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Over-the-air beamforming with reconfigurable intelligent surfaces

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Reconfigurable intelligent surface (RIS)-empowered communication is a revolutionary technology that enables to manipulate wireless propagation environment *via* smartly controllable low-cost reflecting surfaces. However, in order to outperform conventional communication systems, an RIS-aided system with solely passive reflection requires an extremely large surface. To meet this challenge, the concept of active RIS, which performs simultaneous amplification and reflection on the incident signal at the expense of additional power consumption, has been recently introduced. In this paper, deploying an active RIS, we propose a novel beamforming concept, *over-the-air beamforming*, for RIS-aided multi-user multiple-input single-output (MISO) transmission schemes without requiring any pre/post signal processing hardware designs at the transmitter and receiver sides. In the proposed over-the-air beamforming-based transmission scheme, the reflection coefficients of the active RIS elements are customized to maximize the sum-rate gain. To tackle this issue, first, a non-convex quadratically constrained quadratic programming (QCQP) problem is formulated. Then, using semidefinite relaxation (SDR) approach, this optimization problem is converted to a convex feasibility problem, which is efficiently solved using the CVX optimization toolbox. Moreover, taking inspiration from this beamforming technique, a novel high-rate receive index modulation (IM) scheme with a low-complexity sub-optimal detector is developed. Through comprehensive simulation results, the sum-rate and bit error rate (BER) performance of the proposed designs are investigated.

KEYWORDS

reconfigurable intelligent surface (RIS), active RIS, over-the-air beamforming, multi-user (MU) transmission, index modulation (IM)

1 Introduction

Customizing propagation environment *via* reconfigurable intelligent surfaces (RISs) has been an appealing field for wireless communication and provides novel insights about future generation networks. These light-weight and cost-effective electronic elements have been regarded as a game changer technology for conventional communication systems with power-hungry and complex hardware designs (Basar et al., 2019).

Particularly, RISs are programmable metasurfaces that are capable of configuring the propagation environment in a desired manner *via* performing reflection, amplification, absorption, refraction, etc. (Di Renzo et al., 2020). However, the most of the extant literature particularly focuses on the application of the RIS with passive reflection in various emerging systems (Basar et al., 2019; Di Renzo et al., 2020; Gong et al., 2020).

In the early studies, a passive RIS is deployed for enhancing transmit signal quality of single-antenna (Basar, 2019) and multiple-antenna systems (Yu et al., 2019; Yigit et al., 2020; Zhang et al., 2020). In subsequent studies, an RIS is facilitated for numerous objectives of single-user and multi-user systems, such as promoting energy-efficiency (Björnson et al., 2019; Huang et al., 2019), enhancing error performance (Ferreira et al., 2020; Ye et al., 2020) and improving achievable rate (Di et al., 2020; Zhang and Zhang, 2020; Perović et al., 2021). Further, novel deep learning-based solutions for passive RIS designs (Kundu and McKay, 2021; Taha et al., 2021) and security enhanced RIS-aided communication systems (Shen et al., 2019), (Almohamad et al., 2020; Dong and Wang, 2020) are proposed. On the other hand, index modulation (IM) principle, which is emerged as a promising energy-efficient solution to meet high data-rate demand of future wireless networks (Basar et al., 2017), is beneficially amalgamated into the RIS-empowered communication (Basar, 2020; Li et al., 2021). Considering more conventional IM designs (Basar, 2020; Li et al., 2021), put forward RIS-aided receive IM schemes, which maximize the signal powers of the target receive antennas. However, in (Guo et al., 2020; Lin et al., 2020), novel reflection modulation (RM) concepts, which innovatively utilize the RISs for delivering additional information, are proposed. Above all, main limitation of the aforementioned studies is the lack of comprehensive practical insights on considered system configurations. Towards this aim, a low-complexity joint beamforming optimization that considers the effect of hardware impairments on the performance of RIS-aided multi-antenna systems are investigated in (Shen et al., 2021), different RIS prototypes are introduced for real-time implementations in (Dai et al., 2020; Tang et al., 2020), and realistic physical channel models for millimeter-wave (mmWave) (Basar et al., 2021) and sub-6 GHz bands (Yigit et al., 2021a; Kilinc et al., 2021) are presented. Nevertheless, the abovementioned system designs suffer from the multiplicative path attenuation due to the inherent drawback of the RIS-aided designs, and achieve negligible performance gains over the conventional communication systems.

Recently, to tackle above challenges, the concept of active RIS, which performs simultaneous amplification and reflection on the incident wave, is introduced in (Long et al., 2021; Zhang et al., 2021). Accordingly, the magnitudes and the phases of the reflecting elements of the active RIS, which are equipped with additional power amplifiers, are properly tuned in a customized

way (Basar and Poor, 2021). Therefore, at the cost of additional power consumption, active RIS-aided systems are capable of achieving enhanced capacity gains (Long et al., 2021). In a recent study on designing active RISs, *via* leveraging power amplifiers and radio frequency (RF) chains (Nguyen et al., 2022), dynamic and fixed hybrid RIS architectures are constructed. Further, for improving the data rate, a new RM design, which employs the sub-groups of a hybrid RIS as information transfer units, is presented in (Yigit et al., 2021b). In follow-up studies, the concept of the active RIS is deployed for beamforming optimization of the RIS-aided multi-user systems (Gao et al., 2022; Thanh Nguyen et al., 2022). Above all, the potential of the active RIS-aided systems for achieving enormous performance gains will enable to develop promising solutions for future research.

In this study, unlike the conventional precoding techniques that employ power-hungry and hardware-complex devices (Sohrabi and Yu, 2016), for RIS-aided multi-user downlink transmission systems, we propose a novel *over-the-air beamforming* technique with the aid of an active RIS to exploit its capability of manipulating the magnitude of the incident wave. In other words, the main motivation of the over-the-air beamforming scheme is to simplify the transmitter and receiver ends of the overall network while transferring inter-user interference elimination tasks completely to an active RIS. Therefore, this paper proposes two novel over-the-air beamforming schemes that mitigate the burden of signal processing on the transmitter and receiver sides. In the proposed over-the-air beamforming-based transmission scheme, it is assumed that a multi-antenna transmitter serves K single-antenna users through an active RIS without utilizing any other signal processing tasks at the transmitter and the receiver sides. Then, the reflection coefficients of the active RIS is properly adjusted to maximize the sum-rate of the overall system. Moreover, taking inspiration from this over-the-air beamforming concept, a new receive IM scheme that transmits additional information bits to specify the index of the effective received antenna is also proposed. Contrary to the traditional receive IM systems (Zhang et al., 2013; Luo et al., 2021), in the proposed system, since no precoding is applied at the transmitter, the reflection coefficients of the active RIS are rectified to steer the incident signal into the intended receive antenna. On the other hand, since the receive IM scheme benefits from the multi-antenna transmission at the user side and IM system design at the receiver side, it shows the favourable features of both, such as high spectral efficiency and improved performance. In these proposed over-the-air downlink beamforming and over-the-air uplink receive IM schemes, to optimize reflection coefficients of the active RISs, two distinct semidefinite relaxation (SDR)-based optimization problems are formulated, which can be effectively solved through the CVX convex optimization toolbox (Grant and Boyd, 2008). Furthermore, the achievable rate and bit error rate (BER)

performance of the proposed over-the-air beamforming-based transmission schemes are investigated through extensive computer simulations.

