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The Solution for Cooperative Beamforming Design in MIMO Multi-way Relay Networks

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Abstract

In this paper, we study the design of network coding for the generalized transmit scheme in multiple input multiple output Y channel, where K users wish to exchange specified and shared information with each other within two slots. Signal space alignment at each user and the relay is carefully constructed to ensure that the signals from the same user pair are grouped together. The cross-pair interference can be canceled during both multiple accessing channel phase and broadcasting channel phase. The proposed signal processing scheme achieves the degrees of freedom of $\eta(K)=K^2$ with fewer user antennas.

Keywords: Network coding, signal space alignment, degrees of freedom, multi-way relay

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1. Introduction

Recently, there has been growing interest in the application of network coding to wireless communications due to its superior capability to increase system throughput. At the same time, cooperative communications for wireless networks have gained great interest, due to it ability to enhance the performance of wireless networks. The relay networks, specially the multiple input multiple output (MIMO) Y channel relay networks, where additional node acting as a relay is supporting the exchange of information between the network K users, has attracted extensive research attention [1-3].

Signal space alignment (SSA) has been shown, by aligning the signals from the users that want to exchange information at the same dimension, network coding (NC) can be utilized to maximize the utilization of the spatial dimension available at the relay to achieve the optimal degrees of freedom (DoF) [4]. General transmission models of the multi-way relay channel have been studied for two different types of messages: unicast and multicast message. Unicast message is denoted as specified signal, which implies that all the other users see this unicast message as interference signal. On the other hand, multicast message is used for a group of users, and it is denoted as a shared signal for the group. Depending on the transmission models, there are two mainly types of signals settings: Each user intends to convey (K-1) unicast signals for different users via the relay while receiving (K-1) independent unicast signals from the others users by spending only two slots [5]. For example, information exchange happens among all K users in a wireless mesh or ad-hoc system where K nodes are connected by sharing a single relay as star or tree topology. Also, user wants to convey one multicast signal to all other users while receiving (K-1) independent multicast signals from the others users via the relay [6]. We can find various application scenarios in wireless networks, such as video conferencing using Wi-Fi access point and multi-player gaming using smart phones.

The two-way relay (TWR) symmetric channle with four user was proposed in [7], where each user transmit multi message streams to their partner. The DoF can be achieved by $2dK$, where d denotes interference-free streams for each message. A algorithm which can reduce the complexity of relay with simple mapping function and exact the bit error rate (BER) is proposed in [8]. In [9], the authors propose the SSA in Spectral efficiency and is extended to multi-way multi-pair TWR communication system. In [10], the transceiver designs were understood from a unified optimization problem named as QMP which can be applied to multi-cell coordinated beamforming designs, multi-user MIMO beamforming designs. Shin [11] designs linear transmit and receive filter sets which maximize the weighted sum rate while allowing each transmitter to utilize only the local channel state information. At the same time, based on reduced-dimensionality collected, [12] derives linear estimators of stationary random signals.

We show the solution for cooperative beamforming design in MIMO Multi-way relay networks. To be more specific, the main contributions of this paper are summarized as follows:

We propose a novel hybrid transmission scheme for special scenario: multiple users exchange bi-directional multi-pair signals and multi-directional multi-pair signals simultaneously with each other via a relay with multiple antennas. Especially, each user simultaneously sends one multicast shared signals for all users and multiple unicast specified signals for target users.

We adopt SSA both multiple access channel phase and broadcast channel phase. Each user pair who needs network coding designs the transmit beamforming vectors to align two signals in the same dimension in multiple access channel phase. During the broadcast channel phase, the SSA is performed to align the interfering signals at each user for reducing interference.

We investigated the feasibility condition of SSA transmission scheme for DoF when exchanging specified signals and shared signals simultaneously. The proposed scheme obtains the total DoF of K^2 if $M = \left\lceil N/2 \right\rceil + 1$ and $N \geq K(K-1)$ when each user has M antennas and the relay has N antennas. The proposed scheme can achieve higher DoF than Ref. [4] when each signal obtains DoF of 1. The proposed scheme needs fewer user antennas than Ref. [13] in keeping DoF under the same users' number. It has great benefits for practical engineering applications.

The remainder of this paper is organized as follows. Section 2 introduces the system and signal models for MIMO Multi-way relay networks. In section 3, we investigate the DoF that can be achieved according to transmit scheme for the K-user MIMO Y channel.In section 4, we extend the scheme to the general case of multi-user. The simulation result and discussion are given in section 5, followed by some concluding remarks in section 6.

2. System Model

In the following mathematical exposition, superscripts $(\square)^T$, $(\square)^*$, and $(\square)^H$ denote transpose, complex conjugate, and conjugate-transpose, respectively. We consider a MIMO Multi-way relay channel in this section shown as **Fig. 1**. In this channel, K users with M antennas exchange bi-directional multi-pair specified signals and multi-directional multi-pair shared signals simultaneously with each other via a relay with N antennas.

The signal space alignment is similar with interference alignment scheme that maximizing the utility of dimension for desired signal space. However, there is some distinct point. The interference alignment focuses on the overlapping of interference signal vectors to minimize the dimension of signal space occupied by interference signals. While the key idea of signal space alignment is that each user pair who wants to exchange messages cooperatively constructs the transmit beamforming vectors so that two pair signals for the network coding should be aligned within the same spatial signal dimension to jointly perform detection and encoding for network coding at the receiver of the relay [1]. For example, the communication system has three users. User 1 transmits independent codewords $s^{[j,1]}$ by using beamforming vectors $\mathbf{v}^{[j,1]}$ to the relay simultaneously where $j \in \{2,3\}$. The receiver of the relay sees six linearly transformed vectors $\mathbf{H}^{[r,i]}\mathbf{v}^{[j,i]}$ by channel matrices $\mathbf{H}^{[r,i]}$ where $i, j \in \{1,2,3\}$ and $i \neq j$. If the relay has only three antennas, it could not generally detect six independent signal vectors coming from three users. Therefore, each user designs the beamforming directions so that two desired signals for network coding are aligned within the same spatial dimension, i.e., $span\left(\mathbf{H}^{[r,i]}\mathbf{v}^{[j,i]}\right) = span\left(\mathbf{H}^{[r,j]}\mathbf{v}^{[i,j]}\right)$. By doing so, three network coded messages $W^{[2,1]} \oplus W^{[1,2]}$, $W^{[3,1]} \oplus W^{[1,3]}$, and $W^{[2,3]} \oplus W^{[3,2]}$ are obtained from six independent codewords at the relay where $\oplus$ denotes exclusive OR addition.

