analysis, it is too simplistic to reflect the mechanism of the interaction between RIS and the incident electromagnetic field. The model is not fundamentally different from that in traditional MIMO systems. It fails to analyze the electromagnetic characteristics of the RIS adequately. This may result in the designed algorithms being too simple to match the electromagnetic characteristics of RIS and the inaccurate evaluation of system performance.

In RIS-aided communication systems, one of the key issues is to find a reliable and universal electromagnetic model that accurately describes the electromagnetic nature of the RIS. Some researchers are dedicated to studying the RIS from the perspective of the electromagnetic wave propagation theory [21], [22], [23], [24], [25]. In [21], Luo et al. established the RIS scattered models, which can better describe the actual scattering characteristics. In [22], Tang et al. established a path loss model for RIS in free space. In [23], Björnson and Sanguinetti utilized the Green function to model the channel from the transmitter to RIS. In [24], Dardari represented the RIS-aided communication model as several discrete modes by orthogonal basis decomposition. In [25], Bai et al. utilized an electromagnetic model based approach to estimate the received signal and channel matrix.

Furthermore, the concept of holographic RIS has attracted much research interest recently [26], [27], [28], [29], [30], [31], [32], [33]. The characteristic of holographic RIS is to integrate a large number of small and inexpensive reconfigurable components into a holographic array with a spatially continuous aperture [26], [27], [28]. In [29], Zhao et al. proposed a novel compensation method and a vortex beam-based approach, which could achieve the multi-pair data streams transmission with low interference and further reduce the LoS channel correlation. In [30], Wei et al. joint designed the digital, holographic, and passive beamforming to maximize the radar performance and ensure the communication quality. In [31], Ma et al. utilized the holographic principle and Hall effect to design holographic RIS to accomplish communication without channel estimation. In [32] and [33], authors separately utilized the physical optics technology and surface equivalence theorem to model the scattered field expression of holographic RIS, and then derived the path loss model of holographic RIS-aided communication system.

Most of works adopt the RIS phase shift diagonal matrix model to analyze the beam-squint effect. However, in the works on electromagnetic characteristics of holographic RIS, the beam-squint effect is rarely considered. Hence, in this paper, we will analyze the electromagnetic characteristics of the beam-squint effect in holographic RIS-aided wideband

communication systems from the perspective of the electromagnetic wave propagation theory. Our contributions are summarized as follows.

- We establish a holographic RIS-aided wideband communication system model from the perspective of the electromagnetic wave propagation theory. The physical equivalence principle and physical optics technology are utilized to derive the equivalent current density. Subsequently, we obtain the closed form solution of scattered field in wideband far-field scenarios. The holographic RIS phase mode is designed according to the *generalized Snell's law of reflection*.
- We derive the normalized radiation pattern of holographic RIS's scattered electric field and show the phenomenon of the beam-squint effect. Furthermore, we derive the expression of normalized radiation patterns under one-dimensional observation and introduce the new angle space to simplify the expression. In order to clearly describe the impact of beam-squint effect, we define the angle spread range and 3dB beam bandwidth and analyze the regularities of beam offset.
- We derive a closed form solution for the beam coverage range. In order to address the impact of the beam-squint effect, a new codebook design scheme is proposed, which covers the target area with the smallest codebook size. Besides, we introduce the TTD lines into the holographic RIS structure. The beam-squint effect can be mitigated by designing the holographic RIS phase shift and the delay of the TTD lines. The simulation results reveal the influence of different system parameters on the minimum codebook size, and also verify the mitigation effect of TTD lines on beam-squint effect.

The rest of this paper is organized as follows. Section II introduces the model of the holographic RIS-aided wideband communication system model from the perspective of the electromagnetic wave propagation theory. Section III analyzes the holographic RIS electromagnetic characteristics under the beam-squint effect. Section IV proposes a new codebook design scheme based on the beam-squint effect. Section V introduces the TTD lines into the holographic RIS structure to mitigate the beam-squint effect. Finally, simulation results and conclusions are provided in Section VI and Section VII, respectively.

Notation: Vectors and matrices are denoted in bold font; $\mathbf{a} \times \mathbf{b}$ represents the vector cross product of $\mathbf{a}$ and $\mathbf{b}$; $\mathbf{a}|_{z=0}$ represents $\mathbf{a}$ in the case of the x-y plane; $|\cdot|$ denotes the absolute operator; $\|\cdot\|$ is the l_2 -norm operator; $\lceil \cdot \rceil$ represents the ceiling operator.

II. SYSTEM MODEL

We consider a holographic RIS-aided wideband communication system, where the holographic RIS is deployed between a single-antenna transmitter $\mathbb{T}$ and a single-antenna receiver $\mathbb{R}$. The electromagnetic wave emitted by $\mathbb{T}$ is scattered by the holographic RIS and then arrives at $\mathbb{R}$. Without loss of generality, we assume that the direct link from $\mathbb{T}$ to $\mathbb{R}$ is blocked. Besides, we assume that the electromagnetic wave is almost concentrated on the LoS path between holographic RIS and transmitter/receiver [32], [33]. The holographic RIS is a rectangular plate of size $a \times b$, and its thickness is

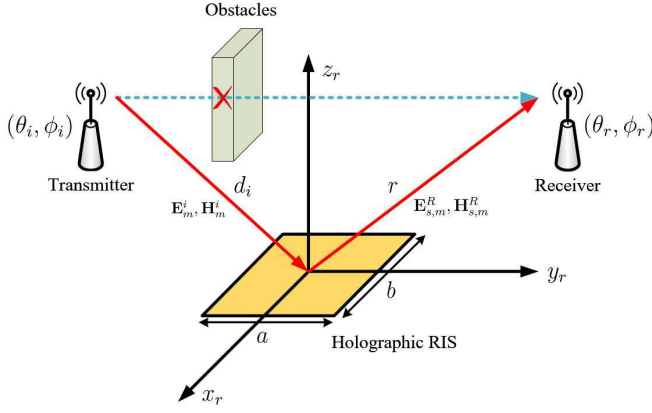


Fig. 1. Holographic RIS-aided wideband communication system.

TABLE I
LIST OF MAIN VARIABLE NOTATIONS

Parameter	Notation
The length of holographic RIS rectangular plate	a
The width of holographic RIS rectangular plate	b
The transmission bandwidth	B
The center frequency	f_c
The partial bandwidth	h
The speed of light	c
The frequency of the m -th frequency point	f_m
The wave number at frequency f_m	k_m
The phase shift of Holographic RIS	β
The electric permittivity	μ
The magnetic permeability	ε
The equivalent electric current density	$\mathbf{J}$
The equivalent magnetic current density	$\mathbf{M}$
The length/width of sub reflection surface	L
The phase mode of the (i, q) -th sub reflection surface	$\beta_{i,q}$
The delay of the (i, q) -th TTD line	$\tau_{i,q}$

negligible compared to the horizontal size. Moreover, the holographic RIS is located along the x - y plane spanned by $\mathbf{e}_x$ and $\mathbf{e}_y$, whose center is exactly located at the origin, as shown in Fig. 1. We denote the region occupied by the holographic RIS as $\mathcal{S}$, the distance from $\mathbb{T}$ to the center of the holographic RIS as d_i , and the distance from the center of the holographic RIS to $\mathbb{R}$ as r . M frequency points are used for the communication system. The transmission bandwidth and center frequency are denoted as B and f_c , respectively. The frequency of the m -th frequency point can be expressed as f_m , where $f_m = f_c - \frac{B}{2} + (m-1)\frac{B}{M-1}$, $m = 1, 2, \dots, M$. To further improve the readability of this paper, we summarize the notations of some main parameters in Table I.

We assume that $\mathbb{T}$ and $\mathbb{R}$ are both in the far field of the holographic RIS, and thus the electromagnetic waves between holographic RIS and transmitter/receiver can be approximately considered as the uniform plane waves. Denote the incident elevation angle and the incident azimuth angle as $\theta_i \in [0, \frac{\pi}{2})$ and $\phi_i \in [0, 2\pi)$, respectively. Without loss of generality, we assume that $\phi_i = \frac{3\pi}{2}$ and the incident electromagnetic field is transverse magnetic x mode, which means that the electric field possesses the x component while the magnetic field possess both y component and z component. The incident electric field $\mathbf{E}_{i,m}$ and magnetic field $\mathbf{H}_{i,m}$ at frequency f_m can be separately expressed as

$$\mathbf{E}_{i,m} = E_i e^{-jk_m(\sin(\theta_i)y) - \cos(\theta_i)z} \mathbf{e}_x, \quad (1)$$

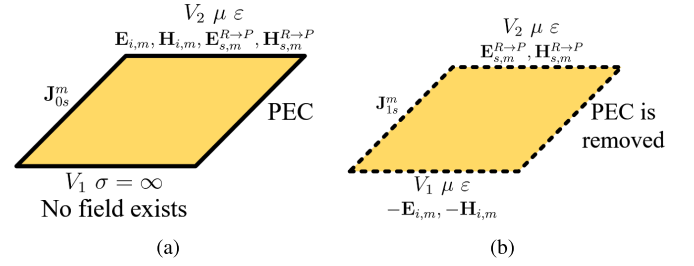


Fig. 2. (a) The original problem. (b) The physical equivalent result to the original problem.

$$\mathbf{H}_{i,m} = \frac{E_i}{\eta} e^{-jk_m(\sin(\theta_i)y) - \cos(\theta_i)z} (\cos(\theta_i)\mathbf{e}_y + \sin(\theta_i)\mathbf{e}_z), \quad (2)$$

where E_i denotes the magnitude of the incident electric field, $\eta = \frac{\mu}{\varepsilon}$ is the magnetic permeability, μ is the electric permittivity, ε is the magnetic permeability, $k_m = \frac{2\pi f_m}{c}$ is the wave number corresponding to f_m , and c is the speed of light. The scattered electric field and magnetic field at frequency f_m are denoted as $\mathbf{E}_{s,m}^R$ and $\mathbf{H}_{s,m}^R$, respectively.

