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Research Article

Differentiated Reception Modes Based Multiple Access

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In recent years, the continuous increase in wireless data services and users' traffic demand has been imposing great challenges on traditional multiple access control (MAC) methods. Some existing MAC techniques improve the communication system's spectral efficiency (SE) via signal processing based cochannel interference (CCI) management. However, no interference management (IM) is free, i.e., its realization is based on the consumption of some communication resources, such as power and degree-of-freedom (DoF), which can also be used for the user's desired data transmission. To lessen the resource cost for IM-based MAC, we exploit interactions among multiple wireless signals to propose a new MAC method, namely, Differentiated Reception Modes based Multiple Access (DRM-MA), in this paper. Under DRM-MA, a central control unit (CCU) is adopted to manage and pair multiple transmitting antennas with their serving receivers (Rxs). The CCU first calculates the phase difference of signals sent from each candidate antenna and perceived by the two receiving antennas of an Rx based on the locations of the transmitting antenna and Rx. Then, the CCU selects and pairs a proper transmitting antenna with each Rx, so that various Rxs can adopt either additive or subtractive reception mode to postprocess the signals received by its two antennas to realize in-phase desired signal construction and inverse-phase interference destruction. DRM-MA can avoid transmission performance loss incurred by signal processing-based IM. Our theoretical analysis and simulation results have shown that DRM-MA can enable concurrent data transmissions of multiple antenna-receiver pairs and output a high system's SE.

1. Introduction

With the continuous growth of users' demand for mobile data services, wireless communication technology has been developing rapidly. Compared to previous communication systems, 5G (the fifth generation) is expected to provide a larger system capacity, higher data rate, lower latency, and more transmission reliability [1]. The Internet of Things (IoT) is a typical application scenario in the 5G era and has been under fast development in recent years, yielding explosive growth of various IoT terminals. It is estimated that by the year 2025 there will be more than 41.6 billion IoT devices connected to the network [2]. The increase of IoT devices and the massive connections of IoT networks impose higher requirements on future wireless communication systems. Due to limited communication resources, efficiently supporting more users with high data transmission quality simultaneously has become a hot topic that is worthy of a thorough investigation.

Traditional orthogonal multiple access (OMA) technologies, including frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and space division multiple access (SDMA), allocate various types of communication resources, such as frequencies, time slots, code-words, and spatial subchannels, to multiple users in an orthogonal way to avoid cochannel interference (CCI) among concurrent data transmissions, hence, realizing resource sharing among multiple users [3]. However, the above OMA methods are featured as fixed resource allocation and have low resource utilization. Therefore, due to the limitation of communication resources (especially the spectrum resource) and the rapid increase in the number of wireless users, OMA is facing a great challenge. By dynamically sharing frequency resources to multiple users, ALOHA, carrier sense multiple access (CSMA) [4, 5], and cognitive radio (CR) [6] have been proposed successively, with which the spectrum utilization can be effectively improved. However, such random/opportunistic MACs have collision and transmission failure problems, hence incurring resource waste, to remedy this deficiency, additional cost, and resource consumption (e.g., retransmission and reservation overhead) result.

In recent years, nonorthogonal multiple access (NOMA), which is regarded as a promising MAC method that can be applied in 5G, has been invented and attracted a lot of attention. Uplink NOMA [7] allows multiple transmitters (Txs) to transmit to their common receiver (Rx) via the same frequency channel in a non-orthogonal way. The Rx can employ successive interference cancellation (SIC) [8] to mitigate CCI. However, SIC has an error propagation problem [9] which incurs a high bit-error rate (BER) of the subsequently decoded user data, thus limiting its application. By noting that increasing the number of receiving antennas can strengthen Rx's spatial signal processing capability, and the data carried in multiple concurrent signals can be distinguished and recovered in the spatial domain [10], some researchers incorporate multiantenna with SIC to balance the complexity and BER performance of communication systems [11, 12]. However, due to equipment constraints such as hardware size and complexity, it is impractical to increase the number of receiving antennas without limit, especially for mobile devices. Therefore, some researchers exploit interactions among multiple wireless signals to design multiuser communication schemes. The authors of [13, 14] proposed interference neutralization (IN) in which the desired Tx constructs and sends a neutralizing signal of the same amplitude and opposite phase with respect to the interference perceived by its serving Rx so that the neutralizing signal can counteract the interference at the Rx. Since the power cost for generating the neutralizing signal is high, [15] designed interference steering (IS). By constructing a steering signal at the serving Tx, only the projection of the interference on the desired transmission at the interfered Rx is mitigated, hence, yielding the steered disturbance to be orthogonal to the desired signal.

Based on the above discussion, we will propose a novel MAC method, called Differentiated Reception Modes based Multiple Access (DRM-MA) in this paper. By exploiting interactions among wireless signals, DRM-MA lets mobile users adopt either additive or subtractive reception mode based on the phase difference of the signals sent from their serving and interfering antennas and perceived by their two receiving antennas so that the desired signals and the interferences can be constructively and destructively combined at each Rx. In this way, concurrent data transmissions of multiple antenna-receiver pairs are realized. Compared to traditional signal processing-based MAC methods discussed in the previous paragraph, our method does not incur a signal processing burden at either side of the communication link. However, to realize the method, the central control unit (CCU) needs to determine the serving antenna for each Rx, hence incurring some computational complexity.

The main contributions of this paper are two-fold:

(i) *Proposal of DRM-MA*. By exploiting interactions among two wireless signals, an Rx can select the appropriate reception mode according to the phase difference of the signals sent from the antennas of serving Tx and interfering Tx and observed by its receiving antennas, respectively. Then, the desired signal components can be constructively combined while the interferences are neutralized with each other at the Rx

(ii) *Development of Antenna Selection Criterion*. Aiming at strengthening the desired signal and suppressing the CCI as much as possible, various candidate transmitting antenna sets are calculated, from which the serving antenna for each Rx is then selected, and accordingly, each Rx determines its reception mode

The rest of the paper is organized as follows. Section 2 describes the system model while Section 3 details the design of DRM-MA. In Section 4, we evaluate the performance of DRM-MA. Finally, we conclude the paper in Section 5.

Throughout this paper, we use the following notations. Let $|\cdot|$ denote the absolute value of a scalar. argmax$\{\cdot\}$ indicates an operation finding the argument that gives the maximum value from a target function.

