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# Reconfigurable Intelligent Surface-Based Quadrature Reflection Modulation

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**Abstract**—Reflection modulation based on reconfigurable intelligent surface (RIS) is considered to be a promising information transfer mechanism that conveys information by reconfiguring incident electromagnetic waves without using radio frequency chains. Existing reflection modulation schemes propose to convey additional information by manipulating the ON/OFF states of reflecting elements, which underuse the potential of the RIS. In this paper, we first propose a new reflection modulation scheme, called RIS-based quadrature reflection modulation (RIS-QRM), to achieve joint passive beamforming and information transfer for RIS-aided single-input single-output wireless communications by assuming that the direct link between the transceivers is blocked. We then extend the RIS-QRM scheme to the multiple-input single-output setting with the direct link between transceivers being taken into account. In this case, an optimization problem is formulated to jointly optimize the active beamforming and the phase shifts of the RIS in order to improve the received signal power at the user. Computer simulation results corroborate the effectiveness of the RIS-QRM scheme. It is shown that in contrast to ON/OFF-based schemes, the RIS-QRM scheme is able to improve the error performance of the additional bits delivered by the RIS without deteriorating that of the bits carried by the constellation symbols.

## I. INTRODUCTION

Reconfigurable intelligent surfaces (RISs) have been envisioned as a promising technology for beyond fifth-generation networks [1]. Specifically, an RIS is a planar surface composed of numerous passive elements, each being a reconfigurable scatterer that reflects the incoming signal with a adjustable phase shift. By properly adjusting the phase shifts, the reflected signals can be added constructively with the signal from the direct path at the receiver to improve the signal-to-noise ratio (SNR) or destructively to mitigate interference/eavesdropping. In the literature, this is referred to as passive beamforming. The advantages of RISs, such as enhancing the communication performance and reducing the energy consumption, have motivated a variety of RIS-aided wireless communication systems, e.g., [2]–[7].

Spatial modulation (SM), which activates only one transmit antenna per time slot to convey one constellation symbol

and embeds additional information in the index of the active antenna, has been receiving significant attention as it is capable of striking an attractive tradeoff between the energy efficiency and the spectral efficiency [8], [9]. A recent generalization is to implement SM by an RIS [10]. In [11], the author proposed to carry out SM on receive antenna indices by an RIS that steers a beam towards a particular receive antenna according to the input information bits. In [12], the authors proposed a passive beamforming and information transfer (PBIT) scheme in which an RIS is used to improve communication performance in the uplink direction and simultaneously deliver additional information via the ON/OFF states of its elements. In order to minimize the communication outage probability, the authors of [13] proposed an RIS-based reflection pattern modulation (RIS-RPM) scheme to achieve PBIT, where the number of RIS elements that are switched ON is fixed at all time slots.

Existing reflection modulation schemes [12]–[14] use the ON/OFF states of the RIS elements to carry additional information and therefore have two main drawbacks. Firstly, since only a portion of the available RIS elements are switched ON, the potential performance improvement offered by an RIS is underused, resulting in relatively low received signal power levels. Secondly, due to the inherent randomness of the RIS configuration that depends on the incoming random bits, the joint optimization of the beamforming at the transceivers and the RIS configuration is a stochastic optimization problem that is difficult to solve in general. To address the above issues, we consider in this paper an RIS-aided downlink multiple-input single-output (MISO) wireless system, and propose a new reflection modulation scheme, referred to as RIS-aided quadrature reflection modulation (RIS-QRM), to achieve PBIT by considering the full reflection capabilities of the RIS. We first consider the single-input single-output (SISO) setting and present the principle of the RIS-QRM scheme. Specifically, all the reflecting elements at the RIS are randomly partitioned into two subsets according to the RIS local data: (i) the phase shifts of the elements in the first subset are tuned to  $-\theta$  and (ii) the phase shifts of the elements in the second subset are tuned to  $-\theta + \pi/2$ , where  $\theta$  is the phase of the cascaded channel associated with the corresponding reflecting element. In this manner, the RIS element partition carries the local data of the RIS. We then extend the RIS-QRM principle to the general MISO setting by taking the direct

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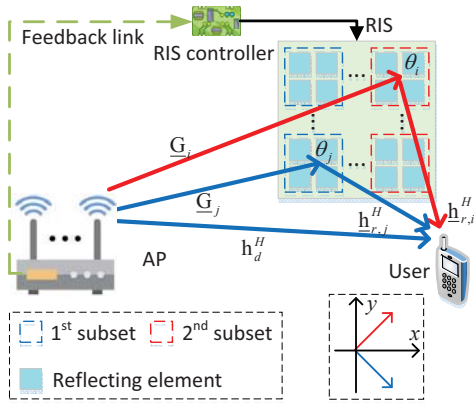


Fig. 1. An illustration of the proposed RIS-QRM system, where the RIS focuses reflected signals towards the user while conveying additional information by the RIS element partition. By adjusting the phase shifts at the RIS, the signals reflected by the first subset differ from those by the second subset by a relative phase shift of  $\pi/2$ .

link between the transceivers into account. In this case, we formulate an optimization problem to jointly optimize the active beamforming at the access point (AP) and the phase shifts of the RIS to improve the received signal power at the user. Extensive computer simulation results are presented to corroborate the effectiveness of the proposed RIS-QRM scheme. In particular, compared to the RIS-RPM scheme, the RIS-QRM scheme is able to improve the error performance of the additional bits delivered by the RIS without deteriorating that of the bits carried on the constellation symbols.

