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# Efficient beamforming method for downlink MU-MIMO broadcast channels

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ABSTRACT

The sum rate maximization in multiuser MIMO broadcast channels is investigated in this paper. Due to the high computational complexity of non-linear dirty paper coding (DPC), zero-forcing dirty paper coding (ZF-DPC) is proposed as an alternative suboptimal approach. However, traditional ZF-DPC method requires that the number of total receive antennas is less than or equal to the number of transmit antennas. In this paper, we consider the scenario where the sum number of receive antennas may be more than the number of transmit antennas. It is shown that the optimal data stream allocation needs exhaustive search over all possibilities, and the complexity is significantly high. We propose a greedy transmit data allocation scheme that allocates one data stream at each step, the corresponding transmit beamforming vector and receive combining vector are designed to avoid interfering with the previous allocated data streams, and the pre-equalization Tomlinson–Harashima Precoder (THP) technique is adopted to pre-cancel the non-causally known interference caused by the previous allocated data streams. The proposed method is computationally efficient thanks to the low complexity. Simulation results show that this novel method outperforms the methods in the literature.



## 1. Introduction

In a downlink multiuser multiple-input multiple-output (MU-MIMO) communication system, a base station with multiple antennas transmits data streams to multiple users, each user is equipped with multiple antennas. It is shown that dirty paper coding (DPC) achieves the sum capacity of this system [1,2]. However, the optimal transmit covariance matrix in DPC is difficult to obtain due to the non-concave optimization problem [2]. To avoid this complex DPC processing, linear processing solutions, such as zero-forcing beamforming (ZFBF) [3] and block diagonalization (BD) [4] techniques are proposed. It is shown that the sum rates of these zero-forcing methods are close to the sum capacity, and they are easy to implement. However, such simple zero-forcing approaches suffer from noise enhancement problem. Moreover, the application scenarios are limited to the situations where the total number of receive antennas is not more than the number of transmit antennas [5].

Another promising approach named zero-forcing DPC (ZF-DPC) [6] is a suboptimal but an intuitive way to achieve DPC by triangularizing the channel. The non-linear ZF-DPC method offers improved sum rate compared with linear beamformings (such as ZFBF and BD). However, ZF-DPC method only supports one single receive antenna for each user. In [7], a successive zero-forcing DPC (SZF-DPC) is proposed which extends the original ZF-DPC method to the scenario where each user can be equipped with multiple receive antennas. However, the total number of receive antennas is still restricted by the number of transmit antennas, and the user order also affects the achievable throughput substantially. In [8], several user selection algorithms are proposed for SZF-DPC strategy. In [9], receive combining technique is adopted, which improves the sum rate and the bit error rate (BER) performance. In [10] and [11], receive combining technique is introduced to ZF-DPC method by taking advantage of the duality between the downlink MU-MIMO broadcast channels and the corresponding virtual uplink multiple access channels. However, this iterative method has high computational complexity when the number of users is large.

Zero-forcing successive allocation (ZF-SA) method proposed in [12] finds transmit beamforming and receive combining vectors of one data stream at each step for the user who can bring the largest increase of the throughput. This technique is very attractive since it does not impose any constraint on the number of receive antennas and the number of users, the interference can also be removed completely. However, all the information contained in MU-MIMO

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broadcast channels is not fully exploited in ZF-SA method since the entire interference is eliminated only by transmit beamforming and receive combining vectors. The performance gap between DPC and ZF-SA method is still significant.

The pre-equalization Tomlinson–Harashima Precoder (THP) technique, proposed in [13] and [14], aims to pre-subtract the non-causally known interference at the transmitter. THP is initially proposed for single-input single-output channels in the presence of inter-symbol interference (ISI), and it is extended to MU-MIMO broadcast channels in [15]. Several different criteria are proposed using THP including zero-forcing (ZF) [15] and minimum mean square error (MMSE) [16]. In [17], two practical THP implementation algorithms are proposed, and the comprehensive performance analysis is carried out in terms of the error covariance matrix, the sum-rate and the computational complexity. In [18] and [19], THP performance is investigated with imperfect channel state information (CSI) at the transmitter. The main idea of THP is that, the non-causally known interference produced by the previous precoded symbols can be pre-canceled before transmission at the transmitter, and the modulo operation can be adopted to ensure that transmit power does not exceed the power constraint. THP can also be used for implementing ZF-DPC method.

