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Novel Multiple RIS-Assisted Communications for 6G Networks

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***Abstract*—As an emerging technique, reconfigurable intelligent surface (RIS) has recently received extensive attention and can be considered as a key enabling technology for future sixth generation (6G) wireless communication networks. In this letter, we propose a novel multiple RIS-assisted single-input-single-output (SISO) wireless communication system working in a domino pattern when obscuration is severe. The upper bound of the ergodic capacity and the outage probability for the proposed system are analyzed and the corresponding closed-form expressions are provided under Nakagami-m fading channels. The general multiple RIS-assisted systems including two RISs and K RISs are analyzed. Numerical results indicate that the number of RISs, the number of RIS elements, and the communication environment can significantly affect the upper bound of the ergodic capacity and the outage probability performance of the proposed system. The feasibility of the proposed system and the accuracy of the upper bound of the ergodic capacity and the outage probability are also verified by the numerical results.**

***Index Terms*—Ergodic capacity, multiple RISs, Nakagami-m fading, outage probability, reconfigurable intelligent surface.**

I. Introduction

Recently, a new technology named reconfigurable intelligent surface (RIS) has been heavily studied. The RIS can convert an uncontrollable wireless channel into a controllable entity, leading to additional transmission gain, especially when the direct link is blocked [1–3]. Different from the existing relaying technology, the RIS is passive and operates in a duplex mode with frequencies ranging from microwave to visible light [4]. Therefore, RIS is cost-efficient and energy-efficient, which is a potential enabling technology for future sixth generation (6G) wireless communication networks [5, 6].

A number of research results have been published on RIS. An overview of RIS technology was provided in [1]. The authors in [7] studied the RIS-assisted unmanned aerial vehicle (UAV) network. In [8], the authors studied the ergodic capacity and the outage probability of the RIS-assisted single-input-single-output (SISO) system in Rician fading channels. The authors in [9] proposed a hybrid system combining RIS and relaying, and studied the achievable data rate in different fading channels.

However, most researches on RIS have focused on the communication system assisted by a single RIS. When the density of obstacles is high in the environment, the high-frequency signals in 6G networks can be severely attenuated [5]. In this case, a single RIS may not be able to establish reliable communication between transceivers. Inspired by this, the authors in [10] proposed a double RIS-assisted communication system, and the joint passive beamforming design and the power scaling under the line-of-sight (LOS) channels were studied. The authors in [11] studied the multiple RIS-assisted communication system, and proposed the concept of cooperative beam routing to maximize the channel power. In this letter, we propose a multiple RIS-assisted multi-hop communication system, in which multiple RISs work in a domino pattern, i.e., the signals are transmitted serially through the intermediate RISs one by one. Note that RIS does not have residual loop-back self-interference or generate new additive noise [4]. Therefore, the proposed system is different from the conventional multiple relays cooperative systems, especially in terms of signal models and signal processing. The main contributions of this letter are provided as follows:

- First, the cascaded two RIS-assisted communication system is proposed. Compared with [10], the upper bound of the ergodic capacity and the outage probability under the Nakagami-m fading channels are provided in the closed-form containing only elementary functions.
- Second, the RIS-assisted system is generalized to K RISs, and a new RIS working pattern, i.e., the domino pattern, is designed for the first time.
- Finally, compared with [11], the impacts of the number of RISs and RIS elements on the ergodic capacity and the outage probability are studied using the closed-form expressions. Simulation results indicate that the domino pattern provides excellent performance when there is no direct communication path between two adjacent nodes. These results provide the guidance on the design of flexible and effective RIS-assisted communications.

The remainder of this letter is organized as follows. Section II presents the system model. The upper bound of the ergodic capacity and the outage probability under Nakagami-m fading

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channels are analyzed in Section III. Section IV provides the simulation results and theoretical analysis. Finally, this letter is concluded in Section V.

