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Multiuser MIMO Precoders With Proactive Primary Interference Cancelation and Link Quality Enhancement for Cognitive Radio Relay Systems

JUINN-HORNG DENG[1], (Member, IEEE), SU-HUA CHEN[2], AND MENG-LIN KU[3], (Member, IEEE)

[1]Department of Communications Engineering, Yuan Ze University, Taoyuan 32003, Taiwan
[2]Research Division of Information and Communications, National Chung Shan Institute of Science and Technology, Taoyuan 90008, Taiwan
[3]Department of Communication Engineering, National Central University, Taoyuan 32001, Taiwan

Corresponding author: Juinn-Horng Deng (jh.deng@saturn.yzu.edu.tw)

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ABSTRACT A novel multiuser multiple-input multiple-output (MU-MIMO) cognitive radio (CR) system with an improved received signal-to-interference-noise ratio (SINR) and enhanced primary user (PU) interference suppression is proposed for systems with the independent parallel streams of CR multiusers communication. In the overlay CR system with a licensed PU and unlicensed CR users (CUs), the performance of PU tends to be degraded by the interference of CU. Likewise, the transmission efficiency of CU tends to be reduced by the interference of PU. In conventional MU-MIMO systems, precoding techniques are mainly designed to constrain the CU transmitted power, which can prevent interference to PU. However, the transmitted signal of PU unavoidably induces some interference to CUs. In performance studies of the conventional CR systems, the signals of PU interference are regarded as white noise. In the paper, a cooperative MU-MIMO CR relay technique is proposed to improve the quality of the CR transceiver via the relay station canceling the PU interference in two time slots. Specifically, the relay station applies MU-MIMO precoding scheme to carry multiple negative PU signals to CUs for canceling PU interference and to acquire an improved received SINR. Furthermore, the proposed MU-MIMO CR relay system is simulated to confirm the performance being better than a conventional CR system. Besides, the sum rate linear growth of the proposed system is due to its robustness against strong interference from the PU, against interference from multiple CUs, and against stream interference.

INDEX TERMS Multiuser MIMO, overlay relay, cognitive radio, precoding technology design, interference cancelation, enhanced link quality.

I. INTRODUCTION

The spectrum of wireless communications is the most valuable resource, and it gradually becomes scarce as wireless data applications become widespread. It is thus paramount to enhance the efficiency of spectrum usage, which has attracted considerable attention in recent years. Furthermore, the demand for wide bandwidth has substantially increased with the vigorous development of high-data-rate wireless services. Previously serviceable allocations of the spectrum will be unable to meet future communications requirements. The Federal Communications Commission reported that the efficiency of spectrum usage for the conventionally fixed spectrum allocation mostly ranges from 15% to 85% [1], [2]. This inefficiency in the use of spectrum resources leaves numerous idle bands underutilized. In general, the opportunity of improving spectrum utilization has great relation to the two features of natural resources, namely temporal and spatial domains; moreover, cognitive radio (CR) has recently become the most promising technique to increase the efficiency of spectrum usage and to resolve the resource problem of the unused spectrum [3], [4].

To improve spectrum usage, a multiuser and multiantenna CR system was proposed in [5]. The system has two types of users, namely licensed primary users (PUs) and unlicensed secondary users (SUs). CR scenarios can be usually classified into three types: interwave, underlay, and overlay [6]. The scenario of this paper is in the "overlay" category. When a PU and multiple unlicensed CR users (CUs) coexist and utilize the same radio resources, each CU receives not only the desired signal but also some interference, because signals are simultaneously emitted from the PU-base station (BS) and CU-BS. In the conventional overlay CR systems, a whitening method [5] was designed for PU interference suppression at each CU receiver. In [7], precoding algorithms were proposed for multiuser multiple-input multiple-output (MU-MIMO) CR downlink systems; these methods regard the mutual interference as composite noise, and thus the methods in [7] are eventually limited by the interference between CU and PU systems, resulting in marked degradation of CR transmission efficiency. Therefore, in this study, we designed new methods for applications in CR overlay systems; these methods enhance CU performance and overcome the CU receiver performance degradation problem caused by strong PU interference.

Cooperative communications [8], [9] hold promise for enhancing the performance of traditional point-to-point communications systems by facilitating cooperation among users and by deploying additional relay stations. A two-hop relay system with a source station, a relay station, and a user station typically has two time slots for signal transmission and reception. In the first time slot, the signals are emitted by source station, then the relay and user stations will receive the signals. In the second time slot, the relay station helps forward the signals to the receiving terminal. In [10], a cooperative mechanism was proposed for a MIMO cooperative system, enabling users to transmit signal for terminal reception through various paths. In this mechanism, the relay station is designed to facilitate the data transmission from the source station. Das *et al.* [11] proposed an amplify-and-forward (AF) relay station which contains an interference cancellation technique to improve the gain of link quality (LQ). Furthermore, Shin *et al.* [12] designed a linear filtering technique for minimizing PU interference. Park *et al.* [13] only studied the independent data transmitting within two time slots, with no regard for CR systems. Other PU interference cancelation (IC) schemes [14] have been designed using a receiver decoding filter according to a minimum sum error (MSE) criterion at CU mobile station (MS) terminals, but the high complexity of these schemes is disadvantageous. Nishimori *et al.* [15] proposed a distributed array (also called a virtual array) and interference compression techniques to cancel the interference from a primary cellular system by exploiting the periodic property of the known training signal of the primary system. Zhao *et al.* [16], [17] proposed the decoding method, i.e., aligning same subspace scheme, at each receiver to eliminate the jamming interferences. It utilized the more degrees of freedom to obtain the free of interference at the receiver. Moreover, the interference alignment techniques in [18] and [19] were proposed to increase the degrees of freedom by achieving the interference-free performance in MIMO systems. The interference alignment problem has been studied for the cognitive radio networks in [20] and [21]. Resazi *et al.* [20] proposed the interference alignment based CR network with the cooperation between PUs to cancel interferences. Tang *et al.* [21] studied the problem of single secondary user interference and interference from a single PU with multiple data streams. In the present paper, we explore the problem of PU interference, as well as interference from multiple CUs and interference from a single CU with multiple data streams. Additionally, although Tang *et al*. did not describe how to acquire a PU interference signal at a relay node, we provide detailed procedures for acquiring a PU signal at a relay station and regenerating the PU signal for a multiuser precoder downlink.

Whereas traditional CR systems consider the PU interference as composite noise, in this paper, a novel cooperative MU-MIMO CR relay scheme is proposed to overcome the problems of conventional CR systems. Further, PU interference can be eliminated at CR user stations and the spectral efficiency is increased, namely sum rate. Moreover, this paper reasons from the premise that the main objective is designed to observe the CU station reception. Through CR relay stations, our proposed system can substantially enhance the transmission quality. In contrast to the cooperative system in [10], where the relay is only designed to assist systems forwarding source signals, a new relaying strategy is designed for proactive PU IC at the CU stations. Further, using the two aforementioned time slots, a precoding scheme and a novel frame structure are proposed to realize the PU interference cancellation at the CU-MS receiver and the zero interference to the PU-MS receiver. Therefore, in the first time slot, the CR relay station only captures the interest signal, namely the PU-BS signal. Next, in the second time slot, a reverse signal of interest is generated by relay station for CU-MS reception. Then, the PU interference from the first time slot will be eliminated at CU-MS. Notably, the MU-MIMO precoding scheme of the relay station is designed to aim at conveying multiple negative PU signals to CU-MSs, which can receive the desired CU signal and cancel the PU-BS interference. Thus, the proposed precoding scheme of the CR relay station can overcome the problem of the PU-BS interference and notably improve the signal-to-interference-noise ratio (SINR) of CU-MS reception. In addition to PU IC, the proposed CR relay precoding design can provide some relay station channel gain and can enhance CU-MS LQ. In [22], we have studied the performance of PU IC scheme. In this paper, the joint PU IC and LQ schemes are proposed to acquire high SINR performance at CU-MS receiver. Furthermore, simulation results demonstrate that the proposed MU-MIMO CR relay scheme can provide bit error rates (BERs) and sum rates that are superior to those of a conventional CR system. Note that the precoding scheme of the proposed CR relay can be robust to resist the strong PU interference, multiple sources of CU interference, and interference from parallel streams, yielding a linear growth for the sum rate when the signal-to-noise ratio (SNR) increases. According to our review of the literature, no study has considered multiple negative PU signal reconstruction through a relay station to proactively eliminate PU interference at CU-MS receivers for multiuser MIMO CR relay systems. Specifically, the main contributions of this paper can be summarized as follows:

1) We propose a novel relaying strategy and a frame structure with two time slots for canceling PU interference at CU-MS terminals.
2) We also propose an advantageous low-complexity multiuser cancelation scheme for suppressing PU interference at CU-MS terminals. In this scheme, the CU-RS station contains multiuser precoders that regenerate negative PU-BS interference for proactive IC at the CU-MS terminals.
3) The CU-RS station estimates the PU interference signals and reconstructs them with multiuser precoders for downlink transmissions to the CU-MS terminals.
4) The precoders of the CU-RS station are proposed by two contiguous precoders to achieve zero interference at the PU-MS and to provide high LQ at the CU-MSs for multiuser downlink systems.