2. System Model

We consider a downlink communication scenario consisting of a central control unit (CCU) and multiple distributedly located transmitting antennas under CCU's control. The antennas are uniformly deployed in the area of $V \times H$. As Figure 1 shows, the antenna whose y- and x-coordinates are v and h, respectively, is denoted as Tx_{vh} ($v \in \{1, 2, \cdots, V\}, h \in \{1, 2, \cdots, H\}$). Tx_{vh} can also be regarded as a single-antenna transmitter. The transmit power of each antenna is P_T. For simplicity, we plot two Rxs, say Rx_m and Rx_k, in the communication environment. Each Rx is equipped with $N_R = 2$ antennas. The two antennas of Rx_m are denoted as m_1 and m_2, while Rx_k's antennas are k_1 and k_2. Let $g_{m_1}^{vh}$ and $g_{m_2}^{vh}$ represent the channel fading coefficients between Tx_{vh} and Rx_m's two antennas. Similarly, $g_{k_1}^{vh}$ and $g_{k_2}^{vh}$ are the fading coefficients between Tx_{vh} and Rx_k's antennas, respectively. We adopt free-space propagation model [16], hence, the power of received signal at antenna κ ($\kappa \in \{m_1, m_2, k_1, k_2\}$) from Tx_{vh} can be computed as $P_\kappa^{vh} = P_T G_{vh} G_\kappa \lambda^2 / \Gamma (4\pi l_\kappa^{vh})^2$ where λ represents the signal's wavelength. G_{vh} and G_κ are the gains of the transmitting antenna Tx_{vh} and receiving antenna κ. Γ is the path-loss factor. l_κ^{vh} denotes the distance from Tx_{vh} to κ. We assume that CCU can accurately obtain the channel coefficients from all transmitting antennas to each receiving antenna of an Rx. By exploiting channel reciprocity [17], the uplink and downlink can have the same channel coefficients.

We employ φ_κ^{vh} to represent the phase of the signal sent from Tx_{vh} and perceived by receiving antenna κ. To reduce signaling overhead, we let Rx_ℓ ($\ell \in \{m, k\}$) only feed back to CCU the midpoint coordinate, i.e., C_ℓ, of the line segment

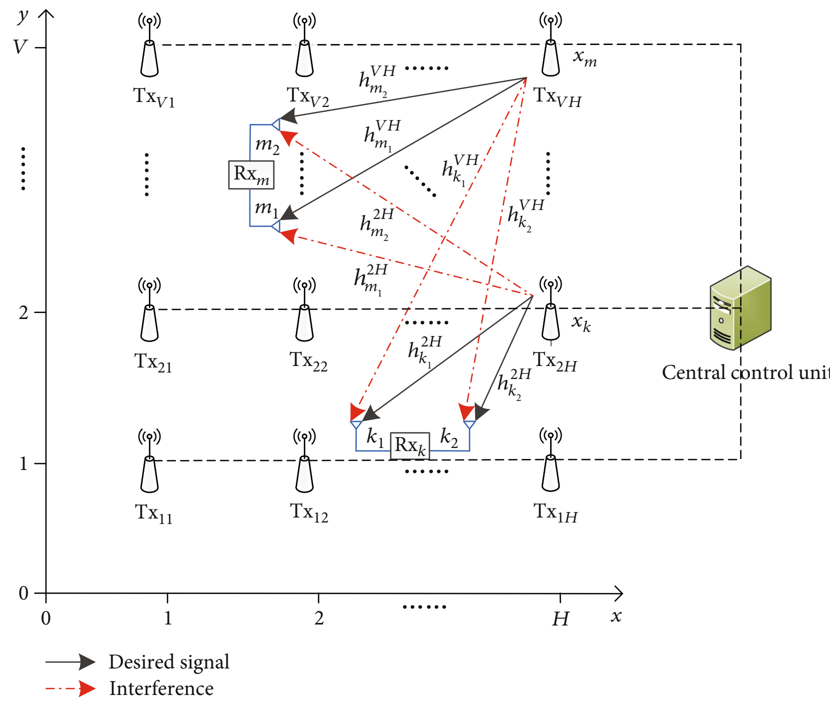


FIGURE 1: System model.

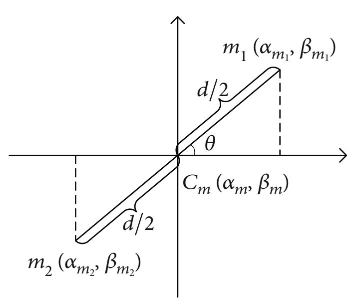


FIGURE 2: Geometrical illustration of Rx_m's two receiving antennas, and $\overline{m_1 m_2}$'s midpoint C_m and phase angle θ.

$\overline{\ell_1 \ell_2}$ between Rx_ℓ's two receiving antennas, and the phase angle θ of $\overline{\ell_1 \ell_2}$ with respect to the horizontal axis. In Figure 2, taking Rx_m as an example, CCU can calculate the coordinates of Rx_m's two receiving antennas, i.e., m_1 and m_2, according to C_m, θ, and antenna spacing d (we assume the distance between Rx's two antennas is available to CCU). As Figure 2 shows, we denote the coordinate of the midpoint of line segment $\overline{m_1 m_2}$ as $C_m(\alpha_m, \beta_m)$, then, the x - and y-coordinates of m_1 can be calculated as $\alpha_{m_1} = \alpha_m + 1/2d \cos \theta$ and $\beta_{m_1} = \beta_m + 1/2d \sin \theta$, respectively. Similarly, the coordinates of receiving antenna m_2 are $\alpha_{m_2} = \alpha_m - 1/2\, d \cos \theta$ and $\beta_{m_2} = \beta_m - 1/2d \sin \theta$.

3. Design of DRM-MA

This section details the design of Differentiated Receive Mode-based Multiple Access (DRM-MA). We will first present the basic principle of DRM-MA and then give the criterion based on which the transmitting antennas serving multiple Rxs are selected and paired with the Rxs; accordingly, and each Rx determines its reception mode.

3.1. Basic Design of DRM-MA. For clarity, we take two Rxs as an example to present the principle of DRM-MA. As Figure 1 shows, we assume that the serving antennas for Rx_m and Rx_k have been determined (the antenna selection method will be given in the next subsection). Without loss of generality, we let antennas $Tx_{v_m h_m}$ and $Tx_{v_k h_k}$ send desired signals to Rx_m and Rx_k, respectively. It should be noticed that $Tx_{v_m h_m}$ causes interference to Rx_k and vice versa. Therefore, we also call $Tx_{v_m h_m}$ and $Tx_{v_k h_k}$ permissive interfering antennas of Rx_k and Rx_m, respectively.

We use x_m and x_k to denote the desired data symbols of Rx_m and Rx_k. Both $Tx_{v_m h_m}$ and $Tx_{v_k h_k}$ send one desired signal to their intended Rx. Then, the mixed signals perceived by antennas m_1 and m_2 of Rx_m, denoted as y_{m_1} and y_{m_2}, respectively, can be expressed as

$$\begin{cases} y_{m_1} = g_{m_1}^{v_m h_m} x_m + g_{m_1}^{v_k h_k} x_k + n_{m_1}, \\ y_{m_2} = g_{m_2}^{v_m h_m} x_m + g_{m_2}^{v_k h_k} x_k + n_{m_2}, \end{cases} \quad (1)$$

where g_κ^τ ($\tau \in \{v_m h_m, v_k h_k\}$ and $\kappa \in \{m_1, m_2\}$) denote the fading coefficient of the channel from Tx_τ to Rx_m's antenna κ. The first term on the right-hand side (RHS) of each sub-equation in Eq. (1) represents for the desired signal from $Tx_{v_m h_m}$, while the second term denotes the interference from $Tx_{v_k h_k}$. The third term is Additive White Gaussian Noise (AWGN) whose element has zero-mean and variance σ_n^2.

