Physical Communication 29 (2018) 156–163

Contents lists available at ScienceDirect

Physical Communication

journal homepage: www.elsevier.com/locate/phycom

Full length article

Optimal selection of spatial dimensions of signal subspace for relay constellation decoding

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ARTICLE INFO

Article history:
Received 20 January 2018
Received in revised form 12 April 2018
Accepted 24 May 2018
Available online 26 May 2018

Keywords:
Signal space alignment
Network coding
Multi-way relay
Signal subspace

ABSTRACT

The dimension of the right null space is only one for traditional signal space alignment with the minimum configuration of antennas. Then, the direction of a pair of alignment signal space is fixed and cannot be flexibly adjusted. Although the different alignment directions are mutually independent to facilitate relay decoding, the minimum Euclidean distance between modulated signals code words is small, which affects the decoding accuracy. In this paper, we design a novel alignment signal transmission scheme using degrees of freedom of null space generated by redundant antennas. The scheme selects the mutually orthogonal space dimension in the redundant null space as the signal alignment direction. It optimizes the minimum Euclidean distance in the system by maximizing the minimum constellation point distance. Simulation results show that the distances between the constellation points of different code symbols become significantly larger. The larger constellation distance of different coded symbols can improve the decoding accuracy. By optimizing the distance between the minimum constellation points, the transmission performance of each link is balanced and the whole system performance is improved.

1. Introduction

One of the core problems facing modern communications is the contradiction between the ever-increasing demands of subscribers and limited spectrum resources. In order to solve this contradiction, many resource allocation technologies have been proposed, such as TDMA, FDMA, CDMA and SDMA. These technologies are at the expense of one-dimensional resources so that multiple users simultaneously communicate. In order to improve the utilization of radio resources, co-channel transmission has been proposed in recent years. This will inevitably lead to serious interference with each other and reduce system performance. Therefore, one of the most important extend directions is to study the management and utilization of interference to obtain higher network performance. Signal space alignment (SSA) is a recent concept that aligns the desired signal component into a smaller subspace to increase data transmission efficiency [1,2]. The core idea of network coding (NC) is that processing information of all nodes in the network received on multiple channels is linearly or non-linearly. This paper specifically refers to the wireless signal superimposed electromagnetic waves at the relay. The idea is then further developed to obtain network coding information [3,4] in two-way relay channel (TWRC). The transmitter wants to deliver multiple packets to each user through a shared link. Each user has its own prior knowledge of a subset of the package. The transmitter sends a signal and all users receive it without noise. The target of index coding (IC) [5,6] is to design the transmission code to minimize the amount of required transmission.

Each node in the cooperative communication system based on relay achieves message exchange between nodes through relay forwarding. We can not only use cooperative communication to improve the system's bandwidth utilization, but also take advantage of distributed spatial diversity to combat the deep signal fading. In a multiple-way relay channel (MWRC), multi-user exchange information through the relay. This technology has gained wide attention among scholars. For the purpose of improving the efficiency of transmission network, a lot of algorithms have been studied to address the interference caused by multiple node transmissions. The physical-layer network coding (PNC) can reduce the signal interaction between different nodes and improve wireless network throughput. The design of relay transmission based PNC has studied several data shared channel transmission models, including two-way relay transmission [7], multi-way relay transmission [8,9], clustered relay transmission [10,11] and heterogeneous networks relay transmission [12].

Most of the existing research results focus on deducing the degree of freedom (DoF) of the system, that is, how to improve the slope of the curve under the signal-to-noise ratio (SNR). One of the main challenges is how to jointly design sending and receiving precoding vectors to improve system transmission efficiency. When antennas configuration is implemented according to the minimum

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https://doi.org/10.1016/j.phycom.2018.05.009
1874-4907/

constraint achieved by SSA, all the dimensions of signal space at the relay are used to transmit the aligned signals. Since the user node does not have sufficient DoF, the design of the transmitting precoding vector cannot be optimized. The precoding design has greater flexibility when nodes have more antennas. Using the redundant signal space, the authors [12] design a heterogeneous network transmission scheme, which transmits both private signals and common signals. Many authors [13,14] have also proposed various schemes for improving system performance using beamforming vector optimization. The existing scheme used redundant antennas to generate different beamforming vectors, and the set of precoding vectors that can provide the orthogonal alignment directions. However, the scheme only randomly selected a set of orthogonal alignment directions in the redundant signal null space. Although this scheme simplifies the ML decoding complexity and improves the decoding reliability, it is not the optimal solution.