II. System Model

A three-hop communication system consisting of the source (S), two RISs (RIS1 and RIS2), and the destination (D) is shown in Fig. 1, where RIS1 and RIS2 are equipped with N_1 and N_2 elements respectively, S and D are each equipped with a single omnidirectional antenna. It is assumed that S-D, RIS1-D, and S-RIS2 do not have direct links due to obscuration. The system works in a time division duplex (TDD) way, where the S and D can communicate with each other in different time slots using channel reciprocity.

The channels of S→RIS1, RIS1→RIS2 and RIS2→D are defined as $\boldsymbol{h}^{SR_1} \in \mathbb{C}^{N_1\times 1}$, $\boldsymbol{H}^{R_1R_2} \in \mathbb{C}^{N_2\times N_1}$ and $\boldsymbol{h}^{R_2D} \in \mathbb{C}^{N_2\times 1}$, respectively. It is assumed that the distance between two RISs is much larger than the interval of each element. The received baseband signal at D can be expressed as

$$y = \sqrt{P_s}\left(\boldsymbol{h}^{R_2D^H}\boldsymbol{\Theta}^{(2)}\boldsymbol{H}^{R_1R_2}\boldsymbol{\Theta}^{(1)}\boldsymbol{h}^{SR_1}\right)x + n \quad (1)$$

where P_s is the transmit power, x is the data symbol with unit power, and n is the additive white Gaussian noise (AWGN) at D with zero mean and variance of σ_N^2. The phase shift matrices of RIS1 and RIS2 are denoted by $\boldsymbol{\Theta}^{(1)}$ and $\boldsymbol{\Theta}^{(2)}$, respectively. Under the unit-gain reflection coefficients assumption, $\boldsymbol{\Theta}^{(1)}$ and $\boldsymbol{\Theta}^{(2)}$ can be expressed as $\boldsymbol{\Theta}^{(1)} = \mathrm{diag}(e^{j\phi_1^{(1)}}, e^{j\phi_2^{(1)}}, \ldots, e^{j\phi_{N_1}^{(1)}})$ and $\boldsymbol{\Theta}^{(2)} = \mathrm{diag}(e^{j\phi_1^{(2)}}, e^{j\phi_2^{(2)}}, \ldots, e^{j\phi_{N_2}^{(2)}})$ [12, 13]. In this letter, we consider the performance of the system in the Nakagami-m fading channels. The elements in $\boldsymbol{h}^{SR_1}$, $\boldsymbol{H}^{R_1R_2}$ and $\boldsymbol{h}^{R_2D}$ can be further expressed as

$$h = \frac{1}{\sqrt{d^a}}\, g e^{j\theta} \quad (2)$$

where $h \in \{h_i^{SR_1}, h_{j,i}^{R_1R_2}, h_j^{R_2D}\}$ denotes the channel fading coefficient of S→RIS1, RIS1→RIS2, RIS2→D links for the i-th element of RIS1 and the j-th element of RIS2, $a \in \{a_{SR_1}, a_{R_1R_2}, a_{R_2D}\}$ and $d \in \{d_{SR_1}, d_{R_1R_2}, d_{R_2D}\}$ denote the path loss exponent and the distance between two adjacent nodes, respectively. The phase $\theta \in \{\theta_i^{SR_1}, \theta_{j,i}^{R_1R_2}, \theta_j^{R_2D}\}$ is uniformly distributed on $(0, 2\pi]$, and $g \in \{g_i^{SR_1}, g_{j,i}^{R_1R_2}, g_j^{R_2D}\}$ follows Nakagami-m distribution with probability density function (PDF) [14]

$$f_g(x) = \frac{2m^m}{\Gamma(m)\Omega^m}x^{2m-1}e^{-\frac{m}{\Omega}x^2} \quad (3)$$

where $\Gamma(\cdot)$ is the gamma function, $\Omega = \mathbb{E}\left[g^2\right]$ is the average power with $\mathbb{E}[\cdot]$ denoting expectation, and $m = \frac{\Omega^2}{\mathbb{E}\left[(g^2-\Omega)^2\right]}$ is the fading figure. In general, $m = 1$ represents the Rayleigh fading channel, and $m = \infty$ represents the additive white Gaussian noise channel without fading.