*Notation:* Superscripts  $\dagger$ ,  $T$ , and  $H$  represent complex conjugate, transpose, and Hermitian transpose operations, respectively.  $\mathbf{1}_{n \times m}$  denotes an all-one matrix of size  $n \times m$ .  $|\cdot|$  denotes the absolute value. For a complex-valued vector  $\mathbf{x}$ ,  $\angle \mathbf{x}$  denotes a column vector with the elements being the phases of the elements in  $\mathbf{x}$ , and  $\text{diag}(\mathbf{x})$  denotes a diagonal matrix with the elements in  $\mathbf{x}$  on its main diagonal.  $\lfloor \cdot \rfloor$  returns the largest integer less than or equal to the argument.  $\binom{\cdot}{\cdot}$  denotes the binomial coefficient.  $\mathbb{A} \setminus \mathbb{B}$  denotes the relative complement of set  $\mathbb{B}$  in set  $\mathbb{A}$ .  $\mathbb{E}[\cdot]$  denotes the expectation.

## II. SYSTEM MODEL AND OVERVIEW OF EXISTING REFLECTION SCHEMES

### A. System Model

As illustrated in Fig. 1, we consider a downlink RIS-aided MISO wireless system, where an RIS consisting of  $L_0$  reflecting elements is deployed to assist the transmission from an AP equipped with  $N$  transmit antennas to a single-antenna user located in its proximity. To reduce the channel estimation overhead and implementation complexity, we recall the RIS-elements grouping method introduced in [15], where the  $L_0$  RIS elements are divided into  $L$  groups, denoted by  $\mathbb{L} \triangleq \{1, 2, \dots, L\}$ , each consisting of  $L_1 = L_0/L$  adjacent elements that have the same reflection coefficient. Moreover, the RIS is connected to a smart controller, which is responsible for exchanging information between the AP and RIS via a feedback link and for the dynamic adjustment on the reflection

of each RIS element. We consider that the RIS is inherently equipped with sensors for monitoring/collecting environmental data (typically low-rate bursty data). Therefore, the RIS needs to report sensed data to the user.

We consider a quasi-static block fading channel model for all individual links, where the channel coefficients remain constant within each fading block and are independent and identically distributed across different fading blocks. Without loss of generality, we focus on the downlink communication in one particular fading block. Let  $\mathbf{h}_d^H \in \mathbb{C}^{1 \times N}$  denote the baseband channel of the AP  $\rightarrow$  user direct link. Let  $\mathbf{G} \in \mathbb{C}^{L_0 \times N} \triangleq [\mathbf{G}_1^H, \mathbf{G}_2^H, \dots, \mathbf{G}_L^H]^H$  and  $\mathbf{h}_r^H \in \mathbb{C}^{1 \times L_0} \triangleq [\mathbf{h}_{r,1}^H, \mathbf{h}_{r,2}^H, \dots, \mathbf{h}_{r,L}^H]$  denote the elementwise baseband channels of the AP  $\rightarrow$  RIS and RIS  $\rightarrow$  user links, respectively, where  $\mathbf{G}_l \in \mathbb{C}^{L_1 \times N}$  and  $\mathbf{h}_{r,l}^H \in \mathbb{C}^{1 \times L_1}$  with  $l = 1, 2, \dots, L$  denote the corresponding elementwise baseband channels associated with the  $l$ -th group. Let  $\boldsymbol{\theta} \triangleq [\beta_1 e^{j\theta_1}, \beta_2 e^{j\theta_2}, \dots, \beta_L e^{j\theta_L}]^H$  denote the reflection coefficients of the  $L$  groups, where  $j = \sqrt{-1}$ ,  $\beta_l \in [0, 1]$  and  $\theta_l \in [0, 2\pi)$  denote the common reflection amplitude and phase shift of the RIS elements in group  $l$ , respectively. For maximizing the reflection power of the RIS and simplifying its hardware design, the reflection amplitude of each RIS element is set to be the maximum value, i.e.,  $\beta_l = 1, \forall l = 1, 2, \dots, L$ . Accordingly, the baseband received signal at the user is given by