The key to obtaining the scattered fields $\mathbf{E}_{s,m}^R$ and $\mathbf{H}_{s,m}^R$ lies in the calculation of equivalent electric current density $\mathbf{J}$ and equivalent magnetic current density $\mathbf{M}$, which depend on the incident field and the RIS phase mode. We first assume that the holographic RIS is replaced by a perfect electric conductor (PEC), which is a common assumption in most of the electromagnetic analysis works about the holographic RIS [32], [33]. We denote the region above and below the PEC as V_2 and V_1 , respectively. The scattered electric field and magnetic field of the PEC at f_m are denoted as $\mathbf{E}_{s,m}^{R \rightarrow P}$ and $\mathbf{H}_{s,m}^{R \rightarrow P}$, respectively. The superscript $R \rightarrow P$ means that the holographic RIS is replaced by a PEC. There are incident fields $\mathbf{E}_{i,m}$, $\mathbf{H}_{i,m}$ and scattered fields $\mathbf{E}_{s,m}^{R \rightarrow P}$, $\mathbf{H}_{s,m}^{R \rightarrow P}$ in V_2 and no fields in V_1 . According to the electromagnetic boundary conditions, we can derive the following relations

$$\mathbf{e}_z \times (\mathbf{E}_{i,m} + \mathbf{E}_{s,m}^{R \rightarrow P})|_{z=0} = 0, \quad (3)$$

$$\mathbf{e}_z \times (\mathbf{H}_{i,m} + \mathbf{H}_{s,m}^{R \rightarrow P})|_{z=0} = \mathbf{J}_{0s}^m, \quad (4)$$

where $\mathbf{J}_{0s}^m$ is the equivalent electric current density. The electromagnetic scattered equation requires that there is only the field that needs to be solved in V_2 . Besides, the electromagnetic scattered equation can only be applied in the same media environment without barriers, while the medium of V_2 is different from that of V_1 . Hence, $\mathbf{J}_{0s}^m$ can not be directly applied to the electromagnetic scattered equation to solve the scattered fields.

Now, we introduce the physical equivalent to determine the expression of equivalent current density. Fig. 2 describes the physical equivalent result of the original problem. After using physical equivalence, we can make only scattered fields $\mathbf{E}_{s,m}^R$ and $\mathbf{H}_{s,m}^R$ exist in V_2 , and the medium of V_1 is set to be the same as that of V_2 , satisfying the conditions of using electromagnetic scattered equation. Besides, the fields in V_1 are set to $-\mathbf{E}_{i,m}$ and $-\mathbf{H}_{i,m}$. In order to satisfy the electromagnetic boundary conditions, we introduce new equivalent current density $\mathbf{J}_{1s}^m$ and equivalent magnetic current density $\mathbf{M}_{1s}^m$ at the boundary of V_1 and V_2 , which can be separately calculated as

$$\mathbf{J}_{1s}^m = \mathbf{e}_z \times (\mathbf{H}_{s,m}^{R \rightarrow P} - (-\mathbf{H}_{i,m}))|_{z=0}, \quad (5)$$

$$\mathbf{M}_{1s}^m = -\mathbf{e}_z \times (\mathbf{E}_{s,m}^{R \rightarrow P} - (-\mathbf{E}_{i,m})) \Big|_{z=0} = 0. \quad (6)$$

According to (5) and (6), the scattered fields are only determined by the equivalent current density $\mathbf{J}_{1s}^m$ at f_m , which avoids the process of using the equivalent magnetic current density $\mathbf{M}_{1s}^m$. However, the equivalent current density $\mathbf{J}_{1s}^m$ is related to $\mathbf{H}_{s,m}^{R \rightarrow P}$, it is impossible to solve the unknown scattered fields at this moment. To deal with this problem, we further utilize the physical optics technology, which assumes that for a large and flat PEC, the tangential component of the incident magnetic field and the scattered magnetic field at the surface is the same [34]. Under this assumption, $\mathbf{J}_{1s}^m$ can be approximately expressed as

$$\mathbf{J}_{1s}^m = 2 \frac{E_{i,m}}{\eta} e^{-jk_m \sin(\theta_i) y_r} \cos(\theta_i) \mathbf{e}_x. \quad (7)$$

After approximation by the physical optics technology, the equivalent current density $\mathbf{J}_{1s}^m$ is completely known.

To further determine the scattering field of RIS, it is necessary to incorporate the phase mode of the RIS into the equivalent current density. Therefore, the actual equivalent current density should be represented as $\mathbf{J}_{1s}^m e^{j\beta(x_r, y_r)}$. Further, we can calculate the vector potential $\mathbf{A}$ [34] at an arbitrary observation point $\mathbf{p} = (\tilde{x}, \tilde{y}, \tilde{z})$ as

$$\mathbf{A} = \mu \iint_S \mathbf{J}_{1s}^m e^{j\beta(x_r, y_r)} \frac{e^{-jk||\mathbf{p}-\mathbf{r}_r||}}{4\pi||\mathbf{p}-\mathbf{r}_r||} dx_r dy_r \quad (8)$$

where $\mathbf{r}_r = (x_r, y_r, 0)$ is the arbitrary point on the holographic RIS. With the help of the transformation relationship between Cartesian and spherical coordinate systems

$$\begin{aligned} \mathbf{e}_\theta &= \cos(\theta) \cos(\phi) \mathbf{e}_x + \cos(\theta) \sin(\phi) \mathbf{e}_y - \sin(\theta) \mathbf{e}_z, \\ \mathbf{e}_\phi &= -\sin(\phi) \mathbf{e}_x + \cos(\phi) \mathbf{e}_y, \end{aligned} \quad (9)$$

the scattered electric field $\mathbf{E}_{s,m}^R$ within the observation angles (θ_r, ϕ_r) at f_m can be approximated as

$$\begin{aligned} \mathbf{E}_{s,m}^R(\theta_r, \phi_r) &= -j \frac{E_i \cos(\theta_i) e^{-jk_m r}}{\lambda r} \iint (\cos(\theta_r) \cos(\phi_r) \mathbf{e}_\theta \\ &\quad - \sin(\phi_r) \mathbf{e}_\phi) e^{j\beta(x_r, y_r)} e^{jk_m u(x_r, y_r)} dx_r dy_r, \end{aligned} \quad (10)$$

where $r = ||\mathbf{p}||$ represents the distance from the observation point to the center of the holographic RIS, and $u(x_r, y_r) = -y_r \sin(\theta_i) + x_r \sin(\theta_r) \cos(\phi_r) + y_r \sin(\theta_r) \sin(\phi_r)$.

The generalized Snell's law of reflection can scatter the incident wave towards any direction by designing the RIS phase [35]. If we intend to maximize the energy of $\mathbf{E}_{s,m}^R$ in the direction of angles (θ_s, ϕ_s) at f_m , the phase shift should be designed from the generalized Snell's law of reflection as

$$\beta(x_r, y_r) = k_m (y_r (\sin(\theta_i) - \sin(\theta_s) \sin(\phi_s)) - x_r \sin(\theta_s) \cos(\phi_s)). \quad (11)$$

The RIS is not a frequency selective device, meaning that the RIS phase shift operation can not change with frequency.

To ensure the overall performance among all frequencies, the holographic RIS phase mode is generally designed as

$$\beta(x_r, y_r) = k_c (y_r (\sin(\theta_i) - \sin(\theta_s) \sin(\phi_s)) - x_r \sin(\theta_s) \cos(\phi_s)). \quad (12)$$

where $k_c = \frac{2\pi f_c}{c}$ represents the wave number corresponding to center frequency f_c . It can be seen that the design criterion of (12) is only optimal for f_c and not optimal for the other frequencies, which will cause the beam-squint effect.

Substituting (12) into (10), we can obtain the closed-form solution of the holographic RIS's scattered electric field as

$$\begin{aligned} \mathbf{E}_{s,m}^R(\theta_r, \phi_r) &= -j \frac{ab \cos(\theta_i) E_i e^{-jk_m r}}{\lambda r} (\cos(\theta_r) \cos(\phi_r) \mathbf{e}_\theta \\ &\quad - \sin(\phi_r) \mathbf{e}_\phi) \text{Sa}\left(\frac{a}{2} u_1\right) \text{Sa}\left(\frac{b}{2} u_2\right) \end{aligned} \quad (13)$$

where $\text{Sa}(x) = \frac{\sin(x)}{x}$, $u_1 = k_c (\xi_m \sin(\theta_r) \cos(\phi_r) - \sin(\theta_s) \cos(\phi_s))$, and $u_2 = k_c (\xi_m (\sin(\theta_r) \sin(\phi_r) - \sin(\theta_i)) - \sin(\theta_s) \sin(\phi_s) + \sin(\theta_i))$.