Note that the joint relay and different time slots design with proactive schemes can be extended to combat the PU-MS interference for CU-MS reception and to provide the high-quality PU-BS signal for PU-MS reception.

The remainder of this paper is organized as follows. The data model of the proposed CR relay structure is described in Section II. The frame structure for PU interference mitigation and CU LQ enhancement is presented in Section III. Section IV proposes the precoding design for the CR relay system with proactive PU IC. Section V provides simulation results, and finally, Section VI concludes the paper.

II. SYSTEM STRUCTURE FOR CR RELAY

The CR relay system structure, as shown in Fig. 1, involves PU-BS, PU-MS, CU-BS, CU-RS, and CU-MS communication units for BS, RS, and user terminal communication. Assume that one PU and multiple CUs coexist in the CR relay downlink system. The signals of CU-BS and PU-BS simultaneously are transmitted to the CU-MS and PU-MS, respectively, resulting in a cochannel interference problem. Because the primary system is a licensed system, it must be operated in a CR interference-free environment with appropriate precoding designs. An MU-MIMO CR relay system is developed whose overall structure diagram is depicted in Figs. 1 and 2, where N_0, N_P, N_T, N_L, and N_k antennas are utilized at the PU-BS, PU-MS, CU-BS, CU-RS, and CU-MS, respectively. The number of antennas for all CU-MS users is denoted by $N_R = \sum_{k=1}^{K} N_k$, where K is the number of CU-MS users. At PU-BS, a data symbol vector $\mathbf{s}_0$ is transmitted and the emitted symbol vector $\mathbf{x}_0$ is encoded by a precoding matrix $\mathbf{P}_0$ over the N_0 transmitting; that is,

$$\mathbf{x}_0 = \mathbf{P}_0 \mathbf{s}_0 \tag{1}$$

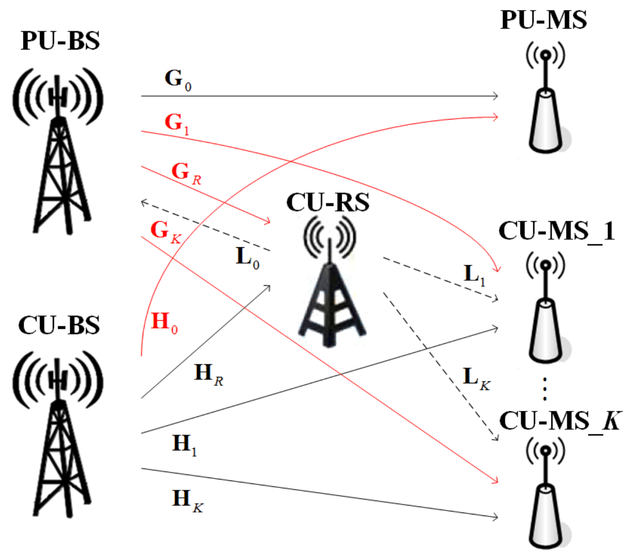

FIGURE 1. Structure of the multiuser MIMO CR relay system.

Then, at CU-BS, the $N_k \times 1$ data symbol vectors $\mathbf{s}_k$ for $k = 1, \cdots, K$ are encoded by the corresponding precoding matrix $\mathbf{P}_k$. The precoded signal $\mathbf{x}$ emitted by N_T transmitting antennas can be expressed by

$$\mathbf{x} = \sum_{k=1}^{K} \mathbf{P}_k \mathbf{s}_k \tag{2}$$

where all symbols $\mathbf{s}_k$ are generated to be independent and identically distributed (i.i.d.) zero mean and unit variance for $k = 1, \cdots, K$; the precoding matrix of the kth CU-MS user is denoted by $\mathbf{P}_k$. As shown in Fig. 1, the MIMO channels $\mathbf{H}_0$, $\mathbf{H}_R$, and $\mathbf{H}_k$, $k = 1, \cdots, K$, are denoted by the channels from the CU-BS to the PU-MS, CU-RS, and kth CU-MS user, respectively. Although Fig. 1 only considers one PU-MS in this paper, it can be extended to multiple PU-MS users. That is, for PU-MS channel models $\mathbf{H}_0$, it can be denoted by $\mathbf{H}_0 = [\mathbf{H}_0^{(1)^T} \mathbf{H}_0^{(2)^T} \cdots \mathbf{H}_0^{(q)^T}]^T$, where $\mathbf{H}_0^{(q)}$ stands for the MIMO channel of the qth PU-MS. Similarly, the MIMO channels from the PU-BS to the PU-MS, CU-RS, and kth CU-MS user, are defined by the matrices $\mathbf{G}_0$, $\mathbf{G}_R$, and $\mathbf{G}_k$, respectively. The matrices $\mathbf{L}_0$ and $\mathbf{L}_k$are the MIMO channels from the CU-RS to the PU-BS and kth CU-MS, respectively. Next, all MIMO channel matrices are assumed to be full rank and are known perfectly at the CU-BS and CU-RS. The MIMO channels are modeled as i.i.d. complex Gaussian with zero-mean and unit variance, which are stationary over the processing interval of interest.

III. FRAME STRUCTURE OF CR RELAY SYSTEM

A novel frame structure for the MU-MIMO CR system with proactive PU IC and CU LQ enhancement within two time slots is developed. As shown in Fig. 3, the overall frame structure of the PU and CU systems involves both downlink and uplink communications. In the first time slot for

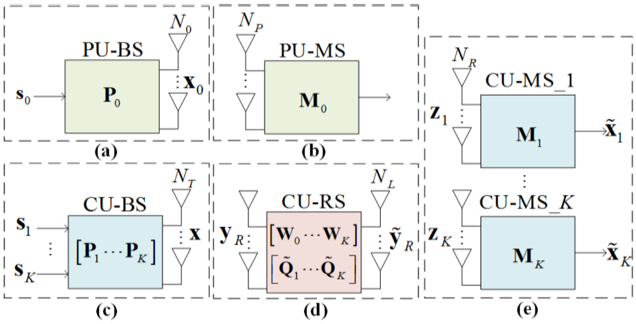

FIGURE 2. Block diagram of the multiuser MIMO CR relay system (a) PU-BS (b) PU-MS (c) CU-BS (d) CU-RS (e) CU-MS.

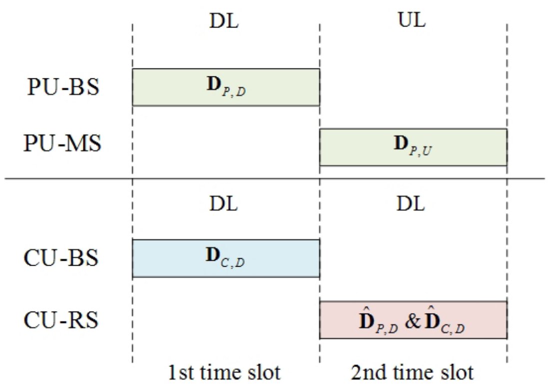

FIGURE 3. Frame structure of multiuser MIMO CR relay with two time slots.

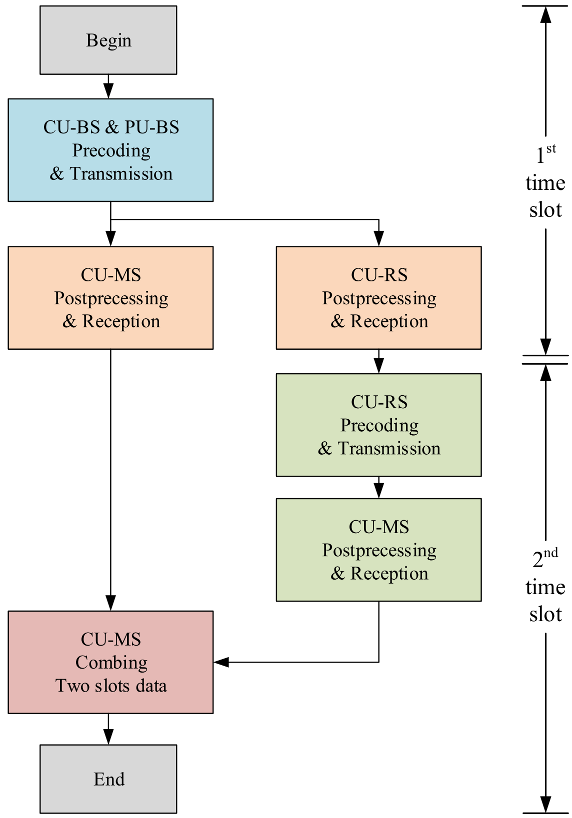

FIGURE 4. Signal processing flow structure of multiuser MIMO CR relay system with two time slots.

downlink communication, the PU-BS and the CU-BS transmit the data $\mathbf{D}_{P,D}$ and $\mathbf{D}_{C,D}$ for the PU-MS and the CU-MS users, respectively. In Figs. 2 and 3, the downlink data from the PU-BS and the CU-BS is received by CU-RS in the first time slot, which an $N_L \times 1$ received data vector is given by

$$\mathbf{y}_R = \mathbf{H}_R\mathbf{P}\mathbf{s} + \mathbf{G}_R\mathbf{x}_0 + \mathbf{n}_r \quad (3)$$

where the overall precoding matrix of the CU-BS is denoted by $\mathbf{P} = [\mathbf{P}_1\mathbf{P}_2 \cdots \mathbf{P}_K]$, $\mathbf{s}$ is the total transmitted data symbol vector of the CU-BS, namely $\mathbf{s} = \left[\mathbf{s}_1^T\mathbf{s}_2^T \cdots \mathbf{s}_K^T\right]^T$, and the noise vector $\mathbf{n}_r$ of the CU-RS has i.i.d. complex Gaussian distribution with zero mean and a covariance matrix$\sigma_r^2\mathbf{I}$, where $\mathbf{I}$ is an identity matrix.