$$\underline{y} = \left( \sum_{l=1}^L \mathbf{h}_{r,l}^H e^{j\theta_l} \mathbf{G}_l + \mathbf{h}_d^H \right) \mathbf{w}x + n \quad (1)$$

where  $\mathbf{w} \in \mathbb{C}^{N \times 1}$  is the digital beamforming vector at the AP,  $x$  is the transmitted signal with power  $P$ , and  $n \sim \mathcal{CN}(0, N_0)$  is the additive white Gaussian noise (AWGN) with noise power  $N_0$ . The transmitted signal  $x$  is drawn from an  $M$ -ary signal constellation, such as the pulse amplitude modulation (PAM), denoted by the set  $\mathbb{M}$  of size  $M$ . Let  $\mathbf{h}_l^H = \mathbf{h}_{r,l}^H \mathbf{G}_l \in \mathbb{C}^{1 \times N}$  with  $l = 1, 2, \dots, L$  denote the effective (aggregated) channel for the AP  $\rightarrow$  group  $l \rightarrow$  user cascaded link in the absence of the corresponding reflection coefficient. Therefore, we have

$$\begin{aligned} \underline{y} &= \left( \sum_{l=1}^L e^{j\theta_l} \mathbf{h}_l^H + \mathbf{h}_d^H \right) \mathbf{w}x + n \\ &= (\boldsymbol{\theta}^H \mathbf{H} + \mathbf{h}_d^H) \mathbf{w}x + n \end{aligned} \quad (2)$$

where  $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \dots, \mathbf{h}_L]^H \in \mathbb{C}^{L \times N}$  denotes the AP-RIS-user cascaded channel matrix in the absence of reflection coefficients. Accordingly, the received SNR is given by

$$\text{SNR} = \frac{P}{N_0} |(\boldsymbol{\theta}^H \mathbf{H} + \mathbf{h}_d^H) \mathbf{w}|^2. \quad (3)$$

For simplicity, we assume in this paper that the perfect channel state information (CSI) of  $\mathbf{H}$  and  $\mathbf{h}_d^H$  is available at the AP.

### B. Overview of Existing Reflection Schemes

A proper RIS configuration based on CSI has a great impact on the communication performance between the AP and the user. To be specific, when the phase shifts of the  $L$  groups are

properly adjusted, the reflected signals by the groups are added constructively (with the signal coming directly from the AP) at the user, thus achieving the maximum SNR. This is referred to as passive beamforming. An RIS, however, despite its functionality of enabling the maximum received SNR, is unable to convey any information of its own. To deliver additional information, the PBIT scheme adjusts the ON/OFF state of each group according to the incoming random bits, while the RIS-RPM scheme intentionally switches off a fixed number of groups. Both schemes perform passive beamforming based on a portion of the available RIS elements, thus inevitably suffering from a received power/SNR loss.

### III. PRINCIPLE OF RIS-QRM

To give an intuitive idea of the operating principle of RIS-QRM, in this section, we assume that the AP is equipped with only one transmit antenna, i.e.,  $N = 1$  with  $\mathbf{G} \equiv \mathbf{g} = [\mathbf{g}_1^H, \mathbf{g}_2^H, \dots, \mathbf{g}_L^H]^H$  and  $\mathbf{H} \equiv \mathbf{h} = [h_1, h_2, \dots, h_L]^H$ . Moreover, we assume that the AP→user direct link is blocked due to obstructions, i.e.,  $\mathbf{h}_d^H \equiv h_d^\dagger = 0$ . We extend the RIS-QRM design to the MISO setting with the AP→user direct link being taken into account in the next section. The baseband received signal in (2) is now expressed as

$$\underline{y} = \boldsymbol{\theta}^H \underline{\mathbf{h}}x + n \quad (4)$$

and thus the preferred phase shifts<sup>1</sup> for achieving coherent signal combination at the user are given by

$$\boldsymbol{\theta}^* \triangleq [\theta_1^*, \theta_2^*, \dots, \theta_L^*] = \angle \underline{\mathbf{h}}. \quad (5)$$

For implicitly conveying the RIS information, the  $L$  groups are randomly partitioned into two subsets: the phase shifts of the first subset with  $p$  groups are tuned to their corresponding preferred phase shifts such that the reflected signals via these  $p$  groups are in phase, while the phase shifts of the second subset with the remaining  $L - p$  groups are tuned to their corresponding preferred phase shifts plus  $\pi/2$  so that the reflected signals via the remaining  $L - p$  groups are in quadrature with those reflected via the first subset. By design, given  $L$  and  $p$ , there are  $\binom{L}{p}$  group-partition realizations. This implies that at most  $b = \lfloor \log_2 \binom{L}{p} \rfloor$  information bits of the RIS can be conveyed by group partitioning. Let  $\mathbb{B} \triangleq \{\mathbb{B}_1, \mathbb{B}_2, \dots, \mathbb{B}_B\}$  denote arbitrary  $B = 2^b$  group-partition realizations, where  $\mathbb{B}_k \triangleq \{\mathbb{I}_k, \mathbb{L} \setminus \mathbb{I}_k\}$  denotes the  $k$ -th group-partition realization with  $\mathbb{I}_k$  representing the indices of the  $p$  (in-phase) groups and  $\mathbb{L} \setminus \mathbb{I}_k$  representing the indices of the remaining  $L - p$  groups,  $k = 1, 2, \dots, B$ . According to the incoming random bits, one group-partition realization is selected, e.g.,  $\{\mathbb{I}, \mathbb{L} \setminus \mathbb{I}\} \in \mathbb{B}$ , such that the phase shift of the RIS elements in the  $l$ -th group ( $l = 1, 2, \dots, L$ ) is given by

