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Interference alignment with iterative channel estimation for the reciprocal $M \times 2$ MIMO X Network

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ABSTRACT

This paper investigates an interference alignment (IA) scheme for a reciprocal multi-input multi-output (MIMO) $M \times 2$ X network where the knowledge of channel state information (CSI) is required. In our proposed approach, singular vectors, calculated from the singular value decomposition (SVD) of channel matrices, are used to compute precoding and zero-forcing (ZF) decoding matrices at transmitters and receivers, respectively. The orthogonality between precoding and decoding vectors that results from SVD is an advantage for realizing IA scheme because we can rely on an iterative scheme, known as iterative power method (IPM). The singular vectors resulting from the IPM approach converge to the actual ones after multiple iterations assuming a common "virtually static" channel between each link. However, due to the fast fading nature of the channel, computed precoding and ZF decoding vectors will be different from those resulting from the SVD of the actual channel. To this end, the IPM applied to get an estimate of precoding and ZF decoding vectors allows a better tracking of the time-varying channel. The bit error rate of the proposed scheme is evaluated by means of Monte Carlo simulations and compared with that achieved by a perfect CSI based system.

1. Introduction

In the context of distributed multiple-input multiple-output (MIMO) wireless networks, an interference channel reveals the communication scenario of transmitter–receiver pairs where each transmitter sends information for its intended receiver and, at the same time, creates interference to the other receivers [1–4]. The X network adds another feature to the interference channel in the sense that not only each transmitter has a message for its corresponding receiver, but it also has other independent messages for each of the other receivers, making other channel models, *i.e.* the Z channel and the interference channel, special cases of an X network [1,3,5]. In addition, the sum-rate offered by X channel is very large compared to the counterparts [3].

The capacity of wireless networks provides an important information about their use for different applications [6]. In a generalized form, the capacity of a network versus signal-to-noise ratio (SNR) can be approximated as

$$C(\text{SNR}) = d \cdot \log(\text{SNR}) + \mathcal{O}(\log(\text{SNR})),$$

where d defines the number of degrees of freedom (DoF). At high SNR values, DoF characterizes the capacity and, for this reason, it is also referred to as the pre-log capacity or multiplexing gain. Employing multiple antennas at each transmitter and each receiver allows to increase DoF further [1,2]. The characterization of DoF for a K-user X network, *i.e.*, for $M = N = K$, was given in [1] while that of an interference network was considered in [2].

Different approaches can be adopted to deal with interference arising in wireless networks [2,4,7,8]. Among these, interference alignment (IA) is a technique where interfering signals at each receiving node are confined into a subspace which does not contain that spanned by the signal of interest. The desired signal can therefore be recovered free from interference [2,7]. The fundamental concepts related to IA were introduced in [2], with emphasis on the temporal domain where a joint design of precoding matrices over multiple symbol extensions of the time-varying channels was proposed. Although [2] focused on the temporal dimension, extension to other dimensions, *i.e.*, frequency, space and codes, is straightforward.

A crucial assumption to achieve IA is that channel state information (CSI) is globally available at each transmitting node [2,9]. Global CSI knowledge allows us to write closed-form expressions for the precoding matrices. However, even if global knowledge is available, closed-form expressions for the precoding matrices can be written only when the number of users is less than three [2]. When a reciprocal MIMO interference channel is considered,

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knowledge of the global CSI is no longer necessary and the IA condition can be achieved by implementing a distributed approach, which only requires knowledge of the local CSI at each node [10]. When ideal CSI is available at the transmitters side, precoding matrices are designed based on the actual knowledge of the MIMO channel eigen structure.

Since ideal channel knowledge is available only in theory, in practical cases one must rely on the use of estimated CSI values. To acquire CSI, the system may resort to either centralized [11] or distributed [12] approaches. While the former relies on a central unit, which calculates CSI and the associated vectors, the latter uses external clocking for synchronization of all nodes for CSI acquisition in a distributed manner. Estimation algorithms are therefore required that involve an exchange of signals between transmitting and receiving nodes. System with fast fading channels must resort to frequent CSI estimation procedure, the absence of which results in CSI mismatch between the transmitter and the receiver, irrespective of the CSI feedback scheme. The presence of a CSI mismatch leads to uncorrelated beamforming and zero-forcing (ZF) decoding vectors used to implement IA, thus degrading the achievable performance [13]. One solution to tackle the effect of CSI mismatch is to adopt a blind transmission scheme that does not require an estimate of the CSI for its operation [14,15]. An IA scheme in which blind transmission is carried out with additional hardware is reported in [15]. However, without additional hardware, the performance of IA system under fast fading degrades rapidly [13].