Based on (3), in the first time slot, the received signal involves the PU interference signal, namely $\mathbf{G}_R\mathbf{x}_0$. If not appropriately handled, it seriously degrades the performance of the CU-MS receiver. In this paper, the design goal of the CU-RS precoder is to create proactive PU IC at multiple CU-MS receivers. In the second time slot, the CU-RS transmits the data $\hat{\mathbf{D}}_{P,D}$ and $\hat{\mathbf{D}}_{C,D}$ for downlink communication. Regarding the downlink data $\hat{\mathbf{D}}_{P,D}$ and $\hat{\mathbf{D}}_{C,D}$ of the CU-RS, they are detected from the received data vector in (3) within the first time slot. The retransmitted data $\hat{\mathbf{D}}_{P,D}$ and $\hat{\mathbf{D}}_{C,D}$ are designed for PU IC and LQ enhancement at the CU-MS, respectively. Note that, based on the overall structure in Fig. 1 and the frame structure in Fig. 3, we can summarize the signal processing flow structure for each station in Fig. 4, i.e., CU-BS, CU-RS, and CU-MS, which can indicate the operation of each station in different time slots. As shown in the 1st time slot, CU-BS, CU-MS, and CU-RS will be active to process the CU-BS and PU-BS signals. Similarly, in the 2nd time slot, the CU-RS signal can be processed by CU-RS and CU-MS stations. They can realize the proactive primary interference cancelation and enhance the link quality performance for CU-MS station. The proposed schemes for all stations are elaborated in Section IV.

IV. PRECODING DESIGN WITH PROACTIVE PU IC AND ENHANCED-CU LQ

A novel linear precoding design is proposed for the CU-BS and the CU-RS. First, the CU-BS with precoding design can provide zero interference to the PU-MS and no multiuser interference (MUI) to the CU-MS. Then, in the first time slot, CU-RS can separate the data of PU-BS and CU-BS, and can reconstruct these data. Next, in the second time slot, the regenerated PU-BS data can be retransmitted for downlink so that the PU-BS interference to the CU-MS during the first time slot can be self-canceled. Moreover, the CU-MS can acquire the retransmitted CU-BS data to improve the LQ. Thus, the two benefits of the proposed MU-MIMO CR relay system can be provided in the novel frame structure, namely zero interference to the PU-MS and the CU-MS, and data reception with improved SINR to the CU-MS.

A. PRECODER AND POSTPROCESSING DESIGN IN THE FIRST TIME SLOT

1) CU-MS RECEPTION AND CU-BS TRANSMISSION

In the first time slot, the PU-BS and CU-BS downlink data can be received by the kth CU-MS, namely

$$\begin{aligned}\mathbf{z}_{k,1} &= \mathbf{H}_k\mathbf{P}\mathbf{s} + \mathbf{G}_k\mathbf{x}_0 + \mathbf{n}_{k,1} \\ &= \mathbf{H}_k\mathbf{P}_k\mathbf{s}_k + \mathbf{H}_k\sum_{\substack{i=1\\ i\neq k}}^{K}\mathbf{P}_i\mathbf{s}_i + \mathbf{G}_k\mathbf{x}_0 + \mathbf{n}_{k,1}\end{aligned} \tag{4}$$

where the PU-BS interference is denoted by $\mathbf{G}_k\mathbf{x}_0$ and $\mathbf{n}_{k,1}$ is the noise vector received by the kth CU-MS in the first time slot, which the noise distribution is i.i.d. complex Gaussian with zero mean and a covariance matrix $\sigma_{k,1}^2\mathbf{I}$. Next, in (4), the precoding matrix $\mathbf{P}_k$ is designed to cancel all CU-MS interference and provide zero interference to the PU-MS. To eliminate all interference in (4), the precoding matrix $\mathbf{P}_k$ is designed to align on the null space of $\hat{\mathbf{H}}_k$, where $\hat{\mathbf{H}}_k$ is defined as $\hat{\mathbf{H}}_k = \left[\mathbf{H}_0^T\mathbf{H}_1^T\ \mathbf{H}_2^T\cdots\ \mathbf{H}_{k-1}^T\ \mathbf{H}_{k+1}^T\cdots\ \mathbf{H}_K^T\right]^T$. Next, singular value decomposition (SVD) for the channel $\hat{\mathbf{H}}_k = \mathbf{U}_{P,k}\mathbf{\Lambda}_{P,k}\left[\mathbf{V}_{P,k}^{(non-zero)}\mathbf{V}_{P,k}^{(zero)}\right]^H$ is applied, and the null space of $\hat{\mathbf{H}}_k$, namely $\mathbf{V}_{P,k}^{(zero)}$, is employed in the precoding matrix $\mathbf{P}_k = \mathbf{V}_{P,k}^{(zero)}$ to cancel all interferences; that is, $\hat{\mathbf{H}}_k\mathbf{P}_k = \mathbf{0}$. In (4), the received data vector involves the composite channel matrix $\{\mathbf{H}_k\mathbf{P}_k\}$. To decouple the composite channel into N_k parallel subchannels and acquire the kth user's zero interference data vector $\mathbf{x}_k$, the SVD of $\mathbf{H}_k\mathbf{P}_k$ with the initial precoding matrix $\mathbf{P}_k = \mathbf{V}_{P,k}^{(zero)}$ can be computed as

$$\begin{aligned}\mathbf{H}_k\mathbf{P}_k &= \mathbf{H}_k\mathbf{V}_{P,k}^{(zero)} \\ &= \tilde{\mathbf{U}}_{P,k}\tilde{\mathbf{\Lambda}}_{P,k}\tilde{\mathbf{V}}_{P,k}^H\end{aligned} \tag{5}$$

From (5), the final precoding matrix $\mathbf{P}_k$ and the postprocessing matrix $\mathbf{M}_k$ are set as

$$\begin{aligned}\mathbf{P}_k &= \mathbf{V}_{P,k}^{(zero)}\tilde{\mathbf{V}}_{P,k} \\ \mathbf{M}_{k,1} &= \tilde{\mathbf{U}}_{P,k}^H\end{aligned} \tag{6}$$

The kth CU-MS receives the final data vector in the first time slot, namely

$$\begin{aligned}\tilde{\mathbf{x}}_{k,1} &= \mathbf{M}_{k,1}\mathbf{z}_{k,1} \\ &= \tilde{\mathbf{U}}_{P,k}^H\mathbf{H}_k\left(\mathbf{V}_{P,k}^{(zero)}\tilde{\mathbf{V}}_{P,k}\right)\mathbf{s}_k + \tilde{\mathbf{U}}_{P,k}^H\mathbf{G}_k\mathbf{x}_0 + \tilde{\mathbf{U}}_{P,k}^H\mathbf{n}_{k,1} \\ &= \tilde{\mathbf{\Lambda}}_{P,k}\mathbf{s}_k + \tilde{\mathbf{U}}_{P,k}^H\mathbf{G}_k\mathbf{x}_0 + \tilde{\mathbf{U}}_{P,k}^H\mathbf{n}_{k,1} \\ &= \tilde{\mathbf{\Lambda}}_{P,k}\mathbf{s}_k + \tilde{\mathbf{G}}_k\mathbf{x}_0 + \tilde{\mathbf{n}}_{k,1}\end{aligned} \tag{7}$$

where $\tilde{\mathbf{G}}_k = \tilde{\mathbf{U}}_{P,k}^H\mathbf{G}_k$ and $\tilde{\mathbf{n}}_{k,1} = \tilde{\mathbf{U}}_{P,k}^H\mathbf{n}_{k,1}$.