III. ANALYSIS OF HOLOGRAPHIC RIS ELECTROMAGNETIC CHARACTERISTICS UNDER THE BEAM-SQUINT EFFECT

We define the normalized radiation pattern of holographic RIS's scattered electric field at f_m as

$$S_{n,m}(\theta_i, \theta_s, \theta_r, \phi_s, \phi_r) = \frac{||\mathbf{E}_{s,m}^R||^2}{||\mathbf{E}_{s,m}^R||_{max}^2} \quad (14)$$

Substituting $\mathbf{E}_{s,m}^R(\theta_r, \phi_r)$ into (14), we can derive the normalized radiation pattern of holographic RIS's scattered electric field as (15), as shown at the bottom of the page. In a two-dimensional scene, the angles corresponding to the maximum energy of $S_{n,m}(\theta_i, \theta_s, \theta_r, \phi_s, \phi_r)$ will gradually approach (θ_s, ϕ_s) as the size of RIS increases. This is because that the influence of $(\cos^2(\theta_r) \cos^2(\phi_r) + \sin^2(\phi_r))$ will gradually decrease with the increase of RIS size, which makes the Sa function dominant in $S_{n,m}(\theta_i, \theta_s, \theta_r, \phi_s, \phi_r)$ when the observation angles (θ_r, ϕ_r) change. Hence, we only focus on the influence of the Sa function and redefine the normalized radiation pattern as

$$S_{n,m}(\theta_i, \theta_s, \theta_r, \phi_s, \phi_r) = \left(\text{Sa}\left(\frac{a}{2} u_1\right) \text{Sa}\left(\frac{b}{2} u_2\right) \right)^2, \quad (16)$$

where $u_1 = k_c (\xi_m \sin(\theta_r) \cos(\phi_r) - \sin(\theta_s) \cos(\phi_s))$, $u_2 = k_c (\xi_m (\sin(\theta_r) \sin(\phi_r) - \sin(\theta_i)) - \sin(\theta_s) \sin(\phi_s) + \sin(\theta_i))$, and $\xi_m = \frac{f_m}{f_c}$ represents the ratio of the current frequency to the center frequency. In particular, when $(\theta_r, \phi_r) = (\theta_s, \phi_s)$, the normalized radiation pattern can be rewritten as

$$S_{n,m}(\theta_i, \theta_s, \theta_s, \phi_s, \phi_s) = \left(\text{Sa}\left(\frac{a}{2} u_3\right) \text{Sa}\left(\frac{b}{2} u_4\right) \right)^2, \quad (17)$$

where $u_3 = k_c (\xi_m - 1) \sin(\theta_s) \cos(\phi_s)$ and $u_4 = k_c (\xi_m - 1) (\sin(\theta_s) \sin(\phi_s) - \sin(\theta_i))$.

$$S_{n,m}(\theta_i, \theta_s, \theta_r, \phi_s, \phi_r) \propto (\cos^2(\theta_r) \cos^2(\phi_r) + \sin^2(\phi_r)) \left(\text{Sa}\left(\frac{a}{2} u_1\right) \text{Sa}\left(\frac{b}{2} u_2\right) \right)^2, \quad (15)$$

Besides, according to the properties of Sa function, the angles $(\theta_{r,m}^{max}, \phi_{r,m}^{max})$ corresponding to the maximum energy satisfy

$$\xi_m \sin(\theta_{r,m}^{max}) \cos(\phi_{r,m}^{max}) - \sin(\theta_s) \cos(\phi_s) = 0, \quad (18)$$

$$\xi_m \sin(\theta_{r,m}^{max}) \sin(\phi_{r,m}^{max}) - \sin(\theta_s) \sin(\phi_s) - (\xi_m - 1) \sin(\theta_i) = 0. \quad (19)$$

When $\phi_s \neq \frac{\pi}{2}, \frac{3\pi}{2}$ and $\theta_s \neq 0$, we can derive $\theta_{r,m}^{max}$ and $\phi_{r,m}^{max}$ as (20) and (21), as shown at the bottom of the page, and the derivation process can be found in the Appendix A. It can be seen that when $f_m = f_c$, we have $(\theta_{r,m}^{max}, \phi_{r,m}^{max}) = (\theta_s, \phi_s)$, i.e., the angles corresponding to the maximum energy are exactly the desired angles. If $f_m \neq f_c$, we have $(\theta_{r,m}^{max}, \phi_{r,m}^{max}) \neq (\theta_s, \phi_s)$, i.e., the angles corresponding to the maximum energy deviate from the desired angles, which is the most intuitive phenomenon of beam-squint effect, as shown in Fig. 3.

Subsequently, we consider three special cases: $\phi_s = \frac{\pi}{2}$, $\phi_s = \frac{3\pi}{2}$ and $\theta_s = 0$. Taking $\phi_s = \frac{3\pi}{2}$ as an example, we can rewrite (18) and (19) as

$$\xi_m \sin(\theta_{r,m}^{max}) \cos(\phi_{r,m}^{max}) = 0, \quad (22)$$

$$\xi_m \sin(\theta_{r,m}^{max}) \sin(\phi_{r,m}^{max}) + \sin(\theta_s) - (\xi_m - 1) \sin(\theta_i) = 0. \quad (23)$$

For $\frac{\sin(-\theta_s) + (\xi_m - 1) \sin(\theta_i)}{\xi_m} > 0$, the angles corresponding to the maximum energy can be expressed as $\theta_{r,m}^{max} = \arcsin\left(\frac{\sin(-\theta_s) + (\xi_m - 1) \sin(\theta_i)}{\xi_m}\right)$ and $\phi_{r,m}^{max} = \frac{\pi}{2}$. For $\frac{-\sin(\theta_s) + (\xi_m - 1) \sin(\theta_i)}{\xi_m} < 0$, the angles corresponding to the maximum energy $\theta_{r,m}^{max} = -\arcsin\left(\frac{\sin(-\theta_s) + (\xi_m - 1) \sin(\theta_i)}{\xi_m}\right)$ and $\phi_{r,m}^{max} = \frac{3\pi}{2}$. Hence, if we set the incident angle $\phi_i = \frac{3\pi}{2}$, the desired angles ϕ_s corresponding to the maximum energy always satisfies that $\phi_s = \frac{\pi}{2}$ or $\phi_s = \frac{3\pi}{2}$, which means that the angles $(\theta_{r,m}^{max}, \phi_{r,m}^{max})$ at any frequency must be on the y-z plane. In the cases of $\theta_s = 0$ and $\phi_s = \frac{\pi}{2}$, the conclusion is the same. It is reasonable to carry out one-dimensional observation on the y-z plane in these three cases, and (16) can be rewritten as

$$S_{n,m}(\theta_i, \theta_s, \theta_r) = \left(\frac{\sin\left(\frac{b}{2} k_c (\xi_m \sin(\theta_r) - \sin(\theta_s) - (\xi_m - 1) \sin(\theta_i))\right)}{\frac{b}{2} k_c (\xi_m \sin(\theta_r) - \sin(\theta_s) - (\xi_m - 1) \sin(\theta_i))} \right)^2, \quad (24)$$

where the domain of definition of θ_s and θ_r is extend to $(-\frac{\pi}{2}, \frac{\pi}{2})$. When θ_r takes a negative value, its observation point is located in the left half plane of the y-z plane; when θ_r takes a positive value, its observation point is located in the right half plane of the y-z plane. Similarly, the positive and negative of θ_s determines the position of the angle corresponding to the maximum energy.

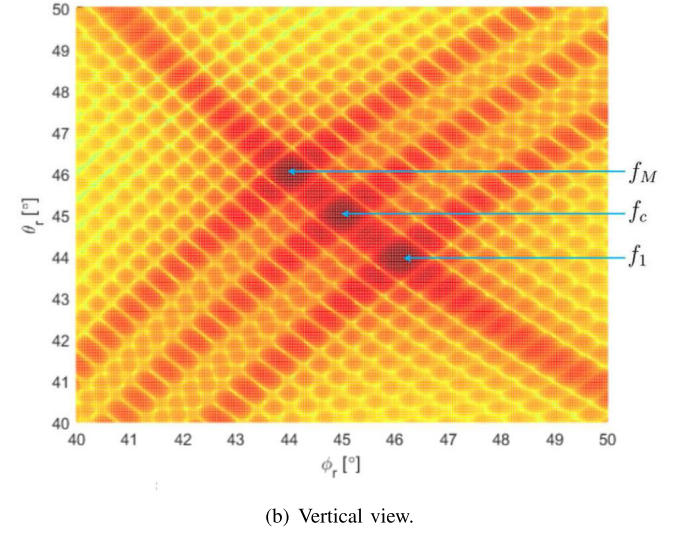
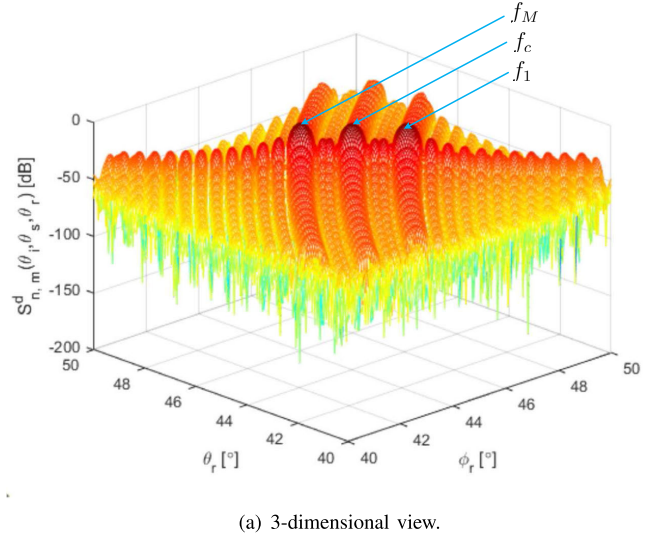


Fig. 3. (a) The 3-dimensional view of the beam-squint effect. (b) The vertical view of the beam-squint effect.