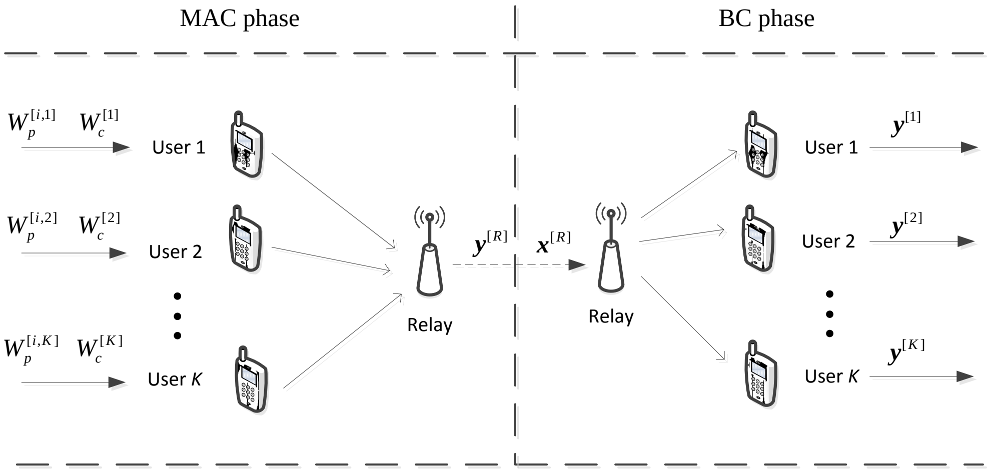

Fig. 1. System model for MIMO Multi-way relay network

In the first time slot, which is called a multiple access phase (MAC). We design network coding with chain property for schared signals. Therefore, to accomplish this, two precoding vectors are constructed for each user by using SSA. Each user sends specified signal $W_p^{[i,j]}$ and shared signal $W_c^{[i]}$ using symbols $\mathbf{s}_p^{[i,j]}$ and $\mathbf{s}_c^{[i]}$ along with precoding vectors $\mathbf{v}_p^{[i,j]}$ and $\mathbf{v}_{c,1}^{[i]}, \mathbf{v}_{c,2}^{[i]}$, which expressed by $\mathbf{x}^{[i]} = \sum_{j \neq i} \mathbf{v}_p^{[j,i]} s_p^{[j,i]} + \sum_{t=1}^{2} \mathbf{v}_{c,t}^{[i]} s_c^{[i]}$.

$$\mathbf{y}^{[R]} = \sum_{i=1}^{K} \mathbf{H}^{[R,i]} \mathbf{x}^{[i]} + \mathbf{n}^{[R]} \tag{1}$$

where $\mathbf{H}^{[R,i]}$ represents the $N \times M$ channel matrix from user i to the relay, $\mathbf{x}^{[i]} \in \mathbb{C}^{M}$ denotes transmit vector at user *i*, and $\mathbf{n}^{[R]} \in \mathbb{C}^{N}$ denotes an additive white Gaussian noise (AWGN) vector. The user has an average power constraint, $\mathrm{E}\left[Tr\left(\mathbf{x}^{[i]} \mathbf{x}^{[i]^H} \right) \right] \le SNR$. The channel is assumed to be quasi-static and each entry of the channel matrix is an independently and identically distributed (i.i.d.) zero mean complex Gaussian random variable with unit variance, i.e., $NC(0,1)$.

During broadcast channel (BC) phase, the relay generates new transmitting signals $\mathbf{x}^{[R]}$ and broadcasts them to all users. The received signal vector at user *i* is given by:

$$\mathbf{y}^{[i]} = \mathbf{Q}^{[i]} \mathbf{H}^{[i,R]} \mathbf{x}^{[R]} + \mathbf{Q}^{[i]} \mathbf{n}^{[i]} \tag{2}$$

where $\mathbf{Q}^{[i]}$ denotes the receiving precoding matrix , $\mathbf{H}^{[i,R]}$ denotes the $M \times N$ channel matrix from the relay to user *i*, $\mathbf{x}^{[R]} \in \mathbb{C}^{N}$ is the transmit vector at the relay, and $\mathbf{n}^{[i]} \in \mathbb{C}^{M}$ denotes the AWGN vector. The transmit signal at the relay is subject to the average power constraint $\mathrm{E}\left[Tr\left(\mathbf{x}^{[R]} \mathbf{x}^{[R]^H} \right) \right] \le SNR$.

3. Design of Cooperative Beamforming

In this section, we investigate the DoF that can be achieved according to transmit scheme for the *K*-user MIMO Y channel.

3.1 Case of Four User (*K* = 4)

We first explain the idea of the proposed scheme in case of $K=4, N=12, M=7$. Then, we will extend the program to more number of users. During the MAC phase, each user transmits three specified signals and two shared signals for the other three users to the relay simultaneously (copies of the same shared signal) while user 1 and user 4 send only one shared signal, respectively. The receiver of relay sees eighteen independent signals which consist of twelve specified signals and six shared signals. Each user designs the beamforming directions so that two desired specified signals for network coding should be aligned within the same spatial dimension, i.e., $span\left(\mathbf{H}^{[R,i]}\mathbf{v}_p^{[j,i]}\right)=span\left(\mathbf{H}^{[R,j]}\mathbf{v}_p^{[i,j]}\right)$. Specially, the six signal dimensions can be chosen firstly for the specified signals $W_p^{[i,j]}$ as $\mathbf{U}_p=\left[\mathbf{u}_p^{\pi(1,2)} \quad \mathbf{u}_p^{\pi(1,3)} \quad \mathbf{u}_p^{\pi(1,4)} \quad \mathbf{u}_p^{\pi(2,3)} \quad \mathbf{u}_p^{\pi(2,4)} \quad \mathbf{u}_p^{\pi(3,4)}\right]$ where $\mathbf{u}_p^{\pi(i,j)}=\mathbf{H}^{[R,i]}\mathbf{v}_p^{[j,i]}=\mathbf{H}^{[R,j]}\mathbf{v}_p^{[i,j]}$ denotes the intersection subspace between the *i*-th user and *j*-th user with the index function $\pi(i,j)$.