2) CU-RS RECEPTION

As shown in Figs. 2 and 3, the downlink data from the PU-BS and CU-BS is received by the CU-RS in the first time slot, which yields an $N_L \times 1$ received data vector:

$$\begin{aligned}\mathbf{y}_R &= \mathbf{H}_R\mathbf{P}\mathbf{s} + \mathbf{G}_R\mathbf{x}_0 + \mathbf{n}_r \\ &= \sum_{k=1}^{K}\mathbf{H}_{R,k}\mathbf{s}_k + \mathbf{G}_R\mathbf{x}_0 + \mathbf{n}_r\end{aligned} \tag{8}$$

where the composite channel $\mathbf{H}_{R,k}$ is $\mathbf{H}_{R,k} = \mathbf{H}_R\mathbf{P}_k$. From (8), the data of the CU-BS and PU-BS can be separated and reconstructed by the following procedures. First, CU-RS with a postprocessing filter $\mathbf{W}_0$ can suppress the CU-BS data and get the PU-BS data; specifically, the filtered signal is given by

$$\begin{aligned}\mathbf{y}_{R,0} &= \mathbf{W}_0\mathbf{y}_R \\ &= \mathbf{W}_0\mathbf{G}_R\mathbf{x}_0 + \mathbf{W}_0\mathbf{n}_r\end{aligned} \tag{9}$$

where the postprocessing matrix is denoted by $\mathbf{W}_0$, which can extract the PU-BS data. To cancel all the CU-BS data in (8), the null space of $\tilde{\mathbf{H}}_{R,0}$ is adopted to use for the postprocessing matrix $\mathbf{W}_0$, which $\tilde{\mathbf{H}}_{R,0}$ is defined as $\tilde{\mathbf{H}}_{R,0} = \left[\mathbf{H}_{R,1}\mathbf{H}_{R,2}\cdots\mathbf{H}_{R,K}\right]$. The composite channel matrix $\tilde{\mathbf{H}}_{R,0}$ can then be decomposed by the SVD; that is,

$$\tilde{\mathbf{H}}_{R,0} = \left[\mathbf{U}_{W,0}^{(non-zero)}\mathbf{U}_{W,0}^{(zero)}\right]\mathbf{\Lambda}_{W,0}\mathbf{V}_{W,0}^H \tag{10}$$

where the null space of $\tilde{\mathbf{H}}_{R,0}$ is denoted by $\mathbf{U}_{W,0}^{(zero)H}$. In addition, the postprocessing matrix $\mathbf{W}_0 = \mathbf{U}_{W,0}^{(zero)H}$ is obtained to cancel all CU-RS data; that is, $\mathbf{W}_0\tilde{\mathbf{H}}_{R,0} = \mathbf{0}$.

However, the CU-RS can suppress the PU-BS data and obtain the CU-BS data. The kth CU-BS data vector can be acquired by the kth postprocessing filter $\mathbf{W}_k$; that is,

$$\begin{aligned}\mathbf{y}_{R,k} &= \mathbf{W}_k\mathbf{y}_R \\ &= \mathbf{W}_k\mathbf{H}_{R,k}\mathbf{s}_k + \mathbf{W}_k\mathbf{n}_r\end{aligned} \tag{11}$$

where $\mathbf{W}_k$ is designed to retain the kth CU-BS data vector, and cancel the CU-BS and PU-BS data vectors. To achieve this goal, SVD is applied to decompose the composite channel $\tilde{\mathbf{H}}_{R,k} = \left[\mathbf{G}_R\mathbf{H}_{R,1}\cdots\mathbf{H}_{R,k-1}\mathbf{H}_{R,k+1}\cdots\mathbf{H}_{R,K}\right]$; that is, $\tilde{\mathbf{H}}_{R,k} = \left[\mathbf{U}_{W,k}^{(non-zero)}\mathbf{U}_{W,k}^{(zero)}\right]\mathbf{\Lambda}_{W,k}\mathbf{V}_{W,k}^H$. Subsequently, the null space of $\tilde{\mathbf{H}}_{R,k}$, namely $\mathbf{U}_{W,k}^{(zero)H}$, is employed in the postprocessing matrix $\mathbf{W}_k = \mathbf{U}_{W,k}^{(zero)H}$ to cancel the PU and all other CU interference; that is, $\mathbf{W}_k\tilde{\mathbf{H}}_{R,k} = \mathbf{0}$.

After the PU-BS and CU-BS data are acquired in (9) and (11), the reconstructed PU-BS and CU-BS data with precoding matrices $\mathbf{T}_k$ and $\mathbf{F}_k$ for the kth CU-MS can be expressed by

$$\bar{\mathbf{y}}_k = \mathbf{T}_k\mathbf{y}_{R,0} + \mathbf{F}_k\mathbf{y}_{R,k} \tag{12}$$

where $\mathbf{T}_k$ is the precoding matrix for the kth CU-MS, which is used to eliminate the PU-BS interference $\mathbf{G}_R\mathbf{x}_0$ in (8), and $\mathbf{F}_k$ is the postprocessing matrix used to obtain the parallel streams of the kth CU-MS $\mathbf{s}_k$ through a zero-forcing method, given by

$$\mathbf{F}_k = \left(\mathbf{W}_k\mathbf{H}_{R,k}\right)^{\dagger} = \left[\left(\mathbf{W}_k\mathbf{H}_{R,k}\right)^H\left(\mathbf{W}_k\mathbf{H}_{R,k}\right)\right]^{-1}\left(\mathbf{W}_k\mathbf{H}_{R,k}\right)^H \quad (13)$$

where † is the pseudo-inverse operation.

B. PRECODER AND POSTPROCESSING DESIGN IN THE SECOND TIME SLOT

1) CU-RS TRANSMISSION

In the second time slot, the multiple reconstructed data vectors $\bar{\mathbf{y}}_k$ for $k = 1, 2, \cdots, K$ are transmitted by CU-RS with the precoding design $\mathbf{Q}_k$ to cancel other users' data. The CU-RS transmits data vector as follows:

$$\tilde{\mathbf{y}}_R = \sum_{k=1}^{K}\beta\mathbf{Q}_k\bar{\mathbf{y}}_k \quad (14)$$

where β is a scaling parameter to satisfy the CU-RS transmission power constraint. Then, the transmission power P_R of the CU-RS is calculated as

$$\begin{aligned} P_R &= E\left\{\left\|\tilde{\mathbf{y}}_R\right\|^2\right\} \\ &= E\left\{\left\|\sum_{k=1}^{K}\beta\mathbf{Q}_k\left(\mathbf{T}_k\mathbf{y}_{R,0}+\mathbf{F}_k\mathbf{y}_{R,k}\right)\right\|^2\right\} \\ &= \beta^2\cdot E\left\{\left\|\begin{array}{c}\sum_{k=1}^{K}\mathbf{Q}_k\mathbf{T}_k\left(\mathbf{W}_0\mathbf{G}_R\mathbf{x}_0+\mathbf{W}_0\mathbf{n}_r\right) \\ +\sum_{k=1}^{K}\mathbf{Q}_k\mathbf{F}_k\left(\mathbf{W}_k\mathbf{H}_{R,k}\mathbf{s}_k+\mathbf{W}_k\mathbf{n}_r\right)\end{array}\right\|^2\right\} \\ &= \beta^2\left\{tr\left(\tilde{\mathbf{Q}}\tilde{\mathbf{Q}}^H\right)+tr\left(\overline{\mathbf{Q}}\overline{\mathbf{Q}}^H\right)+\sigma_{n_r}^2 tr\left(\hat{\mathbf{Q}}\hat{\mathbf{Q}}^H\right)\right\} \end{aligned} \quad (15)$$

where $\tilde{\mathbf{Q}} = \sum_{k=1}^{K}\mathbf{Q}_k\mathbf{T}_k\mathbf{W}_0\mathbf{G}_R$, $\overline{\mathbf{Q}} = \sum_{k=1}^{K}\mathbf{Q}_k\mathbf{F}_k\mathbf{W}_k\mathbf{H}_{R,k}$, and $\hat{\mathbf{Q}} = \sum_{k=1}^{K}\mathbf{Q}_k\left(\mathbf{T}_k\mathbf{W}_0+\mathbf{F}_k\mathbf{W}_k\right)$. Then, the scaling parameter maintaining the transmission power constraint can be expressed as follows:

$$\beta = \sqrt{P_R}\left\{tr\left(\tilde{\mathbf{Q}}\tilde{\mathbf{Q}}^H\right)+tr\left(\overline{\mathbf{Q}}\overline{\mathbf{Q}}^H\right)+\sigma_{n_r}^2 tr\left(\hat{\mathbf{Q}}\hat{\mathbf{Q}}^H\right)\right\}^{-\frac{1}{2}} \quad (16)$$

2) CU-MS RECEPTION

In the second time slot, after the signal transmitted from the CU-RS passes through the MIMO channel $\mathbf{L}_k$, as shown in Fig. 2, the kth CU-MS receives the data vector with the equalization scaling factor β, namely

$$\begin{aligned} \mathbf{z}_{k,2} &= \frac{1}{\beta}\left(\mathbf{L}_k\tilde{\mathbf{y}}_R+\mathbf{n}_{k,2}\right) \\ &= \mathbf{L}_k\mathbf{Q}_k\mathbf{T}_k\mathbf{W}_0\mathbf{G}_R\mathbf{x}_0+\mathbf{L}_k\mathbf{Q}_k\mathbf{F}_k\mathbf{W}_k\mathbf{H}_{R,k}\mathbf{s}_k \\ &\quad +\mathbf{L}_k\mathbf{Q}_k\mathbf{T}_k\mathbf{W}_0\mathbf{n}_r+\mathbf{L}_k\mathbf{Q}_k\mathbf{F}_k\mathbf{W}_k\mathbf{n}_r+\frac{1}{\beta}\mathbf{n}_{k,2} \\ &= \mathbf{L}_k\mathbf{Q}_k\mathbf{T}_k\mathbf{W}_0\mathbf{G}_R\mathbf{x}_0+\mathbf{L}_k\mathbf{Q}_k\mathbf{F}_k\mathbf{W}_k\mathbf{H}_{R,k}\mathbf{s}_k+\tilde{\mathbf{n}}_{k,2} \end{aligned} \quad (17)$$