In this paper, the spatial alignment vector with orthogonality is designed in the redundant null space, and the decoding algorithm is simplified by projecting the constellation point to the alignment axis. By using the optimization criterion with maximizing the minimum constellation points' distance, the constellation point decoding ability can be balanced to improve the whole performance of the communication system. In the next section, we descript the traditional signal space alignment K-user MIMO Y channel. We explain why the BER performance of traditional signal space alignment is not very good in Section 3. In this section, we also try to use orthogonal projection technology to achieve multiple alignment directions orthogonal to each other in the signal space. Then, we introduce our strategy by controlling the optimal minimum constellation points distance between the aligned signals at the relay and discuss the optimization strategy. Simulation results show that the method greatly enhances the accuracy of decoding in Section 4. Finally, we summarize the main ideas and conclusions of the full text in Section 5.

2. System model

The relay transmission system shown in Fig. 1 is composed of K users and one relay. In this K-user MIMO Y relay channel, each user sends $K-1$ independent messages $W_{j,i}$ with $j \in \{1,2,\ldots,K\}/\{i\}$ to all other users with M antennas while receiving messages $\hat{W}_{i,j}$ with $j \in \{1,2,\ldots,K\}/\{i\}$ from all other users. There is no direct communication link between users. The information interaction is achieved by a common relay.

The first transmission phase is called multiple access channel (MAC) phase. Original message $W_{j,i}$ of user i uses its precoding vector $\mathbf{v}_{j,i}$ to send its signal $s_{j,i}$. The signal at the transmitting antenna is: $\mathbf{x}_i = \sum_{j=1,j\neq i}^{K}\mathbf{v}_{j,i}s_{j,i}$ for $i = 1,2,\ldots,K$. Therefore, the received signals of relay are obtained by:

$$\mathbf{y}^r = \sum_{i=1}^{K}\mathbf{H}_{r,i}\mathbf{x}_i + \mathbf{n}_r = \sum_{i=1}^{K}\mathbf{H}_{r,i}\sum_{j=1,j\neq i}^{K}\mathbf{v}_{j,i}s_{j,i} + \mathbf{n}_r \tag{1}$$

where user i transmits signal to relay through the uplink channel state information matrix $\mathbf{H}_{r,i}$, and $\mathbf{n}_r$ is additive white Gaussian noise (AWGN) vector with independent and identically distributed (i.i.d.). The relay decodes the received signals and constructs the PNC signals $\mathbf{x}_r$.

In the broadcasting (BC) phase, all users receive broadcast signals $\mathbf{x}_r$ from the relay. Then, the receipt signal at user j is:

$$\mathbf{y}_j = \sum_{j=1}^{K}\mathbf{H}_{j,r}\mathbf{x}_r + \mathbf{n}_j \tag{2}$$

where $\mathbf{H}_{j,r}$ is the downlink channel state information matrix from the relay to user j, and $\mathbf{n}_j$ is additive Gaussian noise vector with i.i.d. The CSI is assumed to be i i.i.d., and satisfies the semi static Rayleigh fading.

Precoding vectors of user nodes are designed using the traditional signal space alignment scheme. The core problem of SSA of network coded signals is to design the precoding vectors $\mathbf{v}_{j,i}$ and $\mathbf{v}_{i,j}$ so that these uplink channel $\mathbf{H}_{r,i}\mathbf{v}_{j,i}$ and $\mathbf{H}_{r,j}\mathbf{v}_{i,j}$ are aligned at the relay. i.e., $span\left(\mathbf{H}_{r,i}\mathbf{v}_{j,i}\right) = span\left(\mathbf{H}_{r,j}\mathbf{v}_{i,j}\right)$. It reduces the number of independent streams received by the relay and is easy to decode. It means that the intersection subspace of two matrices is equivalent. In order to design the sending precoding vectors $\mathbf{v}_{j,i}$ and $\mathbf{v}_{i,j}$ to satisfy this condition, the precoding vectors $\mathbf{v}_{j,i}$ and $\mathbf{v}_{i,j}$ can be solved by the following formula.

$$\begin{bmatrix}\mathbf{I}_N & -\mathbf{H}_{r,i} & \mathbf{0}\\ \mathbf{I}_N & \mathbf{0} & -\mathbf{H}_{r,j}\end{bmatrix}\begin{bmatrix}\mathbf{u}_{ij}\\ \mathbf{v}_{j,i}\\ \mathbf{v}_{i,j}\end{bmatrix} = \mathbf{0} \tag{3}$$

where $\mathbf{u}_{ij}$ represents the basis vector of the alignment direction between user i and user j.

