Abstract—This paper presents an optimized distributed multiple-input multiple-output (OD-MIMO) for cooperative communication in wireless relay networks. The set of cooperating nodes is a priori unknown. In order to avoid the centralized stream and pilot allocation procedure, a fixed signature vector (SV) is assigned for each node in the network. We analyze the constraints of the proposed scheme, and derive an optimization criterion for the decision of the SVs. A gradient-based algorithm for SV design is provided. Simulation results show that the performance loss of OD-MIMO compared to centralized distributed MIMO is small for large number of cooperative relay nodes.

Index Terms—Distributed MIMO, gradient algorithm, cooperative relay.

I. INTRODUCTION

In this letter, a distributed MIMO scheme is applied to wireless dynamic relay networks, where each relay node (RN) is equipped with a single antenna. The type of situation arises, for example, when RNs employ decode-and-forward relaying and cyclic redundancy check codes, only a priori unknown part of nodes can successfully decode and retransmit the message, i.e., the cooperating RNs are not aware of their partners. Many schemes have been proposed to construct distributed nodes as a virtual multiantenna node using MIMO to get spatial multiplexing gains [1], [2]. However, if these centralized distributed MIMO (CD-MIMO) schemes are applied to the above scenario, they all need to first identify which RNs are active, and then centralize allocate stream and pilot between them. The overhead of these CD-MIMO schemes will reduce the multiplexing gain.

Recently, a randomized space-time coding (RSTC) scheme has been proposed for cooperation among RNs to provide spatial diversity gains without utilizing the centralized control information [3]. In [4], an optimized distributed STBC scheme has been proposed where each node in the network is assigned a unique signature vector (SV). It achieves a better performance than the RSTC scheme by employing a gradient-based algorithm for the SV optimization. However, the spectrum efficiency of these schemes is not high because only a single stream can be sent to the destination node.

In this letter, we extend the signature vector idea to the distributed MIMO with multistream to increase the spectrum efficiency and eliminate the centralized control information. We analyze the constraints of the proposed scheme, and derive an optimization criterion for the SVs based on the maximization of the channel capacity of the relay network. To solve this optimization problem, a gradient-based algorithm is provided.

Notation: $\mathbb{E} (\cdot)$, $(\cdot)^H$, $\| \cdot \|$ and $\cdot > 1\cdot$ denote statistical expectation, Hermitian transposition, the norm of a vector, and the cardinality of a set, respectively. In addition, $\det (\cdot)$, $\tr (\cdot)$, $\rank (\cdot)$, and $\| \cdot \|_F$ refer to the determinant, trace, rank, and Frobenius norm of a matrix, respectively. Finally, $\mathbf{I}_X$ is an $X \times X$ identity matrix.

II. SYSTEM MODEL

In this work, we consider a two-hop system model with $N$ cooperating RNs. Each RN is assigned a number $n, n \in \mathcal{N}, \mathcal{N} \equiv \{1, 2, ..., N\}$ and a SV. The set of all SVs is denoted by $\mathcal{W}$. Out of the $N$ nodes, only a priori unknown subset of nodes $S \subseteq \mathcal{N}$ with size $N_S \equiv |S|$ can decode and relay the message successfully. Those nodes are called active RNs in this letter. For example, in the two-hop scenario considered in Fig. 1, in the first stage, the source node (SN) broadcasts the message to the RNs. In the second stage, only the active RNs send message to the destination node (DN).

In the following, we’ll discuss how to send multistream while avoiding the stream and pilot allocation between active RNs by introducing SVs. Every active RN generates $K$ streams by a serial-to-parallel converter. Then the signal can be written as a vector:

$$s_{MIMO}^i = (s_{MIMO_1}^i, s_{MIMO_2}^i, \ldots, s_{MIMO_K}^i),$$

where $i$ represents the $i$th modulated symbol in each frame. By introducing the SV, the $i$th symbol transmitted at the $n$th active RN is given as follows:

$$s_{r_n}^i = s_{MIMO}^i w_n,$$

where the SV $w_n$ is a column vector with $K$ elements.