The complex channel coefficient g_κ^τ can be expressed as [18]

$$g_\kappa^\tau = |g_\kappa^\tau| e^{j\varphi_\kappa^\tau}, \tag{2}$$

where $|g_\kappa^\tau|$ denotes the amplitude fading, and $\varphi_\kappa^\tau \in [0, 2\pi]$ is the phase offset yielded by the channel.

Substituting Eq. (2) into Eq. (1), we can get

$$\begin{cases} y_{m_1} = \left|g_{m_1}^{v_m h_m}\right| x_m e^{j\varphi_{m_1}^{v_m h_m}} + \left|g_{m_1}^{v_k h_k}\right| x_k e^{j\varphi_{m_1}^{v_k h_k}} + n_{m_1}, \\ y_{m_2} = \left|g_{m_2}^{v_m h_m}\right| x_m e^{j\varphi_{m_2}^{v_m h_m}} + \left|g_{m_2}^{v_k h_k}\right| x_k e^{j\varphi_{m_2}^{v_k h_k}} + n_{m_2}. \end{cases} \tag{3}$$

From Eq. (3), we can obtain the phase difference of the desired signal components perceived by Rx_m's two antennas as $\Delta\varphi_m^{v_m h_m} = |\varphi_{m_1}^{v_m h_m} - \varphi_{m_2}^{v_m h_m}|$. If $(\Delta\varphi_m^{v_m h_m}) \bmod (2\pi) = \pi$ (mod $(\cdot)$ represents modulo operation) holds, Rx_m can simply subtract one antenna's received signal from the other, so that the in-phase superposition of the desired signal is realized. Otherwise, if $(\Delta\varphi_m^{v_m h_m}) \bmod (2\pi) = 0$ holds, Rx_m can add the received signals of its two antennas to achieve the in-phase desired signal combination. Meanwhile, m_1 and m_2 also receive interference from $Tx_{v_k h_k}$ (see the second terms on the RHS of Eq. (3)). If the phase difference of the two interfering components satisfies $(\Delta\varphi_m^{v_k h_k}) \bmod (2\pi) = \pi$, Rx_m should add up the two interferences to mitigate their influence. Otherwise, if $(\Delta\varphi_m^{v_k h_k}) \bmod (2\pi) = 0$ holds, Rx_m should subtract one disturbance from the other to realize interference cancellation. Likewise, Rx_k can realize desired signal construction and interference destruction based on the phase difference of two desired/interfering signal components at its antennas. Therefore, in the use of DRM-MA, CCU first calculates the phase difference of signals sent from each candidate antenna and perceived by the two receiving antennas of an Rx based on the locations of the transmitting antenna and Rx, then determines the Rx's reception mode according to the phase difference.

Upon employing various reception modes, i.e., additive or subtractive, each Rx realizes both desired signal strengthening and interference cancellation. Without loss of generality, we take $(\Delta\varphi_m^{v_m h_m}) \bmod (2\pi) = \pi$ and $(\Delta\varphi_m^{v_k h_k}) \bmod (2\pi) = 0$ as an example, then, Rx_m can adopt subtractive mode to get the following equation.

$$\begin{aligned} y_m = &\underbrace{\left(\left|g_{m_1}^{v_m h_m}\right| e^{j\varphi_{m_1}^{v_m h_m}} - \left|g_{m_2}^{v_m h_m}\right| e^{j\varphi_{m_2}^{v_m h_m}}\right) x_m}_{\text{In-phase desired signal construction.}} \\ &+ \underbrace{\left(\left|g_{m_1}^{v_k h_k}\right| e^{j\varphi_{m_1}^{v_k h_k}} - \left|g_{m_2}^{v_k h_k}\right| e^{j\varphi_{m_2}^{v_k h_k}}\right) x_k}_{\text{Inverse-phase interference destruction.}} + n_m. \end{aligned} \tag{4}$$

Since $|g_{m_1}^{v_m h_m}| e^{j\varphi_{m_1}^{v_m h_m}}$ and $|g_{m_2}^{v_m h_m}| e^{j\varphi_{m_2}^{v_m h_m}}$ are known to Rx_m, Rx_m can adopt coefficient $(|g_{m_1}^{v_m h_m}| e^{j\varphi_{m_1}^{v_m h_m}} - |g_{m_2}^{v_m h_m}| e^{j\varphi_{m_2}^{v_m h_m}})^{-1}$ to postprocess y_m to obtain the estimated desired signal as

$$\hat{y}_m = \left(\left|g_{m_1}^{v_m h_m}\right| e^{j\varphi_{m_1}^{v_m h_m}} - \left|g_{m_2}^{v_m h_m}\right| e^{j\varphi_{m_2}^{v_m h_m}}\right)^{-1} y_m. \tag{5}$$

Meanwhile, the phase difference of the desired and interfering signal sent from $Tx_{v_m h_m}$ and $Tx_{v_k h_k}$, respectively, and received by Rx_k's two antennas k_1 and k_2 should satisfy $(\Delta\varphi_k^{v_k h_k}) \bmod (2\pi) = 0$ and $(\Delta\varphi_k^{v_m h_m}) \bmod (2\pi) = \pi$. In such a case, Rx_k can employ additive mode to get the following equation.

$$\begin{aligned} y_k = &\underbrace{\left(\left|g_{k_1}^{v_k h_k}\right| e^{j\varphi_{k_1}^{v_k h_k}} + \left|g_{k_2}^{v_k h_k}\right| e^{j\varphi_{k_2}^{v_k h_k}}\right) x_k}_{\text{In-phase desired signal construction.}} \\ &+ \underbrace{\left(\left|g_{k_1}^{v_m h_m}\right| e^{j\varphi_{k_1}^{v_m h_m}} + \left|g_{k_2}^{v_m h_m}\right| e^{j\varphi_{k_2}^{v_m h_m}}\right) x_m}_{\text{Inverse-phase interference destruction.}} + n_k. \end{aligned} \tag{6}$$

Then, by adopting $(|g_{k_1}^{v_k h_k}| e^{j\varphi_{k_1}^{v_k h_k}} + |g_{k_2}^{v_k h_k}| e^{j\varphi_{k_2}^{v_k h_k}})^{-1}$ to postprocess y_k, Rx_k can get the estimated signal as

$$\hat{y}_k = \left(\left|g_{k_1}^{v_k h_k}\right| e^{j\varphi_{k_1}^{v_k h_k}} + \left|g_{k_2}^{v_k h_k}\right| e^{j\varphi_{k_2}^{v_k h_k}}\right)^{-1} y_k. \tag{7}$$

We can see from Eqs. (4) and (6) that employing additive and subtractive mode, respectively, Rx_m and Rx_k can postprocess the received signals of their antennas. In this way, the desired signal is strengthened while the disturbance is suppressed, thus realizing DRM-MA.