We can further derive the angle $\theta_{r,m}^{max}$ corresponding to the maximum energy at f_m as

$$\theta_{r,m}^{max} = \arcsin\left(\frac{\sin(\theta_s) + (\xi_m - 1) \sin(\theta_i)}{\xi_m}\right). \quad (25)$$

Then, we set $S_{n,m}(\theta_i, \theta_s, \theta_r) = 0.5$ and solve for the value of $|\theta_r - \theta_{r,m}^{max}|$. By doubling the value of $|\theta_r - \theta_{r,m}^{max}|$, we can calculate the 3dB beam bandwidth at f_m in θ space as

$$BW_m = \sqrt{6} \frac{c}{\pi b f_m \cos(\theta_{r,m}^{max})}, \quad (26)$$

where the detailed derivation can be found in Appendix B. In addition, we define a virtual angle space Ψ to replace

$$\theta_{r,m}^{max} = \arcsin\left(\sqrt{\left(\frac{\sin(\theta_s) \cos(\phi_s)}{\xi_m}\right)^2 + \left(\frac{\sin(\theta_s) \sin(\phi_s) + (\xi_m - 1) \sin(\theta_i)}{\xi_m}\right)^2}\right), \quad (20)$$

$$\phi_{r,m}^{max} = \arctan\left(\frac{\sin(\theta_s) \sin(\phi_s) + (\xi_m - 1) \sin(\theta_i)}{\sin(\theta_s) \cos(\phi_s)}\right). \quad (21)$$

physical angle space θ , and their mapping relationship can be represented as

$$\Psi = \sin(\theta), \quad (27)$$

where $\Psi \in (-1, 1)$. Correspondingly, we have $\Psi_i = \sin(\theta_i)$, $\Psi_s = \sin(\theta_s)$ and $\Psi_r = \sin(\theta_r)$. Subsequently, $\{\theta_i, \Psi_i\}$ are collectively referred to as incident angles, $\{\theta_s, \Psi_s\}$ are collectively referred to as the desired angles, and $\{\theta_r, \Psi_r\}$ are collectively referred to as observation angles. The normalized radiation pattern of holographic RIS's scattered electric field in Ψ space can be expressed as

$$S_{n,m}^{\Psi}(\Psi_i, \Psi_s, \Psi_r) = \left(\frac{\sin(\frac{b}{2} k_c (\xi_m (\Psi_r - \Psi_s) - (\xi_m - 1) \Psi_i))}{\frac{b}{2} k_c \xi_m (\Psi_r - \Psi_s - (\xi_m - 1) \Psi_i)} \right)^2. \quad (28)$$

Similarly, we can derive the angle $\Psi_{r,m}^{max}$ corresponding to the maximum energy at f_m in Ψ space as

$$\Psi_{r,m}^{max} = \sin(\theta_{r,m}^{max}) = \frac{\Psi_s + (\xi_m - 1) \Psi_i}{\xi_m}. \quad (29)$$

The 3dB beam bandwidth at f_m in Ψ space can be calculated as

$$BW_m^{\Psi} = \sqrt{6} \frac{c}{\pi b f_m}, \quad (30)$$

where the detailed derivation can also be found in Appendix B.

We can observe that BW_m^{Ψ} is inversely proportional to the size b of the holographic RIS and varies with frequency f_m . Besides, BW_m^{Ψ} is more concise than BW_m in expression. In the subsequent content of this section, we will utilize Ψ space to analyze the beam width. Specially, we define $BW_c^{\Psi} = \sqrt{6} \frac{c}{\pi b f_c}$. Besides, we can find that the direction of the beam-squint effect is regular. For $\Psi_s > \Psi_i$, if $\xi_m > 1$, we have $\Psi_s > \Psi_{r,m}^{max}$, and if $\xi_m < 1$, we have $\Psi_s < \Psi_{r,m}^{max}$. For $\Psi_s < \Psi_i$, if $\xi_m > 1$, we have $\Psi_s < \Psi_{r,m}^{max}$, and if $\xi_m < 1$, we have $\Psi_s > \Psi_{r,m}^{max}$. In other words, the relationship between the incident angle and the desired angle determines the direction of beam offset at different frequencies. Besides, in Ψ space, we can define the angle spread range as the absolute value of the difference between the angles with the maximum energy corresponding to the highest frequency and the lowest frequency, which can be calculated as

$$AS = |\Psi_{r,M}^{max} - \Psi_{r,1}^{max}| = \frac{h \Psi_s}{1 - \frac{h^2}{4}}, \quad (31)$$

where $h = \frac{B}{f_c}$ represents the partial bandwidth, and AS increases with the increase of partial bandwidth h and desired angle Ψ_s .

IV. BEAM COVERAGE ANALYSIS AND CODEBOOK DESIGN SCHEME BASED ON BEAM-SQUINT EFFECT

In this section, we use $\beta(\Psi_s)$ to represent the holographic RIS phase mode, which is equivalent to a codeword corresponding to the desired angle Ψ_s . We define the beam coverage of $\beta(\Psi_s)$ as

$$\mathcal{R}(\beta(\Psi_s)) = \{\Psi_r \in [-1, 1] : \min_{f_m} S_{n,m}^{\Psi}(\Psi_i, \Psi_s, \Psi_r) \geq S_{thr}^{\Psi}\}, \quad (32)$$

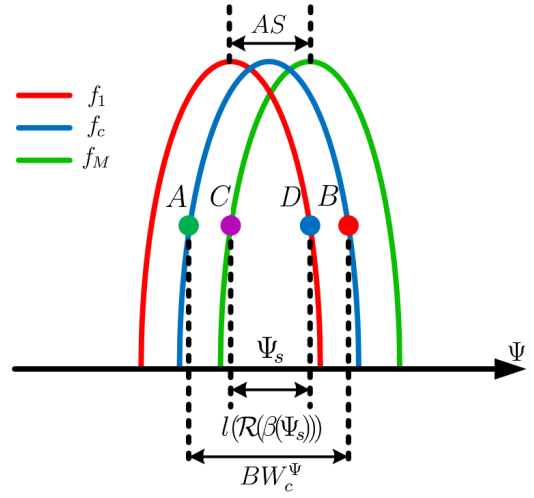


Fig. 4. Illustrations of the angle spread range, 3dB beam width and beam coverage range.

where S_{thr}^{Ψ} is the threshold and generally set to 0.5. The performance at all frequencies is required to be higher than the threshold [36]. The width of $\mathcal{R}(\beta(\Psi_s))$ is defined as $l(\mathcal{R}(\beta(\Psi_s)))$, which represents the beam coverage range. Noted that the angle spread range AS , 3dB beam width BW_m^{Ψ} and beam coverage range $l(\mathcal{R}(\beta(\Psi_s)))$ are three different concepts. BW_m^{Ψ} is only used for a specific frequency, which is the width from the 3dB point on the left to the 3dB point on the right of the corresponding radiation pattern. AS and $l(\mathcal{R}(\beta(\Psi_s)))$ are defined for all frequencies, and AS is the difference between the angles with the maximum energy corresponding to the highest frequency and the lowest frequency. Fig. 4 vividly shows the relationship among AS , BW_m^{Ψ} and $l(\mathcal{R}(\beta(\Psi_s)))$.

Taking $\Psi_s < \Psi_i$ as an example, under the narrow band assumption, we have $l(\mathcal{R}(\beta(\Psi_s))) = BW_c^{\Psi}$, that is, the width of the AB segment. Under the wideband assumption, $l(\mathcal{R}(\beta(\Psi_s)))$ should be the width from the left 3dB point corresponding to the highest frequency to the right 3dB point corresponding to the lowest frequency, that is, the width of the CD segment. Specifically, the coordinates of points A , B , C and D in the Fig. 4 can be obtained as $p_A = \Psi_s - \frac{BW_c^{\Psi}}{2}$, $p_B = \Psi_s + \frac{BW_c^{\Psi}}{2}$, $p_C = \Psi_{r,M}^{max} - \frac{BW_M^{\Psi}}{2}$, and $p_D = \Psi_{r,1}^{max} + \frac{BW_1^{\Psi}}{2}$. Hence, considering the beam-squint effect, we can derive the actual coverage range $l(\mathcal{R}(\beta(\Psi_s)))$ as

$$l(\mathcal{R}(\beta(\Psi_s))) = \frac{h(\Psi_s - \Psi_i) + BW_c^{\Psi}}{1 - \frac{1}{4}h^2} = \frac{h(\Psi_s - \Psi_i) + \frac{\sqrt{6}c}{\pi b f_c}}{1 - \frac{1}{4}h^2}. \quad (33)$$

Similarly, if considering $\Psi_s > \Psi_i$, the coordinates of points C and D can be denoted as $p_C^2 = \Psi_{r,1}^{max} - \frac{BW_1^{\Psi}}{2}$ and $p_D^2 = \Psi_{r,M}^{max} - \frac{BW_M^{\Psi}}{2}$. At this time, $l(\mathcal{R}(\beta(\Psi_s)))$ is the width from the left 3dB point corresponding to the lowest frequency to the right 3dB point corresponding to the highest frequency, which can be expressed as

$$l(\mathcal{R}(\beta(\Psi_s))) = \frac{-h(\Psi_s - \Psi_i) + BW_c^{\Psi}}{1 - \frac{1}{4}h^2} = \frac{-h(\Psi_s - \Psi_i) + \frac{\sqrt{6}c}{\pi b f_c}}{1 - \frac{1}{4}h^2}. \quad (34)$$

The difference between (33) and (34) is the sign of the term $h(\Psi_s - \Psi_i)$. It can be seen that $l(\mathcal{R}(\beta(\Psi_s)))$ depends on partial bandwidth h , center frequency f_c , the size b of holographic RIS and the absolute value $|\Psi_s - \Psi_i|$ of the difference between the desired angle and the incident angle. To be specific, the closer the distance between the desired angle and the incident angle, the greater the beam coverage range. Note that, the default sign of $l(\mathcal{R}(\beta(\Psi_s)))$ here is positive. If the value of h or $|\Psi_s - \Psi_i|$ is large, the sign of $l(\mathcal{R}(\beta(\Psi_s)))$ will become negative, which has no practical significance. At this time, the beam coverage range is 0.

Remark 1: In some works, the authors consider the beam at each subcarrier to be an independent scan and do not take into account the 3dB beamwidth [37], [38]. The definition of the total beam coverage range at all subcarriers is similar to that of the angle spread range AS in this paper. The large bandwidth can also increase the beam coverage range. As the bandwidth increases, the beam offset at different subcarriers becomes more significant, resulting in an expanded beam coverage range. However, in this paper, we define the beam coverage range as (34) from the perspective of the electromagnetic wave propagation theory. The beams at all frequencies are applied to the same scan, and the performance at each frequency must exceed a certain threshold to ensure the quality of communication [36]. The beam coverage range is influenced by partial bandwidth h , desired angle Ψ_s , holographic RIS's size b , and incident angle Ψ_i . The beam-squint effect will reduce the beam coverage range. In other words, whether the beam coverage range is reduced or expanded due to the beam squint effect depends on the definition of the beam coverage range.