In this paper, we propose a novel successive allocation method under the assumption of perfect CSI at the base station. One data stream is assigned at each step to the user who brings the largest increase of the global throughput, the non-causally known interference is pre-subtracted through the pre-equalization THP technique before transmission, and the remaining interference is eliminated by the transmit beamforming and receive combining vectors. Note that the whole interference is removed completely only through beamforming vectors design in ZF-SA method [12], the degrees of freedom for choosing appropriate beamforming vectors in the proposed method are much larger compared with ZF-SA method, which results in improved sum rate gains. Compared with SZF-DPC method proposed in [7], receive combining vectors are introduced to further improve the sum rate, and the total number of receive antennas can be larger than that of transmit antennas in the proposed method.

The main contributions of this paper are summarized as follows.

- A new greedy data stream allocation method in multiuser MIMO broadcast channels is proposed. Since the pre-equalization THP technique is used to pre-subtract the non-causally known interference at the base station, compared with ZF-SA method in [12], the proposed method has a significant sum rate improvement.
- The proposed method can be considered as a practical implementation and general version of SZF-DPC method in [7]. SZF-DPC method only supports the case where the total number of receive antennas is not more than that of transmit antennas. In the proposed method, the receive combining technique is adopted, and the data streams are assigned to the users successively. The total number of receive antennas can be larger than that of transmit antennas.
- One pair of transmit beamforming and receive combining vectors are determined at each step, which is computational efficient, and easy to implement.

The rest of the paper is organized as follows. Section 2 presents MU-MIMO broadcast channels and DPC strategy, then overviews ZF-DPC, SZF-DPC and ZF-SA methods. In Section 3, we first describe the proposed beamforming method, then the pre-equalization THP technique is introduced. In Section 4, the computational complexity of the proposed method is analyzed, and compared to that of ZF-SA method. Numerical simulation results are provided in Section 5, followed by concluding remarks in Section 6.

*Notation*: Standard notations are used in this paper. Bold lower case and upper case letters describe vectors and matrices, respectively; $\boldsymbol{A}^{\dagger}$, $\boldsymbol{A}^{H}$, and $\boldsymbol{A}^{T}$ represent pseudo inverse, Hermitian transpose and transpose of matrix $\boldsymbol{A}$, respectively; diag( $\boldsymbol{A}$) and tr( $\boldsymbol{A}$) denote a vector containing the diagonal elements and the trace of $\boldsymbol{A}$, respectively; $|\boldsymbol{A}|$ and $\boldsymbol{A}_{i,j}$ are the determinant and the element in row $i$ and column $j$ of $\boldsymbol{A}$, respectively; $\boldsymbol{I}_i$ is the $i \times i$ identity matrix; $\boldsymbol{0}$ is the zero vector in which every element is zero.

## 2. System model and methods in the literature

Consider the downlink MU-MIMO broadcast channels with $K$ users, where a base station is equipped with $N_t$ transmit antennas and transmits $\sum_k L_k = L$ data streams to the users, each user has $N_{r,k}$ receive antennas and receives $L_k$ data streams. Since the channel gains vary with different users [5,12], an appropriate $L_k$ $(0 \le L_k \le N_{r,k})$ for the $k$th $(\forall k)$ user has to be found to maximize the global throughput. In this paper, we propose a novel data stream allocation and beamforming design algorithm. The proposed method assigns a number of data streams for each user and the corresponding transmit beamforming and receive combining vectors are designed to optimize the global throughput under the total transmit power constraint $P_T$.

