Reconfigurable Intelligent Surface Assisted Communications Using Dynamic Rotations

Ke Wang, Chan-Tong Lam, and Benjamin K. Ng
Faculty of Applied Sciences, Macao Polytechnic University
Macao S.A.R, China
Emails: {ke.wang; ctlam; bng}@ipm.edu.mo

***Abstract*—In this paper, we propose a rotatable reconfigurable intelligent surface (RIS) assisted system to enhance the transmission quality of wireless communications. The RIS is able to rotate for maximizing the cascaded channel gain dynamically. In particular, we first introduce a continuous-time propagation model for the rotatable RIS-aided communication system. Then, a rotation angle optimization problem is formulated and solved, which boosts the channel gain of the cascaded link. Besides, we derive the expression of the spectral efficiency for the proposed system. Numerical evaluations reveal that the dynamic rotation strategy can not only enhance spectral efficiency and reduce delay spread but is still effective when rotation errors exist.**

***Index Terms*—Reconfigurable intelligent surface, rotation angle optimization, spectral efficiency**

I. Introduction

Reconfigurable intelligent surface (RIS) is a planar surface made up of an array of sub-wavelength passive reflecting elements, each of which can cause a tunable amplitude and/or phase shift on the incident signal in real-time independently [1]. It has recently been considered a promising technology for creating smart radio environments [2]. In particular, the RIS can be designed to jointly optimize active and passive beamforming [3], achieve high spectral and efficiency [4], mitigate Doppler effects [5], [6], enhance signal-to-noise ratio coverage [7], etc. Compares to the decode-and-forward relay, the RIS is preferable both in terms of minimizing the transmit power and maximizing the energy efficiency due to its passiveness when we need very high data rates [8].

However, the above works [3]–[5], [7], [8] only considered the RIS with isotropic elements, which is not realistic in practical scenarios. Matthiesen *et al*. [9] proposed to use useful information such as location and mobility pattern to design the RIS phase shift set in advance, and more importantly, the authors showed that when the RIS on the earth is rotated by 45°, the channel gain from the RIS can be increased by almost 6 dB in the Low Earth Orbit satellite scenario. In fact, the effective area of the element varies with the rotation and location of the RIS [7], [10]. Besides, Cheng *et al*. [11] revealed that in order to maximize the received power, the RIS should be oriented optimally to make it in the specular reflection state. The same result is also shown in [10]. The authors in [12] examined the potential of rotation of the RIS. Specifically, they introduced the extra degree of freedom introduced by the rotation angle to improve the performance of RIS-assisted wireless communication systems.

As a result of the mobility of users (e.g., vehicles), conventional nonrotatable RIS has a variable effective area. Different from [7], [9]–[11], in this paper, we consider the cascaded link gain maximization using rotatable RIS under the continuous time propagation model. Our contributions are as follows:

- We propose a continuous-time propagation model with rotatable RIS.
- We formulate a rotation angle optimization problem and obtain the optimal rotation angle that can maximize the instantaneous channel gain of the cascaded link.
- We derive a spectral efficiency (SE) expression for the proposed system.
- We reveal that the dynamic rotation strategy not only enhances SE and reduces delay spread, but is still effective even with rotation errors.

Notation: Lower-case boldface letters denote the column vector. The function $(x \bmod y)$ refers to the remainder of the division of x by y. Superscript $[\cdot]^{\mathrm{T}}$ stands for transpose operation. Besides, $\jmath \triangleq \sqrt{-1}$, $|\cdot|$ symbolizes the absolute value, $\mathcal{U}$ is uniform distribution, and $\|\cdot\|$ represents the l_2 norm.