where $\tilde{\mathbf{n}}_{k,2}$ is the composite noise with $\mathbf{n}_{k,2}$ and $\mathbf{n}_r$, namely $\tilde{\mathbf{n}}_{k,2} = \mathbf{L}_k\mathbf{Q}_k\mathbf{T}_k\mathbf{W}_0\mathbf{n}_r + \mathbf{L}_k\mathbf{Q}_k\mathbf{F}_k\mathbf{W}_k\mathbf{n}_r + \frac{1}{\beta}\mathbf{n}_{k,2}$. For the $\mathbf{n}_{k,2}$, it is the noise vector of the kth CU-MS in the second time slot, which the noise distribution is the complex Gaussian with zero mean and variance $\sigma_{k,2}^2$. Next, the precoding matrix $\mathbf{Q}_k$ of the CU-RS is utilized to cancel other users' data and to provide the no interference state for the PU-BS. Thus, the composite channel matrix $\overline{\mathbf{H}}_{L,k} = \left[\mathbf{L}_0^T\mathbf{L}_1^T\cdots\mathbf{L}_{k-1}^T\mathbf{L}_{k+1}^T\cdots\mathbf{L}_K^T\right]^T$ can be subjected to SVD, namely

$$\overline{\mathbf{H}}_{L,k} = \mathbf{U}_{L,k}\mathbf{\Lambda}_{L,k}\left[\mathbf{V}_{L,k}^{(non-zero)}\mathbf{V}_{L,k}^{(zero)}\right]^H \quad (18)$$

where $\mathbf{V}_{L,k}^{(zero)}$ is the null space of $\overline{\mathbf{H}}_{L,k}$. Furthermore, the kth CU-RS can acquire the precoding matrix $\mathbf{Q}_k = \mathbf{V}_{L,k}^{(zero)}$ to nullify all interference components, that is, $\overline{\mathbf{H}}_{L,k}\mathbf{Q}_k = \mathbf{0}$.

Next, for the parallel streams processing, the received data in (17) contains the composite channel matrix $\mathbf{L}_k\mathbf{Q}_k$. In order to acquire the kth the user's non-interfering data vector $\mathbf{x}_k$ in the second time slot, the system must compute the SVD of $\mathbf{L}_k\mathbf{Q}_k$ with the initial precoding matrix $\mathbf{Q}_k = \mathbf{V}_{L,k}^{(zero)}$, which can be used to decouple the composite channel into N_k parallel streams, namely

$$\mathbf{L}_k\mathbf{Q}_k = \tilde{\mathbf{U}}_{L,k}\tilde{\mathbf{\Lambda}}_{L,k}\tilde{\mathbf{V}}_{L,k}^H \quad (19)$$

Then, we can use the final precoding matrix $\mathbf{Q}_k$ in the CU-RS and the postprocessing $\mathbf{M}_{k,2}$ in the CU-MS; that is,

$$\begin{aligned} \mathbf{Q}_k &= \mathbf{V}_{L,k}^{(zero)}\tilde{\mathbf{V}}_{L,k} \\ \mathbf{M}_{k,2} &= \tilde{\mathbf{U}}_{L,k}^H. \end{aligned} \quad (20)$$

The final received data vector of in the second time slot is given by

$$\begin{aligned} \tilde{\mathbf{x}}_{k,2} &= \mathbf{M}_{k,2}\mathbf{z}_{k,2} \\ &= \mathbf{M}_{k,2}\mathbf{L}_k\mathbf{Q}_k\mathbf{T}_k\mathbf{W}_0\mathbf{G}_R\mathbf{x}_0 \\ &\quad +\mathbf{M}_{k,2}\mathbf{L}_k\mathbf{Q}_k\mathbf{F}_k\mathbf{W}_k\mathbf{H}_{R,k}\mathbf{s}_k+\mathbf{M}_{k,2}\tilde{\mathbf{n}}_{k,2} \\ &= \tilde{\mathbf{U}}_{L,k}^H\mathbf{L}_k\mathbf{Q}_k\mathbf{T}_k\mathbf{W}_0\mathbf{G}_R\mathbf{x}_0+\tilde{\mathbf{\Lambda}}_{L,k}\mathbf{s}_k+\tilde{\mathbf{U}}_{L,k}^H\tilde{\mathbf{n}}_{k,2}. \end{aligned} \quad (21)$$

Finally, from (7) and (21), we can find the precoding matrix $\mathbf{T}_k$ to cancel the PU interference. To eliminate the PU interference $\tilde{\mathbf{G}}_k\mathbf{x}_0$ of $\tilde{\mathbf{x}}_{k,1}$ in (7) within the first time slot, the received data vector $\tilde{\mathbf{x}}_{k,2}$ in (21) can be utilized. Specifically, the precoding matrix $\mathbf{T}_k$ in $\tilde{\mathbf{x}}_{k,2}$ can be calculated to specify the opposite signal that can cancel out the PU interference $\tilde{\mathbf{G}}_k\mathbf{x}_0$ as follows:

$$\tilde{\mathbf{U}}_{L,k}^H\mathbf{L}_k\mathbf{Q}_k\mathbf{T}_k\mathbf{W}_0\mathbf{G}_R = -\tilde{\mathbf{G}}_k \quad (22)$$

where $\mathbf{W}_0$ and $\mathbf{Q}_k$ are the given postprocessing and precoding matrices of the CU-RS, respectively. $\mathbf{L}_k$ and $\mathbf{G}_R$ are the known MIMO channel matrices. Therefore, the precoding matrix $\mathbf{T}_k$ can be obtained by

$$\mathbf{T}_k = -\left(\tilde{\mathbf{U}}_{L,k}^H \mathbf{L}_k \mathbf{Q}_k\right)^{\dagger} \tilde{\mathbf{G}}_k \left(\mathbf{W}_0 \mathbf{G}_R\right)^{\dagger} \tag{23}$$

Finally, after the application of the aforementioned solution in (23) to (21), the received data vector $\tilde{\mathbf{x}}_{k,2}$ can be rewritten as

$$\tilde{\mathbf{x}}_{k,2} = -\tilde{\mathbf{G}}_k \mathbf{x}_0 + \tilde{\mathbf{\Lambda}}_{L,k} \mathbf{s}_k + \tilde{\mathbf{U}}_{L,k}^H \tilde{\mathbf{n}}_{k,2} \tag{24}$$

C. FIND RECEIVED SIGNAL AND SYSTEM PERFORMANCE

In (7) and (24), the received data vectors $\tilde{\mathbf{x}}_{k,1}$ and $\tilde{\mathbf{x}}_{k,2}$ of the kth CU-MS in two time slots can be summed to cancel the PU-BS interference and to obtain an improved received SINR and high LQ, as follows:

$$\begin{aligned} \tilde{\mathbf{x}}_k &= \tilde{\mathbf{x}}_{k,1} + \tilde{\mathbf{x}}_{k,2} \\ &= \left(\tilde{\mathbf{\Lambda}}_{P,k} \mathbf{s}_k + \tilde{\mathbf{G}}_k \mathbf{x}_0 + \tilde{\mathbf{n}}_{k,1}\right) \\ &\quad + \left(-\tilde{\mathbf{G}}_k \mathbf{x}_0 + \tilde{\mathbf{\Lambda}}_{L,k} \mathbf{s}_k + \tilde{\mathbf{U}}_{L,k}^H \tilde{\mathbf{n}}_{k,2}\right) \\ &= \left(\tilde{\mathbf{\Lambda}}_{P,k} + \tilde{\mathbf{\Lambda}}_{L,k}\right) \mathbf{s}_k + \left(\tilde{\mathbf{U}}_{P,k}^H \mathbf{n}_{k,1} + \tilde{\mathbf{U}}_{L,k}^H \tilde{\mathbf{n}}_{k,2}\right) \end{aligned} \tag{25}$$

where $\tilde{\mathbf{n}}_{k,1}$ and $\tilde{\mathbf{n}}_{k,2}$ are the composite noise values of the first and second time slots, respectively. In (25), $\tilde{\mathbf{\Lambda}}_{P,k}$ and $\tilde{\mathbf{\Lambda}}_{L,k}$ are diagonal matrices, of which the ith diagonal elements are $\tilde{\lambda}_{P,k,i}$ and $\tilde{\lambda}_{L,k,i}$, respectively. Thus, the received data of the ith stream of the kth CU-MS can be expressed as

$$\tilde{x}_{k,i} = \left(\tilde{\lambda}_{P,k,i} + \tilde{\lambda}_{L,k,i}\right) s_{k,i} + \tilde{\mathbf{m}}_{P,k,i} \mathbf{n}_{k,1} + \tilde{\mathbf{m}}_{L,k,i} \tilde{\mathbf{n}}_{k,2} \tag{26}$$