In the downlink transmission, the received signal $\boldsymbol{y}_k \in \mathbb{C}^{L_k \times 1}$ by the $k$th user after the receive combining filter is

$$\begin{aligned}\boldsymbol{y}_k = \;& \boldsymbol{U}_k^H \boldsymbol{H}_k \boldsymbol{V}_k \sqrt{\boldsymbol{P}_k} \boldsymbol{x}_k \\ & + \boldsymbol{U}_k^H \boldsymbol{H}_k \left( \sum_{l=1, l \neq k}^{K} \boldsymbol{V}_l \sqrt{\boldsymbol{P}_l} \boldsymbol{x}_l \right) + \boldsymbol{U}_k^H \boldsymbol{n}_k \quad (1 \le k \le K)\end{aligned} \tag{1}$$

where $\boldsymbol{H}_k \in \mathbb{C}^{N_{r,k} \times N_t}$ denotes the channel between the transmitter and the $k$th user; $\boldsymbol{x}_k \in \mathbb{C}^{L_k \times 1}$ is the transmit vector of the $k$th user and satisfies $\mathbb{E}\{\boldsymbol{x}_k \boldsymbol{x}_k^H\} = \boldsymbol{I}_{L_k}$; $\boldsymbol{V}_k \in \mathbb{C}^{N_t \times L_k}$ denotes the transmit beamforming matrix with normalized columns $\| \boldsymbol{v}_{l_k} \| = 1$ $(1 \le l_k \le L_k)$; $\boldsymbol{U}_k \in \mathbb{C}^{N_{r,k} \times L_k}$ is the receive combining matrix with normalized columns $\| \boldsymbol{u}_{l_k} \| = 1$ $(1 \le l_k \le L_k)$; $\boldsymbol{P}_k$ is a diagonal matrix and $\text{diag}(\boldsymbol{P}_k) \in \mathbb{R}_+^{L_k \times 1}$ represents the assigned power for the data streams of the $k$th user; $\boldsymbol{n}_k \backsim \mathcal{CN}(0, \sigma^2 \boldsymbol{I}_{N_{r,k}})$ is the additive zero-mean complex white Gaussian noise (AWGN) vector with covariance matrix $\sigma^2 \boldsymbol{I}_{N_{r,k}}$ observed at the $k$th user. The rate of the $k$th user over MU-MIMO broadcast channels can be presented as [12]

$$R_k = \log \frac{|\sigma^2 \boldsymbol{I}_{N_{r,k}} + \sum_{j=1}^{K} \boldsymbol{U}_k^H \boldsymbol{H}_k \boldsymbol{V}_j \boldsymbol{P}_j \boldsymbol{V}_j^H \boldsymbol{H}_k^H \boldsymbol{U}_k|}{|\sigma^2 \boldsymbol{I}_{N_{r,k}} + \sum_{\substack{j=1 \\ j \neq k}}^{K} \boldsymbol{U}_k^H \boldsymbol{H}_k \boldsymbol{V}_j \boldsymbol{P}_j \boldsymbol{V}_j^H \boldsymbol{H}_k^H \boldsymbol{U}_k|} \tag{2}$$

In (2), $\boldsymbol{P}_k$ is restricted by the total transmit power $P_T$ at the base station, i.e., $\sum_{k=1}^{K} \text{tr}(\boldsymbol{P}_k) = P_T$.

Under a natural user order, the base station first finds the transmit beamforming vector for the first user, then when the base station chooses the transmit beamforming vector for the second user, the non-causal interference produced by the first user is known.

In [20], the case where an additive white Gaussian noise channel corrupted by an interference known at the transmitter but unknown at the receiver is modeled as

$$Y = X + S + Z \tag{3}$$

where $X$ and $Y$ are the desired and received signals, respectively, $S$ is the non-causally known interference at the transmitter, and $Z$ is the unknown Gaussian noise. [20] shows that the capacity of this channel under the transmit power constraint is the same as if $S$ did not exist. If this DPC strategy is used, in which the interference produced by the previous coded users can be pre-canceled