II. System Model

We consider a downlink transmission model where a rotatable RIS consisting of $M \times N$ reflecting elements is deployed on a base station (BS) side to assist the wireless transmission from the BS to a mobile user with a speed of v meters / second (m/s). The BS and the user both equip single isotropic antenna, and with the positions $\boldsymbol{p}_{\mathrm{BS}} = [x_{\mathrm{BS}}, h_{\mathrm{BS}}, z_{\mathrm{BS}}]^{\mathrm{T}}$ and $\boldsymbol{p}_{\mathrm{User}}(t) = [x_0 + v \cdot t, h_{\mathrm{User}}, z_{\mathrm{User}}]^{\mathrm{T}}$, respectively. Note that x_0 is the position of the user when $t = 0$, and the heights of the RIS, the BS, and the user are h_{RIS}, h_{BS} and h_{User}, respectively, as Fig. 1 shows. The RIS is a uniform planar array that is placed on a rectangular grid spaced a and b apart in the three-dimensional Cartesian coordinate system. Furthermore, the channel state information (CSI) can be partly obtained in advance[1].

The position of the (m, n)-th element of the rotatable RIS on the $x - y$ plane is

$$\hat{\boldsymbol{p}}_{m,n} = \left[\omega(m, a, \sqrt{M}), \omega(n, b, \sqrt{M}) + h_{\mathrm{RIS}}, 0\right]^{\mathrm{T}}, \qquad (1)$$

[1]If the mobility pattern is predicted (e.g., mobility patterns [9], [13] and positioning information [6]), the CSI can be obtained in advance.

where $\omega(m,a,\sqrt{M}) = a(m-0.5((\sqrt{M}+1) \bmod 2))$, $m \in \Omega(\sqrt{M})$ with $\Omega(\sqrt{M}) = \{((\sqrt{M}+1) \bmod 2)) - \lfloor\frac{\sqrt{M}}{2}\rfloor, \ldots, \lfloor\frac{\sqrt{M}}{2}\rfloor\}$, where $\lfloor\cdot\rfloor$ is the floor function. Besides, $\omega(n,b,\sqrt{M})$ is obtained in the same way as $\omega(m,a,\sqrt{M})$.

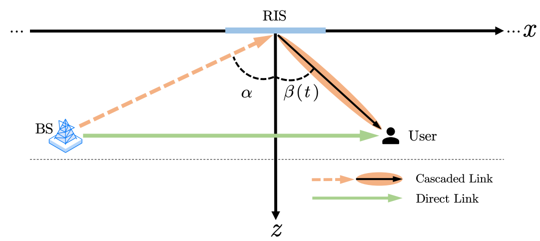

Fig. 1. The RIS without rotation.

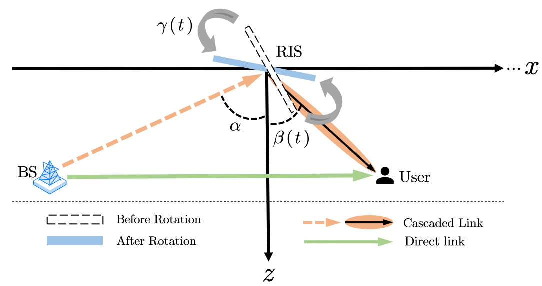

Fig. 2. The RIS with rotations.

In this paper, we assume the RIS can counterclockwise rotate $\gamma(t) \in [-\pi/2, \pi/2]$ degrees around the y-axis. Therefore, the practical position vector of the (m,n)-th element of the RIS is

$$\boldsymbol{p}_{m,n}(t) = \boldsymbol{\Gamma}^{\mathrm{T}}(t)\hat{\boldsymbol{p}}_{m,n}, \tag{2}$$

where $\boldsymbol{\Gamma}(t)$ is

$$\boldsymbol{\Gamma}(t) = \begin{bmatrix} \cos(\gamma(t)) & 0 & \sin(\gamma(t)) \\ 0 & 1 & 0 \\ -\sin(\gamma(t)) & 0 & \cos(\gamma(t)) \end{bmatrix}. \tag{3}$$

Therefore, $\boldsymbol{p}_{m,n}(t)$ can be changed at each different time t. In order words, the rotation angle $\gamma(t)$ is a function of t. Note that the rotation RIS is different from the moving RIS on the vehicle [14], although their positions are all related to the time t. Besides, suppose the channels are all light-of-sight (LoS), and small-scale fading is ignored. Thus, at time t, the instantaneous gain for the direct link between the BS and the user is

$$A_0(t) = \frac{\lambda_c}{4\pi d_0(t)}, \tag{4}$$

where λ_c denotes the wavelength of the carrier signal, and $d_0(t) = \|\boldsymbol{p}_{\mathrm{User}}(t) - \boldsymbol{p}_{\mathrm{BS}}\|$ is the Euclidean distance between the BS and the user at time t.

