Impact of Reconfigurable Intelligent Surface Geometry on Communication Performance

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Abstract—When beamforming is applied at the transmitter, only part of reconfigurable intelligent surfaces (RISs) might be active, and it becomes indispensable to study the impact of RIS geometry. This letter aims at evaluating RIS geometry, ranging from linear (1D), and planar (2D), to cylindrical (3D) structures. We first derive the effective illuminated elements of different RIS topologies and determine the resulting signal-to-noise ratio (SNR) and outage probability. Then, we investigate the optimal RIS location to trade off active area versus received power considering near-field propagation. Numerical results quantify the benefit of RIS geometric compactness and provide their applicable ranges.

Index Terms—Geometric structure, outage probability, performance, reconfigurable intelligent surface, signal-to-noise ratio.

I. INTRODUCTION

RECONFIGURABLE intelligent surface (RIS) technology is attracting much interest for the sixth-generation (6G) communication system. It becomes an essential component when blockages occur between transmitter (Tx) and receiver (Rx) [1]. Passive RIS furthermore has the potential to combine a high signal-to-noise ratio (SNR) with high energy efficiency by implementing an optimal phase-shift scheme [2]. Existing studies have unfolded the performance analysis and signal processing of RIS-assisted wireless communications [3]. In general, they can be categorized into the following kinds: i) from the perspective of propagation channels, the links between the Tx and RIS, Rx and RIS are assumed to follow Rayleigh [4], Rician [5], or Nakagami-m [6] distributions, mostly assuming the far-field propagation; ii) from the perspective of frequency bands, the operating band spans from sub-6 GHz [7] to millimeter-wave bands [8]; iii) from the perspective of application scenarios, the deployments of RIS spread over the cellular system [9], and vehicular system [10], mainly for outdoor environments. Hence, there is a lack of research on indoor deployments with near-field effects.

The dominant RIS geometry assumption in existing studies is the two-dimensional (2D) prototype [11], which is the natural interpretation of a surface. Another hypothesis is that all elements in a RIS are actively reflecting the incoming wave, and contributing to the SNR gain [12]. Such assumptions might hold in far-field scenarios, it is not effective when the RIS is only partially illuminated due to the large aperture, the short distance between the transceiver and the RIS in an indoor environment, or a high-directional beam pattern used in Tx. When the beam in the near field is focused locally, the impact of the RIS compactness might be important. Thus, the performance benefit of the 2D surface, by comparison with other geometries, such as linear (1D), and cylindrical (3D) ones, needs more analysis. For analytical rigor and completion, this letter aims to evaluate almost all possible RIS geometries.

Nonetheless, a few studies have investigated the partially illuminated RIS. In [13], the authors approximated the illuminated RIS area from the conical main lobe as a circular area and then determined the effective number of RIS elements. Their extended work in [14] considered an ellipse as the illuminated area by incorporating an incident angle. Authors in [15] investigated the RIS efficiency indicated by the received power for different user directions, while modeling the partial RIS illumination as an elliptical area that degrades to a circle in the normal direction. However, these works merely focused on 2D RIS and studied the deployment of RIS with limited flexibility. In our work, the illuminated area is a function of the half-power beam-width (HPBW), the distance, as well as both azimuth and elevation of departure (AoD and EoD). To our best knowledge, this is the first study that investigates the influence of different RIS geometries on communication performance considering more practical 3D deployment of RIS. The main contributions are as follows.

- We theoretically formulate the illuminated area and the effective number of different RIS geometries, as functions of the distance, the HPBW, and the angles of departure.
- We consider the near-field effects in the path loss and obtain near-field distances for different RIS geometries. We then derive the outage probability employing the moment matching method, under the Rician fading channel, which is applied for any effective number of RIS elements.
- We compare the effective number of elements, received power, SNR, and outage probability for different geometries, to provide practical deployment insights. Moreover, the optimal location of RIS is also investigated to realize the optimal SNR and the minimum outage probability.