$$\phi_l = \begin{cases} \theta_l^*, & l \in \mathbb{I} \\ \theta_l^* + \pi/2, & l \in \mathbb{L} \setminus \mathbb{I} \end{cases} \quad (6)$$

<sup>1</sup>The AP feedbacks the preferred phase shifts to the RIS which adjusts the reflections of its elements accordingly.

Accordingly, the RIS configuration that carries its own information bits can be expressed as

$$\boldsymbol{\phi} \triangleq [e^{j\phi_1}, e^{j\phi_2}, \dots, e^{j\phi_L}]^H = \text{diag}(\boldsymbol{\theta}^*)\mathbf{s} \quad (7)$$

where  $\mathbf{s} \triangleq [s_1, s_2, \dots, s_L]^H$  carries the RIS information with each entry given by

$$s_l = \begin{cases} 1, & l \in \mathbb{I} \\ j, & l \in \mathbb{L} \setminus \mathbb{I} \end{cases}, \quad l = 1, 2, \dots, L. \quad (8)$$

Let  $\mathbb{S} \triangleq \{\mathbf{s}_1, \mathbf{s}_2, \dots, \mathbf{s}_B\}$  denote the set of all possible realizations of  $\mathbf{s}$ . With the information embedded in the RIS configuration, the baseband received signal at the user is given by

$$y = \boldsymbol{\phi}^H \underline{\mathbf{h}}x + n = \mathbf{s}^H \text{diag}(\boldsymbol{\theta}^*)^H \underline{\mathbf{h}}x + n. \quad (9)$$

Define  $\mathbf{v} \triangleq [v_1, v_2, \dots, v_L]^H = \text{diag}(\boldsymbol{\theta}^*)^H \underline{\mathbf{h}}$ , where  $v_l = |h_l|$  denotes the effective cascaded channel from the AP to the user via the  $l$ -th group with the preferred phase shift,  $l = 1, 2, \dots, L$ . Then, we have

$$y = \mathbf{s}^H \mathbf{v}x + n = \left( \sum_{l \in \mathbb{I}} v_l + j \sum_{l \in \mathbb{L} \setminus \mathbb{I}} v_l \right) x + n. \quad (10)$$

Suppose that the CSI of  $\mathbf{v}$  is perfectly known at the user, which can be obtained by downlink pilot training. Then, the maximum-likelihood (ML) estimate of  $\langle x, \mathbf{s} \rangle$  is given by

$$\langle \hat{x}, \hat{\mathbf{s}} \rangle = \arg \min_{x \in \mathbb{M}, \mathbf{s} \in \mathbb{S}} |y - \mathbf{s}^H \mathbf{v}x|^2. \quad (11)$$

It is worth pointing out that although the proposed RIS-QRM scheme has the same spectral efficiency as the RIS-RPM scheme (i.e.,  $b + \log_2 M$ ), the former improves the received power by reactivating the inactive elements of the latter, thus increasing the achievable rate in the low SNR regime.

### IV. EXTENSION TO MISO SETTING

We extend the RIS-QRM design for the SISO setting to the MISO case with the AP→user direct link being taken into account. In this more general case, the active beamforming at the AP needs to be appropriately designed to improve the communication performance together with the passive beamforming at the RIS. Specifically, we jointly optimize the active beamforming at the AP and the phase shifts of the RIS based on the CSI of  $\mathbf{H}$  and  $\mathbf{h}_d^H$  to improve the received signal power at the user. Note that this is effective in improving the error performance of the bits carried on  $x$  as well as  $\mathbf{s}$ , as it will be shown in the simulation results.