Therefore, the received signal at D can be rewritten as

$$y = \sqrt{P_s}\left(\sum_{i=1}^{N_1}\sum_{j=1}^{N_2} h_j^{R_2D} e^{j\phi_j^{(2)}} h_{j,i}^{R_1R_2} e^{j\phi_i^{(1)}} h_i^{SR_1}\right)x + n \quad (4)$$

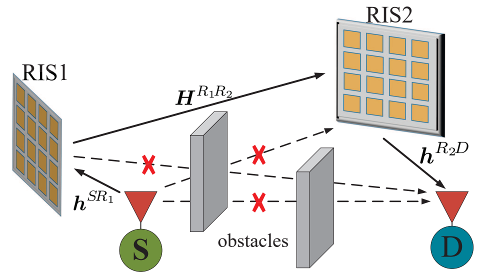

Fig. 1. Multiple RIS-assisted communication system with two RISs.

the signal-to-noise ratio (SNR) of the received signal at D can be given as

$$\rho = \frac{\left(\sum_{i=1}^{N_1}\sum_{j=1}^{N_2} h_j^{R_2D} e^{j\phi_j^{(2)}} h_{j,i}^{R_1R_2} e^{j\phi_i^{(1)}} h_i^{SR_1}\right)^2 P_s}{\sigma_N^2}. \quad (5)$$

It is assumed that perfect channel state information (CSI) is known and ideal passive beamforming is performed on RIS1 and RIS2 [15–17]. Therefore, the phases of RIS1 and RIS2 can satisfy the following condition [10]

$$\phi_i^{(1)} = -\arg(h_{j,i}^{R_1R_2}) - \arg(h_i^{SR_1}) \quad (6a)$$

$$\phi_j^{(2)} = -\arg(h_j^{R_2D}) \quad (6b)$$

where $\arg(\cdot)$ denotes the operation to extract the phase. The received SNR at D can be maximized by phase cancellation in (6). Then, (4) can be further simplified as

$$y = \sqrt{P_s}\left(\sum_{i=1}^{N_1}\sum_{j=1}^{N_2} |\, h_j^{R_2D} \,||\, h_{j,i}^{R_1R_2} \,||\, h_i^{SR_1} \,|\right)x + n \quad (7)$$

the maximum SNR at D can be obtained as

$$\rho_{\max} = \frac{\left(\sum_{i=1}^{N_1}\sum_{j=1}^{N_2} |\, h_j^{R_2D} \,||\, h_{j,i}^{R_1R_2} \,||\, h_i^{SR_1} \,|\right)^2 P_s}{\sigma_N^2} = \rho_0 A^2 \quad (8)$$

where $A = \sum_{i=1}^{N_1}\sum_{j=1}^{N_2} g_j^{R_2D} g_{j,i}^{R_1R_2} g_i^{SR_1}$ and $\rho_0 = P_s/(\sigma_N^2 d_{SR_1}^{a_{SR_1}} d_{R_1R_2}^{a_{R_1R_2}} d_{R_2D}^{a_{R_2D}})$ stands for the transmit SNR.

III. Performance Analysis

In this section, the upper bound of the ergodic capacity and the outage probability for the two RIS-assisted system under Nakagami-m fading channels will be analyzed, and then we generalize this RIS-assisted system with two RISs to the system with K RISs.