The rest of the paper is organized as follows. In Section 2, after giving a short review of the conventional zero-forcing (ZF) precoding, we introduce the system model of the proposed over-the-air beamforming-based multi-user multi-antenna transmission scheme. In Section 3, the over-the-air beamforming-based receive IM scheme and its low-complexity receiver detection are introduced. Section 4 provides the achievable rate and BER results of the proposed over-the-air beamforming based transmission systems, and the conclusions are drawn in Section 5.

Notations: Throughout this paper, matrices and vectors are denoted by boldface upper-case and boldface lower-case letters, respectively $(\cdot)^T$ represents transpose and $(\cdot)^H$ denotes the Hermitian transpose operation. $\|\cdot\|$, $\text{rank}(\cdot)$, $\text{Tr}(\cdot)$ and $\text{diag}(\cdot)$ are stand for rank, trace and diagonalization of a matrix, respectively. Absolute value of a scalar is denoted by $|\cdot|$, while \circ represents the Hadamard product. $\mathbb{E}\{\cdot\}$ is used for expectation and $\mathcal{CN}(\mu, \sigma^2)$ represents a complex Gaussian random variable with μ mean and σ^2 variance. \mathbf{I} stands for the identity matrix, while $\mathcal{O}(\cdot)$ denotes big \mathcal{O} notation.

2 Over-the-air beamforming with RIS

In this section, after a review of conventional transmit precoding, the over-the-air beamforming concept is introduced for multi-user multiple-input single-output (MISO) downlink transmission systems.

2.1 Conventional transmit precoding

Considering a typical multi-user downlink transmission system without an RIS, a base station (BS) transmitter (T) with T_x antennas is assumed to perform ZF precoding to alleviate interference between K single-antenna users (Spencer et al., 2004). Let $\mathbf{F} \in \mathbb{C}^{K \times T_x} = \sqrt{L_D} \bar{\mathbf{F}}$ represents the channel matrix of the direct links between the T and the users, where $\bar{\mathbf{F}} \in \mathbb{C}^{K \times T_x}$ is modeled as independent Rayleigh fading channel matrix with $\sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$ and L_D is the corresponding path attenuation, which is calculated as $L_D = C_0 d_D^{-\beta_D}$, where C_0 is the reference path attenuation at a distance of 1 meter (m) and d_D is the distance between T and the users. Then, the received signal of the k -th user (U_k), for $k \in \{1, 2, \dots, K\}$, becomes

$$y_k = \mathbf{f}_k \mathbf{w}_k^H x_k + \sum_{i \neq k}^K \mathbf{f}_i \mathbf{w}_i^H x_i + c_k \tag{1}$$

where x_k being an M -ary phase shift keying (PSK) signal to be transmitted over the k -th transmit antenna. Here, $\mathbf{f}_k \in \mathbb{C}^{1 \times T_x}$ is

the k -th row of the channel matrix \mathbf{F} corresponding to the channel vector between T- U_k , $\mathbf{w}_k \in \mathbb{C}^{1 \times T_x}$ is the precoding vector for U_k and $c_k \sim \mathcal{CN}(0, \sigma_s^2)$ is the static noise at U_k . Therefore, the signal-to-interference-plus-noise-ratio (SINR) at U_k can be calculated as

$$\gamma_k = \frac{\|\mathbf{f}_k \mathbf{w}_k^H\|^2}{\sum_{i \neq k}^K \|\mathbf{f}_i \mathbf{w}_i^H\|^2 + \sigma_s^2} \tag{2}$$

Moreover, the overall transmit ZF precoding matrix, exploiting the perfect CSI, can be obtained as (Spencer et al., 2004)

$$\mathbf{W} = \sqrt{\zeta} (\mathbf{F}^H \mathbf{F})^{-1} \mathbf{F}^H \tag{3}$$

where $\mathbf{W} \in \mathbb{C}^{T_x \times K} = [\mathbf{w}_1^H, \dots, \mathbf{w}_K^H]$ and ζ is a scaling constant to meet the total power constraint P_T , such that $\mathbb{E}\{\mathbf{W} \mathbf{W}^H\} = P_T$.

2.2 System model of over-the-air beamforming with RIS

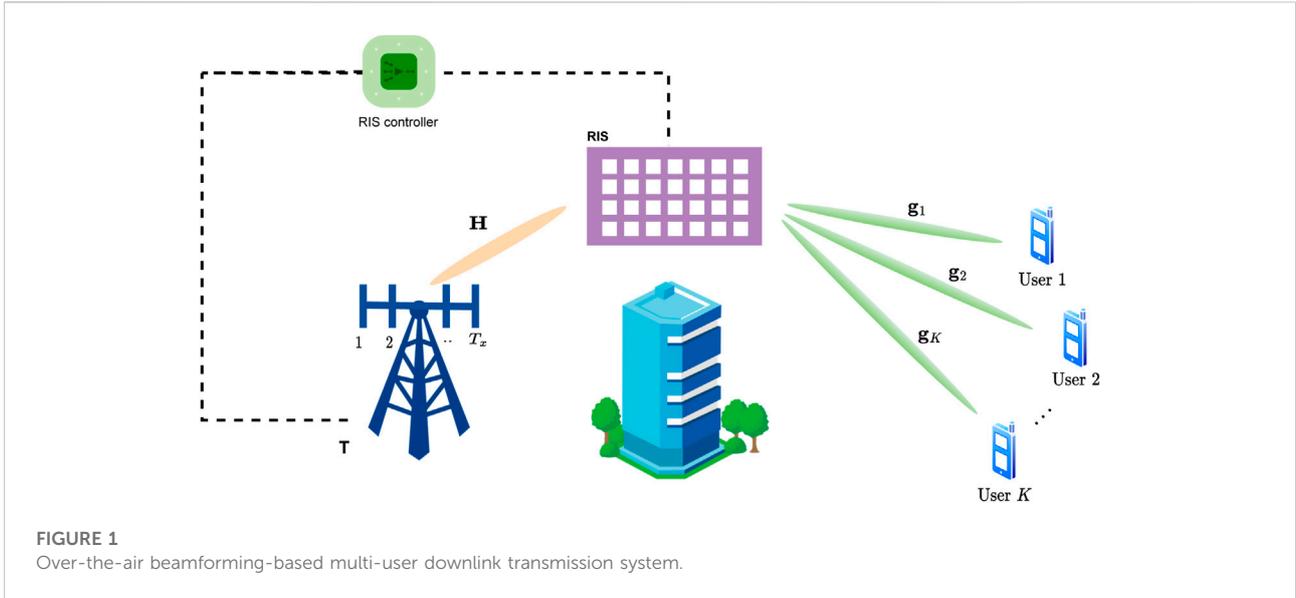
In this subsection, after a brief introduction of the active RIS concept, the system model of the over-the-air beamforming-based multi-user transmission system is introduced.