For the shared signals, user 1 and user 4 send signals $W_c^{[1]}$ and $W_c^{[4]}$ using symbols $\mathbf{s}_c^{[1]}$ and $\mathbf{s}_c^{[4]}$ along with precoding vectors $\mathbf{v}_{c,2}^{[1]}$ and $\mathbf{v}_{c,1}^{[4]}$, as expressed by $\mathbf{x}_c^{[1]}=\mathbf{v}_{c,2}^{[1]}s_c^{[1]}$, $\mathbf{x}_c^{[4]}=\mathbf{v}_{c,1}^{[4]}s_c^{[4]}$, while user 2 and user 3 use two different precoding vectors $\mathbf{v}_{c,1}^{[i]}$ and $\mathbf{v}_{c,2}^{[i]}$ for symbol $\mathbf{s}_c^{[2]}$ and $\mathbf{s}_c^{[3]}$ to transmit signals $W_c^{[2]}$ and $W_c^{[3]}$. It is expressed by $\mathbf{x}_c^{[i]}=\mathbf{v}_{c,1}^{[i]}s_c^{[i]}+\mathbf{v}_{c,2}^{[i]}s_c^{[i]}, i=[1,4]\, and \;\; \mathbf{v}_{c,1}^{[1]}=\mathbf{v}_{c,2}^{[4]}=\mathbf{0}$.

The proposed precoding scheme of shared signal is aiming at obtaining three network coding signals with chain property, i.e., $W_c^{[1]}\oplus W_c^{[2]}$, $W_c^{[2]}\oplus W_c^{[3]}$, $W_c^{[3]}\oplus W_c^{[4]}$ at the relay. All users carefully choose the precoding vectors in order to satisfy the conditions of SSA for an encryption signal. These are given by $span\left(\mathbf{H}^{[R,i]}\mathbf{v}_{c,2}^{[i]}\right)=span\left(\mathbf{H}^{[R,i+1]}\mathbf{v}_{c,1}^{[i+1]}\right)$, $i=[1,3]$. We obtain the three signal dimensions for the shared signals as $\mathbf{U}_c=\left[\mathbf{u}_{c,1} \quad \mathbf{u}_{c,2} \quad \mathbf{u}_{c,3}\right]$ where $\mathbf{u}_{c,i}=\mathbf{H}^{[R,i]}\mathbf{v}_{c,2}^{[i]}=\mathbf{H}^{[R,i+1]}\mathbf{v}_{c,1}^{[i+1]}, i=[1,3]$ denotes the intersection subspace between the *i*-th user and (*i*+1)-th user with the index *i*.

The received signal at the relay is given by

$$\begin{aligned}\mathbf{y}^{[R]}&=\sum_{i=1}^{4}\mathbf{H}^{[R,i]}\left(\sum_{j\neq i}\mathbf{v}_p^{[j,i]}s_p^{[j,i]}+\sum_{t=1}^{2}\mathbf{v}_{c,t}^{[i]}s_c^{[i]}\right)+\mathbf{n}^{[R]}\\&=\left[\mathbf{U}_p \quad \mathbf{U}_c\right]\mathbf{s}^{[R]}+\mathbf{n}^{[R]}\end{aligned} \tag{3}$$

where $\mathbf{v}_{c,1}^{[1]}=\mathbf{v}_{c,2}^{[4]}=\mathbf{0}_{M\times 1}$. We define $\mathbf{s}^{[R]}=\left[\mathbf{s}_p^{[R]} \quad \mathbf{s}_c^{[R]}\right]^T$, $\mathbf{s}_p^{[R]}=\left[L_{p,1}^{[R]}(s_p^{[1,2]},s_p^{[2,1]}) \quad \dots \quad L_{p,6}^{[R]}(s_p^{[3,4]},s_p^{[4,3]})\right]^T$,

$\mathbf{s}_c^{[R]} = \left[L_{c,1}^{[R]}(s_c^{[1]}, s_c^{[2]}) \quad L_{c,2}^{[R]}(s_c^{[2]}, s_c^{[3]}) \quad L_{c,3}^{[R]}(s_c^{[3]}, s_c^{[4]}) \right]^T$ and $\mathbf{U} = \left[\mathbf{U}_p \quad \mathbf{U}_c \right]$ denotes the effective channel matrix, $L_{p,m}^{[R]}$ and $L_{c,m}^{[R]}$ are the m-th linear combination of the transmitted specified and shared signals at the relay.

The each column of $\mathbf{U}$ is linearly independent with probability one [1], i.e., $\Pr\left[\det(\mathbf{U}) = 0\right] = 0$. Employing the SSA-NC, each user is able to send three independent specified data signals for network coding and two shared data signals for network code chain structure at the relay. Therefore, $\mathbf{s}^{[R]}$ can be obtained by elimination the inter-signal space interference using a zero-forcing (ZF) decoder, which is $\mathbf{s}^{[R]} = \mathbf{U}^{-1}\mathbf{y}^{[R]} + \mathbf{U}^{-1}\mathbf{n}^{[R]}$. The nine network coding signals $\hat{W}_{p,\pi(i,j)}^{[R]} = W_p^{[i,j]} \oplus W_p^{[i,j]}$, $i, j \in [1,4]$, $\hat{W}_{c,\pi(l,l+1)}^{[R]} = W_c^{[l]} \oplus W_c^{[l+1]}$, $l \in [1,3]$ are then obtained by applying the physical-layer network coding (PNC) modulation-demodulation mapping principle into each symbol $s_i^{[R]}$ via a signal dimension.

During the BC phase, the relay broadcasts the network coding signals $\hat{W}_{p,\pi(i,j)}^{[R]}$ and $\hat{W}_{c,\pi(i,j)}^{[R]}$ to all users using encoded streams $\mathbf{s}_R = \left[s_{R,p}^1 \quad \dots \quad s_{R,p}^6 \quad s_{R,c}^1 \quad s_{R,c}^2 \quad s_{R,c}^3 \right]^T$ along beamforming vectors $\mathbf{T}_R = \left[\mathbf{T}_p^1 \quad \dots \quad \mathbf{T}_p^6 \quad \mathbf{T}_c^1 \quad \mathbf{T}_c^2 \quad \mathbf{T}_c^3 \right]$.