A. System with Two RISs

1) Ergodic Capacity: Through the above analysis of the statistics of the CSI, it is difficult to calculate directly the ergodic capacity $C = \mathbb{E}\left[\log_2\left(1+\rho_{\max}\right)\right]$. With the help of Jensen's inequality [18], the upper bound of the ergodic capacity C_{upper} can be obtained as [8]

$$C_{\text{upper}} = \log_2\left(1 + \mathbb{E}\left[\rho_{\max}\right]\right) \geq \mathbb{E}\left[\log_2\left(1+\rho_{\max}\right)\right]. \quad (9)$$

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The channel coefficients $g_i^{SR_1}$, $g_{j,i}^{R_1R_2}$ and $g_j^{R_2D}$ are independent Nakagami-m random variables, the mean and variance of their products are respectively as [14]

$$\mu = \left(\frac{\Gamma(m+0.5)\sqrt{\Omega}}{\Gamma(m)\sqrt{m}}\right)^3 \tag{10}$$

and

$$\sigma^2 = \Omega^3 \left(1 - \frac{1}{m^3}\left(\frac{\Gamma(m+0.5)}{\Gamma(m)}\right)^6\right). \tag{11}$$

It is assumed that RIS1 and RIS2 have a sufficient number of elements, i.e., $N_1 \gg 1$ and $N_2 \gg 1$, with the help of the central limit theorem (CLT), A defined in (8) converges to a Gaussian distributed random variable with parameters $\mu_A = N_1N_2\mu$ and $\sigma_A^2 = N_1N_2\sigma^2$. Then, the expectation of the received maximum SNR at D can be obtained as

$$\mathbb{E}[\rho_{\max}] = \rho_0 \left(N_1N_2\Omega^3 + N_1N_2\left(\frac{\Gamma(m+0.5)\sqrt{\Omega}}{\Gamma(m)\sqrt{m}}\right)^6 (N_1N_2-1)\right). \tag{12}$$

Consequently, the C_{upper} of the proposed system under Nakagami-m fading environments can be given in (13) at the top of next page. It is a closed-form expression for the upper bound of the ergodic capacity containing only elementary functions, which can efficiently evaluate the ergodic capacity performance of the two RIS-assisted system.

2) Outage Probability: Next, we will analyze the outage probability of this two RIS-assisted system, which is defined as the probability that the instantaneous SNR drops below a predetermined threshold ρ_{th} , it can be expressed as [8]

$$P_{\text{out}} = \Pr\left(\rho_{\max} \leq \rho_{\text{th}}\right) \tag{14}$$

or

$$P_{\text{out}} = \Pr\left(A \leq \sqrt{\frac{\rho_{\text{th}}}{\rho_0}}\right). \tag{15}$$

According to the analysis, it is known that A is the random variable following Gaussian distribution, i.e., $A \sim CN(\mu_A, \sigma_A^2)$. Exploiting the cumulative distribution function (CDF) of Gaussian distribution, the outage probability of the system can be given in (16) on next page, it is a closed-form expression containing only elementary functions.

B. System with Multiple RISs

We generalize this RIS-assisted system with two RISs to the system with K RISs. Due to dense obstacles, by deploying the RIS at each reflection point, the K RISs can work in a domino pattern, i.e., the signals are transmitted serially through the intermediate RISs one by one. Fig. 2 shows the special case when $K = 2$ and $K = 3$, that is, S communicates with D1 ($K=2$), S communicates with D2 ($K=3$). In the system with K RISs, we denote the link from the source to the first RIS as $\boldsymbol{h}^{SR}$, the link from the $(k-1)$-th RIS to the k-th RIS as $\boldsymbol{H}^{(l)}$, and the link from the K-th RIS to the destination as $\boldsymbol{h}^{RD}$ for $k = 2, 3, \ldots, K$ and $l = 2, 3, \ldots, K$. The received baseband signal at D can be given as

$$y = \sqrt{P_s}\left(\boldsymbol{h}^{RD^H} \prod_{\substack{k=2,\ldots,K\\ l=2,\ldots,K}} \left(\boldsymbol{\Theta}^{(k)}\boldsymbol{H}^{(l)}\right)\boldsymbol{\Phi}^{(1)}\boldsymbol{h}^{SR}\right)x + n \tag{17}$$