3.2. Design of Antenna Selection Criterion. In the previous subsection, we have presented the basic idea of DRM-MA under the assumption that serving antennas for Rxs have been determined. In this subsection, we will still take two Rxs as an example to design the serving antenna selection criterion.

To select the proper antenna to serve an Rx, say Rx_m, CCU needs to calculate the coordinates of m_1 and m_2 based on the information of C_m, d, and θ and then compute the phase of the signal sent from each candidate antenna Tx_{vh} $(v \in \{1, 2, \cdots, V\}, h \in \{1, 2, \cdots, H\})$ and perceived by Rx_m's receiving antenna κ $(\kappa \in \{m_1, m_2\})$ as

$$\varphi_\kappa^{vh} = \frac{2 l_\kappa^{vh} \pi}{\lambda} = \frac{2 l_\kappa^{vh} \pi f}{c}, \tag{8}$$

where f denotes the frequency of the transmitted signal and λ is the signal's wavelength. c represents the speed of light. l_κ^{vh} is the distance from Tx_{vh} to Rx_m's antenna κ.

Table 1: Determining candidate serving antenna set (SAS) and Rx's reception mode (RM) under $K = 2$.

Case	SAS for Rx_m	SAS for Rx_k	Rx_m's RM	Rx_k's RM
I	$\mathfrak{R}_{oo}^{mk}$	$\mathfrak{R}_{ee}^{mk}$	Subtractive	Additive
II	$\mathfrak{R}_{oe}^{mk}$	$\mathfrak{R}_{eo}^{mk}$	Subtractive	Subtractive
III	$\mathfrak{R}_{eo}^{mk}$	$\mathfrak{R}_{oe}^{mk}$	Additive	Additive
IV	$\mathfrak{R}_{ee}^{mk}$	$\mathfrak{R}_{oo}^{mk}$	Additive	Subtractive

Then, we can get the phase difference $\Delta\varphi_m^{vh}$ of the signals sent from Tx_{vh} and received by Rx_m's two antennas as

$$\Delta\varphi_m^{vh} = \left|\varphi_{m_1}^{vh} - \varphi_{m_2}^{vh}\right| = \frac{2\pi f\left|l_{m_1}^{vh} - l_{m_2}^{vh}\right|}{c}. \quad (9)$$

Since we employ the free-space propagation model, in what follows, we only consider the influence of the signal's propagation on φ_κ^{vh} and $\Delta\varphi_m^{vh}$. Without loss of generality, we take Rx_m as an example. If $(\Delta\varphi_m^{vh}) \bmod (2\pi) = \pi$ holds, we store Tx_{vh} in a transmitting antenna set Ω_o^m. Otherwise, if $(\Delta\varphi_m^{vh}) \bmod (2\pi) = 0$ holds, Tx_{vh} is added to transmitting antenna set Ω_e^m. When an antenna in sets Ω_o^m and Ω_e^m is selected to serve Rx_m, Rx_m needs to adopt additive and subtractive reception modes accordingly. Similarly, transmitting antenna sets Ω_o^k and Ω_e^k for Rx_k can be obtained.

Next, we calculate intersections of Rx_m's sets Ω_o^m and Ω_e^m and Rx_k's Ω_o^k and Ω_e^k, respectively, to obtain four candidate transmitting antenna sets, i.e., $\mathfrak{R}_{oo}^{mk} = \Omega_o^m \bigcap \Omega_o^k$, $\mathfrak{R}_{oe}^{mk} = \Omega_o^m \bigcap \Omega_e^k$, $\mathfrak{R}_{eo}^{mk} = \Omega_e^m \bigcap \Omega_o^k$, and $\mathfrak{R}_{ee}^{mk} = \Omega_e^m \bigcap \Omega_e^k$, as given in Table 1. Accordingly, four differentiated reception modes of the two Rxs can be determined. Taking candidate antenna set $\mathfrak{R}_{oo}^{mk}$ as an example, the subscript *oo* indicates that the phase difference of signals sent from each antenna in set $\mathfrak{R}_{oo}^{mk}$ and perceived by the two receiving antennas of both Rx_m and Rx_k is odd times of π. That is, when an antenna in $\mathfrak{R}_{oo}^{mk}$ serves Rx_m or Rx_k, either Rx_m or Rx_k should adopt the subtractive reception mode to strengthen its desired signal. As for $\mathfrak{R}_{eo}^{mk}$, its subscript *eo* indicates that the phase difference of the signals sent from $\mathfrak{R}_{eo}^{mk}$'s antenna and observed by Rx_m's and Rx_k's two antennas is even and odd times of π, respectively. Therefore, when an antenna in $\mathfrak{R}_{eo}^{mk}$ is selected to serve Rx_m or Rx_k, Rx_m should adopt additive mode, while Rx_k should use subtractive, to strengthen their desired signal. As Table 1 shows, Rx_m and Rx_k can adopt either identical reception modes (cases II and III) or different modes (cases I and IV) in terms of their serving transmitting antenna sets.

In practice, when selecting a serving antenna for an Rx, not only does the desired signal at the intended Rx need to be strong but also the interference to other unintended Rxs should be as small as possible. In what follows, we will present the serving antenna selection criterion on the premise that the candidate serving antenna sets have been determined.

Without loss of generality, we take the case I in Table 1 as an example. When a candidate $Tx_{vh} \in \mathfrak{R}_{oo}^{mk}$ serves Rx_m and interferes with Rx_k, Rx_m adopts subtractive mode to subtract the desired signal perceived by one antenna from the other. Then, we can have•

$$\Delta A_m^{vh} = \left|g_{m_1}^{vh}\right| e^{j\varphi_{m_1}^{vh}} - \left|g_{m_2}^{vh}\right| e^{j\varphi_{m_2}^{vh}}. \quad (10)$$

As for Rx_k, it employs additive reception mode to alleviate the interference sent from Tx_{vh} and received by its two antennas. We can get

$$\Sigma A_k^{vh} = \left|g_{k_1}^{vh}\right| e^{j\varphi_{k_1}^{vh}} + \left|g_{k_2}^{vh}\right| e^{j\varphi_{k_2}^{vh}}. \quad (11)$$