Also, the instantaneous gain for the cascaded link at time t is

$$A_{m,n}(t) = \frac{\lambda_c^2\sqrt{G_{m,n}^{\mathrm{BS}} G_{m,n}^{\mathrm{User}}(t)}}{16\pi^2 d_{\mathrm{BS}}^{m,n}(t) d_{m,n}^{\mathrm{User}}(t)}, \tag{5}$$

where $d_{\mathrm{BS}}^{m,n}(t) = \|\boldsymbol{p}_{m,n}(t) - \boldsymbol{p}_{\mathrm{BS}}\|$ and $d_{m,n}^{\mathrm{User}}(t) = \|\boldsymbol{p}_{\mathrm{User}}(t) - \boldsymbol{p}_{m,n}(t)\|$ are the distance between the (m,n)-th element of the RIS and the BS, and the one between the user and the (m,n)-th element of the RIS, respectively. Besides, $G_{m,n}^{\mathrm{BS}}(t)$ is the gain of the (m,n)-th element of the RIS when the observation point is the BS, and $G_{m,n}^{\mathrm{User}}(t)$ is the gain of the (m,n)-th element of the RIS when the observation point is the user. Note that we assume $h_{\mathrm{BS}} \approx h_{\mathrm{User}} \approx h_{\mathrm{RIS}}$, thus the BS, the user and the center of the RIS can be assumed on the same plane. Therefore, $G_{m,n}^{\mathrm{BS}} \approx \frac{4\pi}{\lambda_c^2} ab\cos(\alpha)$ and $G_{m,n}^{\mathrm{User}}(t) \approx \frac{4\pi}{\lambda_c^2} ab\cos(\beta(t))$, where

$$\alpha = \arccos\left(\frac{z_{\mathrm{BS}}}{\|\boldsymbol{p}_{\mathrm{BS}}\|}\right) \in [0, \pi/2] \tag{6}$$

and

$$\beta(t) = \arccos\left(\frac{z_{\mathrm{User}}(t)}{\|\boldsymbol{p}_{\mathrm{User}}(t)\|}\right) \in [0, \pi/2], \tag{7}$$

as Fig. 2 shows. Besides, the relative position between the (m,n)-th element and the BS varies with the time t. Therefore, (5) can be rewritten as[2]

$$A_{m,n}(t) \approx \frac{ab}{4\pi d_{\mathrm{BS}}^{m,n}(t) d_{m,n}^{\mathrm{User}}(t)} \sqrt{\cos(\alpha)\cos(\beta(t))}, \tag{8}$$

It is clear that different from the conventional nonrotatable RIS, the RIS in this paper can be controlled by rotating the RIS $\gamma(t)$ degrees. That is to say, it is possible to find a rotation angle to maximize $A_{m,n}(t)$. However, it is important to note that the optimal rotation angle cannot be obtained. This is because we can only rotate the RIS $\gamma(t)$ degree once at each time t, but the RIS is with MN elements and each of them has its own optimal rotation angle. Therefore, we take the center of the RIS as the location of the element in the rotation angle optimization problem. It can be predicted that there are few losses by this assumption but still, the RIS can benefit from the rotation strategy.

Moreover, the time delays of the direct link and cascaded link at time t are

$$\tau_0(t) = \frac{d_0(t)}{c_0}, \tag{9}$$

and

$$\tau_{m,n}(t) = \frac{d_{\mathrm{BS}}^{m,n}(t) + d_{m,n}^{\mathrm{User}}(t)}{c_0}, \tag{10}$$

respectively. It is noteworthy that the nonrotatable [13] and the rotatable RIS cases have the same $\tau_0(t)$ but different $\tau_{m,n}(t)$, since the $\boldsymbol{p}_{m,n}(t)$ varies over time at the latter case.