2.2.1 Active RIS

The principal drawback of RIS-aided communication systems is the inherent multiplicative path attenuation along the RIS-aided indirect link, which is hardly compensated by the RIS with passive reflecting elements (Basar and Poor, 2021; Zhang et al., 2021). Therefore, to overcome this challenge, an RIS architecture with active reflecting elements that enable to configure both the magnitude and phase of the incident wave at the expense of an additional power consumption, is recently proposed (Khoshafa et al., 2021; Zhang et al., 2021). Therefore, unlike the passive RISs, the active RISs reflect incident signal with amplification *via* employing additional power circuitry. Although the active reflecting elements have a similar capability of amplifying the incident signal as in the full-duplex amplify-and-forward (AF) relays, their hardware constructions are completely different from each other. While the AF relays embody a circuitry for amplification in their hardware constructions and they are also externally equipped with high power-consuming RF chains to transmit and receive signals (Wu and Zhang, 2019), the active reflecting elements employ reflective-type power amplifiers to simultaneously rectify the magnitude and phase of the incident wave (Zhang et al., 2021).

2.2.2 System model

An overwhelming literature on passive RIS-aided multi-user transmission deploys the RIS as a passive beamformer after a preprocessing is conducted at the transmitter (Wu and Zhang, 2019; Yan et al., 2020). However, in the proposed over-the-air



beamforming concept, to avoid power-hungry hardware constructions at the transmitter and the users, exploiting simultaneous amplification and reflection capabilities of the active reflecting elements, both active and passive beamforming are carried out at an active RIS. Accordingly, the reflection coefficients of the active RIS are optimized to maximize the achievable rate of the overall system.

As given in Figure 1, in the proposed scheme, the direct transmission links between T with T_x antennas and K single-antenna users are neglected due to obstacles, thus, the communication is established through an active RIS with N reflecting elements. In the proposed over-the-air beamforming-based multi-user transmission, it is assumed that T and the users have the perfect channel state information (CSI) about T-RIS and RIS-users channels, which is conveyed to a smart RIS controller *via* a feedback control link (Wu and Zhang, 2019). Moreover, at the transmitter side, without requiring any additional signal processing approaches for interference mitigation, the overall signal is conveyed to the users through the RIS. Hence, unlike the traditional beamforming techniques that employ complex and power-hungry signal processing hardware (El Ayach et al., 2014; Sohrabi and Yu, 2016), the RIS is designed as a beamformer to alleviate multi-user interference by adjusting the amplitude and phase of each reflecting element. Towards this aim, the RIS elements are assumed to be equipped with additional power circuitry to modify both the magnitude and the phase of the incident signal (Yigit et al., 2021b; Zhang et al., 2021; Nguyen et al., 2022). Furthermore, in the proposed system, since all transmit antennas simultaneously convey their own M -PSK modulated signals, a spectral efficiency of $\eta_{MU} = T_x \log_2(M)$ [bits/s/Hz] is achieved.

Let us assume that the channels between T-RIS are presented by the matrix $\mathbf{H} \in \mathbb{C}^{N \times T_x} = \sqrt{L_T} \bar{\mathbf{H}}$ and $\mathbf{g}_k \in \mathbb{C}^{1 \times N} = \sqrt{L_k} \bar{\mathbf{g}}_k$ represents the vector of channel coefficients between the RIS and U_k , where L_T and L_k correspond to path attenuation between T-RIS and RIS- U_k links for $k \in \{1, 2, \dots, K\}$, respectively. Here, for d_T and d_k being the corresponding distances, using a well-known distance-dependent model, the path attenuations are obtained as $L_T = C_0 d_T^{-\beta_T}$ and $L_k = C_0 d_k^{-\beta_k}$, where β_T and β_k are the path loss exponents at T-RIS and RIS- U_k , respectively. In the proposed system, the matrix $\bar{\mathbf{H}} \in \mathbb{C}^{N \times T_x}$ and the vector $\bar{\mathbf{g}}_k \in \mathbb{C}^{1 \times N}$ are both modeled as Rayleigh fading channels, whose each element is an independent and identically distributed (i.i.d.) Gaussian random variable with $\sim \mathcal{CN}(0, 1)$.

In addition, the RIS architecture that is equipped with additional power circuitry to operate as an active RIS (Zhang et al., 2021), is represented in a diagonal matrix $\Psi \in \mathbb{C}^{N \times N} = \text{diag}\{\alpha_1 e^{j\phi_1}, \alpha_2 e^{j\phi_2}, \dots, \alpha_N e^{j\phi_N}\}$, where α_n and $\phi_n \in [-\pi, \pi]$ being the amplitude and phase of the n -th reflecting element for $n \in \{1, 2, \dots, N\}$. It is worth noting that since active reflecting elements are capable to amplify the incident signal, the magnitude of each reflecting element is greater than unity, i.e., $\alpha_n > 1$. Therefore, for $\bar{T}_x = T_x/K$ being the number of the transmit antennas allocated to each user and $\mathbf{x}_k \in \mathbb{C}^{\bar{T}_x \times 1}$ being the signal vector to be transmitted to the k -th user, the received signal at U_k is obtained as

$$y_k = \sqrt{P_k} \mathbf{g}_k \Psi \mathbf{H} \mathbf{x} + \mathbf{g}_k \Psi \mathbf{v} + n_k \quad (4)$$

where $\mathbf{x} \in \mathbb{C}^{T_x \times 1} = [\mathbf{x}_1^T, \mathbf{x}_2^T, \dots, \mathbf{x}_K^T]^T$ and $\mathbb{E}\{\mathbf{x}^H \mathbf{x}\} = 1$. Here, P_k is the transmit power dissipated to the k -th user, the vector $\mathbf{v} \in \mathbb{C}^{1 \times N}$ represents the thermal noise generated from power amplifier circuits of active reflecting elements (Zhang et al., 2021) and n_k is the static noise term at U_k , where $\mathbf{v} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_N \sigma_v^2)$ and

$n_k \sim \mathcal{CN}(0, \sigma_s^2)$ for σ_v^2 and σ_s^2 being the corresponding noise variances of dynamic and static noise figures, respectively. Moreover, at the user side, since the received superposed signal at U_k (4) includes the targeted and interference signals, it can be rewritten as

$$y_k = \sqrt{P_k} \mathbf{g}_k \Psi \mathbf{H}_k \mathbf{x}_k + \sqrt{P_k} \sum_{i \neq k}^K \mathbf{g}_k \Psi \mathbf{H}_i \mathbf{x}_i + \mathbf{g}_k \Psi \mathbf{v}^T + n_k \quad (5)$$

where $\mathbf{H} = [\mathbf{H}_1, \mathbf{H}_2, \dots, \mathbf{H}_K]$ and $\mathbf{H}_k \in \mathbb{C}^{N \times T_x}$ is the channel matrix between the transmit antenna group dedicated to k -th user and the RIS. At this point, the SINR at U_k can be calculated as:

$$\gamma_k = \frac{P_k \|\mathbf{g}_k \Psi \mathbf{H}_k\|^2}{P_k \sum_{i \neq k}^K \|\mathbf{g}_k \Psi \mathbf{H}_i\|^2 + \|\mathbf{g}_k \Psi \mathbf{v}^T\|^2 + \sigma_s^2} \quad (6)$$

Accordingly, the sum-rate of the overall system becomes:

$$R = \sum_{k=1}^K \log_2(1 + \gamma_k). \quad (7)$$

Then, to maximize this sum-rate, the reflection coefficients of the active RIS elements are optimized. In what follows, the corresponding problem formulation and the proposed solution are presented.