The beam coverage range corresponding to a phase mode $\beta(\Psi_s)$ is limited. If we expect to cover a target area $[\Psi_{min}, \Psi_{max}]$, we must utilize the multiple phase modes, and the desired angle Ψ_s corresponding to each phase mode takes different values, such that all the phase modes form a codebook $\mathcal{C}$. The union of the beam coverage ranges of all phase modes in codebook $\mathcal{C}$ covers the target area $[\Psi_{min}, \Psi_{max}]$. We aim to use the minimum codebook size $|\mathcal{C}|_{min}$ to cover the target area. Under the narrow band assumption, the beam coverage range of each phase mode is the same, and its value can be expressed as $BW_c^\Psi = \sqrt{6 \frac{c}{\pi b f_c}}$. Hence, the minimum codebook size required can be directly calculated as

$$|\mathcal{C}|_{min} = \left\lceil \frac{\Psi_{max} - \Psi_{min}}{BW_c^\Psi} \right\rceil. \quad (35)$$

Under the wideband assumption, we consider the beam-squint effect. We could determine the value of $|\mathcal{C}|_{min}$ through the following steps. First, we initialize the parameters. We set the coordinate of point C corresponding to the initial phase mode to coincide with the left endpoint of the target area (i.e., $p_c^1 = \Psi_{min}$). Then, we calculate Ψ_s . If $\Psi_s < \Psi_i$, then Ψ_s is the angle corresponding to the initial phase mode. Otherwise, let $p_c^2 = \Psi_{min}$, and calculate the corresponding Ψ_s as the angle corresponding to the initial phase mode. After obtaining Ψ_s , we set the count variable $l = 1$ and record the coordinate p_D^{ini} of point D corresponding to the initial phase mode. Subsequently, we conduct the cycle operation. We set the coordinate of point C corresponding to the new initial phase mode to coincide with the coordinate of point

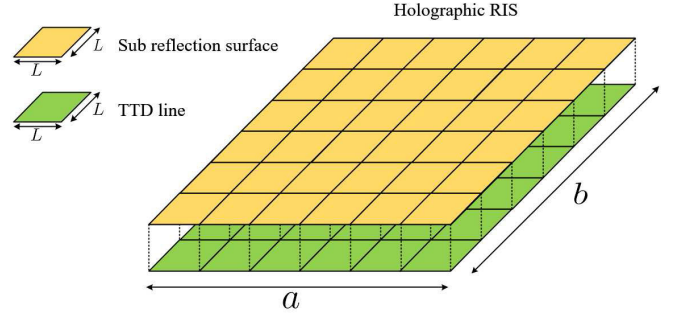


Fig. 5. Illustrations of the RIS structure with TTD lines.

D corresponding to the last cycle (i.e., $p_c^1 = p_D^{ini}$). Similarly, we solve the angle Ψ_s corresponding to the new phase mode. After obtaining Ψ_s , we set $l = l + 1$ and update p_D^{ini} to the coordinate of point D corresponding to the current new phase mode. If the updated p_D^{ini} satisfies $p_D^{ini} > \Psi_{max}$, the cycle is terminated. Finally, we obtain the minimum codebook size $|\mathcal{C}|_{min} = l$.

Although the value of $|\mathcal{C}|_{min}$ is determined, the codebook design scheme is not unique. For example, we also can set the coordinate of point D corresponding to the initial phase mode to coincide with the right endpoint of the target area, and then make the coordinate of point D corresponding to the new phase mode coincide with the coordinate of point C corresponding to the last cycle in the cycle operation stage. Besides, we can set Ψ_s corresponding to the initial phase mode as $\frac{\Psi_{min} + \Psi_{max}}{2}$. Then we can add new phase modes on the left and right sides of the initial phase mode simultaneously in the cycle operation.

V. HOLOGRAPHIC RIS PHASE DESIGN WITH TRUE-TIME-DELAY LINES

In the holographic RIS-aided wideband system, the essence of the beam-squint effect is that the RIS phase shift operation cannot change with frequency. A feasible and effective solution is to introduce the TTD lines into the holographic RIS structure to mitigate the beam-squint effect [15], [19]. In the ideal case, each RIS element should be equipped with a TTD line. Correspondingly, in the holographic RIS scenario, the time delay introduced by the holographic RIS surface is a continuous function of two-dimensional physical space, which can be expressed as $\tau(x_r, y_r)$. According to the Fourier transform of the unit impulse function, the equivalent phase mode of holographic RIS can be derived as $\beta(x_r, y_r) - 2\pi f_m \tau(x_r, y_r)$. It can be seen that the introduction of TTD lines causes the frequency selectivity in holographic RIS phase modes.

The actual current density of holographic RIS with TTD lines can be expressed as $\mathbf{J}_{1s}^m e^{j\beta(x_r, y_r) - 2\pi f_m \tau(x_r, y_r)}$. According to (10), the scattered electric field within the observation angles (θ_r, ϕ_r) at f_m can be expressed as

$$\begin{aligned} \mathbf{E}_{s,m}^{R,d}(\theta_r, \phi_r) = & -j\omega \frac{\mu e^{-jk_m r}}{4\pi r} \iint_S \mathbf{J}_{1s}^m e^{j(\beta(x_r, y_r) - 2\pi f_m \tau(x_r, y_r))} \\ & \times e^{jk_m(x_r \sin(\theta_r) \cos(\phi_r) + y_r \sin(\theta_r) \sin(\phi_r))} \\ & \times dx_r dy_r. \end{aligned} \quad (36)$$

where the superscript d represents the result after introducing the TTD line. However, the hardware cost and power consumption of TTD lines are much higher than those of phase shifters, such that it is impractical to equip each holographic RIS element with a TTD line. Specifically, holographic RIS is divided into $I \times Q$ sub reflection surfaces, and the size of each sub reflection surface is $\frac{a}{I} \times \frac{b}{Q}$. Without loss of generality, we assume $\frac{a}{I} = \frac{b}{Q} = L$. Within each sub reflection surface, there is a shared TTD line, which means that the introduced delay is the same constant.

Denote the delay parameter of the (i, q) -th sub reflection surface as $\tau_{i,q}$. The scattered electric field can be rewritten as

$$\begin{aligned} \mathbf{E}_{s,m}^{R,d}(\theta_r, \phi_r) &= -j\omega \frac{\mu e^{-jk_m r}}{4\pi r} \\ &\times \sum_{i=1}^I \sum_{q=1}^Q e^{-jk_m c\tau_{i,q}} \int \int_{S_{i,q}} \mathbf{J}_{1s}^m e^{j\beta_{i,q}(x_r, y_r)} \\ &\times e^{jk_m(x_r \sin(\theta_r) \cos(\phi_r) + y_r \sin(\theta_r) \sin(\phi_r))} \\ &\times dx_r dy_r. \end{aligned} \quad (37)$$

where $S_{i,q}$ represents the the integral region of the (i, q) -th sub reflection surface, and $\beta_{i,q}(x_r, y_r)$ is the phase mode of the (i, q) -th sub reflection surface. The beam-squint effect is mainly reflected in the phase term. When designing the phase mode of each sub reflection surface, the phase difference at the central frequency f_c should be eliminated to achieve coherent superposition at the current sub reflection surface. According to the *generalized Snell's law of reflection*, the phase shift can be designed as

$$\begin{aligned} \beta_{i,q}(x_r, y_r) &= k_c((y_r - (q-1)L)(\sin(\theta_i) - \sin(\theta_s) \sin(\phi_s)) \\ &- (x_r - (i-1)L) \sin(\theta_s) \cos(\phi_s)). \end{aligned} \quad (38)$$

Substituting (38) into (37), we can obtain

$$\begin{aligned} \mathbf{E}_{s,m}^{R,d}(\theta_r, \phi_r) &= -j\omega \frac{E_i \mu \cos(\theta_i) L^2 e^{-jk_m r}}{2\pi r \eta} \text{Sa}\left(\frac{L}{2} u_1\right) \text{Sa}\left(\frac{L}{2} u_2\right) \\ &\times \sum_{i=1}^I \sum_{q=1}^Q e^{-jk_m c\tau_{i,q}} e^{j(i-1)Lv_1} e^{j(q-1)Lv_2} \mathbf{e}_x, \end{aligned} \quad (39)$$

where $v_1 = k_m \sin(\theta_r) \cos(\phi_r)$, and $v_2 = k_m(\sin(\theta_r) \sin(\phi_r) - \sin(\theta_i))$.