Then, we should select the Tx_{vh} that can maximize ΔA_m^{vh}, denoted as $Tx_{v_m h_m}$, as Rx_m's serving antenna; that is, ($Tx_{v_m h_m} = \arg\max_{Tx_{vh} \in \mathfrak{R}_{oo}^{mk}} \{\Delta A_m^{vh}\}$). However, by taking the interference from Tx_{vh} to Rx_k into account, we should employ $(\Sigma A_k^{vh})^{-1}$ as another factor affecting Rx_m's serving antenna selection. That is, since ΣA_k^{vh} indicates residual interference at Rx_k, we should use an antenna yielding as small ΣA_k^{vh} as possible to serve Rx_m. Based on the above discussion, to take both desired signal strengthening at Rx_m and interference cancellation at Rx_k into consideration, an antenna outputting the largest $\mu_{mk}^{vh} = \xi\Delta A_m^{vh} + (1 - \xi)(\Sigma A_k^{vh})^{-1}$ where $\xi \in [0, 1]$ is a weight coefficient and should be selected to serve Rx_m. Specifically, in this example, we determine Rx_m's serving antenna according to $(Tx_{v_m h_m} = \arg\max_{Tx_{vh} \in \mathfrak{R}_{oo}^{mk}} \{\mu_{mk}^{vh}\})$. If one prefers a better performance of Rx_m, a larger ξ should be adopted; otherwise, if one wants the interference at Rx_k to be small, a smaller ξ should be used.

In the previous design, we simply assume that the phase difference of signal components perceived by an Rx's two antennas is either odd or even times of π, based on which the candidate serving antenna sets can be determined. However, in practice, the phase difference is usually not exactly the odd or even times of π. In such a situation, we need to introduce a tolerance coefficient ε to relax the requirement of the phase difference of signals at Rx's two antennas. Otherwise, too strict a phase difference requirement may yield an empty candidate serving antenna set, hence incurring the unavailability of DRM-MA.

Based on the above discussion, we adopt $(\Delta\varphi_m^{vh}) \bmod (2\pi) = \pi \pm \varepsilon$ and $(\Delta\varphi_m^{vh}) \bmod (2\pi) = \pm\varepsilon$ instead of $(\Delta\varphi_m^{vh}) \bmod (2\pi) = \pi$ and $(\Delta\varphi_m^{vh}) \bmod (2\pi) = 0$, respectively, as the criterion to determine the candidate serving antenna sets. In this way, we can ensure that the candidate serving antenna set is not empty by using a proper ε. However, this will incur nonideal in-phase construction of desired signal and inverse-phase interference destruction at Rx. To solve this problem, Rx can perform phase compensation according to the phase difference of the signals perceived by its two antennas [19], and then accurate in-phase desired signal superposition and inverse-phase interference cancellation can be realized. The stronger the phase compensation capability of the Rx is, the larger ε can be used.

It should be noticed that although phase compensation can yield the phase difference of the signal components perceived by Rx's two antennas to be exactly odd times or even times of π, the signal components' amplitudes may not be the same, hence incurring residual interference at Rx. Fortunately, since the size of Rx and its antenna spacing are small, the difference in propagation distance from the interfering antenna to Rx's two receiving antennas is limited. Therefore, the influence of residual interference is negligible. For space limit, we omit the detailed discussion about the residual interference in this paper.

3.3. Extended Design of DRM-MA. In previous subsections, we simply assume two Rxs for clarity. In this subsection, we will extend DRM-MA to a multi-Rx situation to show its scalability.

We let the number of Rxs be three, i.e., Rx_m, Rx_k, and Rx_s are in the communication scenario. First, CCU calculates the phase difference of the signals sent from each Tx_{vh} and perceived by the Rxs' receiving antennas. Then, an antenna set suitable for serving each Rx under additive and subtractive reception modes can be obtained. We denote the set of serving antennas for Rx_ϖ under additive and subtractive modes as Ω_e^ϖ and Ω_o^ϖ, respectively, where $\varpi \in \{m, k, s\}$. Then, we select one set from the serving antenna sets of Rx_m, Rx_k, and Rx_s in turn and calculate the intersection of the three selected sets, so that eight cases of candidate serving antenna sets can be obtained as $\mathfrak{R}_{ooo}^{mks} = \Omega_o^m \bigcap \Omega_o^k \bigcap \Omega_o^s$, $\mathfrak{R}_{ooe}^{mks} = \Omega_o^m \bigcap \Omega_o^k \bigcap \Omega_e^s$, $\mathfrak{R}_{oeo}^{mks} = \Omega_o^m \bigcap \Omega_e^k \bigcap \Omega_o^s$, $\mathfrak{R}_{oee}^{mks} = \Omega_o^m \bigcap \Omega_e^k \bigcap \Omega_e^s$, $\mathfrak{R}_{eoo}^{mks} = \Omega_e^m \bigcap \Omega_o^k \bigcap \Omega_o^s$, $\mathfrak{R}_{eoe}^{mks} = \Omega_e^m \bigcap \Omega_o^k \bigcap \Omega_e^s$, $\mathfrak{R}_{eeo}^{mks} = \Omega_e^m \bigcap \Omega_e^k \bigcap \Omega_o^s$, and $\mathfrak{R}_{eee}^{mks} = \Omega_e^m \bigcap \Omega_e^k \bigcap \Omega_e^s$. As Table 2 shows, the above eight sets correspond to eight combinations of the three Rxs' reception modes. Taking $\mathfrak{R}_{eee}^{mks}$ as an example, its subscript is *eee*, this indicates that when an antenna in set $\mathfrak{R}_{eee}^{mks}$ serves Rx_ϖ ($\varpi \in \{m, k, s\}$), the phase difference of the signals perceived by Rx_ϖ's two antennas is even times of π, thus Rx_ϖ should adopt subtractive reception mode.

Based on the various combinations of the serving antenna sets, the reception modes of multiple Rxs can be determined. Since there is always no cooperation among multiple Rxs, Rxs' reception modes should be determined by the CCU and then informed to each Rx. We further present the extension of DRM-MA to the case of K ($K > 2$) Rx. First, we index all Rxs from 1 to K. For simplicity, we replace the subscripts o and e of the candidate serving antenna sets with binary numbers 0 and 1, respectively. In this way, the string composed of o and e can be equivalent to a binary code. Provided with K Rxs, DRM-MA first calculates Ω_e^ϖ and Ω_o^ϖ where $\varpi \in \{1, 2, \cdots, K\}$ for each Rx, based on which 2^K cases of candidate serving antenna sets, denoted as $\mathfrak{R}_{b_1 \cdots b_K}^{1 \cdots K}$ where $b_1 \cdots b_K$ can be either $o(0)$ or $e(1)$, can be obtained. Next, we can select any one of the 2^K candidate antenna sets (e.g., case I in Table 2) and mark it as the serving antenna set for Rx_1 (e.g., as for case I in Table 2, $\mathfrak{R}_{ooo}^{mks}$ whose subscript is 000 serves Rx_m). Then, we select the serving antenna set for Rx_2 (e.g., as for case I in Table 2, $\mathfrak{R}_{eeo}^{mks}$ whose subscript is 110 serves Rx_k); the 1st and 2nd bits of Rx_2's serving antenna set's subscript should be opposite to those of Rx_1's, while the rest bits of the two Rxs' serving antenna sets' subscripts are the same. As for Rx_3 (under $K = 3$, according to Table 2, $\mathfrak{R}_{eoe}^{mks}$ whose subscript is 101 serves Rx_s); the 1st and 3rd bits of Rx_3's serving antenna set's subscript should be opposite to those of Rx_1's, while the remaining bits of the two Rxs' sets' subscripts are the same. As for Rx_K, the 1st and Kth bits of its serving antenna set need to be opposite to those Rx_1's, while the remaining bits of the two Rxs's sets' subscripts are the same.