In [16,17], a semi-blind, iterative algorithm is described where the eigen structure of a reciprocal MIMO link with one transmitter and one receiver is estimated by using a modified version of a so-called algebraic "iterative power method" [18]. The algorithm is implemented by exploiting the knowledge of the eigen structure associated with the singular value decomposition (SVD) of channel matrices that are locally available at each transmitting and receiving node. The resulting singular vectors after each iteration results from a common channel matrix that tend to ideal CSI [19] (we use the term correlation to explain this effect) and can be considered as an ideal method to perform IA in fast fading channel. One of the main characteristics of the proposed algorithm is that of lending itself to the application of iterative methods for estimating the eigen structure of the channel matrices. As a consequence, the proposed approach does not require the knowledge of exact channel matrices at the transmitter. Though several iterative schemes were proposed in point-to-point communications [16,17,20,21] and for interference channels [4,8], from the authors' knowledge, similar approaches were not considered in X networks. To this end, the application of such an iterative power method (IPM) is here proposed for the first time in the context of an IA scheme.

In this paper, we propose an IA scheme for an $M \times 2$ MIMO X network that exploits channel reciprocity. Reciprocity allows for implementation of an iterative scheme for estimating orthogonal singular vectors which further removes the burden to have perfect CSI for achieving IA. Beamforming vectors, defining the columns of the precoding matrices, are obtained from a linear combination of vectors resulting from the application of the IPM on channel matrices. The main idea is to choose a reference direction that is related to one of the left singular vectors of the channel matrix associated with one of the interfering signals. Then the alignment of the remaining interfering signal is achieved by computing the projections of its related channel matrices' left singular vectors along the reference direction. The weights resulting from such projections turn out to be the coefficients of the linear combination that is used to shape the beamforming vectors at the transmitters side. Hence, a dedicated feedback channel is required to send only the weights from the receivers to the transmitters, making the system semi-blind. With the beamforming and zero-forcing vectors of the $M \times 2$ MIMO X network defined, the proposed scheme is extended to $2 \times M$ MIMO X network by exploiting the reciprocity property. The proposed algorithm can be implemented both in the version with ideal channel state information and in that where the channel matrices' eigen structure is estimated by means of an iterative method. The proposed iterative method based IA scheme is compared with an IA scheme that uses ideal channel knowledge [1,2].

The paper is organized as follows. A review of conventional IA is provided in Section 2. In Section 3 a detailed explanation of the proposed IA scheme is given together with the iterative technique used to obtain the estimation of channels' eigen structure. Section 4 is devoted to numerical results while conclusions are drawn in Section 5.

Notation

The following notation is used in the paper: $(.)^T$, $(.)^*$ and $(.)^H$ correspond to transpose, complex conjugate and transpose conjugate, respectively. $(.)^{-1}$ is used for inverse of matrix and $\|.\|$ denotes Euclidean norm. Vectors and matrices are represented by lower case and upper case boldface letters, respectively.

2. Interference alignment in X network

An X channel which is the simplest model of an X network, with 2 transmitters sending separate symbols to 2 receivers is considered here (*i.e.*, $M = N = 2$). Later we generalize our scheme to $M \times 2$ or $2 \times N$ X networks.

2.1. IA in two-user MIMO X channel

The diagram of the considered two-user MIMO X channel is shown in Fig. 1. Both the transmitters and receivers are equipped with A antennas. The $A \times 1$ received signal vectors for user 1 and user 2 are,

$$\mathbf{y}_1 = \mathbf{H}_{11}\mathbf{x}_1 + \mathbf{H}_{12}\mathbf{x}_2 + \mathbf{n}_1 \tag{1}$$

and

$$\mathbf{y}_2 = \mathbf{H}_{21}\mathbf{x}_1 + \mathbf{H}_{22}\mathbf{x}_2 + \mathbf{n}_2, \tag{2}$$

respectively, where $\mathbf{x}_i$ is the $A \times 1$ signal vector transmitted by user i, $\mathbf{H}_{ji}$ is an $A \times A$ channel matrix between transmitter i and receiver j, with $i, j \in \{1, 2\}$, and $\mathbf{n}_j$ is an $A \times 1$ vector of independent and identically distributed (i.i.d) complex Gaussian random variables with zero mean and variance σ_n^2. Each transmitter is intended to transmit independent messages to each of the receivers separately.

The lower and upper bound of achievable DoF for an X-channel are [1],

$$\frac{MNA}{M + N - 1/A} \le DoF \le \frac{MNA}{M + N - 1}. \tag{3}$$

The number of antennas at each node is chosen in such a way that the DoF is an integer value, *i.e*, $A = M + N - 1$. For the two-user X channel we choose $A = 3$ for achieving the desired, integer DoF upperbound of 4 .

The two transmitted vectors are given by

$$\mathbf{x}_1 = \mathbf{b}_{11}x_{11} + \mathbf{b}_{21}x_{21} \tag{4}$$

and

$$\mathbf{x}_2 = \mathbf{b}_{12}x_{12} + \mathbf{b}_{22}x_{22}, \tag{5}$$

where x_{ji} is the message to be transmitted from transmitter i to receiver j and $\mathbf{b}_{ji}$ is the beamforming vector associated with x_{ji}. By substituting (4) and (5) in (1) and (2), respectively, we get

$$\mathbf{y}_1 = \mathbf{H}_{11}\mathbf{b}_{11}x_{11} + \mathbf{H}_{11}\mathbf{b}_{21}x_{21} + \mathbf{H}_{12}\mathbf{b}_{12}x_{12} + \mathbf{H}_{12}\mathbf{b}_{22}x_{22} + \mathbf{n}_1$$