In order to eliminate the delay difference between different sub reflection surfaces, the delay parameters $\tau_{i,q}$ of the TTD line of each sub reflection surface should be designed as

$$\tau_{i,q} = \frac{(i-1)L \sin(\theta_s) \cos(\theta_s) + (q-1)L(\sin(\theta_s) \sin(\theta_s) - \sin(\theta_s))}{c}. \quad (40)$$

Substituting (9) and (40) into (39), we can further calculate

$$\begin{aligned} \mathbf{E}_{s,m}^{R,d}(\theta_r, \phi_r) &= -j\omega \frac{E_i \mu \cos(\theta_i) L^2 e^{-jk_m r}}{2\pi r \eta} \\ &\times \text{Sa}\left(\frac{L}{2} u_1\right) \text{Sa}\left(\frac{L}{2} u_2\right) \\ &\times B_I\left(\frac{L}{2} v_3\right) B_Q\left(\frac{L}{2} v_4\right) e^{j(I-1)\frac{L}{2} v_3} e^{j(Q-1)\frac{L}{2} v_4} \\ &\times (\cos(\theta_r) \cos(\phi_r) \mathbf{e}_\theta - \sin(\phi_r) \mathbf{e}_\phi), \end{aligned} \quad (41)$$

where $B_I(x) = \frac{\sin(Ix)}{\sin(x)}$, $v_3 = k_m(\sin(\theta_r) \cos(\phi_r) - \sin(\theta_s) \cos(\psi_s))$, $v_4 = k_m(\sin(\theta_r) \sin(\phi_r) - \sin(\theta_s) \sin(\psi_s))$, and the detailed derivation can be found in the Appendix C. Similarly, substituting (41) into (14) and focusing on the influence of the Sa function, we can express the normalized radiation pattern of $\mathbf{E}_{s,m}^{R,d}(\theta_r, \phi_r)$ as

$$\begin{aligned} S_{n,m}^d(\theta_i, \theta_s, \theta_r, \phi_s, \phi_r) &= \left(\frac{1}{IQ} \text{Sa}\left(\frac{L}{2} u_1\right) \text{Sa}\left(\frac{L}{2} u_2\right) B_I\left(\frac{L}{2} v_3\right) B_Q\left(\frac{L}{2} v_4\right) \right)^2. \end{aligned} \quad (42)$$

Compared with (16), we can find that the TTD lines can cause significant changes in the expression of normalized radiation pattern, and the angle spread range caused by the beam-squint effect is almost eliminated, which will be further verified in subsequent simulations. Specifically, when the observation angles satisfy $(\theta_r, \phi_r) = (\theta_s, \phi_s)$, the normalized radiation pattern can be rewritten as

$$S_{n,m}^d(\theta_i, \theta_s, \theta_s, \phi_s, \phi_s) = \left(B_I\left(\frac{L}{2} u_3\right) B_Q\left(\frac{L}{2} u_4\right) \right)^2. \quad (43)$$

Compared (43) with (17), we can see that the TTD lines make the normalized radiation pattern of a large holographic RIS with size $a \times b$ equivalent to the normalized radiation pattern of a small sub reflection surface with size $L \times L$. When the holographic RIS size $a \times b$ is fixed, the performance improves as the size L of the sub reflection surface decreases. However, the number of TTD lines required will increase, which will cause an increase in hardware costs.

VI. NUMERICAL SIMULATION

In this section, we provide the simulation results to evaluate the beam-squint effect of holographic RIS. The distance between the transmitter and the holographic RIS is set to $d_i = 100$ m, and the distance between the holographic RIS and the receiver is set to $r = 100$ m. The magnitude of the incident electric field is set to $E_i = 1$. The default center frequency is set to $f_c = 28$ GHz, the default bandwidth is set to $B = 1$ GHz, the partial bandwidth is $h = \frac{B}{f_c} = 0.035$, and the total number of frequency points in the wideband system is set to $M = 64$. The default size of holographic RIS is set to 30 times the wavelength corresponding to the center frequency, i.e., $a = b = 30 \frac{c}{f_c}$. The Rayleigh distance [R4] can be computed as $Z = \frac{2(\sqrt{2}a)^2}{\lambda} = 3600\lambda \approx 38.57$ m. The distance of 100 m can meet the requirements for the transmitter and receiver to be located in the far-field region of RIS. The incident angles of holographic RIS is set to $\theta_i = 30^\circ$, and the angle with the maximum energy is set to $\theta_s = 45^\circ$, i.e., $\Psi_s = \sin(\theta_s) = \frac{\sqrt{2}}{2}$. The target area is set to $[\Psi_{min}, \Psi_{max}] = [\sin(40^\circ), \sin(50^\circ)]$.

Fig. 6 demonstrates the phenomenon of the beam-squint effect in θ space. This only shows the normalized radiation pattern $S_{n,m}(\theta_i, \theta_s, \theta_r)$ corresponding to the center frequency f_c , lowest frequency f_1 , and highest frequency f_M within $\theta_r \in [40^\circ, 50^\circ]$. In order to observe the beam-squint effect more clearly, we set $a = b = 100 \frac{c}{f_c}$ and $B = 2$ GHz. It can be seen that the maximum energy direction of $S_{n,m}(\theta_i, \theta_s, \theta_r)$ corresponding to f_c is exactly θ_s , but the maximum energy directions of $S_{n,m}(\theta_i, \theta_s, \theta_r)$ corresponding to f_1 and f_M

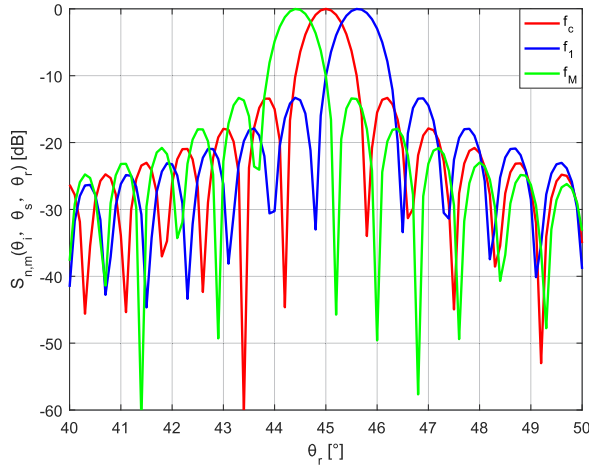


Fig. 6. The varying normalized radiation pattern versus observation angle θ_r for different frequency f_m .

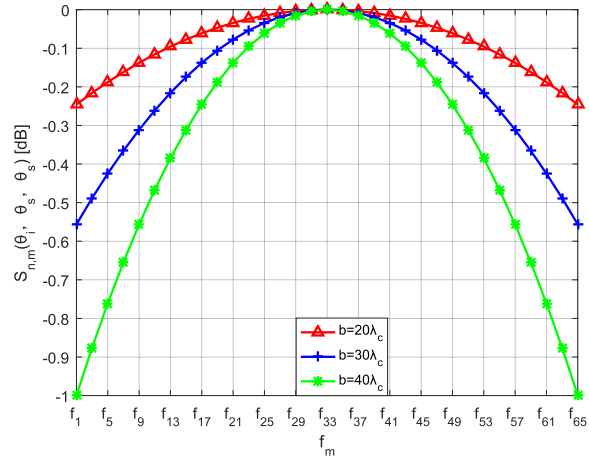


Fig. 7. The varying normalized radiation pattern versus frequency f_m for different RIS size b .

deviate from θ_s , which is the most intuitive phenomenon of beam-squint effect. Besides, the maximum energy directions of $S_{n,m}(\theta_i, \theta_s, \theta_r)$ corresponding to f_M and f_1 separately deviate to the left and right of θ_s , which is consistent with the regularities of beam-squint effect derived in Section III.

Fig. 7 shows the variation of the normalized radiation pattern $S_{n,m}(\theta_i, \theta_s, \theta_r)$ in the observation direction $\theta_r = \theta_s$ versus frequency f_m . At the same time, we consider the influence of holographic RIS size b . Specifically, we select three specific values $20\frac{c}{f_c}$, $30\frac{c}{f_c}$ and $40\frac{c}{f_c}$. The value of $S_{n,m}(\theta_i, \theta_s, \theta_r)$ at other frequencies is lower than that at the center frequency, which is the intuitive phenomenon of the beam-squint effect. The reason is that the phase mode at these frequencies does not match the optimal mode. Especially at the edge frequency f_1 and f_M , the performance loss caused by the beam-squint effect is very serious. Besides, with the decrease of holographic RIS size b , the value of $S_{n,m}(\theta_i, \theta_s, \theta_r)$ at other frequencies ($f \neq f_c$) will rise, and the gap between different frequencies will also decrease, that is, the reduction of holographic RIS size will mitigate the beam-squint effect.

As shown in Fig. 8, we provide the relationship between the parameters related to the beam-squint effect in Ψ space and the partial bandwidth h , including the angle spread range AS , the 3dB beam bandwidth BW_c^Ψ and beam coverage

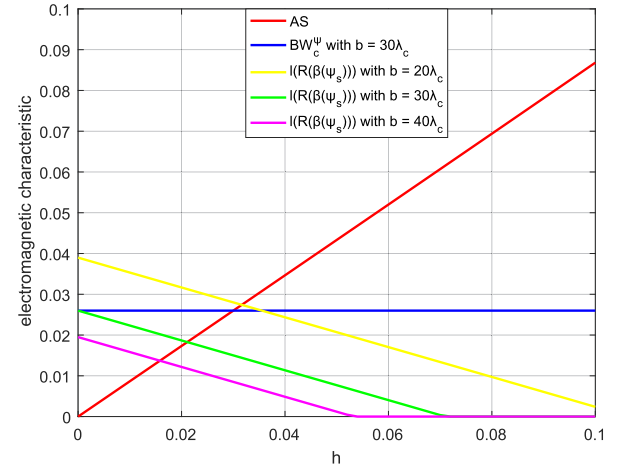


Fig. 8. The parameters related to the beam-squint effect versus partial bandwidth h .

range $l(\mathcal{R}(\beta(\Psi_s)))$. Notice that we change h by modifying the system bandwidth B , and the center frequency f_c remains unchanged. We also consider the influence of holographic RIS size b . Specifically, we select three specific values $20\frac{c}{f_c}$, $30\frac{c}{f_c}$ and $40\frac{c}{f_c}$. We set the desired angles corresponding to the maximum energy to $\Psi_s = \sin(\theta_s) = \frac{\sqrt{3}}{2}$. It can be seen that when the value of h is small, AS is approximately proportional to h , because the numerator $h\Psi_s$ dominates in (33), and the influence of the denominator $1 - \frac{h^2}{4}$ can be ignored. And BW_c^Ψ is independent of h , while $l(\mathcal{R}(\beta(\Psi_s)))$ is related to h . Specifically, when the value of h is small, $l(\mathcal{R}(\beta(\Psi_s)))$ decreases approximately linearly with the increase of h . When h exceeds a certain value, $l(\mathcal{R}(\beta(\Psi_s)))$ becomes 0, indicating that the partial bandwidth h of the wideband system should not be set too high. Otherwise, it will lead to a very narrow beam coverage range. Moreover, when the system parameters are the same, $l(\mathcal{R}(\beta(\Psi_s)))$ always does not exceed BW_c^Ψ . If and only if $h = 0$, that is, without considering the beam-squint effect, the values of $l(\mathcal{R}(\beta(\Psi_s)))$ and BW_c^Ψ are equal. Finally, $l(\mathcal{R}(\beta(\Psi_s)))$ decreases with the increase of b , indicating that small-sized holographic RIS can provide a larger beam coverage range. Hence, compared to narrowband systems, it is necessary to compromise the impact of holographic RIS size b in wideband systems. The increase in holographic RIS size can further compensate for system path loss and spatial energy leakage [39], but at the same time, it will reduce the beam coverage range and exacerbate the impact of the beam-squint effect.