Since all RNs receive the same message, all $N_S$ active RNs have the same $s_{MIMO}^i$. Signals transmitted from all active RNs can be represented as a vector:

$$s_r^i = s_{MIMO}^i (w_1, w_2, \ldots, w_{N_S}) = s_{MIMO}^i W_S,$$

where $W_S$ is the matrix of all SVs.
where \( W_S \) represents a weight matrix which is composed of all active RNs' SVs. Thus \( K \) streams can be transmitted to the DN in one time slot without stream allocation between active RNs.

Let us assume that the channels \( H_S \) between the \( N_S \) RNs and the DN are flat, then the \( i \)th received signal at the DN is given as follows:

\[
    r[i] = s_{MIMO}[i]W_SH_S + n[i] = s_{MIMO}[i]H_{eq} + n[i],
\]

where \( n[i] \) is a complex Gaussian random variable with mean zero and variance \( N_0 \). \( H_{eq} \) is the equivalent channel which can be estimated if all active RNs simultaneously transmit the same orthogonal training sequences. Thus the pilot allocation between active RNs is avoided. Assuming perfect channel estimation, the signals after minimum mean square error (MMSE) de-mapping are represented as follows:

\[
    y[i] = r[i]H_{eq}H_{eq}^H + N_0I_K)^{-1}.
\]

Finally, the estimates of the transmitted symbols \( s_{MIMO}[i] \) can be ML detected from the signals \( y[i] \).

III. OPTIMIZATION OF THE SIGNATURE VECTORS

In this section, we determine the constraints of the proposed scheme and derive the proposed optimization criterion.

A. Constraints of the Design

1) Constraint of the Stream Number \( K \): From Eq. (5), the rank of \( H_{eq} \) must not be less than \( K \) in order to detect the \( K \) streams. The rank of \( H_{eq} \) can be described as follows:

\[
    \text{rank}(H_{eq}) = \min(\text{rank}(W_S H_S)), \text{rank}(H_S)),
\]

if each element of \( H_S \) and \( W_S \) is independent, then

\[
    \text{rank}(H_{eq}) = \min(K, N_S), \min(N_S, M) = \min(K, N_S, M).
\]

Thus the problem can be described as follows:

\[
    K \leq \min(K, N_S, M). \tag{8}
\]

The constraint of the stream number is that \( K \leq \min(M, N_S) \).

2) Constraint of the Signature Vectors: In general, total transmission power should be constant. From Eq. (3), average power of the signal \( s_r[i] \) transmitted from the active RNs is:

\[
    E_s = \varepsilon (s_r[i]s_r^H[i]) = \varepsilon (s_{MIMO}[i]W_S W_H^H s_{MIMO}[i]) = \varepsilon (\text{tr}(s_{MIMO}[i]W_S W_H^H s_{MIMO}[i])) = \text{tr}(W_H^H \varepsilon (s_{MIMO}[i]s_{MIMO}[i]) W_S).
\]

If each element of \( s_{MIMO}[i] \) is uncorrelated, then

\[
    \varepsilon (s_{MIMO}[i]s_{MIMO}[i]) = \frac{E_s}{K}I_K,
\]

thus the constraint of the weight matrix \( W_S \) is given as:

\[
    \text{tr}(W_S^H W_S) = |W_S|^2 = K. \tag{11}
\]

If the equal power allocation is employed in the active RNs, then the constraint of the SVs is that \( \|w_n\|^2 = K/N_S \).

B. Optimization Criterion

Since the SVs are one part of the equivalent channel, a natural optimization criterion for the set of SVs \( W \) is the maximization of the equivalent channel capacity. However, the hard problem is that how many and which RNs are active is not a priori known. To simplify it, we assume that \( |S| = N_a \) nodes are active and introduce the cost function \( G_S \equiv \text{det}(I_M + \gamma H_S^H W_S^H W_S H_S) \), where \( \gamma = \frac{P}{E_s} \). We define the optimum set of signature vectors as:

\[
    W_{opt} = \arg \max_S \{ \min_{|S| = N_a} \{ G_S \} \}, \tag{12}
\]

subject to \( \|w_n\|^2 = K/N_a, \quad 1 \leq n \leq N \), i.e., \( W_{opt} \) maximizes of the minimum channel capacity over all \( \binom{N_a}{N} \) possible sets \( S \). Therefore, the optimized SVs can be obtained, no matter which RNs are active. The impact of the difference between the actual number of active RNs \( N_S \) and the design parameter \( N_a \) will be discussed in the following section.