1) *Joint Active and Passive Beamforming*: Our objective is to maximize the received signal power at the user by jointly optimizing the active beamforming at the AP and phase shifts of the RIS, subject to the power budget of the AP and the unit-modulus reflection constraint of the RIS. The optimization problem is formulated as follows.

$$(P1): \max_{\mathbf{w}, \boldsymbol{\theta}} \left| (\boldsymbol{\theta}^H \mathbf{H} + \mathbf{h}_d^H) \mathbf{w} \right|^2 \quad (12)$$

$$\text{s.t. } \|\mathbf{w}\|^2 \leq 1 \quad (13)$$

$$0 \leq \theta_l < 2\pi, \quad l = 1, 2, \dots, L. \quad (14)$$

It is easily verified that this problem is always feasible, since there exists at least one solution that satisfies the constraints in (13) and (14), e.g.,  $\boldsymbol{\theta} = \mathbf{1}_{L \times 1}$  and  $\mathbf{w} = \frac{(\mathbf{1}_{1 \times L} \mathbf{H} + \mathbf{h}_d^H)^H}{\|\mathbf{1}_{1 \times L} \mathbf{H} + \mathbf{h}_d^H\|}$ . However, it is non-convex since the objective function in (12) is not jointly concave with respect to  $\mathbf{w}$  and  $\boldsymbol{\theta}$ , and the unit-modulus constraint in (14) is non-convex. This problem can be suboptimally solved by leveraging the alternating optimization (AO) technique. Specifically, based on the triangle inequality, we have

$$|(\boldsymbol{\theta}^H \mathbf{H} + \mathbf{h}_d^H) \mathbf{w}| \leq |\boldsymbol{\theta}^H \mathbf{H} \mathbf{w}| + |\mathbf{h}_d^H \mathbf{w}| \quad (15)$$

which holds with equality if and only if  $\angle \boldsymbol{\theta}^H \mathbf{H} \mathbf{w} = \angle \mathbf{h}_d^H \mathbf{w}$ . Note that since the received signal power increases monotonically with the transmit power (i.e.,  $P \|\mathbf{w}\|^2$ ), the inequality constraint in (13) needs to be met with equality at the optimal solution, i.e.,  $\|\mathbf{w}^*\|^2 = 1$ . Therefore, for a fixed active beamforming direction  $\mathbf{w}$ , problem (P1) is equivalent to the following optimization problem.

$$\text{(P2): } \max_{\boldsymbol{\theta}} |\boldsymbol{\theta}^H \mathbf{H} \mathbf{w}|^2 \quad (16)$$

$$\text{s.t. } 0 \leq \theta_l < 2\pi, \quad l = 1, 2, \dots, L \quad (17)$$

$$\angle \boldsymbol{\theta}^H \mathbf{H} \mathbf{w} = \angle \mathbf{h}_d^H \mathbf{w}. \quad (18)$$

The optimal solution to problem (P2) is given by  $\boldsymbol{\theta} = e^{j(\angle \mathbf{H} \mathbf{w} - \angle \mathbf{h}_d^H \mathbf{w})}$ , where the preferred phase shift of the RIS elements in the  $l$ -th group is given by

$$\theta_l = \angle \mathbf{h}_d^H \mathbf{w} - \angle \mathbf{h}_l^H \mathbf{w}, \quad l = 1, 2, \dots, L. \quad (19)$$

Then, for a given  $\boldsymbol{\theta}$  in (19), the optimal  $\mathbf{w}$  is the well-known maximum-ratio transmission (MRT) solution, i.e.,  $\mathbf{w} = \frac{(\boldsymbol{\theta}^H \mathbf{H} + \mathbf{h}_d^H)^H}{\|\boldsymbol{\theta}^H \mathbf{H} + \mathbf{h}_d^H\|}$ .  $\boldsymbol{\theta}$  and  $\mathbf{w}$  are alternately optimized until the fractional increase of (12) is less than a sufficiently small value  $\epsilon > 0$  or the maximum number of iterations, denoted by  $\zeta$ , is reached. The iterative process is summarized in Algorithm 1. We note that this iterative process is guaranteed to converge since the objective value in (12) is non-decreasing over the iterations and the optimal objective value is upper-bounded.

2) *Reflection Modulation Design:* We assume to use the optimal active beamforming and phase shifts obtained from problem (P1), denoted by  $\mathbf{w}^*$  and  $\boldsymbol{\theta}^*$ . Note that the preferred phase shifts in (19) make the signals from the AP to the user via the RIS in phase with the signal over the AP→user direct link so as to achieve coherent signal combination at the user. For implicitly conveying the RIS information, the  $L$  groups are randomly partitioned into two subsets: the phase shifts of the first subset with  $p$  groups are tuned to their corresponding preferred phase shifts, while the phase shifts of the second subset with the remaining  $L - p$  groups are tuned to their corresponding preferred phase shifts plus  $\pi/2$  so that the signals from the AP to the user via the remaining  $L - p$  groups are orthogonal to the signal over the AP→user

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**Algorithm 1** AO Algorithm for Solving Problem (P1)

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**Input:**  $\epsilon, \zeta$

1: Initialize the active beamforming  $\mathbf{w}^{(1)} := \mathbf{h}_d / \|\mathbf{h}_d\|$  and set the iteration number  $q := 1$