Now, we will show how we transmit these network coded signals to the corresponding users. In a similar way as in the MAC phase, we can also align the user pair's received signal space. We first design the combining matrices $\mathbf{q}_p^{[i,j]}$ and $\mathbf{q}_p^{[j,i]}$ for decoding the specified signals $W_p^{[i,j]}$ and $W_p^{[j,i]}$. They should satisfy the following condition as: $span\left(\mathbf{q}_p^{[i,j]}\mathbf{H}^{[i,R]}\right) = span\left(\mathbf{q}_p^{[j,i]}\mathbf{H}^{[j,R]}\right)$. Then we design the combining matrices $\mathbf{q}_c^{[i,j]}$ and $\mathbf{q}_c^{[j,i]}$ for decoding the shared signals $W_c^{[i]}$ and $W_c^{[j]}$ as: $span\left(\mathbf{q}_c^{[i,j]}\mathbf{H}^{[i,R]}\right) = span\left(\mathbf{q}_c^{[j,i]}\mathbf{H}^{[j,R]}\right)$. We denote $\mathbf{z}_p^{\pi p(i,j)}$ and $\mathbf{z}_c^{\pi c(i,j)}$ are unit vector for the specified and shared signals in the intersection subspace between the channel of user i and user j. The total effective channel matrix $\mathbf{Z} = \left[\mathbf{z}_p^{\pi p(1,2)} \quad \cdots \quad \mathbf{z}_p^{\pi p(3,4)} \quad \mathbf{z}_c^{\pi c(1,2)} \quad \cdots \quad \mathbf{z}_c^{\pi c(3,4)} \right]^H$ is composed of these aligned vectors. Let us denote $\tilde{\mathbf{Z}}_p^{\pi p(i,j)}$ as the matrix which excludes the aligned signal space vector of the index $\pi p(i, j)$ for the specified signal, i.e., $\mathbf{z}_p^{\pi p(i,j)}$, excluded from the matrix $\mathbf{Z}$. $\tilde{\mathbf{Z}}_c^{\pi c(i,j),\pi c(m,n)}$ is the matrix which excludes the aligned signal space vectors of the index $\pi c(i, j)$ and $\pi c(m,n)$ for the shared signal, $m \neq n \neq i \neq j$ i.e., $\mathbf{z}_c^{\pi c(i,j)}$ and $\mathbf{z}_c^{\pi c(m,n)}$, excluded from the matrix $\mathbf{Z}$. The aligned signals $W^{[i,j]}$ are interferences for the rest aligned signals. Therefore, the relay employs transmit beamforming to suppress the specified interference, i.e., $\mathbf{T}_p^1 \in null\left(\tilde{\mathbf{Z}}_p^{\pi p(1,2)}\right)$, $\mathbf{T}_p^2 \in null\left(\tilde{\mathbf{Z}}_p^{\pi p(1,3)}\right)$, $\mathbf{T}_p^3 \in null\left(\tilde{\mathbf{Z}}_p^{\pi p(1,4)}\right)$, $\mathbf{T}_p^4 \in null\left(\tilde{\mathbf{Z}}_p^{\pi p(2,3)}\right)$, $\mathbf{T}_p^5 \in null\left(\tilde{\mathbf{Z}}_p^{\pi p(2,4)}\right)$, $\mathbf{T}_p^6 \in null\left(\tilde{\mathbf{Z}}_p^{\pi p(3,4)}\right)$. For the shared interference, $\mathbf{T}_c^1 \in null\left(\tilde{\mathbf{Z}}_c^{\pi c(1,2),\pi c(3,4)}\right)$, $\mathbf{T}_c^2 \in null\left(\tilde{\mathbf{Z}}_c^{\pi c(1,3),\pi c(2,4)}\right)$, $\mathbf{T}_c^3 \in null\left(\tilde{\mathbf{Z}}_c^{\pi c(1,4),\pi c(2,3)}\right)$.

The received signal at user 1 can be expressed as

$$\begin{aligned}\hat{\mathbf{y}}^{[1]} &= \mathbf{Q}^{[1]}\mathbf{H}^{[1,R]}\left(\sum_{m=1}^{6}\mathbf{T}_p^m s_{R,p}^m + \sum_{n=1}^{3}\mathbf{T}_c^n s_{R,c}^n\right) + \hat{\mathbf{n}}^{[1]} \\ &= \hat{\mathbf{H}}^{[1,R]}\begin{bmatrix} s_{R,p}^1 & s_{R,p}^2 & s_{R,p}^3 & s_{R,c}^1 & s_{R,c}^2 & s_{R,c}^3 \end{bmatrix}^T + \hat{\mathbf{n}}^{[1]} \qquad (4)\end{aligned}$$

where $\mathbf{Q}^{[1]} = \begin{bmatrix} \mathbf{q}_p^{[1,2]} & \mathbf{q}_p^{[1,3]} & \mathbf{q}_p^{[1,4]} & \mathbf{q}_c^{[1,2]} & \mathbf{q}_c^{[1,3]} & \mathbf{q}_c^{[1,4]} \end{bmatrix}^T$, and $\hat{\mathbf{H}}^{[1,R]}$ denotes the effective channel matrix from the relay to user 1 which is diagonal matrix.

After self-interference cancellation, user 1 detects the three desired specified signals coming from user 2, user 3 and user 4, i.e., $s_p^{[1,2]}$, $s_p^{[1,3]}$ and $s_p^{[1,4]}$, and the three encrypted shared signals. The decryption procedure is performed by successive network code decoding scheme. In the same manner, other all users can decode three specified signals and three shared signals. It lead to achieve the total DoF $\eta(4)=16$ when M=7, N=12. The detail of the proposed scheme is shown in **Table 1**.