Fig. 9 depicts the variation of the required minimum codeword number $|\mathcal{C}|_{min}$ with partial bandwidth h in the case that the size of holographic RIS b selects three specific values of $20\frac{c}{f_c}$, $30\frac{c}{f_c}$ and $40\frac{c}{f_c}$. The value range of h is set to $h \in [0, 0.05]$. Without loss of generality, we set the incident angle θ_i to correspond exactly to the left endpoint of the target area. As can be seen, $|\mathcal{C}|_{min}$ increases with the increase of h . Specifically, the case of $h = 0$ corresponds to the scenario without beam-squint effect, where the beam coverage range satisfies $l(\mathcal{R}(\beta(\Psi_s))) = BW_c^\Psi$, and $|\mathcal{C}|_{min} = \lceil \sin(60^\circ) - \frac{\sin(30^\circ)}{BW_c^\Psi} \rceil$. Furthermore, when h is fixed, $|\mathcal{C}|_{min}$ increases with the increase of b . The above results are in line with expectations, as the beam coverage range $l(\mathcal{R}(\beta(\Psi_s)))$ of a single codeword decreases with the increase of h and b .

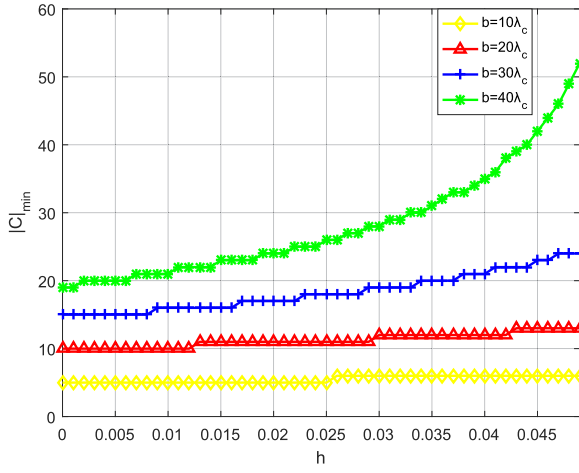


Fig. 9. The size of the minimum codebook versus partial bandwidth h for different RIS size b .

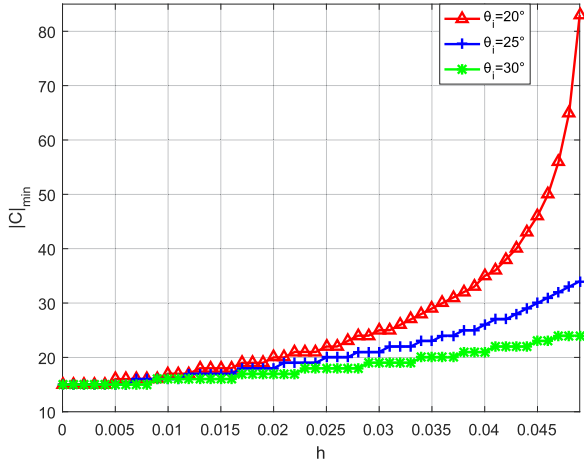


Fig. 10. The size of the minimum codebook versus partial bandwidth h for different incident angle θ_i .

Therefore, while keeping other parameters constant, as h or b increases, we need more codewords to cover the entire target area.

As shown in Fig. 10, we consider the variation of the minimum codebook size $|C|_{min}$ with partial bandwidth h in the case that the incident angle θ_i selects three specific values of 20° , 25° and 30° . The value range of h is set to $h \in [0, 0.05]$. The phenomenon is similar to that in Fig. 9, $|C|_{min}$ increases with the increase of h . Furthermore, it can be observed that when h is fixed, different incident angles θ_i can lead to different $|C|_{min}$. Specifically, as the incident angle gradually moves away from the target area, $|C|_{min}$ increases accordingly. As the incident angle gradually moves away from the target area, The incident angle away from the target area will increase $|\Psi_s - \Psi_i|$, and the beam coverage range of a single codeword will decrease. And we need more codewords to cover the entire target area. If the incident angle is too far from the target area, the algorithm may not converge. Hence, the selection of the incident angle is important. The position of the transmitter can be flexibly adjusted. For example, in holographic RIS-aided wideband communication scenarios where the transmitter is deployed on an unmanned aerial vehicle (UAV), the position of the UAV should be adjusted so that the value of the holographic RIS incident angle is as

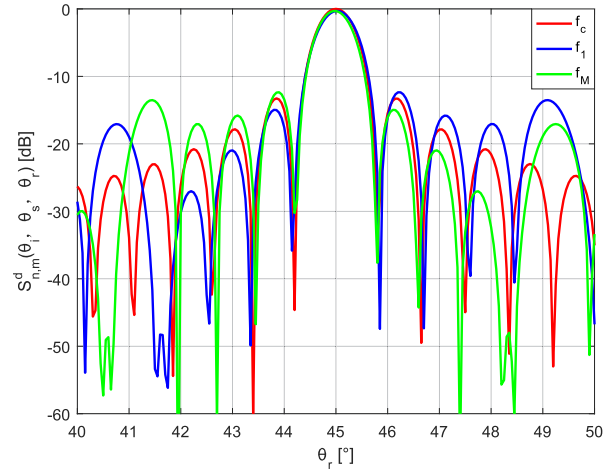


Fig. 11. The varying normalized radiation pattern with TTD lines versus observation angle θ_r for different frequency f_m .

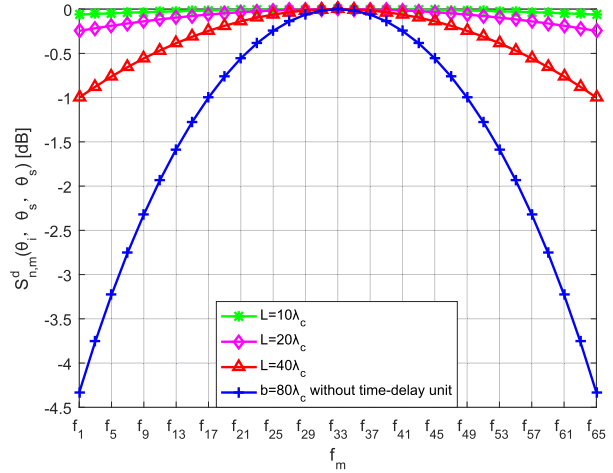


Fig. 12. The varying normalized radiation pattern with TTD lines versus frequency f_m for different RIS sub reflection surface size L .

close as possible to the target area, which is convenient to use a small number of codewords to cover the target area.

Fig. 11 depicts the effect of TTD lines on the normalized radiation pattern $S^d_{n,m}(\theta_i, \theta_s, \theta_r)$. Here we shows the normalized radiation pattern $S^d_{n,m}(\theta_i, \theta_s, \theta_r)$ corresponding to f_c , f_1 , and f_M within $\theta_r \in [40, 50]$. We set $a = b = 100 \frac{c}{f_c}$, $L = 20 \frac{c}{f_c}$ and $B = 2$ GHz. Compared with Fig. 6, it can be seen that after introducing the TTD line, the angles corresponding to the maximum energy of all frequencies are corrected to the desired angle, which eliminates the angle spread range.

Fig. 12 characterizes the variation of the normalized radiation pattern $S^d_{n,m}(\theta_i, \theta_s, \theta_r)$ with frequency f_m at the observation angle $\theta_r = \theta_s$. We compare the situation with and without TTD lines, and consider the influence of holographic RIS sub reflection surface size L . Specifically, holographic RIS size is set to three specific values: $10 \frac{c}{f_c}$, $20 \frac{c}{f_c}$, and $40 \frac{c}{f_c}$. The TTD lines can significantly improve performance at frequencies other than the center frequency. As L decreases, $S^d_{n,m}(\theta_i, \theta_s, \theta_r)$ at frequencies other than the center frequency will increase, and the performance gap between different frequencies will also decrease, mitigating the beam-squint effect. When the size of holographic RIS is fixed, the smaller the size L of the sub reflection surface, the better the RIS

performance. However, more TTD lines need to be introduced, which will increase the hardware cost accordingly. There is a trade-off problem between performance and hardware cost.

VII. CONCLUSION

In this paper, we focused on the beam-squint effect in a holographic RIS-aided wideband communication system. We first analyzed the holographic RIS electromagnetic characteristics at frequencies other than the center frequency when the phase mode did not match the optimal mode. Specifically, we derived the angle corresponding to the maximum energy at different frequencies under the beam-squint effect, 3dB beam bandwidth, and the regularities of beam offset. Besides, we defined the beam coverage range, derived its closed form solution, and provided a codebook design scheme that satisfies the minimum codebook size. Finally, we introduced TTD lines into the holographic RIS structure to mitigate the beam-squint effect. The simulation results demonstrated the influence of the beam-squint effect, revealed the influence of different system parameters on beam coverage range and minimum codebook size, and also verified the mitigation effect of TTD lines on the beam-squint effect.