2.3 Problem formulation and proposed solution

In the over-the-air beamforming-based multi-user transmission scheme, interference cancellation is performed at the RIS without employing any additional integrated high-cost signal processing circuitry, such as multiple RF chains, either at T or user sides. For this purpose, the reflection coefficients of the RIS are adjusted to maximize the SINR of the intended U_k . Therefore, to deal with this problem, the following QCQP problem is formulated.

$$(P1): \max_{\Psi} \gamma_k \quad (8)$$

$$\text{s.t. } P_k \|\mathbf{g}_k \Psi \mathbf{H}_k\|^2 \geq \Gamma_k \left(P_k \sum_{i \neq k}^K \|\mathbf{g}_k \Psi \mathbf{H}_i\|^2 + \|\mathbf{g}_k \Psi \mathbf{v}^T\|^2 + \sigma_s^2 \right) \quad (9)$$

$$P_{BS} \|\Psi \mathbf{H}\|^2 + \|\Psi\|^2 \sigma_s^2 \leq P_A \quad (10)$$

where Γ_k is the minimum SINR requirement of U_k , $P_{BS} = KP_k$, and P_A is the maximum reflection power introduced by the active reflecting elements. Please note that for the over-the-air beamforming-based multi-user systems, the total power P_T is the sum of power dissipated at the transmitter (P_{BS}) and the RIS (P_A), that is $P_T = P_A + P_{BS}$, while for the conventional

transmission without RIS, P_T denotes to total power consumed at the transmitter. Then, using the Cauchy-Schwarz inequality, the constraint in (10) can be rewritten as

$$\|\Psi\|^2 \leq \frac{P_A}{P_{BS} \|\mathbf{H}\|^2 + \sigma_s^2} \quad (11)$$

Therefore, since the problem (P1) is non-convex and it is difficult to obtain an optimal solution, we resort to the SDR technique and define new variables $\mathbf{A}_k \in \mathbb{C}^{N \times N} = \mathbf{H}_k \mathbf{H}_k^H$, $\mathbf{B}_k \in \mathbb{C}^{N \times N} = \mathbf{g}_k \mathbf{g}_k^H$ and $\mathbf{V} = \mathbf{v} \mathbf{v}^H$. In light of these, the SINR of the k -th user in (6) can be rewritten as

$$\gamma_k = \frac{P_k \text{Tr}(\mathbf{Q}_k \mathbf{Z})}{\sum_{i \neq k} P_k \text{Tr}(\mathbf{Q}_i \mathbf{Z}) + \text{Tr}(\mathbf{Q}_m \mathbf{Z}) + \sigma_s^2} \geq \Gamma_k \quad (12)$$

where $\mathbf{Q}_k \in \mathbb{C}^{N \times N} = \mathbf{A}_k \circ \mathbf{B}_k$, $\mathbf{Q}_i \in \mathbb{C}^{N \times N} = \mathbf{A}_i \circ \mathbf{B}_k$ and $\mathbf{Q}_m \in \mathbb{C}^{N \times N} = \mathbf{V}_k \circ \mathbf{B}_k$, while $\mathbf{Z} \in \mathbb{C}^{N \times N} = \mathbf{z} \mathbf{z}^H$ for $\mathbf{z} \in \mathbb{C}^{N \times 1}$ being a vector consisting the non-zero diagonal elements of the reflection matrix Ψ , i.e., $\mathbf{z} = [\alpha_1 e^{j\phi_1}, \alpha_2 e^{j\phi_2}, \dots, \alpha_N e^{j\phi_N}]^H$ (Zhang, 2017; Ye et al., 2020). Therefore, the maximization problem (P1) is equivalently defined as.

$$(P2): \max_{\Psi} \gamma_k \quad (13)$$

$$\text{s.t. } P_k \text{Tr}(\mathbf{Q}_k \mathbf{Z}) - \Gamma_k \left(\sum_{i \neq k} P_k \text{Tr}(\mathbf{Q}_i \mathbf{Z}) + \text{Tr}(\mathbf{Q}_m \mathbf{Z}) + \sigma_s^2 \right) \geq 0 \quad (14)$$

$$\text{Tr}(\mathbf{Z}) \leq \frac{P_A}{P_{BS} \text{Tr}(\mathbf{H} \mathbf{H}^H) + \sigma_s^2} \quad (15)$$

Here, \mathbf{Z} is a positive semidefinite matrix and $\text{rank}(\mathbf{Z}) = 1$. However, since the rank-one constraint is non-convex, we remove this constraint and reformulate (P2) as a convex feasibility problem as follows.

$$(P3): \text{Find } \mathbf{Z} \quad (16)$$

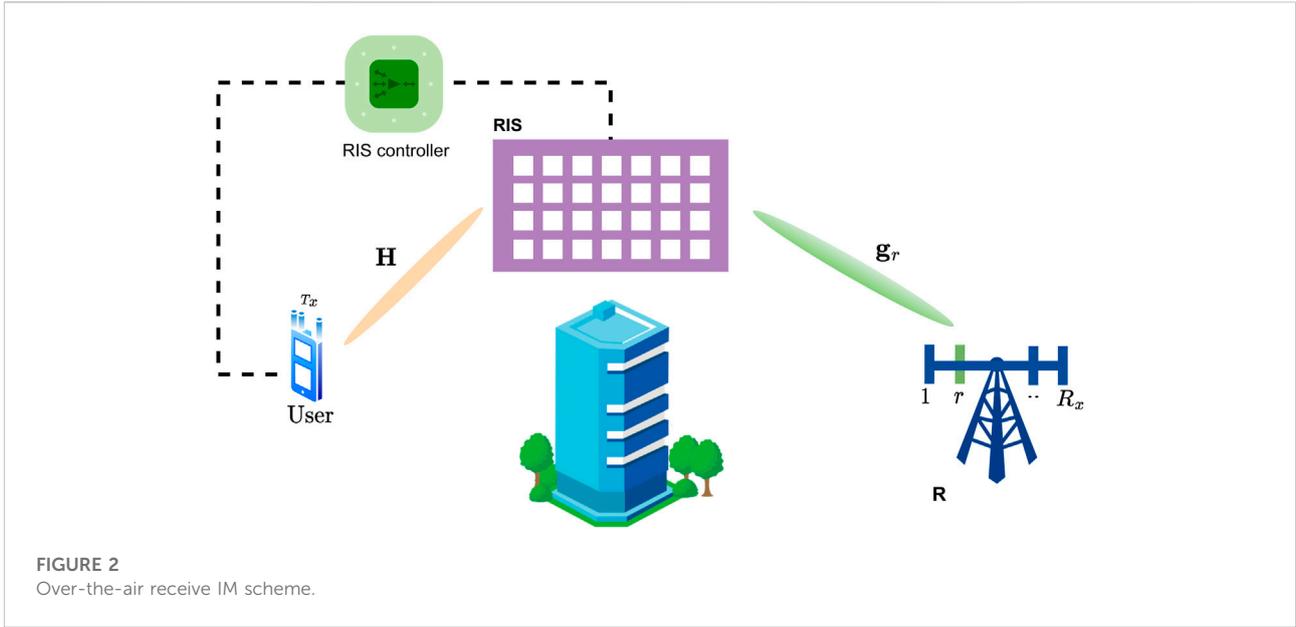
$$\text{s.t. } P_k \text{Tr}(\mathbf{Q}_k \mathbf{Z}) - \Gamma_k \left(\sum_{i \neq k} P_k \text{Tr}(\mathbf{Q}_i \mathbf{Z}) + \text{Tr}(\mathbf{Q}_m \mathbf{Z}) + \sigma_s^2 \right) \geq 0 \quad (17)$$