Table 1. Cooperative beamforming design in MIMO multi-way relay network

Initialization step:

$K=4$: the number of users
$M=7$: the number of antennas for each user
$N=12$: the number of antennas for shared relay
Each user sends K-1 private and two common messages to the relay (copies of the same common message), but user 1 and user K send only one common message

Main step:

1. During MAC phase, using SSA algorithm

$$span\left(\mathbf{H}^{[R,i]}\mathbf{v}_p^{[j,i]}\right) = span\left(\mathbf{H}^{[R,j]}\mathbf{v}_p^{[i,j]}\right)$$

$$span\left(\mathbf{H}^{[R,i]}\mathbf{v}_{c,2}^{[i]}\right) = span\left(\mathbf{H}^{[R,i+1]}\mathbf{v}_{c,1}^{[i+1]}\right)$$

We get the precoding vectors $\mathbf{v}_p^{[j,i]}$ and $\mathbf{v}_{c,t}^{[i]}$.

2. The relay receive the signals

$$\mathbf{y}^{[R]} = \sum_{i=1}^{4}\mathbf{H}^{[R,i]}\left(\sum_{j\neq i}\mathbf{v}_p^{[j,i]}s_p^{[j,i]} + \sum_{t=1}^{2}\mathbf{v}_{c,t}^{[i]}s_c^{[i]}\right) + \mathbf{n}^{[R]}$$

3. The relay applies the network coding

$$\hat{W}_{p,\pi(i,j)}^{[R]} = W_p^{[i,j]} \oplus W_p^{[i,j]}$$

$$\hat{W}_{c,\pi(i,j)}^{[R]} = W_c^{[i]} \oplus W_c^{[j]}$$

4. During the BC phase, the SSA is performed again to align the interfering signals at each user for reducing interference.

$$span\left(\mathbf{q}_p^{[i,j]}\mathbf{H}^{[i,R]}\right) = span\left(\mathbf{q}_p^{[j,i]}\mathbf{H}^{[j,R]}\right)$$

$$span\left(\mathbf{q}_c^{[i,j]}\mathbf{H}^{[i,R]}\right) = span\left(\mathbf{q}_c^{[j,i]}\mathbf{H}^{[j,R]}\right)$$

We use $\mathbf{q}_p^{[i,j]}$ and $\mathbf{q}_c^{[i,j]}$ to construct the receiving precoding matrix $\mathbf{Q}^{[i]}$.

5. Accoring null space, we construct relay transmitting precoding vectors $\mathbf{T}_p^m, \mathbf{T}_c^n$.

6. The user *i* receives the desired signals
$$\hat{\mathbf{y}}^{[i]} = \mathbf{Q}^{[i]}\mathbf{H}^{[i,R]}\left(\sum_{m=1}^{6}\mathbf{T}_p^m s_{R,p}^m + \sum_{n=1}^{3}\mathbf{T}_c^n s_{R,c}^n\right) + \hat{\mathbf{n}}^{[i]}$$
7. We get desired specified signals and shared signals.

3.2 Case of Five User (*K* = 5)

We consider $N = 20, M = 11$. During the MAC phase, each user transmits four specified and two shared streams to the relay (copies of the same shared signal). The receiver of relay sees thirty independent signals which consist of twenty specified signals and ten shared signals. Each user designs the precoding vectors so that two desired signals for network coding should be aligned within the same spatial dimension.

The transmit scheme is part of the same as the case of *K*=4 except for the shared signals. Each of all users sends shared signal two times along with two different beamforming directions $\mathbf{v}_{c,1}^{[i]}$ and $\mathbf{v}_{c,2}^{[i]}$, especially include user 1 and user 5, as expressed by $\mathbf{x}_c^{[i]} = \mathbf{v}_{c,1}^{[i]} s_c^{[i]} + \mathbf{v}_{c,2}^{[i]} s_c^{[i]}$, $i \in [1,5]$. The proposed precoding scheme of shared signal is aiming at obtaining five network coding signals with circle property, i.e. $\hat{W}_{c,\pi(i,i+1)}^{[R]} = W_c^{[i]} \oplus W_c^{[i+1]}$, $i \in [1,4]$ and $\hat{W}_{c,\pi(5,1)}^{[R]} = W_c^{[5]} \oplus W_c^{[1]}$. These are given by $span\left(\mathbf{H}^{[R,i]}\mathbf{v}_{c,2}^{[i]}\right) = span\left(\mathbf{H}^{[R,i+1]}\mathbf{v}_{c,1}^{[i+1]}\right)$ $i = [1,4]$ and $span\left(\mathbf{H}^{[R,5]}\mathbf{v}_{c,2}^{[5]}\right) = span\left(\mathbf{H}^{[R,1]}\mathbf{v}_{c,1}^{[1]}\right)$. We obtain the three signal dimensions for the shared signals as $\mathbf{U}_c = \left[\mathbf{u}_{c,1} \quad \mathbf{u}_{c,2} \quad \mathbf{u}_{c,3} \quad \mathbf{u}_{c,4} \quad \mathbf{u}_{c,5}\right]$ where $\mathbf{u}_{c,i} = \mathbf{H}^{[R,i]}\mathbf{v}_{c,2}^{[i]} = \mathbf{H}^{[R,i+1]}\mathbf{v}_{c,1}^{[i+1]}$, $i = [1,4]$ and $\mathbf{u}_{c,5} = \mathbf{H}^{[R,5]}\mathbf{v}_{c,2}^{[5]} = \mathbf{H}^{[R,1]}\mathbf{v}_{c,1}^{[1]}$. During the BC phase, we first design the combining matrices $\mathbf{q}_p^{[i,j]}$ and $\mathbf{q}_p^{[j,i]}$ for decoding the specified signals $W_p^{[i,j]}$ and $W_p^{[j,i]}$. They should satisfy the following condition as: $span\left(\mathbf{q}_p^{[i,j]}\mathbf{H}^{[i,R]}\right) = span\left(\mathbf{q}_p^{[j,i]}\mathbf{H}^{[j,R]}\right)$. Then we design the combining matrices $\mathbf{q}_c^{[i,j]}$ and $\mathbf{q}_c^{[j,i]}$ for decoding the shared signals $W_c^{[i]}$ and $W_c^{[j]}$ as: $span\left(\mathbf{q}_c^{[i,j]}\mathbf{H}^{[i,R]}\right) = span\left(\mathbf{q}_c^{[j,i]}\mathbf{H}^{[j,R]}\right)$. We denote $\mathbf{z}_p^{\pi p(i,j)}$ and $\mathbf{z}_c^{\pi c(i,j)}$ are unit vector for the specified and shared signals in the intersection subspace between the channel of user *i* and user *j*. The total effective channel matrix $\mathbf{Z} = \left[\mathbf{z}_p^{\pi p(1,2)} \cdots \mathbf{z}_p^{\pi p(4,5)} \mathbf{z}_c^{\pi c(1,2)} \cdots \mathbf{z}_c^{\pi c(4,5)}\right]^H$ is composed of these aligned vectors. For the purpose of interference elimination, $\mathbf{T}_c^i$ must lie in the null spaces of channel matrices between other nodes and the relay, i.e., $\mathbf{T}_c^1 \in null\left(\tilde{\mathbf{Z}}_c^{\pi c(1,2),\pi c(3,4)}\right)$, $\mathbf{T}_c^2 \in null\left(\tilde{\mathbf{Z}}_c^{\pi c(1,3),\pi c(2,5)}\right)$, $\mathbf{T}_c^3 \in null\left(\tilde{\mathbf{Z}}_c^{\pi c(1,4),\pi c(3,5)}\right)$, $\mathbf{T}_c^4 \in null\left(\tilde{\mathbf{Z}}_c^{\pi c(1,5),\pi c(2,4)}\right)$, $\mathbf{T}_c^5 \in null\left(\tilde{\mathbf{Z}}_c^{\pi c(2,3),\pi c(4,5)}\right)$.