where $\tilde{\mathbf{m}}_{P,k,i}$ and $\tilde{\mathbf{m}}_{L,k,i}$ are the ith row vectors of $\tilde{\mathbf{U}}_{P,k}^H$ and $\tilde{\mathbf{U}}_{L,k}^H$, respectively. Note that $\tilde{\lambda}_{P,k,i}$ and $\tilde{\lambda}_{L,k,i}$ in (26) are the eigenvalues of the composite channels of the direct link and relay link, respectively. The direct link is denoted by the link path between the CU-BS and the CU-MS. The relay link is denoted by the link path between the CU-RS and the CU-MS. The two eigenvalues represent the channel quality levels of the two links. Thus, the received signal in (26) contains the data of interest with the received channel gain $\left(\tilde{\lambda}_{P,k,i} + \tilde{\lambda}_{L,k,i}\right)^2$ and the composite noise from the two time slots. The SINR of each stream can be obtained as

$$SINR_{k,i} = \frac{\left(\tilde{\lambda}_{P,k,i} + \tilde{\lambda}_{L,k,i}\right)^2}{N_{k,1}^{(i)} + N_{k,2}^{(i)}} \tag{27}$$

where the received noise power values of the ith stream of the kth CU-MS are denoted by $N_{k,1}^{(i)}$ and $N_{k,2}^{(i)}$ in the first and second time slots; that is,

$$\begin{aligned} N_{k,1}^{(i)} &= E\left(\left|\tilde{\mathbf{m}}_{P,k,i} \mathbf{n}_{k,1}\right|^2\right) \\ &= \mathbf{m}_{k,i} \cdot \sigma_{k,1}^2 \mathbf{I} \cdot \mathbf{m}_{k,i}^H \\ &= \sigma_{k,1}^2 \\ N_{k,2}^{(i)} &= E\left(\left|\tilde{\mathbf{m}}_{L,k,i} \tilde{\mathbf{n}}_{k,2}\right|^2\right) \\ &= \tilde{\mathbf{m}}_{L,k,i}\left(\sigma_r^2 \tilde{\mathbf{L}}_k + \frac{1}{\beta^2}\sigma_{k,2}^2 \mathbf{I}\right)\tilde{\mathbf{m}}_{L,k,i}^H \\ &= \sigma_r^2\left(\tilde{\mathbf{m}}_{L,k,i} \tilde{\mathbf{L}}_k \tilde{\mathbf{m}}_{L,k,i}^H\right) + \frac{1}{\beta^2}\sigma_{k,2}^2 \end{aligned}$$

with

$$\begin{aligned} &E\left(\mathbf{n}_{k,1}\mathbf{n}_{k,1}^H\right) \\ &= \sigma_{k,1}^2 \mathbf{I} \\ &E\left(\tilde{\mathbf{n}}_{k,2}\tilde{\mathbf{n}}_{k,2}^H\right) \\ &= E\left\{\begin{matrix}\left(\mathbf{L}_k\mathbf{Q}_k\mathbf{T}_k\mathbf{W}_0\mathbf{n}_r + \mathbf{L}_k\mathbf{Q}_k\mathbf{F}_k\mathbf{W}_k\mathbf{n}_r + \frac{1}{\beta}\mathbf{n}_{k,2}\right) \\ \left(\mathbf{L}_k\mathbf{Q}_k\mathbf{T}_k\mathbf{W}_0\mathbf{n}_r + \mathbf{L}_k\mathbf{Q}_k\mathbf{F}_k\mathbf{W}_k\mathbf{n}_r + \frac{1}{\beta}\mathbf{n}_{k,2}\right)^H\end{matrix}\right\} \\ &= \left\{\begin{matrix}\mathbf{L}_k\mathbf{Q}_k\left(\mathbf{T}_k\mathbf{W}_0 + \mathbf{F}_k\mathbf{W}_k\right)E\left(\mathbf{n}_r\mathbf{n}_r^H\right) \\ \left(\mathbf{T}_k\mathbf{W}_0 + \mathbf{F}_k\mathbf{W}_k\right)^H \mathbf{Q}_k^H\mathbf{L}_k^H\end{matrix}\right\} + \frac{1}{\beta}E\left(\mathbf{n}_{k,2}\mathbf{n}_{k,2}^H\right) \\ &= \sigma_r^2\mathbf{N} + \frac{1}{\beta^2}\sigma_{k,2}^2\mathbf{I} \end{aligned}$$

and $\tilde{\mathbf{L}}_k$ being the composite matrix $\tilde{\mathbf{L}}_k = \mathbf{L}_k\mathbf{Q}_k\left(\mathbf{T}_k\mathbf{W}_0 + \mathbf{F}_k\mathbf{W}_k\right)\left(\mathbf{T}_k\mathbf{W}_0 + \mathbf{F}_k\mathbf{W}_k\right)^H \mathbf{Q}_k^H\mathbf{L}_k^H$. Finally, the total sum rate of the proposed MU-MIMO CR relay system is obtained by

$$R = \frac{1}{2}\sum_{k=1}^{K}\sum_{i=1}^{N_k}\log_2\left(1 + SINR_{k,i}\right) \tag{28}$$

where $\frac{1}{2}$ is owing to the two-hop communication.

D. COMPLEXITY ANALYSIS

This section analyzes the computational complexity of the proposed schemes in all stations. For simplicity, only the number of complex multiplications of dominated operations, e.g., SVD and matrix inversion, is considered in the analysis. First, the CU-BS precoder design with the null space calculation is considered. The number of multiplication operations is about $O(\sum_{k=1}^{K}(\sum_{i=1, i\neq k}^{K} N_i + N_P)^3)$ due to the SVD of $\hat{\mathbf{H}}_k$. Next, for the CU-RS station, the major computations of the postprocessing filters are the null space calculations of $\tilde{\mathbf{H}}_{R,0}$ and $\tilde{\mathbf{H}}_{R,k}$. The number of complex multiplications is about $O\left(N_T^3\right) + O\left(KN_T^3\right)$. Another computational loads of CU-RS precoder design are the null space calculation of $\overline{\mathbf{H}}_{L,k}$ and the inversion calculation of precoder matrix $\mathbf{T}_k$, for which the number of complex multiplications is about

$$O(\sum_{k=1}^{K}((\sum_{i=1, i\neq k}^{K} N_i + N_0)^3 + N_k^3 + N_0^3)).$$

Finally, the CU-MS station with the SVD of parallel streams processing in (19) is considered. The number of multiplication operations is about $O\left(N_k^3\right)$ for the kth CU-MS user. In summary, the approximate major complexity of the CU-BS, CU-RS, and CU-MS stations is given in Table I. Note that it is obviously shown that the computational load of CU-RS station is larger than CU-BS and CU-MS stations.

TABLE 1. Computational complexity of all stations.

Stations	Computational Complexity
CU-BS Station	$O\left(\sum_{k=1}^{K}\left(\sum_{\substack{i=1\\i\neq k}}^{K} N_i + N_P\right)^3\right)$
CU-RS Station	$O(N_T^3)+O(KN_T^3)+ O\left(\sum_{k=1}^{K}\left(\left(\sum_{\substack{i=1\\i\neq k}}^{K} N_i + N_0\right)^3 + N_k^3 + N_0^3\right)\right)$
CU-MS Station (for kth user)	$O(N_k^3)$

TABLE 2. Number of transceiver antennas.

Antenna \ Case	Two Cognitive Users	Three Cognitive Users	Four Cognitive Users
PU-BS transmitting antenna N_0	4	4	4
PU-MS receiving antenna N_P	2	2	2
CU-RS transmitting/receiving antenna N_L	10	12	14
CU-BS transmitting antenna N_T	6	8	10
CU-MS receiving antenna N_R	2	2	2

V. COMPUTATION SIMULATIONS

In this section, simulation results are conducted to demonstrate the performance of the proposed precoding and post-processing design in the MU-MIMO CR relay system. For all simulations, the number of transmitting and receiving antennas for the CU-BS, CU-RS, CU-MS, PU-BS, and PU-MS is shown in Table II. Each user's 16QAM data symbol is demultiplexed into two parallel substreams. Thus, for the PU-MS and CU-MS, each user is equipped with two receiving antennas for the reception of two substreams. For the CU-BS and CU-RS, more antennas can be provided to support the transmission and reception of multiuser signals. Each element of uncorrelated MIMO channels is generated by i.i.d. complex Gaussian random variables with zero mean and unit variance. As a performance index, the input CPR is defined as the ratio of the CU signal power to the PU signal power. Furthermore, the input SNR is defined as the ratio of the CU signal power to the noise power. For all Monte Carlo simulations in the present work, the packet length of each substream is 100,000 symbols and a new MU-MIMO fading channel is realized for each simulation run.

For the first simulation, the sum rate performance of the proposed MU-MIMO precoding scheme and the conventional CR transceiver with two CU-MS are illustrated in Fig. 5. Table I indicates that for the case with two CU-MS users, the numbers of antennas of the PU-BS, PU-MS, CU-RS, CU-BS, and CU-MS are $N_0 = 4$, $N_P = 2$, $N_L = 10$,

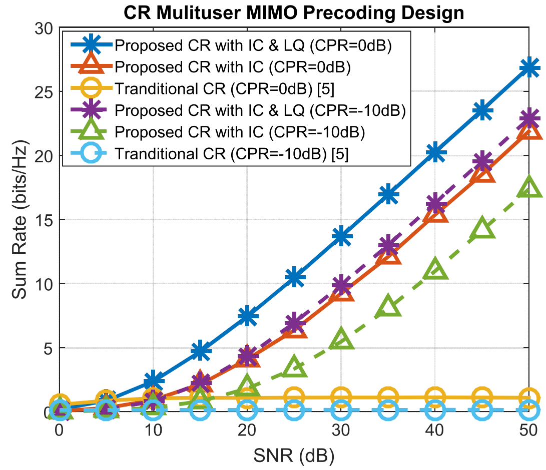

FIGURE 5. Sum rate as a function of SNR for the traditional CR system, the proposed scheme with only IC, and proposed CR relay system with IC & LQ.