$$\text{Tr}(\mathbf{Z}) \leq \frac{P_A}{P_{BS} \text{Tr}(\mathbf{H} \mathbf{H}^H) + \sigma_s^2} \quad (18)$$

Finally, through the existing solvers of CVX toolbox (Grant and Boyd, 2008), a feasible solution of (P3) satisfying the inequality constraints in (17) and (18) is obtained. However, after the relaxation, the optimal solution of (P3) cannot always ensure the rank-one solution. Therefore, for $\tilde{\mathbf{Z}}$ being the optimal solution of the problem (P3), using the eigenvalue decomposition of $\tilde{\mathbf{Z}} = \mathbf{U} \Sigma \mathbf{U}^H$, the estimated \mathbf{z} is sub-optimally obtained as

$$\tilde{\mathbf{z}} = \mathbf{U} \Sigma^{1/2} \mathbf{e}^H \quad (19)$$

where $\mathbf{e} \in \mathbb{C}^{1 \times N}$ is a Gaussian random vector with $\sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$, where $\mathbf{U} \in \mathbb{C}^{N \times N}$ is a unitary matrix of eigenvectors and



$\Sigma \in \mathbb{C}^{N \times N}$ is a diagonal matrix of eigenvalues. Then, after determining optimized reflection matrix, the RIS performs over-the-air beamforming in order to alleviate the user interference.

3 Over-the-air receive index modulation

In this section, the proposed over-the-air beamforming concept is adopted to a novel receive IM transmission scheme. Considering the over-the-air beamforming approach given in Section II, a single-user uplink transmission of an active RIS-aided IM transmission system is developed.

3.1 System model of over-the-air receive IM

As given in Figure 2, in the proposed IM system, due to presence of the obstacles over the direct links, a multi-antenna user communicates with an R_x -antenna receiver (R) through an RIS with N reflecting elements. Besides, an RIS controller is attached to the RIS that exchanges the information through a feedback control link. In the proposed system, considering the IM transmission principle (Basar, 2020), an over-the-air receive IM scheme is developed. Unlike traditional receive IM schemes (Stavridis et al., 2012; Zhang et al., 2013; Luo et al., 2021) that deploy transmit precoding techniques via high-cost hardware devices for preprocessing the transmit signal before its transmission, the proposed receive IM scheme employs the

RIS as a signal processing unit and apply an over-the-air beamforming at the RIS. In the over-the-air receive IM scheme, at the user side, a conventional multi-antenna transmission is considered. Moreover, in order to attain higher data rates, extra information bits are conveyed via indicating the active receive antenna index. Therefore, the incoming information bits are used to determine the modulated M -PSK symbols for each of the available T_x transmit antennas, as well as to specify the active receive antennas, one out of R_x receive antennas. Therefore, the spectral efficiency achieved by this novel receive IM scheme is calculated as

$$\eta_{IM} = T_x \log_2(M) + \log_2(R_x) \quad [\text{bits/s/Hz}]. \quad (20)$$

In this system, the information of the active receive antenna index and perfect channel knowledge of user-RIS and RIS-R links is shared by the user to the RIS through the smart controller. Then, the reflection coefficient of the RIS elements are adjusted to ensure that the target receive antenna has the strongest received signal power. In other words, by the means of active reflecting elements, the RIS acts as a kind of digital beamformer and steers the overall signal along the desired receive antenna direction.

Let the multi-path fading channels between user-RIS and RIS-R links are modeled as the independent Rayleigh fading channels, which are denoted by the channel matrices of $\mathbf{H} \in \mathbb{C}^{N \times T_x}$ and $\mathbf{G} \in \mathbb{C}^{R_x \times N} = [\mathbf{g}_1^T, \mathbf{g}_2^T, \dots, \mathbf{g}_{R_x}^T]^T$, respectively, where $\mathbf{g}_r \in \mathbb{C}^{1 \times N}$ is the r -th row of the channel matrix \mathbf{G} corresponding to the channel vector between the RIS and the r -th receive antenna for $r \in \{1, 2, \dots, R_x\}$. Therefore, for x_t being the M -PSK modulated signal transmitted from the t -th transmit antenna, the overall transmit signal becomes

$\mathbf{x} \in \mathbb{C}^{T_x \times 1} = [x_1, \dots, x_{T_x}]^T$, where $\mathbb{E}\{\mathbf{x}^H \mathbf{x}\} = 1$ and $t \in \{1, 2, \dots, T_x\}$. Then, the received signal at the target receive antenna r is obtained as

$$y_r = \sqrt{P_{BS}} \mathbf{g}_r \Psi_r \mathbf{H} \mathbf{x} + \mathbf{g}_r \Psi_r \mathbf{v} + n_r \quad (21)$$

where $\Psi_r \in \mathbb{C}^{N \times N}$ is the optimized diagonal reflection matrix for the corresponding r -th receive antenna. It is worth noting that according to incoming spatial bits, if the r -th receive antenna is activated, it is ensured that the signal power of the r -th received antenna is much stronger than the others:

$$\|\mathbf{g}_r \Psi_r \mathbf{H}\|^2 \gg \sum_{i \neq r}^{R_x} \|\mathbf{g}_i \Psi_r \mathbf{H}\|^2. \quad (22)$$

Therefore, to address this problem, for $\Theta_r = \text{diag}(\mathbf{g}_r) \mathbf{H}$ and $\mathbf{z} \in \mathbb{C}^{1 \times T_x} = \text{diag}(\Psi_r)$, a QCQP optimization problem is formulated as.

$$(P4): \max_{\Psi} \mathbf{z}^H \Theta_r \Theta_r^H \mathbf{z} \quad (23)$$

$$\text{s.t. } P_{BS} \|\Psi_r \mathbf{H}\|^2 + \|\Psi_r\|^2 \sigma_s^2 \leq P_A. \quad (24)$$