[2]It is noteworthy that change of $d_{\mathrm{BS}}^{m,n}(t) d_{m,n}^{\mathrm{User}}(t)$ caused by the rotation is very limited. Thus, $d_{\mathrm{BS}}^{m,n}(t) d_{m,n}^{\mathrm{User}}(t) \approx d_1 d_{m,n}^{\mathrm{User}}(t)$, where d_1 is the distance between the nonrotatable RIS and the BS.

If $\phi_{m,n}(t) \in (0, 2\pi]$ denotes the continuous phase shift of the (m,n)-th element on the RIS, $\Theta_0(t) \triangleq e^{-\jmath 2\pi f_c \tau_0(t)}$ and $\Theta_{m,n}(t) \triangleq e^{-\jmath 2\pi f_c \tau_{m,n}(t) - \jmath \phi_{m,n}(t)}$ are the phase parts of the direct and the cascaded link parts, respectively. Thus, the received corresponding complex baseband signal is

$$y(t) = S_0(t)\Theta_0(t) + \sum_{m=1,n=1}^{m,n} S_{m,n}(t)\Theta_{m,n}(t) + w, \quad (11)$$

where

$$S_0(t) = A_0(t)\left\{\sqrt{P_t}x(t - \tau_0(t))\right\}, \quad (12)$$

and

$$S_{m,n}(t) = A_{m,n}(t)\left\{\sqrt{P_t}x(t - \tau_{m,n}(t) - \frac{\phi_{m,n}(t)}{2\pi f_c})\right\}. \quad (13)$$

Note that $x(t)$ is the transmit signal with $\mathbb{E}\{|x(t)|^2\} = 1$, P_t is fixed transmit power, f_c is carrier frequency, and w is a white Gaussian noise process with power spectral density N_0. We assume the RIS and the transceiver are all without hardware impairments in this paper.

III. Rotation Angle Optimization and Received Power Maximization

In this section, we first optimize $A_{m,n}(t)$ in (8) in order to maximize the instantaneous gain for the cascaded link. Based on the obtained optimal rotation angle, we then design the phase shift set that can maximize the received power.

A. Rotation Angle Optimization

Based on (8), if we want to maximize the instantaneous gain $A_{m,n}(t)$ of the cascaded link, we can either minimize $d_{\mathrm{BS}}^{m,n}(t)d_{m,n}^{\mathrm{User}}(t)$ or maximize $\cos(\alpha)\cos(\beta(t))$, or do both. However, minimizing $d_{\mathrm{BS}}^{m,n}(t)d_{m,n}^{\mathrm{User}}(t)$ is unrealistic, because 1) the locations of the BS, the RIS are almost static and 2) although rotating the RIS can change the $d_{\mathrm{BS}}^{m,n}(t)d_{m,n}^{\mathrm{User}}(t)$, the distance of the change is so small that can be omitted. Therefore, maximizing $\cos(\alpha)\cos(\beta(t))$ is an achievable choice to obtain $\max\{A_{m,n}(t)\}$.

Consider the BS and the starting point of the user has the same position, i.e., $x_0 = x_{\mathrm{BS}}$. Then, in order to maximize $\cos(\alpha)\cos(\beta(t))$, the RIS should be firstly rotated until $\beta(t) = \alpha$ at $t = 0$ s. Then, when the user leaves the BS at time t, we define $\psi(t) \triangleq \alpha + \beta(t)$. Note that $\psi(t)$ can be shown as a constant at time t. Therefore, maximizing the instantaneous channel gain for the cascaded link can be transformed into the optimization problem below.