Table 2: Determining candidate serving antenna set (SAS) and Rx's reception mode (RM) under $K = 3$.

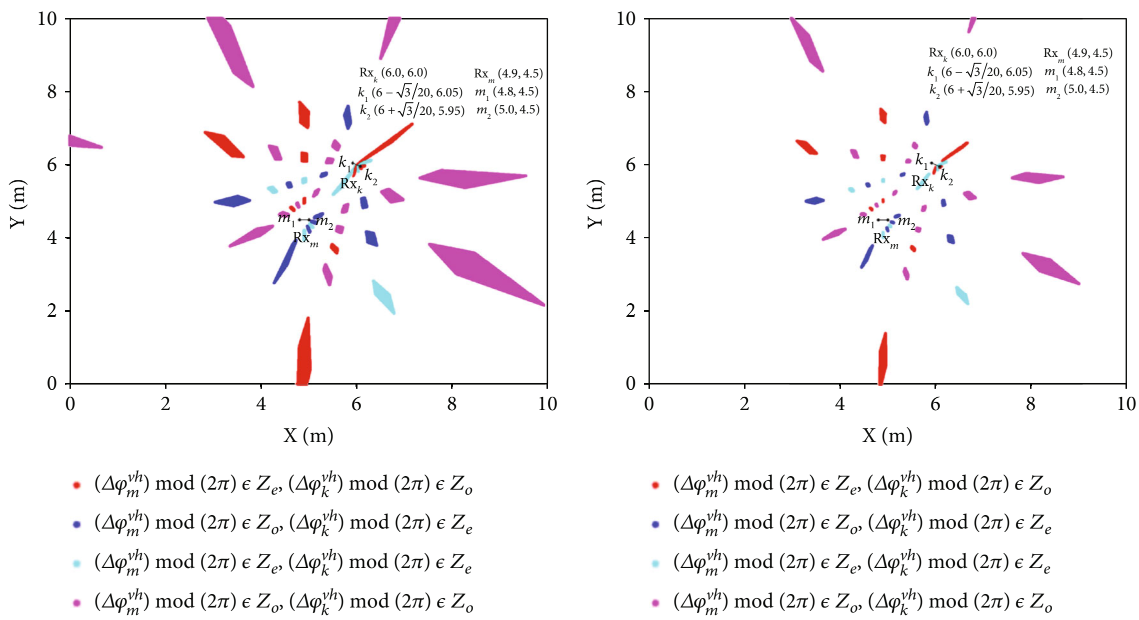
Case	SAS for Rx_m	SAS for Rx_k	SAS for Rx_s	Rx_m's RM	Rx_k's RM	Rx_s's RM
I	$\mathfrak{R}_{ooo}^{mks}$	$\mathfrak{R}_{eeo}^{mks}$	$\mathfrak{R}_{eoe}^{mks}$	Subtractive	Additive	Additive
II	$\mathfrak{R}_{ooe}^{mks}$	$\mathfrak{R}_{eee}^{mks}$	$\mathfrak{R}_{eoo}^{mks}$	Subtractive	Additive	Subtractive
III	$\mathfrak{R}_{oeo}^{mks}$	$\mathfrak{R}_{eoo}^{mks}$	$\mathfrak{R}_{eee}^{mks}$	Subtractive	Subtractive	Additive
IV	$\mathfrak{R}_{oee}^{mks}$	$\mathfrak{R}_{eoe}^{mks}$	$\mathfrak{R}_{eeo}^{mks}$	Subtractive	Subtractive	Subtractive
V	$\mathfrak{R}_{eoo}^{mks}$	$\mathfrak{R}_{oeo}^{mks}$	$\mathfrak{R}_{ooe}^{mks}$	Additive	Additive	Additive
VI	$\mathfrak{R}_{eoe}^{mks}$	$\mathfrak{R}_{oee}^{mks}$	$\mathfrak{R}_{ooo}^{mks}$	Additive	Additive	Subtractive
VII	$\mathfrak{R}_{eeo}^{mks}$	$\mathfrak{R}_{ooo}^{mks}$	$\mathfrak{R}_{oee}^{mks}$	Additive	Subtractive	Additive
VIII	$\mathfrak{R}_{eee}^{mks}$	$\mathfrak{R}_{ooo}^{mks}$	$\mathfrak{R}_{oeo}^{mks}$	Additive	Subtractive	Subtractive

Based on the above process, 2^K combinations of serving antenna sets for K Rxs can be obtained. Then, an Rx, say $Rx_{\widehat{k}}$ ($\widehat{k} \in \{1, \cdots, K\}$) can determine its reception mode in terms of the $\widehat{k}^{th}$ bit of its serving antenna set's subscript. Specifically, if the $\widehat{k}^{\text{th}}$ bit is $o(0)$, $Rx_{\widehat{k}}$ should adopt subtractive mode; otherwise, for $e(1)$, additive reception mode should be used. We take case I in Table 2 as an example, the first user Rx_m adopts subtractive mode according to the 1st bit of $\mathfrak{R}_{ooo}^{mks}$'s subscript. Similarly, the second user Rx_k employs additive mode based on the 2nd bit of $\mathfrak{R}_{eeo}^{mks}$'s subscript. As for the last user Rx_s, its uses additive mode according to the 3rd bit of $\mathfrak{R}_{eoe}^{mks}$)'s subscript.

Based on the above descriptions, DRM-MA can be applied to the communication scenario with K Rxs.

4. Evaluations

In this section, we use MATLAB to evaluate the performance of the proposed DRM-MA. We consider a communication scenario of $10\text{m} \times 10\text{m}$, in which multiple antennas, denoted as Tx_{vh} ($v \in \{1, 2, \cdots, V\}, h \in \{1, 2, \cdots, H\}$), are uniformly distributed. The transmit power of Tx_{vh} is P_T. The



(a) $\varepsilon = \pi/10$ (b) $\varepsilon = \pi/18$

Figure 3: Distribution of candidate serving antennas for Rx_m and Rx_k under various εs.