Then, resorting to SDR, the problem (P4) is expressed as.

$$(P5): \max_{\Psi} \text{Tr}(\Delta_r \mathbf{Z}) \quad (25)$$

$$\text{s.t. } \text{Tr}(\Delta_r \mathbf{Z}) - \delta_r \sum_{i \neq r}^{R_x} \text{Tr}(\Delta_i \mathbf{Z}) \geq 0 \quad (26)$$

$$\text{Tr}(\mathbf{Z}) \leq \frac{P_A}{P_{BS} \text{Tr}(\mathbf{H} \mathbf{H}^H) + \sigma_s^2}. \quad (27)$$

Here, for $\delta_r \gg 1$, $\Delta_r \in \mathbb{C}^{N \times N} = \Theta_r \Theta_r^H$ and $\mathbf{Z} = \mathbf{z} \mathbf{z}^H$, the problem (P5) is solved using CVX solvers (Grant and Boyd, 2008). Then, following the same processes as in the multi-user downlink transmission in Section II, the sub-optimal estimate of \mathbf{z} , is obtained as given in (19). Then, the resulting RIS reflection matrix enables that the overall signal is oriented in the direction of the target receive antenna.

3.2 Low-complexity successive greedy detector

In the subsection that follows, a sub-optimal successive detection algorithm for the proposed receive IM scheme is proposed. In the proposed system, after the optimization of the reflection matrix Ψ_r for the specified r -th receive antenna, it is straightforward to exploit a maximum likelihood (ML) detector that jointly estimates the ‘‘spatial symbol’’ r and the overall transmit signal vector \mathbf{x} as follows

$$[\hat{r}, \hat{\mathbf{x}}] = \arg \min_{r, \mathbf{x}} \sum_{j=1}^{R_x} |y_j - \sqrt{P_{BS}} \mathbf{g}_j \Psi_r \mathbf{H} \mathbf{x}|^2. \quad (28)$$

However, in the proposed receive IM scheme, in order to save the computational complexity, instead of considering joint

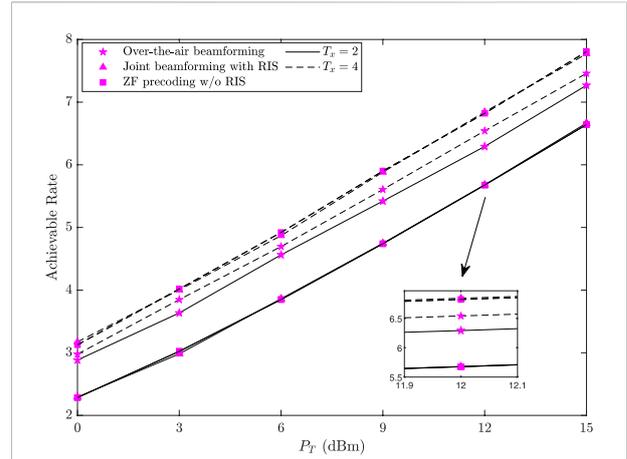


FIGURE 3 Comparison of the achievable rate performance of the proposed over-the-air beamforming with traditional ZF precoding (Spencer et al., 2004) and joint beamforming with RIS (Wu and Zhang, 2019) for single-user system configurations.

detection, the receiver reconstructs the transmit information via a low-complexity greedy detector that perform the successive detection in the following way. First, using amplitude detectors, the index of the active receive antenna is detected as

$$\hat{r} = \arg \max_{j \in \{1, \dots, R_x\}} |y_j|. \quad (29)$$

Then, exploiting the ML detector, the transmit signal vector \mathbf{x} is estimated, by considering all possible \mathbf{x} realizations, as follows

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x}} |y_{\hat{r}} - \sqrt{P_{BS}} \mathbf{g}_{\hat{r}} \Psi_{\hat{r}} \mathbf{H} \mathbf{x}|^2. \quad (30)$$

Moreover, from the computational complexity standpoint, we note that since the complexity of SDR problem (P5) is $\mathcal{O}(N^{4.5})$ (Luo et al., 2010), the overall complexity of the greedy detector approximates to $\sim \mathcal{O}(M^{T_x} + T_x)$, while the complexity for the joint ML detector is $\sim \mathcal{O}((M^{T_x} + T_x + N^{4.5})R_x^2)$, which grows exponentially with increasing N and R_x . Therefore, comparing to the joint ML detection, the proposed greedy detector offers a significant reduction in computational burden.

4 Numerical results

In this section, the sum-rate and BER performance of the proposed over-the-air beamforming-based single-user and multi-user downlink transmission, and uplink receive IM schemes are presented through the Monte Carlo simulations. Moreover, comparing to the ZF-based conventional transmission (Spencer et al., 2004; Zhang et al., 2013) and the state-of-the-art

RIS-aided joint beamforming schemes (Wu and Zhang, 2019), the improved performance of the over-the-air beamforming-based systems are illustrated.

In all computer simulations, the following system setups are considered: the reference path loss value is $C_0 = -30$ dBm, the noise variances are $\sigma_v^2 = \sigma_s^2 = -90$ dBm, the path loss exponents for the RIS-aided systems are $\beta_T = 2.2$ and $\beta_k = 2.8$ and for the conventional direct transmission, it is $\beta_D = 3.5$ (Nguyen et al., 2022), the distances are $d_T = 20$, $d_R = 30$ m and $d_D = 50$ m.

4.1 Downlink transmission

In this subsection, the numerical results of the proposed over-the-air beamforming and the benchmark schemes for single-user and multi-user downlink systems are demonstrated.

4.1.1 Single-user

The following computer simulation results are performed for single-user MISO transmission schemes.

In Figure 3, for a single-user downlink transmission ($K = 1$) with $T_x \in \{2, 4\}$ and $N = 16$, the achievable rate performance of the proposed over-the-air beamforming scheme as a function of total transmit power P_T is compared to the traditional ZF precoding (Spencer et al., 2004) and the passive RIS-aided joint active and passive beamforming techniques (Wu and Zhang, 2019). Here, while P_T is the overall power consumed at the transmitters of the traditional ZF precoding and joint beamforming transmission schemes, it corresponds to the total power dissipated between the transmitter (P_{BS}) and the RIS (P_A) for the proposed over-the-air transmission, where $P_T = P_{BS} + P_A$ for $P_{BS} = 0$ dBm. Moreover, as discussed in Section 2.1, the reference ZF precoding considers a traditional single-hop transmission without RIS that performs transmit precoding before the signal transmission (Spencer et al., 2004). On the other hand, in the joint active and passive beamforming scheme, a passive RIS-aided single-user transmission with the existence of direct links between the transmitter and the user, is considered, where the digital beamforming at the transmitter and analog beamforming at a passive RIS *via* phase shifters are jointly optimized to enhance the received SNR of the user (Wu and Zhang, 2019). For this purpose, similar to our proposed beamforming technique, a QCQP-based non-convex optimization problem is formulated and an SDR-based solution is performed *via* CVX solvers (Wu and Zhang, 2019). The results show that although a direct link between the transmitter and the user does not exist in the proposed active RIS-aided over-the-air beamforming scheme, a considerably better performance achievement is observed for $T_x = 2$ compared to the traditional ZF and joint beamforming with passive RIS-aided transmission schemes.