$$\text{(P1)}: \quad \max_{\alpha(t),\beta(t)} \quad A_{m,n}(\alpha, \beta(t)) \quad (14)$$

$$\text{s.t.} \quad \alpha + \beta(t) = \psi(t), \quad (15)$$

Proposition 1: At time t, the solution of (P1) is

$$\beta(t) = \alpha = \frac{\psi(t)}{2} \quad (16)$$

Proof: We omit (t) for brevity. Since $\alpha + \beta = \psi$, we define $f(\alpha, \psi) \triangleq \cos(\alpha)\cos(\beta) = \cos(\alpha)\cos(\psi - \alpha)$. Then, $\frac{\partial}{\partial\alpha}f(\alpha,\psi) = -2\sin(\alpha)\cos(\alpha)\cos(\psi) + \sin(\psi)(\cos^2(\alpha) - \sin^2(\alpha))$. It can be shown that when $\psi = 2\alpha$, $\frac{\partial}{\partial\alpha}f(\alpha,\psi) = 0$. Besides, $\frac{\partial^2}{\partial\alpha^2}f(\alpha,\psi) = -4\cos(\alpha)\sin(\alpha)\sin(\psi) - 2\cos(\psi)(\cos^2(\alpha) - \sin^2(\alpha))$, and when $\psi = 2\alpha$, $\frac{\partial^2}{\partial\alpha^2}f(\alpha,\psi) = -2 < 0$. Therefore, $f(\alpha,\psi)$ has the maximal value when $\alpha = \beta = \psi/2$. Consider the definition of $A_{m,n}(t)$ in (8), we complete the proof. ■

Thus, if the RIS is already rotated towards the BS for maximizing the cascaded link gain at $t = 0$ s, then the optimal rotation angle $\gamma(t)$ at time t is

$$\gamma(t) = \frac{\alpha - \beta(t)}{2} \quad (17)$$

B. Received Power Maximization

RIS can align with the direct and the cascaded links [1]. Based on (11) and the optimized rotation angle (17), we can obtain the optimal phase shift is

$$\phi_{m,n}^{*}(t) = 2\pi\left\{f_c\big(\tau_0(t) - \tau_{m,n}(t)\big)\right\}. \quad (18)$$

However, this phase shift set does not work since $\tau_0(t) \le \tau_{m,n}(t)$. This is because the time delay of the cascaded link always equals or is larger than the direct link's [9]. Therefore, the practical phase shift should be designed as

$$\phi_{m,n}^{\mathrm{opt}}(t) = 2\pi\left\{f_c\big(\tau_0(t) - \tau_{m,n}(t)\big) + k_{m,n}^{\mathrm{opt}}(t)\right\}, \quad (19)$$

where $k_{m,n}^{\mathrm{opt}}(t) = \lceil f_c(\tau_{m,n}(t) - \tau_0(t))\rceil$, and $\lceil\cdot\rceil$ is the ceil function. Interestingly, the phase shift set $\phi_{m,n}^{\mathrm{opt}}(t)$ can not only maximize the received power but also remove the Doppler spread and mitigate delay spread simultaneously [13].

IV. Spectral Efficiency Analysis

In this section, we derive the spectral efficiency expression of the proposed rotatable RIS-assisted user communication system. In order to compute the SE, we use the phase shift set $\phi_{m,n}^{\mathrm{opt}}(t)$ in (19). By doing so, we can obtain the spectral efficiency as follow

$$\begin{aligned}\mathrm{SE}(t) &= \mathbb{E}\left\{\log_2\left\{1 + \frac{|y(t) - w|^2}{N_0}\right\}\right\} \\ &= \log_2\left\{1 + \frac{\mathcal{Q}}{N_0}\right\} \quad (20)\end{aligned}$$

where

$$\mathcal{Q} = \mathbb{E}\{|y(t) - w|^2\} = P_t \Big\{ A_0^2(t) + A^\star(t) + \sum_{m=1,n=1}^{M,N} A_{m,n}^2(t) + 2A_0(t) \sum_{m=1,n=1}^{M,N} A_{m,n}(t) \Big\}, \quad (21)$$

and

$$A^\star(t) = A_1(t) \sum_{k \neq 1}^{MN} A_j(t) + A_2(t) \sum_{k \neq 2}^{MN} A_k(t) + \cdots + A_{MN}(t) \sum_{k \neq MN}^{MN} A_k(t) \quad (22)$$

with $k = 1, \ldots, MN$.

Remark 1: It should be emphasized that the cascaded channel gain of every element of the rotatable RIS (8) is suboptimal maximized dynamically at every time t. Thus, for $A_{m,n}(t)$, the rotation angle $\gamma(t)$ is an extra degree of freedom to optimize, which does not consider in the nonrotatable RIS cases [5], [9], [13].