The remainder of this letter is structured as follows. Section II introduces the system model, and the illuminated area when using beamforming in Tx. Section III analyzes the effective number of elements for different RIS geometric structures, and then provides the expression of outage probability. Afterward, Section IV provides analytical results and deployment insights into RISs. Finally, Section V concludes this letter.

II. SYSTEM MODEL

In this section, we introduce the system model, and model SNR as a function of signal transmission, beam patterns, and
channel models. In addition, we calculate the illuminated area, which is essential for determining the effective number of elements and near-field Fraunhofer distance.

A. Signal Transmission

For the system model in Fig. 1, we consider the unfavorable propagation condition, i.e., an absent Line-of-Sight (LoS) path between Tx and Rx, where the RIS can compensate for the path loss. At the Rx, the received signal can be expressed as

\[ y = \sqrt{P_r} \left[ \sum_{i=1}^{N_{\text{eff}}} h_i g_i \right] s + n_0, \]

where \( P_r \) is the received power, \( h_i = \alpha_i e^{-j \omega_i} \) and \( g_i = \beta_i e^{-j \theta_i} \) represent the small-scale fading channels with the phases of \( \omega_i \) and \( \theta_i \) for Tx-RIS and RIS-Rx links, respectively, where \( \alpha_i \) and \( \beta_i \) follow the Rician fading with parameters \( K_1, \Omega_1 \) and \( K_2, \Omega_2 \), respectively, with \( K_{1,2} = \frac{\sigma_{1,2}^2}{\sigma_{1,2}^2} \) denoting the power ratio between the LoS and none-LoS components, and \( \Omega_{1,2} = \sigma_{1,2}^2 + 2 \sigma_{1,2}^2 \). \( \gamma_i \) is the reflection coefficient in the \( i \)-th RIS element. \( s \) and \( n_0 \) represent the transmit signal with \( \mathbb{E}(s^2) = 1 \) and the additive white Gaussian noise with \( n_0 \sim \mathcal{N}(0, \sigma_n^2) \). \( N_{\text{eff}} \) is the effective number of RIS elements.

B. Antenna and Illuminated Area

To study the partial illumination of a large RIS, we denote the HPBW of the transmitting beam as \( \phi \), where the Tx beam pattern can be generated by a simple phased array consisting of multiple antennas, with a steering vector pointing to the RIS center. Based on the cosine model [16], for the \( n \)-th element, the pattern is \( G_t(\varphi_{t,n}) = \cos^2\left(\frac{\pi(\varphi_{t,n} - \varphi_t)}{2\theta} \right) \), with \( \varphi_t \) denoting the azimuth angle between centers of Tx and RIS. Then, the element radiation pattern of the RIS is expressed as \( F(\varphi_{t,n}) = \cos^2\left(\varphi_{t,n} - \varphi_{t,n} \right) \) for \( \varphi_{t,n} \in [-\frac{\pi}{2}, \frac{\pi}{2}] \) and \( \theta_{t,n} \in [-\frac{\pi}{2}, \frac{\pi}{2}] \). \( \varphi_{t,n}, \theta_{t,n} \) denote the AoD and EoD for each element, respectively. The same patterns apply for \( \varphi_{r,n}, \theta_{r,n} \). Besides, an omnidirectional pattern is used for the Rx.

For the illuminated area, we approximate it as an ellipse, and its major axis is denoted by \( a \), which can be calculated as

\[ a = \frac{1}{2} \left( \frac{r_1 \sin(\phi_0)}{\sin(\varphi_t + \phi_0)} + \frac{r_1 \sin(\phi_0)}{\sin(\varphi_t - \phi_0)} \right), \]

where \( a \) can be obtained by applying the Law of Sines, and \( r_1 \) is the 3D distance between the Tx and RIS. Similarly, the minor axis \( b \) can be calculated by

\[ b = \frac{1}{2} \left( \frac{r_1 \sin(\phi_0)}{\cos(\theta_t + \phi_0)} + \frac{r_1 \sin(\phi_0)}{\cos(\theta_t - \phi_0)} \right), \]

where \( \theta_t = \arctan \frac{h_t - h_r}{d_1} \) is the EoD and \( d_1 \) is 2D distance between Tx and RIS \( (d_2) \) for RIS-Rx. The detailed explanation and calculation of \( a \) and \( b \) can be found in the Appendix-A.