2: **repeat**

3: For given  $\mathbf{w}^{(q-1)}$ , obtain the phase shifts  $\boldsymbol{\theta}^{(q)}$  according to (19)

4: For given  $\boldsymbol{\theta}^{(q-1)}$ , perform MRT at the AP based on the combined AP-user channel to obtain the active beamforming  $\mathbf{w}^{(q)}$

5: Update  $q := q + 1$

6: **until** The fractional increase of (12) is less than  $\epsilon$  or  $q > \zeta$

**Output:**  $\mathbf{w}^*$  and  $\boldsymbol{\theta}^*$

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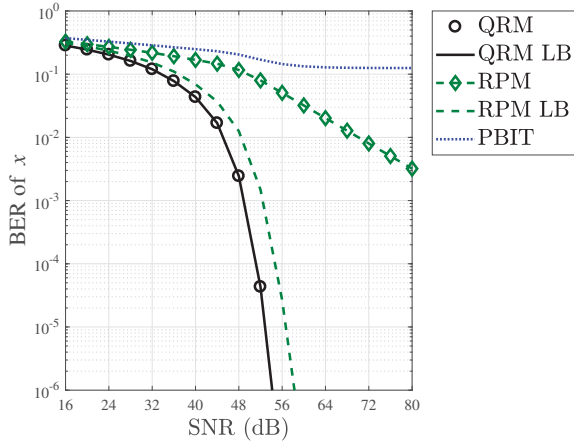
direct link. The baseband received signal at the user is given by

$$\begin{aligned} y &= (\boldsymbol{\phi}^H \mathbf{H} + \mathbf{h}_d^H) \mathbf{w}^* x + n \\ &= (\mathbf{s}^H \text{diag}(\boldsymbol{\theta}^*)^H \mathbf{H} \mathbf{w}^* + \mathbf{h}_d^H \mathbf{w}^*) x + n. \end{aligned} \quad (20)$$

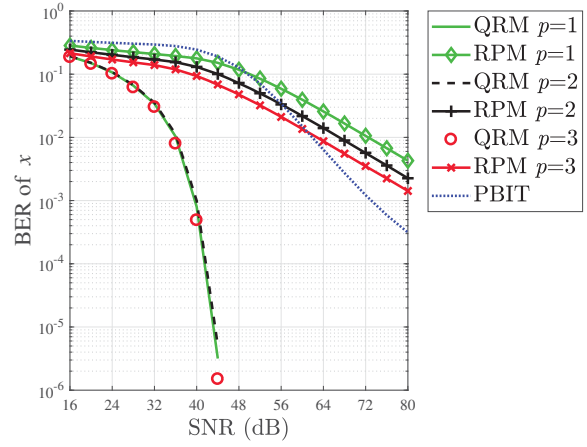
## V. SIMULATION RESULTS AND DISCUSSION

We present computer simulation results to numerically evaluate the performance of the RIS-QRM scheme in terms of bit error rate (BER). The total number of the RIS elements is  $L_0 = 160$ . The channel path loss is modeled as  $\gamma = \gamma_0 D^{-\alpha}$ , where  $\gamma_0$  is the path loss at the reference distance of 1 meter (m),  $D$  and  $\alpha$  are the individual link distance and path loss exponent, respectively. Let  $D_1$ ,  $D_2$ , and  $D_3$  denote the distances of the AP→RIS, RIS→user, and AP→user links, respectively. For small-scale fading, we consider the Rician fading channel model for all individual links. The path loss exponents of these three links are denoted by  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$ , respectively, and the Rician factors of these links are denoted by  $\kappa_1$ ,  $\kappa_2$ , and  $\kappa_3$ , respectively. We set  $D_1 = D_3 = 50$  m and  $D_2 = 5$  m. The reference path loss is  $\gamma_0 = 30$  dB for all individual links. The path loss exponents of the AP→RIS and RIS→user links are  $\alpha_1 = 2.2$  and  $\alpha_2 = 2.6$ , respectively. The Rician factors of the AP→RIS and RIS→user links are  $\kappa_1 = 1$  and  $\kappa_2 = 1$ , respectively. Let  $\gamma_3$  denote the average channel power of the AP→user direct link, which is given by  $\gamma_3 = \gamma_0 D_3^{-\alpha_3}$  unless otherwise specified. We set  $\alpha_3 = 3.3$  and  $\kappa_3 = 0$ . Other parameters are as follows:  $M = 256$ ,  $N_0 = -80$  dBm,  $\zeta = 10$  and  $\epsilon = 10^{-4}$ . The simulation results are averaged over 5, 000 independent fading channel realizations.