where $\boldsymbol{\Phi}^{(1)}$ is the phase shift matrix of the first RIS, and $\boldsymbol{\Theta}^{(k)}$ is the phase shift matrix of the k-th RIS for $k = 2, 3, \ldots, K$. If each RIS is equipped with N elements, after the phase cancellation, (17) can be rewritten as

$$y = \sqrt{P_s}\left(\sum_{i=1}^{N}\cdots\sum_{j=1}^{N} |\, h_j^{RD} \,|\cdots|\, h_i^{SR} \,|\right) x + n. \tag{18}$$

It is assumed that the distance between adjacent nodes is d_p for $p = 1, 2, \ldots, K+1$, and different links have the same path loss exponent a. Therefore, the maximum SNR at D can be obtained as follows

$$\rho_{\max} = \frac{\left(\sum_{i=1}^{N}\cdots\sum_{j=1}^{N} |\, h_j^{RD} \,|\cdots|\, h_i^{SR} \,|\right)^2 P_s}{\sigma_N^2} = \rho_1 B^2 \tag{19}$$

where $B = \sum_{i=1}^{N}\cdots\sum_{j=1}^{N} g_j^{RD}\cdots g_i^{SR}$, $\rho_1 = P_s/(\sigma_N^2 \prod_{p=1}^{K+1} d_p^a)$. If $N \gg 1$, consistent with the above analysis of the system with two RISs, B follows Gaussian distribution, and its mean and variance can be given as follows

$$\mu_A = N^K\left(\frac{\Gamma(m+0.5)\sqrt{\Omega}}{\Gamma(m)\sqrt{m}}\right)^{K+1} \tag{20}$$

and

$$\sigma_B^2 = N^K\Omega^{K+1}\left(1 - \frac{1}{m^{K+1}}\left(\frac{\Gamma(m+0.5)}{\Gamma(m)}\right)^{2(K+1)}\right). \tag{21}$$

After algebraic operations, the upper bound of ergodic capacity for the multiple RIS-assisted system with K RISs can be given in (22), where C_{upper} is mainly dominated by the term $N^K(N^K-1)$. This is consistent with [10] that the power gain of the double RIS-assisted system (i.e., $K=2$) is proportional to N^4. Therefore, a preliminary conclusion can be drawn that increasing the number of RISs or the number of RIS elements can bring a significant improvement in the ergodic capacity. Subsequently, the outage probability of the multiple RIS-assisted system can be given as (23). With the increase of K and N, the outage probability P_{out} is mainly dominated by the term $\sqrt{N^K}$. By increasing the number of RISs or the number of RIS elements, it is possible to maintain a reliable communication, especially for systems with severe obscuration and for cell-edge users. Note that maintaining this reliable communication comes at the cost of increased system complexity. For both channel estimation and the phase shift adjustment of the RIS elements, the number of channels to be processed in the system increases linearly with the number of RISs and the quadratic of the number of RIS elements, i.e., $2N + (K-1)N^2$. For $K \geq 1$, the system complexity in the domino working pattern is about $\mathcal{O}(KN^2)$.

IV. Simulation Results

The theoretical results are verified with computer simulations in this section. The geometry for simulation is shown in Fig. 2, which shows the special cases of the system with two RISs (S→RIS1→RIS2→D1) and three RISs (S→RIS1→RIS2→RIS3→D2). The source is located at the origin, i.e. S = $(0, 0)$, and RIS1 = $(80, 10)$, RIS2 = $(180, 0)$,