APPENDIX A

DERIVATION OF THE ANGLES CORRESPONDING TO THE MAXIMUM ENERGY

According to (18) and (19), we can derive

$$\sin(\theta_{r,m}^{max})\cos(\phi_{r,m}^{max}) = \frac{1}{\xi_m} \sin(\theta_s) \cos(\phi_s), \quad (44)$$

$$\sin(\theta_{r,m}^{max})\sin(\phi_{r,m}^{max}) = \frac{1}{\xi_m} \sin(\theta_s)\sin(\phi_s) - (\xi_m - 1)\sin(\theta_i). \quad (45)$$

Dividing (45) by (44), when $\theta_s \neq 0$, $\phi_s \neq \frac{\pi}{2}$, and $\phi_s \neq \frac{3\pi}{2}$, we can obtain

$$\tan(\phi_{r,m}^{max}) = \frac{\sin(\theta_s)\sin(\phi_s) + (\xi_m - 1)\sin(\theta_i)}{\sin(\theta_s)\cos(\phi_s)}, \quad (46)$$

Besides, by taking the square of (44) and (45) and adding them together, and using the trigonometric function formula $\sin^2(\phi_{r,m}^{max}) + \cos^2(\phi_{r,m}^{max}) = 1$, we can obtain

$$\begin{aligned} & \sin(\theta_{r,m}^{max}) \\ &= \sqrt{\left(\frac{\sin(\theta_s)\cos(\phi_s)}{\xi_m}\right)^2 + \left(\frac{\sin(\theta_s)\sin(\phi_s) + (\xi_m - 1)\sin(\theta_i)}{\xi_m}\right)^2}. \end{aligned} \quad (47)$$

APPENDIX B

DERIVATION OF THE 3dB BEAM BANDWIDTH IN θ SPACE AND Ψ SPACE

To solve for the 3dB beam width in θ space, we need to apply the following Taylor series and trigonometric relationship

$$\frac{\sin^2 x}{x^2} = 1 - \frac{x^2}{3} + O(x^3), \quad (48)$$

$$\sin(\theta_1) - \sin(\theta_2) = (\theta_1 - \theta_2) \cos(\theta_2) + O((\theta_1 - \theta_2)^2). \quad (49)$$

By substituting (48) into (24) and setting $S_{n,m}(\theta_i, \theta_s, \theta_r) = 0.5$, we can obtain

$$S_{n,m}^\Psi(\theta_i, \theta_s, \theta_r) = \frac{1}{2}$$

$$\begin{aligned} & \frac{\left(\frac{b}{2}k_c(\xi_m\sin(\theta_r) - \sin(\theta_s) - (\xi_m - 1)\sin(\theta_i))\right)^2}{3} = \frac{1}{2} \\ & \sin(\theta_r) - \frac{\sin(\theta_s) + (\xi_m - 1)\sin(\theta_i)}{\xi_m} = \frac{\sqrt{6}}{bk_c\xi_m}. \end{aligned} \quad (50)$$

Then, we substitute (25) and (49) into (50) and solve for the value of $|\theta_r - \theta_{r,m}^{max}|$ as

$$|\theta_r - \theta_{r,m}^{max}| = \frac{\sqrt{6}c}{2\pi b f_m \cos(\theta_{r,m}^{max})}. \quad (51)$$

By doubling the value of $|\theta_r - \theta_{r,m}^{max}|$, we can calculate the 3dB beam width in θ space as

$$BW_m = \frac{\sqrt{6}c}{\pi b f_m \cos(\theta_{r,m}^{max})}. \quad (52)$$

Similarly, in Ψ space, by substituting (48) into (28) and setting $S_{n,m}^\Psi(\Psi_i, \Psi_s, \Psi_r) = 0.5$, we can obtain

$$\begin{aligned} & S_{n,m}^\Psi(\Psi_i, \Psi_s, \Psi_r) = \frac{1}{2} \\ & \frac{\left(\frac{b}{2}k_c(\xi_m\Psi_r - \Psi_s - (\xi_m - 1)\Psi_i)\right)^2}{3} = \frac{1}{2} \\ & \Psi_r - \frac{\Psi_s + (\xi_m - 1)\Psi_i}{\xi_m} = \frac{\sqrt{6}}{bk_c\xi_m}. \end{aligned} \quad (53)$$

Then, we substitute (29) into (53) and solve for the value of $|\Psi_r - \Psi_{r,m}^{max}|$ as

$$|\Psi_r - \Psi_{r,m}^{max}| = \frac{\sqrt{6}c}{2\pi b f_m}. \quad (54)$$

By doubling the value of $|\Psi_r - \Psi_{r,m}^{max}|$, we can calculate the 3dB beam width in Ψ space as

$$BW_m = \frac{\sqrt{6}c}{\pi b f_m}. \quad (55)$$

APPENDIX C

DERIVATION OF THE RIS NORMALIZED RADIATION PATTERN WITH TTD LINES

According to (37), the scattered electric field can be expressed as

$$\begin{aligned} \mathbf{E}_{s,m}^{R,d}(\theta_r, \phi_r) &= -jw \frac{\mu e^{-jk_m r}}{4\pi r} \\ &\times \sum_{i=1}^I \sum_{q=1}^Q e^{-jk_m c\tau_{i,q}} \int \int_{\mathcal{S}_{i,q}} \mathbf{J}_{1s}^m e^{j\beta_{i,q}(x_r, y_r)} \\ &\times e^{jk_m(x_r \sin(\theta_r) \cos(\phi_r) + y_r \sin(\theta_r) \sin(\phi_r))} \\ &dx_r dy_r. \end{aligned} \quad (56)$$

Substituting (38) into (56), we first calculate the definite integral part

$$\begin{aligned} & \iint_{\mathcal{S}_{i,q}} \mathbf{J}_{1s}^m e^{j\beta_{i,q}(x_r, y_r)} e^{jk_m(x_r \sin(\theta_r) \cos(\phi_r) + y_r \sin(\theta_r) \sin(\phi_r))} dx_r dy_r \\ &= e^{-jk_c(q-1)L(\sin(\theta_i) - \sin(\theta_s) \sin(\phi_s))} \int_{-\frac{L}{2} + (q-1)L}^{\frac{L}{2} + (q-1)L} e^{ju_2 y_r} dy_r \\ &\times e^{jk_c(i-1)L \sin(\theta_s) \cos(\phi_s)} \int_{-\frac{L}{2} + (i-1)L}^{\frac{L}{2} + (i-1)L} e^{ju_1 x_r} dx_r \mathbf{e}_x, \end{aligned} \quad (57)$$

where $u_1 = k_c(\xi_m \sin(\theta_r) \cos(\phi_r) - \sin(\theta_s) \cos(\phi_s))$, and $u_2 = k_c(\xi_m(\sin(\theta_r) \sin(\phi_r) - \sin(\theta_i)) - \sin(\theta_s) \sin(\phi_s) + \sin(\theta_i))$.

Utilizing the relationship between Euler's formula and complex exponents, the definite integral can be calculated as

$$\int_{-\frac{L}{2}+(i-1)L}^{\frac{L}{2}+(i-1)L} e^{ju_1 x_r} dx_r = 2 \frac{e^{ju_1(i-1)L}}{u_1} \frac{e^{j\frac{L}{2}u_1} - e^{-j\frac{L}{2}u_1}}{2j} \\ = 2 \frac{e^{ju_1(i-1)L}}{u_1} \sin\left(\frac{L}{2}u_1\right), \quad (58)$$

$$\int_{-\frac{L}{2}+(q-1)L}^{\frac{L}{2}+(q-1)L} e^{ju_2 y_r} dy_r = 2 \frac{e^{ju_2(q-1)L}}{u_2} \frac{e^{j\frac{L}{2}u_2} - e^{-j\frac{L}{2}u_2}}{2j} \\ = 2 \frac{e^{ju_2(q-1)L}}{u_2} \sin\left(\frac{L}{2}u_2\right). \quad (59)$$

Substituting (58) and (59) into (57), we can obtain

$$\mathbf{E}_{s,m}^{R,d}(\theta_r, \phi_r) = -jw \frac{E_i \mu \cos(\theta_i) L^2 e^{-jk_m r}}{2\pi r \eta} S_a\left(\frac{L}{2}u_1\right) S_a\left(\frac{L}{2}u_2\right) \\ \times \sum_{i=1}^I \sum_{q=1}^Q e^{-jk_m c \tau_{i,q}} e^{j(i-1)Lv_1} e^{j(q-1)Lv_2} \mathbf{e}_x, \quad (60)$$

where $v_1 = k_m \sin(\theta_r) \cos(\phi_r)$, and $v_2 = k_m(\sin(\theta_r) \sin(\phi_r) - \sin(\theta_i))$. Further, substituting (9) and (40) into (60) and utilizing the sum formula of geometric sequences, we can obtain the final closed form solution of the scattered field as

$$\mathbf{E}_{s,m}^{R,d}(\theta_r, \phi_r) = -jw \frac{E_i \mu \cos(\theta_i) L^2 e^{-jk_m r}}{2\pi r \eta} \\ \times S_a\left(\frac{L}{2}u_1\right) S_a\left(\frac{L}{2}u_2\right) B_I\left(\frac{L}{2}v_3\right) \\ \times B_Q\left(\frac{L}{2}v_4\right) e^{j(I-1)\frac{L}{2}v_3} e^{j(Q-1)\frac{L}{2}v_4} \\ \times (\cos(\theta_r) \cos(\phi_r) \mathbf{e}_\theta - \sin(\phi_r) \mathbf{e}_\phi), \quad (61)$$

where $B_I(x) = \frac{\sin(Ix)}{\sin(x)}$, $v_3 = k_m(\sin(\theta_r) \cos(\phi_r) - \sin(\theta_s) \cos(\phi_s))$, $v_4 = k_m(\sin(\theta_r) \sin(\phi_r) - \sin(\theta_s) \sin(\phi_s))$.

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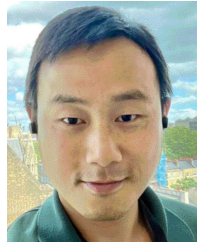
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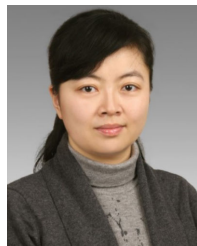
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