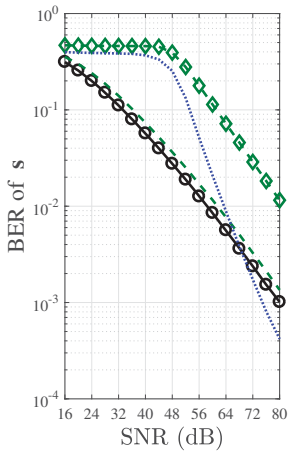
In Fig. 2, we show the error performance of the RIS-QRM scheme versus the SNR assuming  $N = 1$ ,  $L = 2$ ,  $p = 1$ ,  $\gamma_3 = 0$  (i.e., the AP→user direct link is blocked), and 256-PAM. Two existing ON/OFF-based reflection modulation schemes are considered for comparison: i) the RIS-RPM scheme in which the elements in the vector  $\mathbf{s}$  indexed by  $\mathbb{L} \setminus \mathbb{I}$  take the value of 0, i.e.,  $s_l = 0, \forall l \in \mathbb{L} \setminus \mathbb{I}$ ; ii) the PBIT scheme in which the elements in the vector  $\mathbf{s}$  are independently drawn from the set  $\{0, 1\}$  with equiprobability and  $\mathbf{s}$  remains fixed



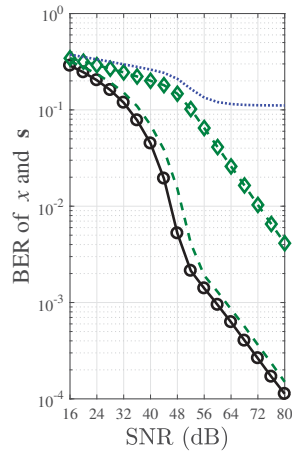
(a) BER of  $x$  versus SNR



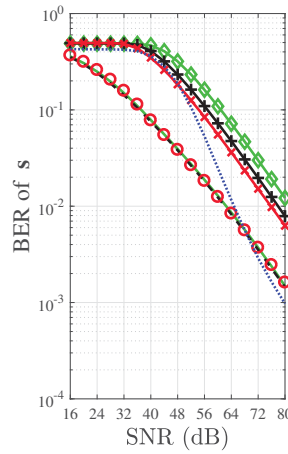
(a) BER of  $x$  versus SNR



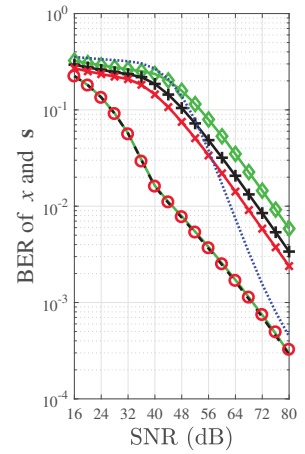
(b) BER of  $s$  versus SNR



(c) BER of  $x$  and  $s$  versus SNR



(b) BER of  $s$  versus SNR



(c) BER of  $x$  and  $s$  versus SNR

Fig. 2. Error performance of different reflection modulation schemes versus the SNR with  $N = 1$ ,  $L = 2$ ,  $p = 1$ ,  $\gamma_3 = 0$ , and 256-PAM.

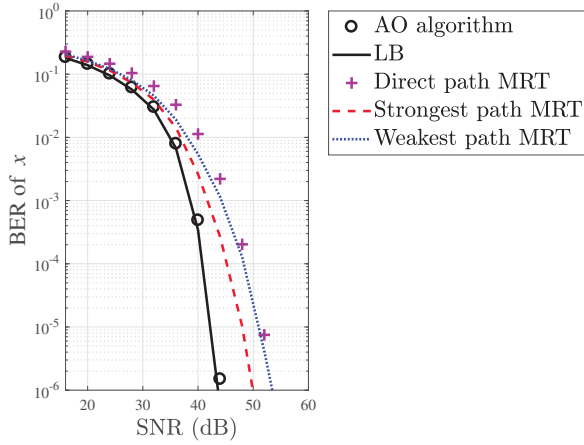
Fig. 3. Error performance of different reflection modulation schemes versus the SNR with  $N = 4$ ,  $L = 4$ ,  $p = \{1, 2, 3\}$ , and 256-PAM.

over  $L/b$  consecutive time slots. The lower bounds (LBs) on the error performance of  $x$  and  $s$  are obtained by assuming that the knowledge of  $s$  and  $x$  are perfectly known when detecting  $x$  and  $s$ . We observe that the proposed scheme not only significantly improves the error performance of  $x$ , but also improves that of  $s$ , as compared to the RIS-RPM scheme. This is attributed to the use of the quadrature component of the combined AP-user channel, which enhances the received SNR and increases the minimum Euclidean distance between all possible realizations of  $s$  by adding additional degrees of freedom.