We note that \( G_S \) is a non-convex function of \( W_S \). Since \( G_S \) depends on \( \gamma \) and \( H_S \), in general the optimum set \( W_{opt} \) will depend on the SNR and \( H_S \). To simplify the cost function, we assume that \( W_S \) and \( H_S \) have full rank, \( K \leq \min(M, N_S) \) and \( \gamma \to \infty \), then \( G_S \) can be expressed as [5]:

\[
    G_S = \text{det}(I_M + \gamma H_S^H W_S^H W_S H_S) \\
    \approx \text{det}(W_S W_S^H) \cdot \prod_{i=1}^{\text{rank}(A_S)} \lambda_i(A_S), \tag{14}
\]

where \( \lambda_i(A_S) \) denote the non-zero eigenvalues of matrix \( A_S \equiv \gamma H_S^H H_S \). Therefore, for high SNRs, the optimum set \( W_{opt} \) is independent from the actual channel information and only depends on \( W_S \). Then the optimization of the set of SVs can be performed off-line. We may replace \( G_S \) in Eq. (12) by \( \text{det}(W_S W_S^H) \).

IV. DESIGN OF THE OPTIMIZED SIGNATURE VECTORS

Due to its non-linear structure, it is in general not possible to find a closed-form solution to the optimization problem in Eqs. (12) and (13). Therefore, we propose a gradient algorithm (GA) for optimizing the SVs and we refer to the corresponding set as \( W_{grad} \). Assuming that \( W_S W_S^H \) is not singular, the gradient of \( G_S \) with respect to \( W_S \) is given by [6]

\[
    \frac{\partial G_S}{\partial W_S} = \text{det}(W_S W_S^H) \cdot (W_S W_S^H)^{-1} \cdot W_S. \tag{15}
\]

The proposed GA can be summarized as follows:

1) Initialization: Set iteration number \( j \) to \( j = 0 \), and generate a random initial set of complex vectors \( w_n[j], 1 \leq n \leq N \), with \( \|w_n[j]\|^2 = K/N_a \).

2) Find worst set \( S_{min}[j] \):

\[
    S_{min}[j] = \arg \min_{|S| = N_a} \{ G_S[j] \}. \tag{16}
\]

3) Adaptation: \( X_{temp} \equiv W_{S_{min}[j]} W_S^H S_{min}[j] + \beta I_K \).
Since the optimization complexity increases with increasing number of active nodes, the actual number of active RNs is not very important.

Figure 2 illustrates the average BER of different schemes for $N_S = 2$, 3 and 5 active RNs while $N_a = 2$, number of potentially cooperating nodes $N = 10$, number of antennas in the DN $M = 2$, and stream number $K = 2$ is assumed. From this figure, the average BER of the OD-MIMO schemes gradually approaches that of the CD-MIMO scheme as the number of active RNs increases. For example, at high SNR, the performance gap between two schemes is 4, 1.5 and 0.6 dB when the number of active RNs is 2, 3 and 5, respectively. This fact agrees with the feature of the proposed OD-MIMO scheme discussed at the end of Section IV. We also note that the OD-MIMO scheme achieves better performance than the RD-MIMO scheme. This fact demonstrates the effectiveness of the gradient-based optimization algorithm.

VI. CONCLUSION

In this letter, we have introduced OD-MIMO for decentralized transmission in cooperative relay networks. Based on the maximization of the channel capacity of the relay network, we have derived a criterion for optimization of the SVs used in OD-MIMO. Furthermore, we have developed a gradient algorithm for efficient SV design. Simulation results have confirmed the excellent performance of the proposed OD-MIMO scheme and shown that the performance loss compared to CD-MIMO gradually becomes smaller as the active RN number increase. Therefore, the OD-MIMO scheme is highly attractive for applications such as ad hoc and sensor networks since the active RN do not have to know which other nodes are active.

REFERENCES