Special Case: If each element of the RIS is with nearly the same maximal gain $A_1(t)$, then we have

$$\mathrm{SE}_{A_1}(t) \approx \log_2 \Big\{ 1 + \frac{\hat{\mathcal{Q}}}{N_0} \Big\}, \quad (23)$$

where

$$\hat{\mathcal{Q}} \approx P_t \Big\{ A_0^2(t) + A_1^2(t)(MN)^2 + 2A_0(t)A_1(t)MN \Big\}. \quad (24)$$

Remark 2: If the direct link is blocked, then the received power $\hat{\mathcal{Q}} \approx A_1^2(t)(MN)^2$ is proportional to $(MN)^2$, which matches with the *square power law* in [3].

V. Simulations Results and Discussions

In this section, numerical examples are provided to validate the results in Section III and IV. Assuming the position of the BS is $\boldsymbol{p}_{\mathrm{BS}}(t) = [-10 \text{ m}, \ h_{\mathrm{BS}} \text{ m}, \ 5 \text{ m}]^{\mathrm{T}}$. For the position of the user, we consider it moves with the speed v m/s along the x-axis from $[-10 \text{ m}, h_{\mathrm{User}} \text{ m}, \ 5 \text{ m}]^{\mathrm{T}}$ to $[10 \text{ m}, h_{\mathrm{User}} \text{ m}, \ 5 \text{ m}]^{\mathrm{T}}$, and the total time is 10 s. Four benchmarks are considered: 1) without RIS, 2) the RIS without rotation (i.e., $\gamma(t)$ is always $0°$), 3) the rotatable RIS is always towards the BS with a fixed γ, and 4) the isotropic RIS on the road side [13]. Related parameters are shown in Table I. Besides, the realization number is 5×10^2.

TABLE I
SIMULATION PARAMETERS

Parameters	**Values**
BS height (h_{BS})	5 m
RIS height (h_{RIS})	5 m
user height (h_{User})	5 m
Speed of the user (v)	2 m/s
Start point of the user (x_0)	-10 m
Transmit power (P_t)	20 dBm
Power spectral density (N_0)	-96 dBm/Hz
Carrier frequency (f_c)	2.4 GHz
The number of elements on RIS ($M \times N$)	64 × 64
Rectangular grid spacing of the RIS (a, b)	$\lambda/(2\sqrt{\pi})$, $\lambda/(2\sqrt{\pi})$
Phase shift set of the RIS ($\phi_{m,n}^{\mathrm{opt}}(t)$)	(19)

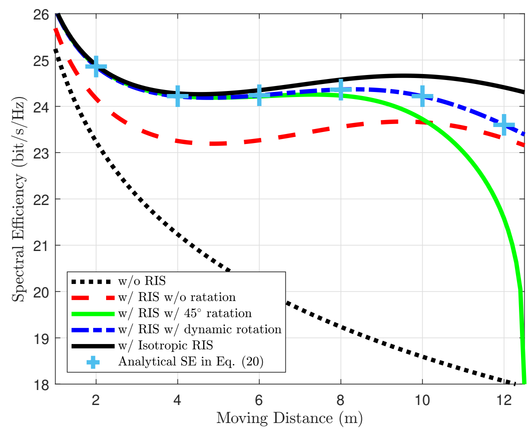

Fig. 3. SE of the RIS for one user pass.

A. Spectral Efficiency for One User Pass

Fig. 3 validates *Proposition 1*. Specifically, the isotropic RIS performs the best, because it is with $G_{m,n}^{\mathrm{BS}}(t) = G_{m,n}^{\mathrm{User}}(t) = 1$, which cannot be obtained in practice. The RIS with the dynamic rotation strategy, i.e., *Proposition 1*, is always with higher SE compared to the RIS with the fixed rotation angle. This is expected since the rotation angle $\gamma(t)$ can maximize the cascaded link gain dynamically at each time t. However, due to the approximation in (8), the dynamic rotation strategy is with some performance losses compared to the isotropic RIS. Interestingly, it can be seen that after a 10 m moving distance, the RIS with the fixed rotation angle performs worse than the nonrotatable RIS. This is because the RIS with a fixed rotation angle provides few effective areas when the user is far away from the BS. Consequently, after a 12.5 m moving distance, the RIS towards the BS is without any effective areas. Besides, the analytical SE result matches well with the simulation result.