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$$C_{\text{upper}} = \log_2\left(1+\rho_0\left(N_1N_2\Omega^3 + N_1N_2\left(\frac{\Gamma(m+0.5)\sqrt{\Omega}}{\Gamma(m)\sqrt{m}}\right)^6(N_1N_2-1)\right)\right). \tag{13}$$

$$P_{\text{out}} = 0.5+0.5\,\text{erf}\left(\left(\sqrt{\frac{\rho_{\text{th}}}{\rho_0}} - N_1N_2\left(\frac{\Gamma(m+0.5)\sqrt{\Omega}}{\Gamma(m)\sqrt{m}}\right)^3\right)\Big/\sqrt{2N_1N_2\Omega^3\left(1-\frac{1}{m^3}\left(\frac{\Gamma(m+0.5)}{\Gamma(m)}\right)^6\right)}\right). \tag{16}$$

$$C_{\text{upper}} = \log_2\left(1+\rho_1\left(N^K\Omega^{K+1} + N^K\left(\frac{\Gamma(m+0.5)\sqrt{\Omega}}{\Gamma(m)\sqrt{m}}\right)^{2(K+1)}(N^K-1)\right)\right). \tag{22}$$

$$P_{\text{out}} = 0.5+0.5\text{erf}\left(\left(\sqrt{\frac{\rho_{\text{th}}}{\rho_1}} - N^K\left(\frac{\Gamma(m+0.5)\sqrt{\Omega}}{\Gamma(m)\sqrt{m}}\right)^{K+1}\right)\Big/\sqrt{2N^K\Omega^{K+1}\left(1-\frac{1}{m^{K+1}}\left(\frac{\Gamma(m+0.5)}{\Gamma(m)}\right)^{2(K+1)}\right)}\right). \tag{23}$$

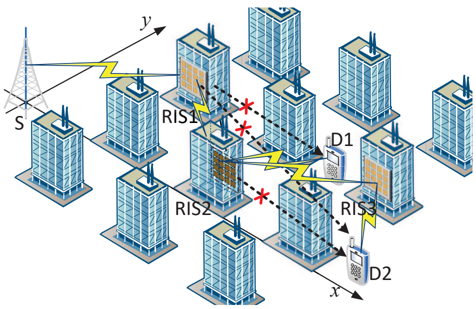

Fig. 2. Simulation environment.

D1 = $(200, 10)$, RIS3 = $(200, 10)$ and D2 = $(220, 0)$. Unless otherwise specified, the Nakagami-m distribution parameters $m = 6.0$, $\Omega = 1.0$, the path loss exponent $a = 2.0$, all paths have the same path loss exponent, all RISs have the same number of elements N, and the outage threshold $\rho_{\text{th}} = 10$ dB. Finally, the system works at a bandwidth of 180 KHz, and the noise power spectral density is -173 dBm/Hz [8]. The results are normalized by $10,000$ Monte Carlo simulations.

Fig. 3 shows the ergodic capacity in a wide SNR range with different N under different fading channel conditions when the system is equipped with two RISs. It can be found that the theoretical value of the upper bound of the ergodic capacity is consistent with the simulated value, which verifies the accuracy of (13). It is noted that when $N = 4$, there is a slight deviation between the theoretical value and the simulated value. This is because when the number of RIS elements is small, CLT will incur large approximation error. With the improvement of the channel environment and the increase in the number of RIS elements, the ergodic capacity has been significantly improved.

In Fig. 4, we show the outage probability of the two RIS-assisted system with different numbers of RIS elements under different fading channel conditions. Similarly, the theoretical value and simulated value are also consistent, which verifies the accuracy of (16). We can find that the outage probability when $m = 6.0$ is lower than that when $m = 2.0$, that is,

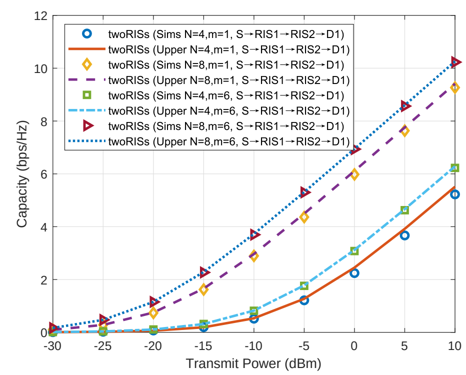

Fig. 3. Ergodic capacity vs transmit power with different N under different channels.