Therefore, the illuminated area on the 2D plane is calculated by \( S_m = \pi ab \) where the area becomes a circle \( (a = b) \) when \( \theta_t = 0^\circ, \varphi_t = 90^\circ \). Moreover, for \( \theta_t = 90^\circ \) or \( \varphi_t = 0^\circ \), it corresponds to the beam parallel to the RIS, thus \( S_m = 0 \).

C. Path Loss and SNR

For path loss, we employ the measurement results from [17]. The received power considering the near field is calculated by

\[ P_r = P_t G_r \frac{\lambda^2 d_k d_y}{64 \pi^3} \sum_{n=1}^{N_{\text{eff}}} \sqrt{G_t(\varphi_{t,n}) F(\varphi_{t,n}) F(\varphi_{r,n})} \]

\[ r_{1,n} r_{2,n}, \]

where \( P_t \) is the transmit power, \( d_k \times d_y \) represents the size of a flat element, often assumed to be sub-wavelength. \( r_{1,n} \) and \( r_{2,n} \) represent 3D distances of Tx-element and element-Rx, respectively. The distances \( r_{1,n}, r_{2,n} \) and angles \( \varphi_{t,n}, \varphi_{r,n} \) are different for each RIS element \( n = 1 \ldots N_{\text{eff}} \) in the near field. When operating in the far field, the plane wave assumption still results in different \( r_{1,n} \) and \( r_{2,n} \) in the 3D structure.

Thus, the instantaneous SNR can be expressed by

\[ \rho_{\text{inst}} = \frac{P_t \sum_{i=1}^{N_{\text{eff}}} \alpha_i \beta_i e^{j(\psi_i - \omega_i - \theta_i)}}{\sigma_n^2}, \]

where the channel phase shift can be perfectly compensated by the RIS, i.e., \( \psi_i = \omega_i + \theta_i \). Hence, it has \( \rho_{\text{max}} = A^2 \rho \), with \( A = \sum_{i=1}^{N_{\text{eff}}} \alpha_i \beta_i \), and \( \rho = \frac{P_t}{\sigma_n^2} \) is the average SNR.

III. KEY ISSUES AND PERFORMANCE

In this section, we first address key issues on the effective number \( N_{\text{eff}} \), the Fraunhofer distance \( d_G, G \in \{1D, 2D, 3D\} \), and element-dependent distances \( r_{1,n} \) and \( r_{2,n} \). Afterward, we derive the outage probability as a function of the SNR.

A. Effective Number of RIS Elements

The effective number of elements in each RIS can be determined by the illuminated area. For the linear RIS, the effective number is mainly determined by the major axis \( a \) because of \( b \geq d_y \), expressed as \( N_{\text{eff}}^{1D} = \left\lfloor \frac{d_y}{a} \right\rfloor \) where we use \( \lfloor \cdot \rfloor \) to discard the partially illuminated element. For a 2D squared RIS, its length can be expressed as \( L_{2D} = (2\sqrt{N} - 1) d_x \). To simplify the scenario analysis, we introduce a parameter \( L_{2D} \) to indicate the relationship between the elliptical illumination and squared RIS areas. We compute \( L_{2D} = (2a - 2d_2)(2b - 2d_2) \), where \( L_{2D} > 0 \) means that the RIS is either fully illuminated (the ellipse dimensions \( a \) and \( b \) are both larger than \( L_{2D} \)) or the area is given by \( S_a \), and \( S_a \) is either partially illuminated in both dimensions so the area is given by the ellipse area \( S_m \). Under this condition, the effective number can be calculated by

\[ N_{\text{eff}}^{2D} = \left\lfloor \frac{N_m}{S_{2D}} \right\rfloor, \quad S_m \geq S_a, L_{2D} > 0, \]