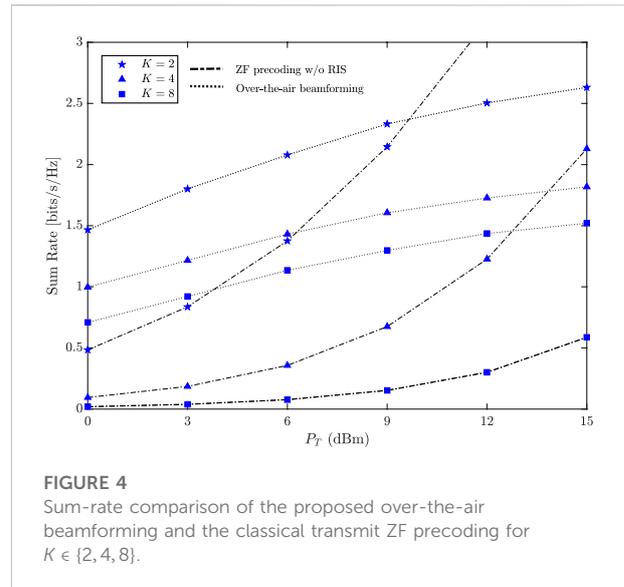


FIGURE 4 Sum-rate comparison of the proposed over-the-air beamforming and the classical transmit ZF precoding for $K \in \{2, 4, 8\}$.

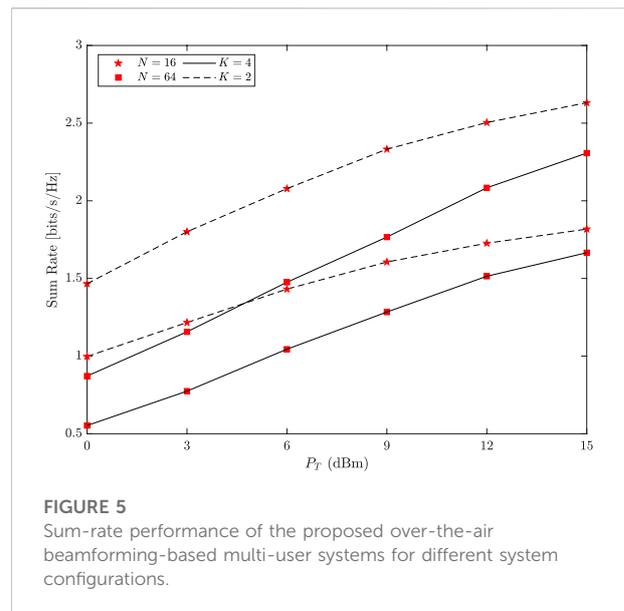


FIGURE 5 Sum-rate performance of the proposed over-the-air beamforming-based multi-user systems for different system configurations.

Moreover, it is shown that increasing T_x results in enhancement of the achievable rate of all systems. However, in the proposed active RIS-aided over-the-air beamforming scheme, as given in (11), since the magnitude of reflection matrix Ψ is restricted with the magnitude of transmission matrix \mathbf{H} , i.e., increasing T_x , a slighter performance improvement is achieved compared to the benchmark schemes. Furthermore, since a small-scale passive RIS is considered, i.e. $N = 16$, an additional performance improvement due to the indirect RIS-aided link is hardly observed in the passive RIS-aided joint

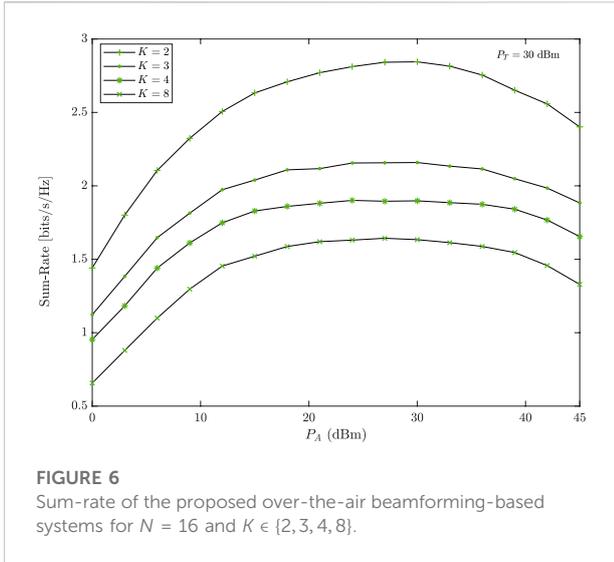


FIGURE 6 Sum-rate of the proposed over-the-air beamforming-based systems for $N = 16$ and $K \in \{2, 3, 4, 8\}$.

beamforming scheme compared to the conventional ZF precoding scheme.

4.1.2 Multi-user

The following results are carried out for downlink multi-antenna transmission schemes, where a single transmit antenna is allocated to each user, i.e., $\bar{T}_x = 1$ and $T_x = K$.

In Figure 4, the sum rate of the downlink multi-antenna transmission scheme based on the conventional transmit ZF precoding (Spencer et al., 2004) and the novel over-the-air

beamforming has been carried out for $K \in \{2, 4, 8\}$, and quadrature PSK (QPSK), i.e., $M = 4$. Comparing these two schemes, it is obvious that at lower P_T values, the over-the-air beamforming based multi-user transmission scheme attains higher sum-rate than the classical transmit ZF precoding technique (Spencer et al., 2004). However, for $K = 2$ and $K = 4$, as P_T increases, the performance of ZF gradually begins to exceed the performance of the proposed beamforming scheme. Nevertheless, for $K = 4$, the ZF precoder achieves only a slight gain over the proposed beamforming concept at $P_T = 15$ dBm. It can be also deduced from Figure 4 that an increase in the total number of users rapidly decreases ZF sum-rate, however, such a severe performance loss is not observed in the proposed over-the-air beamforming-based system. Moreover, when the number of users further increases to $K = 8$, it is observed that the system with the proposed over-the-air beamforming-based scheme outperforms the system with the traditional ZF technique with a significant performance gain.