The received signal at user 1 can be expressed as
$$\hat{\mathbf{y}}^{[1]} = \mathbf{Q}^{[1]}\mathbf{H}^{[1,R]}\left(\sum_{m=1}^{10}\mathbf{T}_p^m s_{R,p}^m + \sum_{n=1}^{5}\mathbf{T}_c^n s_{R,c}^n\right) + \hat{\mathbf{n}}^{[1]}$$

$$= \hat{\mathbf{H}}^{[1,R]} \left[s_{R,p}^{1}, s_{R,p}^{2}, s_{R,p}^{3}, s_{R,p}^{4}, s_{R,c}^{1}, s_{R,c}^{2}, s_{R,c}^{3}, s_{R,c}^{4} \right]^{T} + \hat{\mathbf{n}}^{[1]} \tag{5}$$

where $\mathbf{Q}^{[1]} = \left[\mathbf{q}_{p}^{[1,2]} \quad \mathbf{q}_{p}^{[1,3]} \quad \mathbf{q}_{p}^{[1,4]} \quad \mathbf{q}_{p}^{[1,5]} \quad \mathbf{q}_{c}^{[1,2]} \quad \mathbf{q}_{c}^{[1,3]} \quad \mathbf{q}_{c}^{[1,4]} \quad \mathbf{q}_{c}^{[1,5]} \right]^{T}$. Each user can only detect four signals from five shared signals to get all shared signals. All the nodes can receive the desired signals from the relay. It lead to achieve the total DoF $\eta(5) = 25$.

4. The General case of *K*-user

In this section, we generalize the proposed scheme to the general K-user case, assuming that each user achieves the DoF of 1 for each signal. Since each user transmits total $K-1$ specified signals and one shared signal with two branches, the relay receives $(K-1+1) \times K = K^2$ signals for K users during the MAC phase. The user can transmit $K-1$ specified signals and two branches of one shared signal properly if

$$M \geq (K+1) \tag{6}$$

In order to properly align intersection subspace for specified and shared signals, the beamforming vectors $\mathbf{v}_{p}^{[j,i]}$ and $\mathbf{v}_{c,k}^{[i]}$ should be designed by satisfying $span\left(\mathbf{H}^{[R,i]}\mathbf{v}_{p}^{[j,i]}\right) = span\left(\mathbf{H}^{[R,j]}\mathbf{v}_{p}^{[i,j]}\right)$ and $span\left(\mathbf{H}^{[R,i]}\mathbf{v}_{c,2}^{[i]}\right) = span\left(\mathbf{H}^{[R,i+1]}\mathbf{v}_{c,1}^{[i+1]}\right)$, if

$$2M \succ N+1 \tag{7}$$

There exists intersection subspace constituted by the column space of channel matrices for each user pair.

4.1 *K* is even

As explained in the previous subsection, each user transmits total $K-1$ specified signals and K users can transmit $K(K-1)$ specified signals. For the shared signals, user sends signal with vector is expressed as $\mathbf{x}_{c}^{[i]} = \mathbf{v}_{c,1}^{[i]} s_{c}^{[i]} + \mathbf{v}_{c,2}^{[i]} s_{c}^{[i]}$, $i = [1, K]$ *and* $\mathbf{v}_{c,1}^{[1]} = \mathbf{v}_{c,2}^{[K]} = \mathbf{0}$. All users choose the precoding vectors for shared signals by $span\left(\mathbf{H}^{[R,i]}\mathbf{v}_{c,2}^{[i]}\right) = span\left(\mathbf{H}^{[R,i+1]}\mathbf{v}_{c,1}^{[i+1]}\right)$, $i = [1, K-1]$. It can be called Open-loop Coding Chain.

After SSA-NC, the relay needs $\frac{1}{2}K(K-1)$ dimensional signal space for containing the specified signals and $K-1$ dimensional signal space for the shared signals, which requires

$$N \geq \tfrac{1}{2}K(K-1)+(K-1)=\tfrac{1}{2}(K-1)(K+2) \tag{8}$$

for the relay to properly contain the K^2 signals during the MAC phase.