\[ S_m < S_a, L_{2D} > 0, \]
where $S_1$ is the total area of the RIS. For the scenarios where $l_{2D} \leq 0$, the RIS is partially illuminated in one dimension and fully in the other. As $a \geq b$, $l_{2D} = 0$ holds when $b = l_{2D}/2$, where $N_{2D} = |S_0/2d_s^2|$. For the other condition, the number is calculated as $N_{2D}^{eff} = |S_0 - S_0 - S_4|$. For $a > \frac{l_{2D}}{2}$, $l_{2D} < 0$, where the geometric illustration of $S_1$ is shown in Fig. A1(b). Based on the elliptic Equation, $S_1$ can be calculated as

$$S_1 = \frac{4b}{a} \int_{b/2}^{a} \sqrt{a^2 - x^2} \, dx,$$

$$= \pi ab - \frac{bl_{2D}}{2a} \sqrt{4a^2 - l_{2D}^2} - 2ab \arcsin \frac{l_{2D}}{2a}. \quad (7)$$

For a 3D cylindrical RIS, the height is calculated as $l_{3D} = \sqrt{(d_s d_y + d_z^2)/N}$. The effective number can be determined according to the relation between the illuminated and cylindrical surface. However, due to the nature of the cylinder, the mapping major axis of the ellipse on the cylinder is

$$a^* = \frac{\pi l_{3D}}{4} - \frac{l_{3D}}{2} \arccos \left( \frac{2a}{l_{3D}} \right), \quad a \leq \frac{l_{3D}}{2},$$

where $a^*$ is the arc length in a circle when chord length is $a$.

In summary, the effective number of the 3D RIS for different ranges of $a$ and $b$ can be expressed as

$$N_{3D}^{eff} = \begin{cases} \frac{S_2 + S_3}{2d_z^2}, & a > \frac{l_{3D}}{2}, \ b < \frac{l_{3D}}{2} \\ \frac{\pi a^* b}{2d_z^2}, & a \leq \frac{l_{3D}}{2}, \ b \leq \frac{l_{3D}}{2} \end{cases}$$

where we assume there are $N$ elements on the half of the cylinder for a fair comparison with other geometries, however, the visible number is $N/2$ from Rx, i.e., on a quarter cylinder, due to the 3D structure. Besides, the area $S_3$ is calculated by

$$S_3 = \frac{\pi bl_{3D}}{2a} \sqrt{4a^2 - l_{3D}^2}. \quad (10)$$

We then employ the polar coordinates, denoting $x = a \cos \theta$ and $y = b \sin \theta$, and thus the area of $S_2$ can be calculated by

$$S_2 = 4 \int_{0}^{\pi/2} \frac{ab \sin \theta \cos \theta d\theta}{\arccos \left( \frac{\pi l_{3D}}{4a} \right)},$$

where substituting $a = \frac{l_{3D}}{2}$, it can be seen that $S_2 = \frac{\pi b l_{3D}}{4}$. The same method applies in $r_{2D}$. For the linear RIS, $r_{1, n}$ and $r_{2, n}$ are different for RIS elements $n = 1 \cdots N_{eff}$. For the linear RIS, $r_{1, n}$ and $r_{2, n}$ can be approximately calculated by the Law of cosines, i.e., $r_{1, n} = \sqrt{r_{1}^2 + (nd_s b)^2 + 2r_1 nd_s \cos(\varphi_n)}$, for $n = [-N_{eff}/2, N_{eff}/2]$ with $N_{eff}$ numbers. The same method applies in $r_{2, n}$. We denote the coordinates of Tx, the center of RIS, and Rx as $(0, 0, h_1)$, $(x_s, y_s, h_s)$, and $(x_r, y_r, h_r)$, respectively. For the 2D and 3D RISs, $r_{1, m, n}$ and $r_{2, m, n}$ can be written by

$$r_{1, m, n} = \sqrt{x_m^2 + y_m^2 + (z_m - h_1)^2},$$

$$r_{2, m, n} = \sqrt{(x_m - x_r)^2 + (y_m - y_r)^2 + (z_m - h_r)^2},$$

where then yields the angular information, i.e., $\varphi_{m, n} = \arctan \left( \frac{y_m - y_r}{x_m - x_r} \right), \theta_{m, n} = \arctan \left( \frac{z_m - h_1}{d_{1, m, n}} \right)$, $\varphi_{m, n} = \arctan \left( \frac{y_m - y_r}{x_m - x_r} \right)$, and $\theta_{m, n} = \arctan \left( \frac{z_m - h_r}{d_{1, m, n}} \right)$. We consider the following conditions to express the coordinates of RIS elements:

1. **Fully Illuminated:** The locations of elements in the 2D RIS can be expressed as $(x_m, y_m, z_m) = (x_s + nd_s d_s, y_s + h_s + nd_s)$ for $m, n = [-N_{eff}/2, N_{eff}/2]$ with $N_{eff}$ number. For the 3D RIS, it exists $(x_p, y_p, z_p) = (x_s + \frac{pd'_s}{\cos(pd'/l_{3D})}, y_s + \frac{pd'_s}{\cos(pd'/l_{3D})}, h_s + d_{3D})$ where $q = [-N_{eff}/2, N_{eff}/2]$ with $N_{eff}$ numbers, and $p = [-N_{eff}/2, N_{eff}/2]$ with $N_{eff}$ numbers, and $d_{3D} = \sqrt{d_s^2 + d_z^2 \cos^2(2d_s/l_{3D})}$ is the chord length of the arc length $d_s$, based on the Law of cosines.

2. **Partially Illuminated:** The number of elements in the major and minor axes of an ellipse can be calculated by the values of $a$ and $b$. For the total illuminated number $N_{eff}$, the indexes $(m, n)$ and $(p, q)$ of elements in each column and row can be then determined. Finally, the coordinates $(x_m, y_m)$,
y_{m,n}, z_{m,n}) and (x_{p,q}, y_{p,q}, z_{p,q}) for the 2D and 3D RISs are selected from overall coordinates in the fully illuminated condition.

D. Outage Probability

The outage probability is a popular metric for evaluating the performance, which is defined as the probability that the SNR is smaller than a given threshold $\rho_{th}$, expressed by

$$P_{\text{out}}(\rho_{th}) = \text{Prob}(\rho_{\text{max}} \leq \rho_{th}) = F_{\rho_{\text{max}}}(\rho_{th}),$$  

(12)

where $F_{\rho_{\text{max}}}(\cdot)$ denotes the cumulative distribution function (CDF) of $\rho_{\text{max}} = \rho \sum_{n=1}^N \eta_i^2$ denoting $\eta_i = \alpha_i \beta_i$. With the method of moment matching [4], we can obtain

$$F_{\rho_{\text{max}}}(\rho_{th}) = \frac{\Gamma(N_\text{eff}, \frac{\rho_{th}}{\rho_{\text{max}}})}{\Gamma(N_\text{eff})},$$

where $\Gamma(\cdot, \cdot)$ is the lower incomplete Gamma function, $\Gamma(\cdot)$ is the Gamma function, and

$$\Lambda = \frac{\text{Var} \{ \eta_i \}}{\text{Var} \{ \eta_i \}} = \frac{\sigma^2}{\bar{\eta}^2}$$

and $\Delta = \text{Var} \{ \eta_i \}$ where the variance $\text{Var} \{ \eta_i \} = \mathbb{E} \{ \eta_i^2 \} - (\mathbb{E} \{ \eta_i \})^2 = \Omega_1 \Omega_2 - \mathbb{E} \{ \eta_i \}$ with the expectation $\mathbb{E} \{ \eta_i \} = \pi^2 \text{K}_1(\bar{\eta}^2) \bar{\eta} \text{K}_0(\bar{\eta}^2) \sqrt{\frac{(K_1 + 1)I_0(K_1)}{K_2 I_0(K_2)} + K_2 I_0(K_2)}$ where $I_0$ is the modified Bessel function of the first kind with order $\nu$. For the details, we first approximate $\eta_i$ as Gamma distribution $\eta_i \sim \mathcal{G}(\Lambda, \Delta)$. With the additive characteristics of Gamma distribution, we then have $\Lambda \sim \mathcal{G}(N_{\text{eff}}, \Delta)$. The generalized Gamma distribution is finally used to describe the CDF of $A^2$. The asymptotic analysis of the high SNR regime ($\rho \rightarrow \infty$) shows

$$P_{\text{out}} \rightarrow \frac{\Delta}{\rho_{\text{th}}} \Gamma(\Lambda_{\text{eff}}, \frac{\Lambda_{\text{eff}}}{\Delta}) - \frac{\Lambda_{\text{eff}}}{\Delta}$$