$N_T = 6$, and $N_R = 2$, respectively. In this simulation, if the relay only transmits the reconstructed primary BS signal, it is only used for the primary interference cancelation, and the sum rate performance can be found by the "Proposed CR with IC" curve in Fig. 5. Next, if the relay transmits both of the primary BS and secondary BS signals, it can cancel the primary interference and enhance the link quality (LQ) for CU-MS reception, and the corresponding performance is shown in the "Proposed CR with IC & LQ" curve of Fig. 5. It is obviously shown that the performance gap between two cases is about 8 dB at CPR=0 dB and sum rate=15 bits/Hz. Moreover, as shown in Fig. 5 with CPR = 0 dB and −10 dB, the proposed MU-MIMO CR relay precoding scheme with PU IC and LQ outperforms the proposed scheme with only IC, i.e., $\mathbf{W}_k = 0$ in (11) without LQ design, and also a traditional CR system. However, the conventional overlay CR system [5], which coexists with the primary system by merely using the whitening process for primary BS signals, suffers from performance degradation of the SINR and sum rate owing to the incurred PU interference. Thus, the sum rate performance of the conventional CR degrades more serious as the power of PU interference increases, e.g., CPR=−10 dB. Next, as shown in the two curves of the proposed CR with IC & LQ, when the power of PU interference is increased by 10 dB, the SNR degradation of the proposed scheme is about 5 dB. It reveals the capability of anti-strong PU interference of the proposed scheme. Next, the results in Fig. 5 confirm that the proposed MU-MIMO CR relay precoding schemes can effectively eliminate the PU interference and obtain high LQ with an improved received SINR.

In the second simulation, the sum rate performance is evaluated with different input SNR for the proposed MU-MIMO CR relay system with two CU-MS case. As shown in Fig. 6, the proposed scheme exhibits linear sum rate growth with SNR, which is due to the fact that the PU-BS and CU-BS interferences are canceled by the

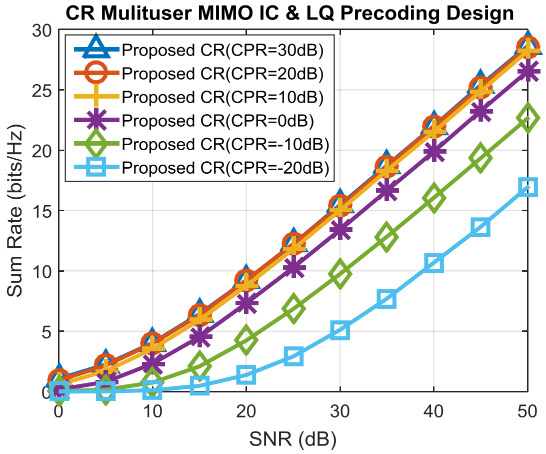

FIGURE 6. Sum rate as a function of SNR in the proposed CR relay systems in different CPR scenarios.

proposed MU-MIMO CR relay precoding method. Further, Fig. 6 shows that the sum rate performance grows as the CPR increases, whereas some minor sum rate enhancement is obtained when the CPR is greater than 10 dB. This is because the CU-BS and PU-BS interferences are canceled and the composite noise in two time slots dominates the sum rate performance when the CPR is greater than 10 dB.

In the third simulation, the sum rate performance is evaluated for different numbers of CU-MS users on the proposed MU-MIMO CR relay precoding system with CPR = 0dB and −20 dB. The numbers of antennas for different CU-MS cases are listed in Table I. Figs. 7(a) and 6(b) show that the sum rate of the proposed scheme grows linearly with higher slopes as the number of CU-MS users increases. As can be observed, the slope of the four-user case in Fig. 7(b) is similar to the slope of the four-user case in Fig. 7(a) for SNRs in the range from 30 to 50 dB. Note that the result confirms that the proposed MU-MIMO CR relay scheme with strong PU interference can successfully eliminate both PU and CU MUIs and can produce high LQ with an improved received SINR.

In the fourth simulation, the BER performance as a function of input SNR is evaluated for the proposed MU-MIMO CR relay scheme with different CPR values and two CU-MS users. Fig. 8 shows that the proposed precoding scheme improves the BER linearly as the SNR increased, without exhibiting an error floor at high SNR values. This indicates that PU interference with different CPR values is indeed successfully canceled by the proposed precoding scheme within the two time slots. Moreover, for comparison of the two curves of CPR=−20 dB and 0 dB, when the power of primary signals is larger than 20 dB, the BER performance is degraded about 15 dB at BER = 10^{-2}. It is shown that the proposed scheme can overcome the strong primary interference effect.

In the fifth simulation, the BER performance is evaluated with the different numbers of CU-MS users for cases in which CPR = −20dB and 20dB. As shown in Figs. 9(a) and 9(b), the proposed scheme again

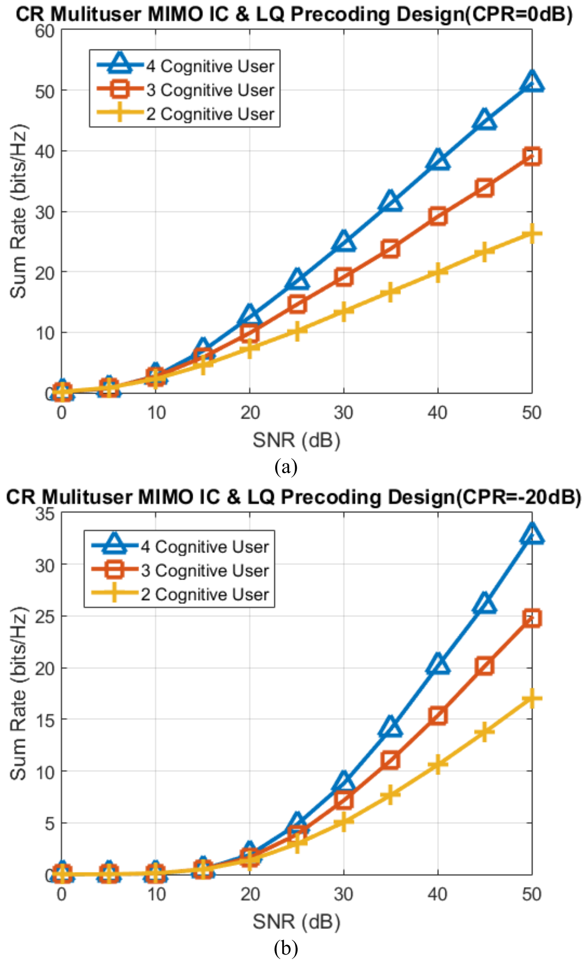

FIGURE 7. Sum rate as a function of SNR in a CR relay system for scenarios with different numbers of cognitive users.(a) CPR = 0 dB. (b) CPR = −20 dB.

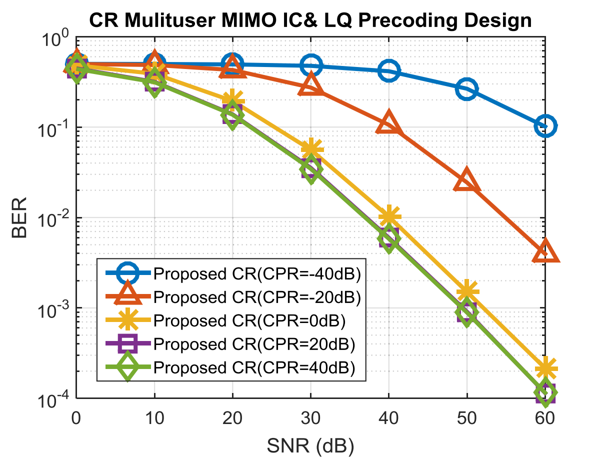

FIGURE 8. BER as a function of SNR in the proposed CR relay system for different CPR scenarios.

successfully cancels the PU interferences and the multiple CU-MS with slight degradation even with higher numbers of CU-MS users. Furthermore, for comparison of the two curves