In a similar way as in the MAC phase, we can also align the user pair's received signal space. The total effective channel matrix $\mathbf{Z} = \left[\mathbf{z}_{p}^{\pi p(1,2)} \quad \cdots \quad \mathbf{z}_{p}^{\pi p(K-1,K)} \, \mathbf{z}_{c}^{\pi c(1,2)} \quad \cdots \quad \mathbf{z}_{c}^{\pi c(K-1,K)} \right]^{H}$ whose size is $(K \times (K-1)) \times N$. Let us denote $\tilde{\mathbf{Z}}_{p}^{\pi p(i,j)}$ as the matrix which excludes the aligned signal space vector of the index $\pi p(i, j)$ for the specified signal. Therefore, if

$$N \geq \left(K \times (K-1)\right) \tag{9}$$

the solution for $null\left(\tilde{\mathbf{Z}}_{p}^{\pi p(i,j)}\right)$ is exist. We can get $\mathbf{T}_{p}^{\pi p(i,j)} \in null\left(\tilde{\mathbf{Z}}_{p}^{\pi p(i,j)}\right)$. For the shared signals, we denote $\tilde{\mathbf{Z}}_c^{\phi(K,i)}$ as the matrix for K users which excludes the aligned signal space vectors of row index, where $\phi(K,i)=\left[\pi c(s,t),\ldots,\pi c(m,n)\right]_{1\times K/2}$ shows that remove $\frac{1}{2}K$ vectors from all $\frac{1}{2}K\times(K-1)$ shared channel vectors while indices are not the same for each row, i.e., excludes $\frac{1}{2}K$ vectors of $\mathbf{z}_c^{\pi c(s,t)},\cdots,\mathbf{z}_c^{\pi c(m,n)}$, $and \quad s\neq t\neq\cdots\neq m\neq n$. We can get $\mathbf{T}_c^i\in null\left(\tilde{\mathbf{Z}}_c^{\phi(K,i)}\right)$.

4.2 *K* is odd

Each user transmits total $K-1$ specified signals and K users can transmit $K(K-1)$ specified signals. For the shared signals, user sends signal with vector is expressed as $\mathbf{x}_c^{[i]}=\mathbf{v}_{c,1}^{[i]}s_c^{[i]}+\mathbf{v}_{c,2}^{[i]}s_c^{[i]}, i=\left[1,K\right]$. All users choose the precoding vectors for shared signals by $span\left(\mathbf{H}^{[R,i]}\mathbf{v}_{c,2}^{[i]}\right)=span\left(\mathbf{H}^{[R,i+1]}\mathbf{v}_{c,1}^{[i+1]}\right)$ and $span\left(\mathbf{H}^{[R,K]}\mathbf{v}_{c,2}^{[K]}\right)=span\left(\mathbf{H}^{[R,1]}\mathbf{v}_{c,1}^{[1]}\right)$, $i=[1,K-1]$. It can be called Closed-loop Coding Chain.

After SSA-NC, the relay needs $\frac{1}{2}K(K-1)$ dimensional signal space for containing the specified signals and K dimensional signal space for the shared signals, which requires

$$N\geq\tfrac{1}{2}K(K-1)+K=\tfrac{1}{2}(K-1)(K+2)+1 \qquad (10)$$

for the relay to properly contain the K^2 signals during the MAC phase.

In a similar way as in K is even, the total effective channel matrix $\mathbf{Z}=\left[\mathbf{z}_p^{\pi p(1,2)}\ \cdots\ \mathbf{z}_p^{\pi p(K-1,K)}\ \mathbf{z}_c^{\pi c(1,2)}\ \cdots\ \mathbf{z}_c^{\pi c(K-1,K)}\right]^H$. The solution for $null\left(\tilde{\mathbf{Z}}_p^{\pi p(i,j)}\right)$ is exist. For the shared signals, we denote $\tilde{\mathbf{Z}}_c^{\phi(K,i)}$ as the matrix for K users which excludes the aligned signal space vectors of index $\pi c(i,j)$, where $\phi(K,i)=\left[\pi c(s,t),\ldots,\pi c(m,n)\right]_{1\times(K-1)/2}$ shows that remove $\frac{1}{2}(K-1)$ vectors from all $\frac{1}{2}K\times(K-1)$ shared vectors and indices are not the same for each row, i.e., excludes $\frac{1}{2}(K-1)$ vectors of $\mathbf{z}_c^{\pi c(s,t)}\cdots\mathbf{z}_c^{\pi c(m,n)}, s\neq t\neq\cdots\neq m\neq n$. Each user can only detect $K-1$ signals from K shared signals to get all shared signals. All the nodes can receive the desired signals from the relay.

As a result, whether K is even or odd, all users achieve the DoF of 1 for each signal, as they are able to transmit $K-1$ specified signals and one shared signal to the desired users without any interference. Thus, the proposed signaling method achieves the DoF of $\eta(K)=K^2$ with the antenna configuration of $M=\left\lceil N/2\right\rceil+1$ and $N\geq K(K-1)$.

Table 2 illustrates that the differences of the proposed scheme when the number of user is even or odd.

Table 2. Compare the operational details for various user numbers.

Parity	***K* is even**	***K* is odd**
Signals Transmission	$\mathbf{x}_c^{[i]}=\mathbf{v}_{c,1}^{[i]}s_c^{[i]}+\mathbf{v}_{c,2}^{[i]}s_c^{[i]}$, $i=\{1,K\}$, and $\mathbf{v}_{c,1}^{[1]}=\mathbf{v}_{c,2}^{[K]}=\mathbf{0}_{M\times1}$	$\mathbf{x}_c^{[i]}=\mathbf{v}_{c,1}^{[i]}s_c^{[i]}+\mathbf{v}_{c,2}^{[i]}s_c^{[i]}, i=\{1,K\}$

Precoding Vectors for Shared Signals	$span\left(\mathbf{H}^{[R,i]}\mathbf{v}_{c,2}^{[i]}\right)=span\left(\mathbf{H}^{[R,i+1]}\mathbf{v}_{c,1}^{[i+1]}\right)$ $i=[1,K-1]$	$span\left(\mathbf{H}^{[R,i]}\mathbf{v}_{c,2}^{[i]}\right)=span\left(\mathbf{H}^{[R,i+1]}\mathbf{v}_{c,1}^{[i+1]}\right)$ $i=[1,K-1]$ and $span\left(\mathbf{H}^{[R,K]}\mathbf{v}_{c,2}^{[K]}\right)=span\left(\mathbf{H}^{[R,1]}\mathbf{v}_{c,1}^{[1]}\right)$
Coding Chain	Open-loop	Closed-loop
The Total of Shared Signal Streams in MAC	$2K-2$	$2K$
The Number of Excluding Shared Vectors from effective channel matrix $\mathbf{Z}$ to get $\tilde{\mathbf{Z}}_c$	$\frac{K}{2}$	$\frac{K-1}{2}$

5. Simulation and Discussion

As size and cost constraints, it is hard to configure more antennas for user nodes. Fewer antennas configure, more conducive to engineering application. **Table 3** illustrates that the proposed scheme requires fewer the number of user antennas than [13] while they achieve the same DoF[1]. Meanwhile, we should see that this reduction of user antennas is achieved at the cost of the requirement of large number of relay antennas.