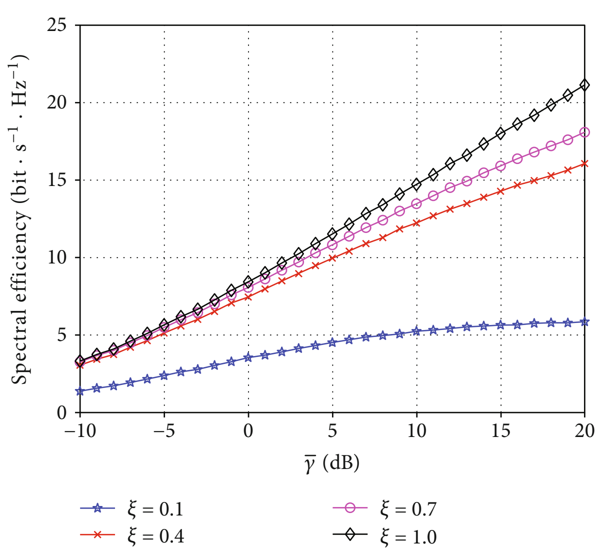


Figure 4: Variation of system's average SE with $\bar{\gamma}$ under various ξs.

carrier frequency is 2.4 GHz. Two Rxs, denoted as Rx_m and Rx_k, are arbitrarily located in the communication area and equipped with two antennas. The distance between Rx's two receiving antennas, d, is 0.2 m. We employ the free space propagation model as given in Section 2. The signal power sent from Tx_{vh} and received by antenna κ ($\kappa \in \{m_1, m_2, k_1, k_2\}$) is $P_\kappa^{vh} = P_T G_{vh} G_\kappa \lambda^2 / \Gamma (4\pi l_\kappa^{vh})^2$ where $G_{vh} = 1$, $G_\kappa = 1$, and $\Gamma = 1$. l_κ^{vh} (measured in meter) is the distance from Tx_{vh} to antenna κ. We adopt the serving antenna selection weight $\xi \in [0, 1]$ and define the signal-to-noise ratio (SNR) as $\bar{\gamma} = 10 \lg (\gamma) dB$ where $\gamma = P_T/\sigma_n^2$ and σ_n^2 represents for the noise power. In determining transmitting antenna sets Ω_o^m and Ω_e^m, we take Tx_{vh} in the range of $\pm\varepsilon$ near odd and even times of π into account. To be specific, we define two phase intervals, $\mathbb{Z}_o = [\pi - \varepsilon, \pi + \varepsilon]$ and $\mathbb{Z}_e = [0, \varepsilon] \bigcup [2\pi - \varepsilon, 2\pi]$. Then, for example, if $(\Delta\varphi_m^{vh})$ mod (2π) $\in \mathbb{Z}_e$ (or $(\Delta\varphi_m^{vh})$ mod $(2\pi) \in \mathbb{Z}_o$) holds, Tx_{vh} can serve Rx_m and Rx_m should employ additive (or subtractive) reception mode.

Figure 3 simulates the distribution of candidate serving antennas for Rx_m and Rx_k in the communication scenario under various εs. As the figure shows, the coordinates of the midpoints of $\overline{m_1 m_2}$ and $\overline{k_1 k_2}$ are set to be $C_m(4.9, 4.5)$ and $C_k(6, 6)$; and accordingly, the antennas' coordinates are $m_1(4.8, 4.5)$, $m_2(5, 4.5)$, $k_1(6 - \sqrt{3}/20, 6.05)$, and $k_2(6 + \sqrt{3}/20, 5.95)$, respectively. As for Tx_{vh} in the red area, on one hand, it yields signals' phase difference at Rx_m satisfying $(\Delta\varphi_m^{vh})$ mod $(2\pi) \in \mathbb{Z}_e$, thus is added to set Ω_e^m; on the other hand, the signals' phase difference at Rx_k satisfies $(\Delta\varphi_k^{vh})$ mod $(2\pi) \in \mathbb{Z}_o$, and hence Tx_{vh} belongs to set Ω_o^k. Therefore, we add Tx_{vh} to the candidate serving antenna set $\mathfrak{R}_{eo}^{mk} = \Omega_e^m \bigcap \Omega_o^k$. Then, if Tx_{vh} in $\mathfrak{R}_{eo}^{mk}$ transmits to Rx_m, Rx_m should employ additive reception mode; if Tx_{vh} in $\mathfrak{R}_{eo}^{mk}$ serves Rx_k, Rx_k should adopt subtractive mode. Similarly, as for Tx_{vh} in the dark blue area, on one hand, it yields signals' phase difference at Rx_m satisfying $(\Delta\varphi_m^{vh})$ mod $(2\pi) \in \mathbb{Z}_o$, thus is added to set Ω_o^m; on the other hand, the signals' phase difference at Rx_k satisfies $(\Delta\varphi_k^{vh})$ mod $(2\pi) \in \mathbb{Z}_e$, and hence, Tx_{vh} belongs to set Ω_e^k. Therefore, we add Tx_{vh} to the candidate serving antenna set $\mathfrak{R}_{oe}^{mk} = \Omega_o^m \bigcap \Omega_e^k$. Accordingly, if Tx_{vh} in $\mathfrak{R}_{oe}^{mk}$ transmits to Rx_m, Rx_m should employ subtractive reception mode; if Tx_{vh} in $\mathfrak{R}_{oe}^{mk}$ serves Rx_k, Rx_k should adopt additive mode.

As for Tx_{vh} in the light blue area, it yields signals' phase difference at Rx_m's and Rx_k's two receiving antennas

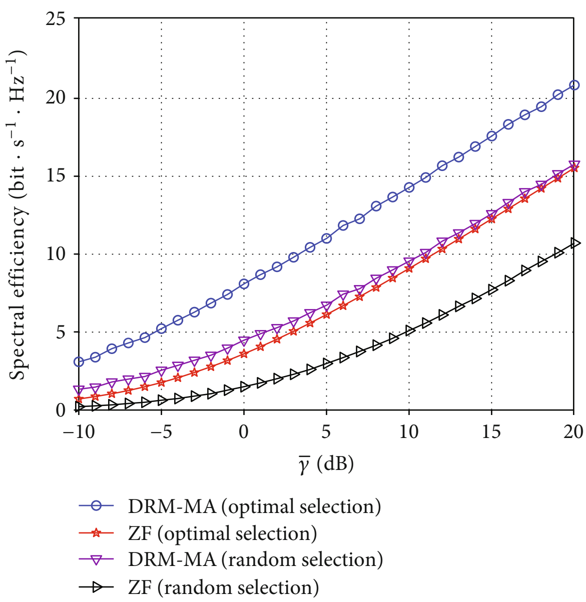


Figure 5: Comparison of DRM-MA and ZF reception.