In Figure 5, the sum-rate of the proposed over-the-air beamforming-based downlink multi-user system is evaluated for different system configurations. In this case, for a constant P_T , the performance of the over-the-air beamforming based systems are investigated for different number of the reflecting elements N , $P_{BS} = 0$ dBm and QPSK signaling. It is observed that increasing RIS size has an adverse affect on the system performance. This results may be explained by the fact that in the over-the-air beamforming design, as given in (11), the power consumed by the reflecting elements is inversely proportional with the magnitude of the channel matrix \mathbf{H} . Therefore, when a constant P_A is considered for $N = 16$ and $N = 64$, it reveals that the

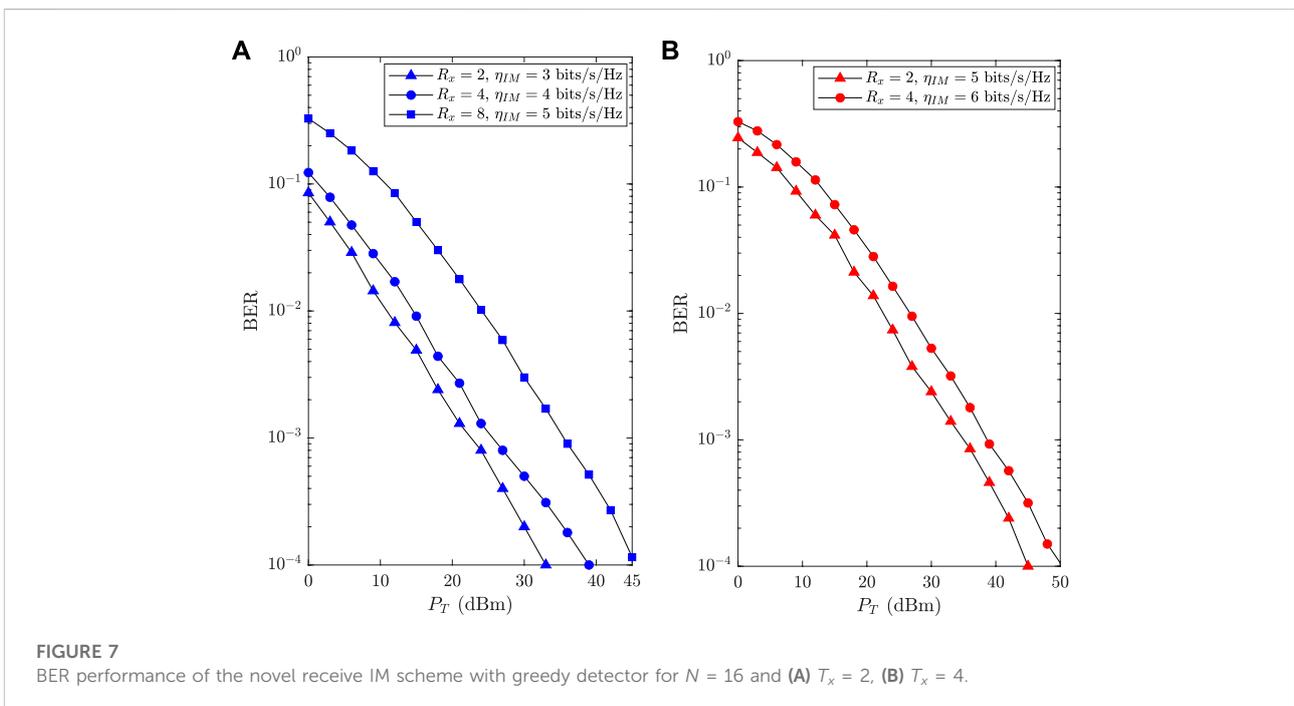
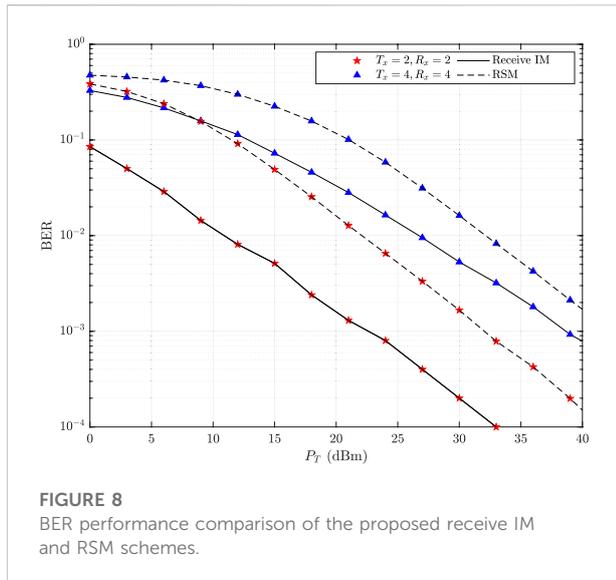


FIGURE 7 BER performance of the novel receive IM scheme with greedy detector for $N = 16$ and (A) $T_x = 2$, (B) $T_x = 4$.



proposed beamforming-based systems with the lower N values show considerably better performance than the ones with the higher N values.

In Figure 6, the effect of increasing reflection power P_A on the sum-rate of the proposed beamforming based systems with QPSK and $P_T = 30$ dBm is investigated for $N = 16$. The results show that in all cases, the increasing P_A improves the system performance up to a certain P_A value, after which the performance begins to degrade. These results indicate the relation between the reflection power constraint P_A and transmitter power P_{BS} in (10). Indeed, in our system design, the overall consumed power P_T is dissipated to the transmitter (P_{BS}) and the RIS (P_A), where $P_T = P_{BS} + P_A$, and for a constant $P_T = 30$ dBm, P_{BS} decreases with increasing P_A . However, it is clear from (6) that the minimizing P_{BS} directly affects the SINR value. Surely, the investigation of this interesting trade-off points out the importance of the power allocation between the transmitter and the RIS, which is an open problem to be addressed in future studies.

4.2 Single-user uplink transmission

In this subsection, the BER performance of the proposed receive IM scheme is evaluated.

In Figure 7, the BER performance of the proposed receive IM scheme with sub-optimal greedy detector is investigated for different RIS-aided MIMO configurations with $N = 16$ and binary PSK (BPSK). Similar to the conventional receive IM schemes (Zhang et al., 2013; Wu et al., 2021), the performance results of the corresponding high-rate systems that employ a) $T_x = 2$ and b) $T_x = 4$ transmit antennas reveal a certain trade-off between system performance and data-rate.

In Figure 8, the BER performance of the transmit ZF precoded receive spatial modulation (RSM) (Zhang et al.,

2013) and the proposed over-the-air receive IM schemes are compared. For $R_x = T_x = 2$, the receive IM and the RSM schemes respectively exploit BPSK and QPSK modulations to achieve $\eta_{IM} = 3$ bits/s/Hz. On the other hand, for $R_x = T_x = 4$ configuration, the receive IM with BPSK and the RSM with 16-PSK assess $\eta_{IM} = 6$ bits/s/Hz. The results demonstrate the significant performance improvement of the proposed receive IM scheme over the traditional ZF precoded RSM (Zhang et al., 2013).

5 Conclusion

In this paper, first, deploying an active RIS, a novel beamforming approach has been proposed for RIS-aided multi-user systems. In the proposed concept, without employing any other signal processing units at the transmitter and/or receiver sides, the reflection coefficients of the active RIS have been customized to mitigate the user interference. To meet this challenge, we have obtained SDR-based solutions *via* CVX software toolbox. Moreover, taking the proposed over-the-air beamforming concept one step further, a low-complexity receive IM scheme has been developed for single-user uplink transmission. Through computer simulations, the enhanced performance of the over-the-air beamforming-based systems over the traditional precoding-based systems have been indicated.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZY, EB, and IA contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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