Table 3. Compare the number of user antennas for various schemes.

Schemes	Number of User Antennas (M)				
	K=4	K=5	K=6	K=7	K=8
Proposed scheme	7	11	16	22	29
Ref. [13]	8	12	18	24	32

In order to better illustrate the algorithm advantage in the antenna utilization, we compare the performance with [13]. In order to better illustrate the different performance of the two schemes, we design user antenna consume (UCA) per DoF to judge the quality of two schemes. We denote UAC which is normalized by the achieving total DoF as $UAC(K)=\frac{the\ number\ of\ \text{each}\ user\ antennas}{DoF}$. **Fig. 2** shows the UAC changing in trend with the number of users. We can conclude from the **Fig. 2** that the proposed scheme consumes fewer users' antennas than Ref. [13] under conditions of achieving the same unit DoF.

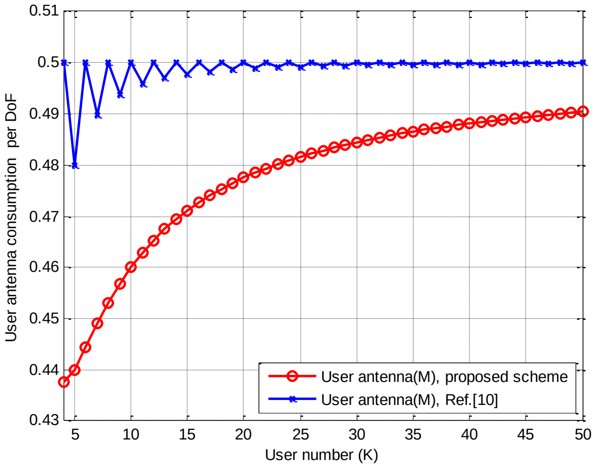

Fig. 2. Compare the number of user antennas consumption

In this paper, whether K is even or odd, all users achieve the DoF of 1 for each signal, as they are able to transmit $K-1$ specified signals and one shared signal to the desired users without any interference. Therefore, the proposed signaling method achieves the DoF of $\eta(K)=K^2$ with the antenna configuration of $M=\left\lceil N/2 \right\rceil+1$ and $N\geq K(K-1)$. As a comparison, the method of [10] can achieve the DoF of $\eta(K)=K^2$ with the antenna configuration of $M=N-\left\lfloor \frac{K-1}{2} \right\rfloor$ and $N\geq\frac{1}{2}(K-1)(K+2)$. As shown in **Fig. 2**, the performance of the proposed scheme is not only better than Ref. [13] but also monotonically increasing. At the same time, we can find from **Table 3** that the changing of the user antennas increasing is linear when the user increasing. However, the changing in Ref. [13] presents ladder form rise. **Fig. 3** compares the two schemes with the difference between the total numbers of antennas. In **Fig.3,** the red curve shows that Ref. [13] need more antennas with users increasing for even users while the blue curve shows that the proposed scheme requires more than one antenna than Ref. [13] for odd users. We can also easily read from the figure that the proposed scheme can save more number of antennas with users increasing for even.

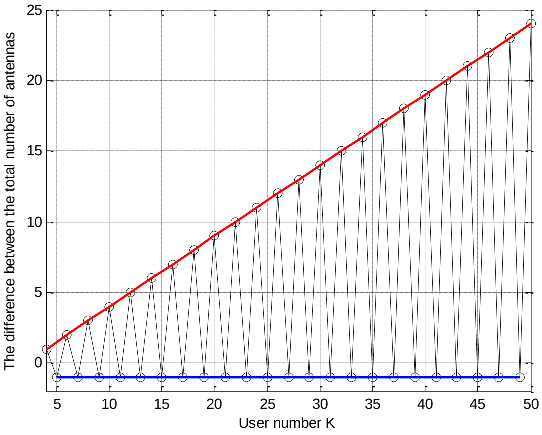

Fig. 3. The difference between the total of number of antennas

We provide the sum rate performance of the proposed scheme through stimulation comparison with Ref. [5]. **Fig.4** shows that the sum rate performance according to various users configuration with different DoF. We can obtain the DoF of 25 for K=5 and 36 for K=6 while DoF of 20 and 30 are achieved with the same user number in [5]. We have shown that signal space alignment for network coding and zero forcing are used during both MAC and BC phase can achieve more DoF by transmitting specified signals and shared signals simultaneously.

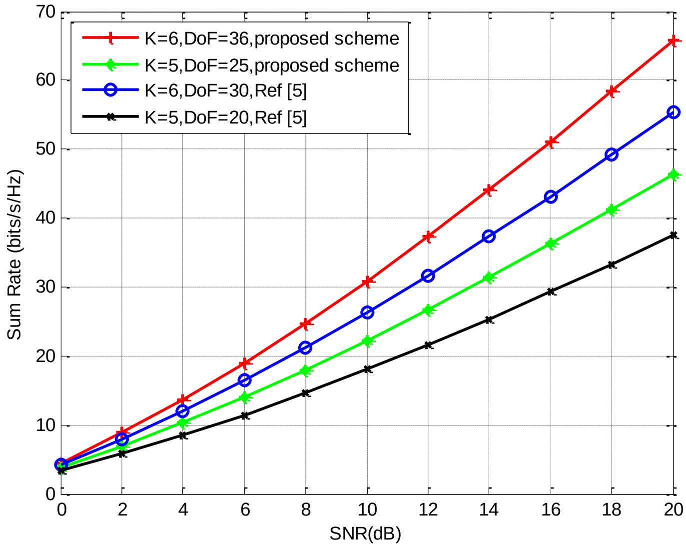

Fig. 4. Sum rate performance comparison between the proposed scheme and Ref. [5]

6. Conclusion

In this paper, we consider mixed signals exchange scenario in multi-way communication systems via the intermediate relay where K users having multiple antennas exchange both specified and shared signals with each other. The original MIMO Y channel is extended into a more generalized circumstance with general signal demands. The proposed signaling method achieves the DoF of $\eta(K) = K^2$ with fewer user antennas.

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