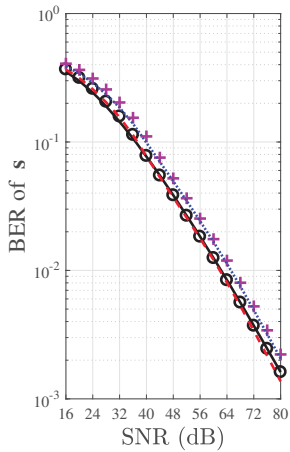
We disclose the impact of  $p$  on the error performance of the RIS-QRM and RIS-RPM schemes in Fig. 3, where  $p$  varies from 1 to 3 and other simulation parameters are  $N = 4$ ,  $L = 4$ ,  $p = \{1, 2, 3\}$ , and 256-PAM. For clarity, the lower bounds are omitted. We observe that the size of the first subset  $p$  has a minor impact on the performance of the proposed scheme, which is due to the reciprocity between the in-phase and quadrature components of the combined AP-user channel. In contrast, the size of the first subset has a significant impact on

the error performance of the RIS-RPM scheme, which can be understood by the fact that the reflection power in this scheme is determined by the number of groups in the first subset. In particular, the proposed scheme is always better than the RIS-RPM scheme, regardless of the value of  $p$ . Compared with the PBIT scheme, the proposed scheme significantly improves the BER performance of  $x$ , which is attributed to the full reflection of the RIS. It is worth noting that the PBIT scheme gives rise to communication outage, which causes an irreducible error floor in the BER performance of  $x$ , as shown in Fig. 2(a). In the BER performance of  $s$ , on the other hand, we observe from Figs. 2(b) and 3(b) that the proposed scheme outperforms the PBIT scheme in the low-to-medium SNR region, while the PBIT scheme shows a slightly superior performance to the proposed scheme at high SNR. This can be understood by the fact that, in order to fairly compare those three schemes with the same information rate, the PBIT scheme adopts repetition coding.

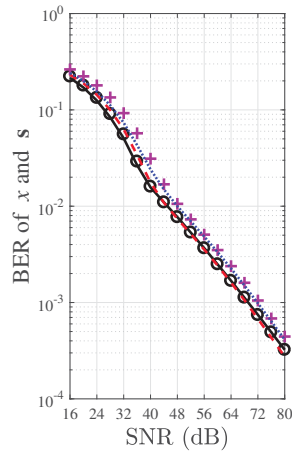
In Fig. 4, we compare the error performance of the proposed RIS-QRM scheme by using different active beamforming



(a) BER of  $x$  versus SNR



(b) BER of  $s$  versus SNR



(c) BER of  $x$  and  $s$  versus SNR

Fig. 4. BER of the RIS-QRM scheme using different active beamforming designs versus the SNR assuming  $N = 4$ ,  $L = 4$ ,  $p = 3$  and 256-PAM.

designs versus the SNR, where  $N = 4$ ,  $L = 4$ ,  $p = 3$  and 256-PAM. The following active beamforming schemes are considered for comparison: 1) the AP-user direct path MRT scheme where the active beamforming at the AP is steered toward the AP-user direct path, i.e.,  $\mathbf{w} = \mathbf{h}_d / \|\mathbf{h}_d\|$ ; 2) the strongest path MRT scheme where the active beamforming at the AP is steered toward the path of the largest channel power gain among the cascaded channels of all groups and the AP-user direct channel, i.e.,  $\mathbf{w} = \mathbf{h}_{\max} / \|\mathbf{h}_{\max}\|$  with  $\mathbf{h}_{\max} = \arg \max\{\|\mathbf{h}_1\|^2, \dots, \|\mathbf{h}_L\|^2, \|\mathbf{h}_d\|^2\}$ ; 3) the weakest path MRT scheme where the active beamforming at the AP is steered toward the path of the smallest channel power gain among the cascaded channels of all groups and the AP-user direct channel, i.e.,  $\mathbf{w} = \mathbf{h}_{\min} / \|\mathbf{h}_{\min}\|$  with  $\mathbf{h}_{\min} = \arg \min\{\|\mathbf{h}_1\|^2, \dots, \|\mathbf{h}_L\|^2, \|\mathbf{h}_d\|^2\}$ . We observe that the AO algorithm outperforms the other schemes, which can be well understood by the fact that the objective of problem (P1) is to maximize the received SNR. Moreover, the performance of the strongest path MRT scheme is better than that of the AP-user direct path MRT scheme and the weakest path MRT scheme.

It is worth noting that the complexity of the strongest path MRT scheme is much lower than that of the AO algorithm.

## VI. CONCLUSIONS

In this paper, we proposed the RIS-QRM scheme to achieve joint PBIT for RIS-aided MISO wireless communication assuming the direct link between the AP and user is not blocked. An optimization problem was formulated to jointly optimize the active beamforming at the AP and the phase shifts of the RIS for improving the received signal power at the user. Computer simulation results corroborated the effectiveness of the RIS-QRM scheme. In particular, the RIS-QRM scheme was shown to be able to improve the error performance of the additional bits delivered by the RIS without deteriorating that of the bits carried on the constellation symbol, as compared to existing ON/OFF-based schemes.

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