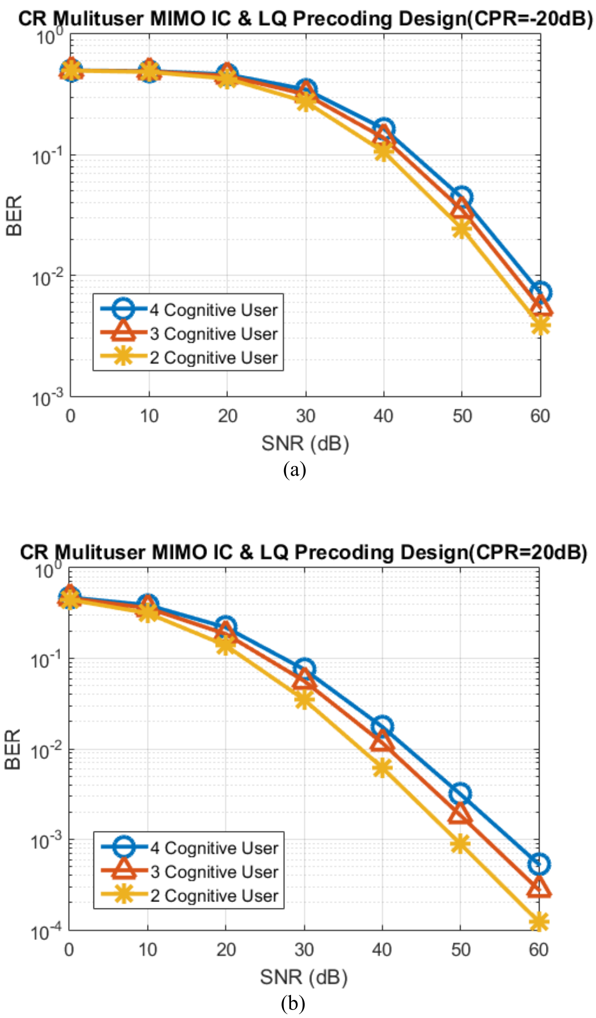

FIGURE 9. BER as a function of SNR for the proposed CR relay system with different numbers of cognitive users. (a) CPR = −20 dB. (b) CPR = 20 dB.

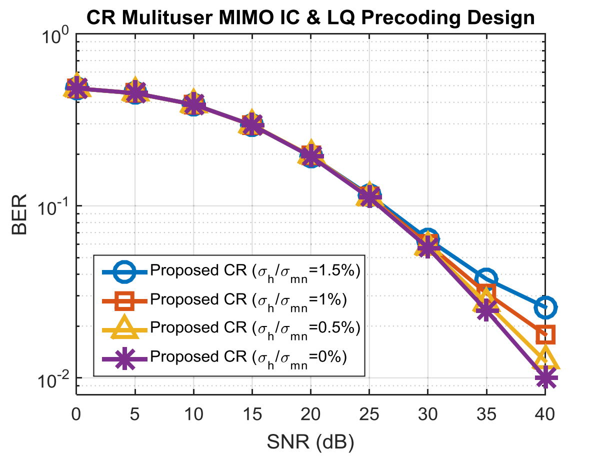

FIGURE 10. BER as a function of SNR for the proposed CR relay system with different channel estimation errors. (CPR = 0 dB).

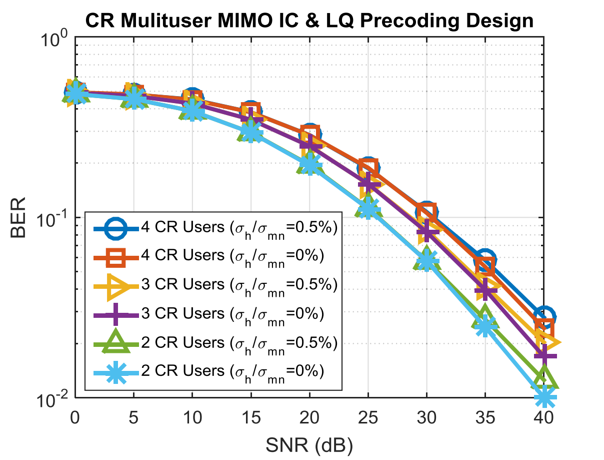

FIGURE 11. BER as a function of SNR for the different numbers of cognitive users with channel estimation error. (CPR = 0 dB).

of 2 cognitive user case with CPR $= -20$ dB and 20 dB in Figs. 9(a) and 9(b), the power of primary signals is increased about 40 dB, the BER performance is degraded about 15 dB at BER $= 10^{-2}$. It indicates that the proposed proactive cancelation scheme can combat the strong primary interference. Next, the resulting linear curves in Figs. 9(a) and 9(b) show that the proposed MU-MIMO CR relay precoding scheme is robust to the strong PU interference and interference from multiple CUs for various SNR values.

In the final simulation, the BER performance is evaluated with the different channel estimation errors for the proposed MU-MIMO CR relay system with the different CU-MS users in which CPR=0 dB. In this case, the channel estimation errors $\tilde{h}_{mn}$ are defined by $\tilde{h}_{mn} = h_{mn} + \sigma_h \Delta h$, where Δh is an i.i.d. zero-mean complex Gaussian random variable with unit variance and σ_h is the deviation of channel error. Note that h_{mn} is the i.i.d. complex Gaussian channel with deviation of σ_{mn} between the nth; CU-BS transmit and the mth CU-MS receive antenna. Similarly, for all MIMO channels, e.g., $\mathbf{G}_k$, $\mathbf{H}_k$, $\mathbf{G}_R$, $\mathbf{H}_R$, and $\mathbf{L}_k$, channel errors are also applied with the i.i.d. complex Gaussian channel variation. In the simulation, the channel error ratios σ_h/σ_{mn} are set with the same value for all channels. Fig. 10 shows the BER performance versus SNR for two CU-MS users with the different σ_h/σ_{mn} ratios. The results confirm that the proposed scheme is quite robust against different channel errors at SNR<25 dB. Besides, as shown in Fig. 10, the proposed scheme is able to offer the reliable BER performance with a degradation of about 0.5 dB, 1.5 dB, and 4 dB for $\sigma_h/\sigma_{mn} = 0.5\%$, 1%, and 1.5%, respectively, at BER $= 3 \times 10^{-2}$. Next, for the different CU-MS case, Fig. 11 shows the BER versus SNR for different CU-MS users with $\sigma_h/\sigma_{mn} = 0\%$ and 0.5%. The result indicates that the BER degradation of 4 CU-MS case is less significant than the 2 and 3 CU-MS cases at SNR=40 dB and $\sigma_h/\sigma_{mn} = 0.5\%$. This is due to the fact that the MIMO channel matrix of 4 CU-MS case has more i.i.d. channel responses to combat the small channel estimation errors effect. Therefore, the proposed scheme is robust to the small estimation errors at SNR<25 dB.

VI. CONCLUSIONS

In this paper, the precoding and postprocessing schemes of the cooperative MU-MIMO CR relay system are proposed for unlicensed CU systems coexisting with a licensed PU. The proposed MU-MIMO CR relay system can provide no interference to the PU link, cancel the interference from the PU system, and demonstrate an improved received SINR from the direct and relay CR links. Further, the CR relay station is designed to cancel PU interference and enhance the link quality of the CR system within the two time slots. Note that the interferences from the PU, multiple CU-MSs, and parallel streams can be eliminated by the proposed precoding and postprocessing schemes. Simulation results prove that the proposed scheme can outperform a conventional CR technique. In addition, we confirm that the proposed MU-MIMO CR relay system operates robustly and provides excellent sum rates and BERs for various numbers of CU-MS users, various levels of PU interference, and various CPR loading effects.

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JUINN-HORNG DENG (M'03) received the Ph.D. degree in communications engineering from National Chiao Tung University, Taiwan, in 2003. From 2003 to 2008, he was with the Electronic System Research Department, Chung Shan Institute of Science and Technology, Taiwan. In 2008, he joined the Faculty of Yuan Ze University, Chungli, Taiwan, where he is currently a Professor with the Department of Communications Engineering. In 2010, he was invited to join the Hawaii Center for Advanced Communications, College of Engineering, University of Hawaii at Manoa, as a Visiting Research Scholar, involved in hybrid smart antennas for wireless communications. He is currently a Vice Director of the Communication Research Center, Yuan Ze University. He has authored over 60 papers and holds six U.S. patents. His research interests include precoding design, communication signal processing, smart antennas, communication transceiver design, RF impairment calibration design, and MIMO techniques for wireless communications. He is a member of the IEICE.

SU-HUA CHEN was born in New Taipei City, Taiwan, in 1992. She received the master's degree in communications engineering with Yuan Ze University, Chungli, Taiwan, in 2016. She is currently with the National Chung Shan Institute of Science and Technology. Her current research interests include MIMO preprocessing, wireless communications, relay, and software-defined radios.

MENG-LIN KU (M'11) received the B.S., M.S., and Ph.D. degrees in communication engineering from National Chiao Tung University, Hsinchu, Taiwan, in 2002, 2003, and 2009, respectively. From 2009 to 2010, he was a Post-Doctoral Research Fellow with Prof. L.-C. Wang in the Department of Electrical and Computer Engineering, National Chiao Tung University, and with Prof. V. Tarokh in the School of Engineering and Applied Sciences, Harvard University. In 2010, he became a Faculty Member with the Department of Communication Engineering, National Central University, Taoyuan, Taiwan, where he is currently an Associate Professor. In 2013, he was a Visiting Scholar with the Signals and Information Group of Prof. K. J. Ray Liu, University of Maryland. His current research interests are in the areas of green communications, cognitive radios, and optimization of radio access. He was a recipient of the Best Counseling Award in 2012 and the university-level Best Teaching Award in 2014, 2015, and 2016 at National Central University. He was also a recipient of the Exploration Research Award of the Pan Wen Yuan Foundation, Taiwan, in 2013.