B. Delay Spread for One User Pass

The delay spread of the RIS-assisted system can be expressed as $\max\{\tau_{m,n}(t) + \phi_{m,n}^{\mathrm{opt}}(t)/(2\pi f_c)\} - \tau_0(t)$ [9]. Fig. 4 shows the delay spread for one user pass with different numbers of total elements. It can be seen that the dynamic rotation can decrease delay spread. This is because the dynamic rotation is able to compensate for the cascaded link distance difference between the elements with different positions on the surface. This result unveils the fact that the delay spread can be mitigated not only by designing the phase shift of the RIS [9] but by rotating the RIS with a suitable angle.

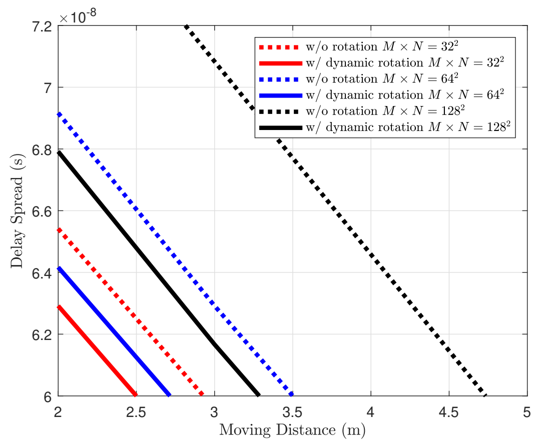

Fig. 4. Delay Spread for one user pass.

C. Rotation with Random Angle Errors

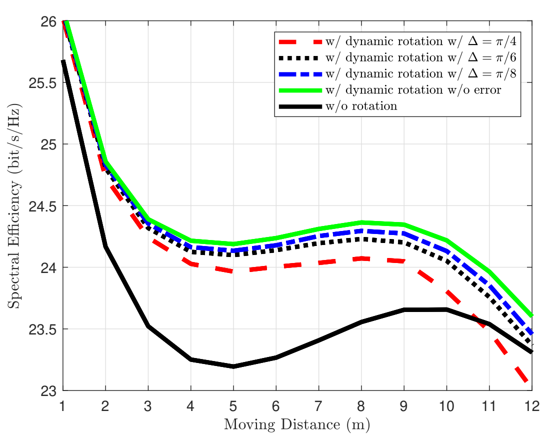

Fig. 5. SE of the rotatable RIS with rotation error for one user pass.

The above analysis and simulation results are all based on the assumption that the rotation angle $\gamma(t)$ is without any rotation errors, which is unrealistic in practice. Consider the time-invariant rotation angle error ζ follows uniform distribution, i.e., $\zeta \sim \mathcal{U}[-\Delta, \Delta]$. Therefore, the practical rotation angle is $\hat{\gamma}(t) = \gamma(t) + \zeta$. Fig. 5 shows the spectral efficiency for the user pass using $\hat{\gamma}(t)$. It can be observed that the spectral efficiency decreases when the rotation angle error ζ becomes serve. However, the spectral efficiency is still better than the case without rotation, even with the rotation error $\Delta = \pi/4$. This result shows the robustness and effectiveness of the proposed rotation strategy (17).

VI. Conclusion

In this paper, we have introduced the continuous-time propagation model with the rotatable RIS at first. Then, based on the model, we have formulated the rotation angle optimization problem and given the optimal rotation angle strategy to maximize the cascaded link gain. Besides, we have derived the expression of the spectral efficiency of the proposed system. Moreover, simulation results have validated all the results, and have shown the dynamic rotation strategy can not only mitigate delay spread but also endure the rotation errors. A rotatable RIS-assisted system in high-speed communications with hardware impairments and rotation errors considering Rician channels is left open for future work.

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