For the verification, we use $K_1 = K_2 = 0$ (Rayleigh), we obtain $\Delta = \frac{\pi^2}{16\pi^2}, \Delta = \frac{16\pi^2}{\pi^2} \sigma_1 \sigma_2$, corresponding to our prior work [4].

IV. NUMERICAL RESULTS

In this section, we present numerical results. The default parameters are employed: $N = 100, P_t = 0$ dBm, $P_h = -100$ dBm, $f = 3.5$ GHz, $(x_s, y_s, h_s) = (0, 0, 3)$ m, $(x_r, y_r, h_r) = (5, 0, 1.5)$ m, $y_s = 2$ m, and $\phi = \{5^\circ, 10^\circ\}$. Some parameters may vary for different analytical purposes.

A. Effective Number and Received Power

We first illustrate the relationships between $N_{\text{eff}}$ and $x_s$ with fixed HPBW $\phi$, as well as $N_{\text{eff}}$ and $\phi$ with fixed $x_s$ in Fig. 3. The slopes of the results demonstrate that $N_{\text{eff}}$ increases faster for compact geometries, hence faster for 3D, 2D, and 1D RIS, respectively. For a short distance and narrow HPBW, resulting in the smallest illumination area, the 3D RIS has the highest $N_{\text{eff}}$. However, by increasing $x_s$ and $\phi$, the 2D and even 1D RIS become more effective. This is mainly caused by the fact that the circular geometry directs some RIS elements away from the Tx and Rx. When increasing $x_s$ and $\phi$, all visible elements will contribute for all geometries, resulting in maximal performances for both the 1D and 2D RIS given by $N_{\text{eff}} = N$. The 3D RIS suffers from reduced visibility, and in our placement assumptions only half of the elements contribute and $N_{\text{eff}} = N/2$. Finally, the critical HPBW $\phi_c$ in Fig. 3(b) verifies the correctness of our theoretical derivation.

To analyze the received power using different RISs, we change both horizontal and vertical locations of the RIS. As shown in Fig. 4, it is found that the 2D RIS allows a higher received power than the other RISs. Moreover, the optimal locations $(x_*, y_*)$ for the 1D, 2D, and 3D RISs are at $(1.58, 3.96)$ m, $(2.01, 3.63)$ m, and $(2.02, 3.63)$ m, while the maximum $P_r$ are $-69$ dBm, $-53$ dBm, and $-59$ dBm, respectively. Overall, $P_r$ for fixed $x_s$ increases for $h_s \leq h_s^*$ and then decreases for a higher $h_s$, due to the heights impacting the 3D distances $r_1, r_2$ with $P_r \sim \frac{1}{r_1^2}$. While for the fixed $h_s$, $P_r$ presents different trends with $x_s$, since the received power is jointly determined by $N_{\text{eff}}, r_1, r_2, \phi_1^\ast, \phi_2^\ast$, based on Eq. (4). Nonetheless, the optimal 3D RIS location for given Tx and Rx locations, and HPBW, can be obtained.