If $N = \frac{K(K-1)}{2}$, $M \geq K-1$ and $2M \geq N+1$ are satisfied, since the null space rank of the matrix in Eq. (3) is greater than or equal to 1, the solution of the signal space alignment solution exist. Then the SSA-NC system achieves DoF of $K(K-1)$ [1].

3. Optimization of relay decoding algorithm

3.1. Performance loss analysis of presence algorithms

The present achievements of research show that the received signal in (1) for relay is rewritten as

$$\mathbf{y}^r = \sum_{i=1}^{K}\mathbf{H}_{r,i}\mathbf{x}_i + \mathbf{n}_r = \begin{bmatrix}\mathbf{u}_{12} & \mathbf{u}_{13} & \cdots & \mathbf{u}_{(K-1)K}\end{bmatrix}\begin{bmatrix}s_{1,2}+s_{2,1}\\ s_{1,3}+s_{3,1}\\ \vdots\\ s_{(K-1),K}+s_{K,(K-1)}\end{bmatrix} + \mathbf{n}_r = \mathbf{U}\mathbf{s} + \mathbf{n}_r \tag{4}$$

where $\mathbf{s} = \left[s_{12} \quad s_{13} \quad \cdots \quad s_{(K-1)K}\right]^T$, and $s_{ij} = s_{i,j} + s_{j,i}, i < j$. For the sake of facilitate the description, we define $\left(1,2,3,\ldots,\frac{(K-1)\times K}{2}-2,\frac{(K-1)\times K}{2}-1,\frac{(K-1)\times K}{2}\right)$ which represents the arrangement of the user pairs sequence $(12, 13, 14, \ldots, (K-2)(K-1), (K-2)K, (K-1)K)$, this is, $\mathbf{u}_{12} \rightarrow \mathbf{u}_1$, $\mathbf{u}_{13} \rightarrow \mathbf{u}_2, \ldots, \mathbf{u}_{(K-1)K} \rightarrow \mathbf{u}_{K\times(K-1)/2}$. $\mathbf{u}_i$, $i \in \{1, K(K-1)/2\}$, is one of the N intersection basis vectors between $\mathbf{H}_{r,j}$ and $\mathbf{H}_{r,k}$. As the entries of $\mathbf{H}_{r,j}$ and $\mathbf{H}_{r,k}$ are generated by a continuous distribution, the probability that a basis vector in the intersection of any two channel matrices lies in the other intersection subspace spanned by the other two channel matrices is zero [12]. Therefore, all columns in the matrix are independent of each other and the size of $\mathbf{U}$ is $N \times \frac{K(K-1)}{2}$. This shows that any intersecting subspace $\mathbf{u}_i$ do not be located in the space formed by any two other intersecting subspaces, i.e. $\mathbf{u}_i \not\subset span\left(\mathbf{u}_j\right) \cup span\left(\mathbf{u}_k\right)$, for $i \neq j \neq k$ and $i,j,k \in \{1,2,\ldots,K(K-1)/2\}$.

Thus, the relay respectively obtains $K(K-1)/2$ NC messages for users to exchange information by using the PNC and Zero-Forcing (ZF) principle with $\mathbf{U}^{-1}\mathbf{y}^r = \mathbf{s} + \mathbf{U}^{-1}\mathbf{n}_r$. Each of them is consisted of the linear sum of two signals from different users, by mitigating inter signal space interference which is $\mathbf{u}_i^H\mathbf{u}_j = 0, i \neq j$. When BPSK is the modulation scheme for users, the decoded signals are ternary symbols at the relay. By applying the physical network coding modulation–demodulation mapping principle [3], the relay