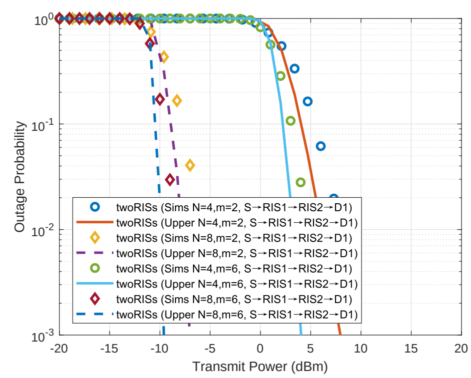

Fig. 4. Outage probability vs transmit power with different N under different channels.

better channel conditions can make the communications more robust. Moreover, as the transmit power increases, the outage probability decreases rapidly, and the decreasing rate is faster with a larger number of RIS elements.

Fig. 5 shows the variation of ergodic capacity with transmit power when RIS3 is deployed to provide additional path, in the case that RIS1 and RIS2 cannot directly communicate with

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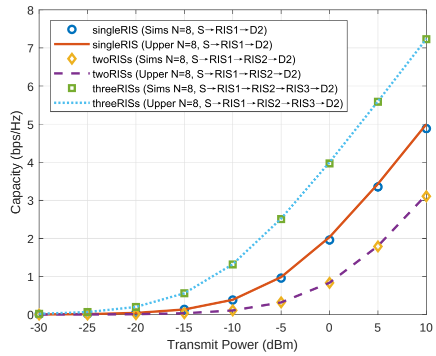

Fig. 5. Ergodic capacity vs transmit power when there is no path for RIS1→D2 and RIS2→D2.

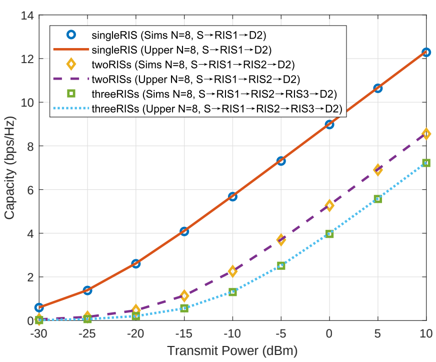

Fig. 6. Ergodic capacity vs transmit power when there are paths for RIS1→D2 and RIS2→D2.

D2 due to obscuration. The channel parameters of RIS1→D2 and RIS2→D2 are $m = 1.0$ and $a = 3.0$. It can be seen that the additional path provided by the RIS3 has greatly improved the ergodic capacity.

Fig. 6 shows the variation of ergodic capacity with transmit power when RIS3 is deployed. Different from Fig. 5, there are direct paths for RIS1→D2 and RIS2→D2, i.e., $m = 6.0$, $a = 2.0$. We can observe that the performance of the S→RIS1→D2 scheme is better than that of the S→RIS1→RIS2→D2 and S→RIS1→RIS2→RIS3→D2 schemes, because the multiplicative path loss between the nodes deteriorates received signal power [4]. Finally, it is concluded that in the domino pattern, when there is no direct communication path between two adjacent nodes, increasing the number of RISs will significantly improve system performance.

V. Conclusions

The multiple RIS-assisted wireless communications under the Nakagami-m channel fading environments have been investigated in this letter. The concise closed-form expressions for the upper bound of the ergodic capacity and the outage probability with two RISs have been derived. Those expressions have been generalized to the RIS-assisted communication system with K RISs. The simulation results have shown that in the domino pattern, when there is no direct communication path between two adjacent nodes, increasing the number of RISs or the number of RIS elements will significantly improve system performance. These results can make the deployment of RIS more flexible and provide useful guidance for the design of practical RIS systems.

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