satisfying $(\Delta\varphi_m^{vh}) \bmod (2\pi) \in \mathbb{Z}_e$ and $(\Delta\varphi_k^{vh}) \bmod (2\pi) \in \mathbb{Z}_e$, respectively. Thus, Tx_{vh} belongs to Ω_e^m and Ω_e^k, yielding candidate serving antenna set $\mathfrak{R}_{ee}^{mk} = \Omega_e^m \bigcap \Omega_e^k$. Accordingly, if Tx_{vh} in $\mathfrak{R}_{ee}^{mk}$ serves Rx_m or Rx_k, either Rx should employ additive reception mode. Similarly, as for Tx_{vh} in the magenta area, it yields signals' phase difference at Rx_m's and Rx_k's two receiving antennas satisfying $(\Delta\varphi_m^{vh}) \bmod (2\pi) \in \mathbb{Z}_o$ and $(\Delta\varphi_k^{vh}) \bmod (2\pi) \in \mathbb{Z}_o$, respectively. Thus, Tx_{vh} belongs to Ω_o^m and Ω_o^k, yielding candidate serving antenna set $\mathfrak{R}_{oo}^{mk} = \Omega_o^m \bigcap \Omega_o^k$. Accordingly, if Tx_{vh} in $\mathfrak{R}_{oo}^{mk}$ serves Rx_m or Rx_k, either Rx should employ subtractive reception mode.

As Figure 3 shows, under a small ε, the ranges of phase intervals $\mathbb{Z}_o$ and $\mathbb{Z}_e$ become small too, hence yielding reduced areas and decreased the number of candidate serving antennas for Rx_m and Rx_k. Given the strong enough phase compensation capability of the Rx, a large ε can be adopted, then, the ranges of phase intervals $\mathbb{Z}_o$ and $\mathbb{Z}_e$ are enlarged, yielding more candidate serving antennas for Rx_m and Rx_k. In what follows, we will evaluate DRM-MA's SE performance and compare it with zero-forcing (ZF) reception. Since DRM-MA employs a single transmitting antenna for each Rx's data transmission, Tx-side array signal processing methods cannot be used in our communication scenario. However, as the Rx is equipped with 2 antennas, the Rx-side array processing such as ZF is taken into account. In the following simulation, we assume 2 Rxs in the communication area and 16 candidate serving antennas are involved in sets $\mathfrak{R}_{oo}^{mk}$ and $\mathfrak{R}_{ee}^{mk}$, respectively. We let $Tx_{v_m h_m}$ in $\mathfrak{R}_{oo}^{mk}$ and $Tx_{v_k h_k}$ in $\mathfrak{R}_{ee}^{mk}$ serve Rx_m and Rx_k. Accordingly, Rx_m and Rx_k adopt subtractive and additive reception mode, respectively. Without loss of generality, we assume that $Tx_{v_m h_m}$ in $\mathfrak{R}_{oo}^{mk}$ serves Rx_m, and $Tx_{v_k h_k}$ in $\mathfrak{R}_{ee}^{mk}$ serves Rx_k. Then, according to Eqs. (10) and (11), we can compute SE of Rx_m and Rx_k as $r_m = \log_2(1 + \|\sqrt{P_T}\Delta A_m^{v_m h_m}\|^2 / \|\sqrt{P_T}\Delta A_m^{v_k h_k}\|^2 + \sigma_n^2)$ and $r_k = \log_2(1 + \|\sqrt{P_T}\Sigma A_k^{v_k h_k}\|^2 / \|\sqrt{P_T}\Sigma A_k^{v_m h_m}\|^2 + \sigma_n^2)$, respectively.

Figure 4 plots the variation of two Rxs' sum SE with $\bar{\gamma}$ under card $(\mathfrak{R}_{oo}^{mk})$ = card $(\mathfrak{R}_{ee}^{mk}) = 16$ where card $(\cdot)$ denotes the number of elements in a set, and $\xi \in \{0.1, 0.4, 0.7, 1.0\}$. As the figure shows, the system's average SE grows with the increase of $\bar{\gamma}$. Under fixed $\bar{\gamma}$, DRM-MA's system SE increases as ξ grows. This is because when ξ is large, a serving transmitting antenna that can yield a high desired data transmission rate is preferred (see Section 3.2). Moreover, since the residual interference is negligible in our system settings when applying DRM-MA, it is better to focus on selecting a good serving antenna for each Rx rather than avoiding residual interference to unintended Rxs. Therefore, we can see from the figure that under $\xi = 1$, DRM-MA outputs the highest system's SE.

Figure 5 plots the variation of two Rxs' sum SE with $\bar{\gamma}$ under DRM-MA and ZF reception. We set card $(\mathfrak{R}_{oo}^{mk})$ = card $(\mathfrak{R}_{ee}^{mk}) = 16$ and $\xi = 1$. To make the simulation results more convincing, both DRM-MA and ZF are divided into two versions for comparison. The method that employs antenna selection given in Section 3.2 is called optimal selection. As its counterpart, method that randomly chooses a serving antenna from $\mathfrak{R}_{oo}^{mk}$ and $\mathfrak{R}_{ee}^{mk}$ for Rx_m and Rx_k is called random selection.

As Figure 5 shows, the SE of DRM-MA (Optimal selection) outputs the highest system's SE. DRM-MA (random selection) ranks second. Then comes ZF (optimal selection). ZF (random selection) yields the lowest system's SE. This is because the optimal selection chooses the best serving antenna that yields the strongest desired signal at its intended Rx; as a comparison, random selection randomly selects an antenna from sets $\mathfrak{R}_{oo}^{mk}$ and $\mathfrak{R}_{ee}^{mk}$ to serve Rx_m and Rx_k, respectively. Moreover, as abovementioned, the residual interference is so small that can be neglected. Therefore, optimal selection excels random selection in the system's SE. Given the fixed antenna selection strategy, DRM-MA outputs higher SE than ZF. This is because, under DRM-MA, each Rx can realize desired signal construction and interference destruction simultaneously via serving antenna selection and reception mode adaptation; and there is no desired signal power loss in the use of DRM-MA. However, as a comparison, ZF causes desired signal's power loss while suppressing the interference [24]. Therefore, DRM-MA is advantageous over ZF in SE.

5. Conclusion

In this paper, we have proposed a novel MAC method called DRM-MA. Based on the phase difference of signals sent from each candidate transmitting antenna and perceived by the two receiving antennas of multiple Rxs, proper serving antennas are selected and paired with the Rxs. Then, each Rx adopts either additive or subtractive reception mode to postprocess the signals received by its two antennas, to realize in-phase desired signal construction and inverse-phase interference destruction simultaneously. In this way, multiple concurrent data transmissions are realized. Our simulation results have shown that DRM-MA can effectively strengthen the desired signal and suppress CCI among coexisting antenna-receiver pairs, hence outputting a high system's SE.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflicts of interest regarding the publication of this paper.

Acknowledgments

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