B. SNR and Outage Probability

Fig. 5(a) illustrates the outage probability for $\phi = \{5^\circ, 10^\circ\}$ and different $K$-factors, with the fixed RIS at $(x_s, y_s, h_s) = (2.2, 3)$ m. The results show the 3D and 2D RISs are superior in performance for the small and large $\phi$, respectively. Because of the LoS gain, the larger $K$-factor results in a lower outage, suggesting $P_{\text{out}}$ under the Rayleigh fading is the upper bound of the Rician fading-based one. For the moving RIS, we show $P_{\text{out}}$ and mean received SNR $\bar{\rho}$ simultaneously in Fig. 5(b).
is found that the maximum SNR is obtained at $x_{\text{opt}} = 4.9, 5.1,$ and $5.6$ m with SNR values of 29.9, 35.8, and 20.2 dB for 3D, 2D, and 1D RIS, respectively, where geometric compactness leads to the difference of $x_{\text{opt}}$ and the 2D RIS can achieve the highest average SNR. Besides, the outage probabilities of 2D and 3D RISs are inversely proportional to the SNR, while $P_{\text{out}}$ decreases with a declined SNR for the 1D RIS in $x_{s} \leq 13.3$ m, which is because $P_{\text{out}}$ is jointly determined by $N_{\text{eff}}$ and $\bar{\rho}$, while $N_{\text{eff}}^\text{3D}$ is increasing in this range. When it reaches the limit number, $P_{\text{out}}$ increases with a decreasing $\bar{\rho}$. Both $P_{\text{out}}$ and $\bar{\rho}$ results indicate the suitable deploying range for 3D and 2D is separated at $x_{s} = 3.4$ m. Besides, the same performance can be obtained for the 1D and 2D RISs when $x_{s} \geq 13.3$ m.

**V. CONCLUSION**

In this letter, we presented a general analytical framework for the impact of geometric structures of RIS on communication performances, under the high-directional transmitting beam. To obtain the illuminated area, effective number, near-field distances, and outage probability, we employed geometry-based and moment-matching-based analytical methods. In summary, analytical results show that the 3D and 2D RISs can be respectively used for the shorter/longer distance and narrower/wider beam-width, e.g., the horizontal distance $x_{s} = 3.4$ m and the HPBW $\phi = 13.8^\circ$ considered as cut-off points for an indoor environment. Besides, for the less near-field propagation effects, the 3D RIS is a better option to deploy than the others, thanks to its higher structural compactness.

**APPENDIX**

**A. Graphical Interpretation of Illuminated Area Calculation**

Consider the 3D deployment of RIS, the beam’s projection on the RIS is influenced by two departure angles from the Tx, i.e., AoD ($\phi_{t}$) and EoD ($\theta_{t}$). The area is structured by four lengths, i.e., $a^\ast, a^\ast, b^\ast, \text{ and } b^\ast$. Based on the Law of Sines, for instance, $\frac{a^\ast}{\sin(\theta_{0})} = \frac{b^\ast}{\sin(\phi_{t} + \theta_{t})}$, these values are given in Fig. A1(a). Note that $\theta_{t} = \frac{\phi_{t}}{2} - \theta_{t}$ in the figure. However, the shape of illuminated area is irregular due to the 3D departure. Specifically, there are $a^\ast \neq a^\ast$ and $b^\ast \neq b^\ast$ for most cases. However, when the Tx and RIS are at the same height, the actual shape is an asymmetric oval ($a^\ast \neq a^\ast$ and $b^\ast = b^\ast$). Herein, we approximately employ an ellipse to express the illuminated area, with the average major axis $a = \frac{1}{2}(a^\ast + a^\ast)$ and the average minor axis $b = \frac{1}{2}(b^\ast + b^\ast)$ by assuming the larger part of the shape filling up the smaller part for average.

**B. Graphical Interpretation of Effective Number Calculation**

For the 2D RIS, as shown in Fig. A1(b), we show the most challenging condition, i.e., $a > \frac{2\phi}{\pi}, b < \frac{2\phi}{\pi}$, where $S_{1}$ can be obtained by the integral of the elliptic Equation, and then the illuminated area can be expressed as $S_{1} - S_{2}$ where $S_{1}$ is given in Eq. (7). It is also a challenging condition for the 3D RIS. However, because of the structure of the cylinder, we separate the illuminated area into $S_{2} + S_{3}$, which can be obtained by the integral operation using the polar coordinate, where $S_{2}$ and $S_{3}$ are given in Eq. (11) and Eq. (10), respectively.

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