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Zero-forcing DPC beamforming design for multiuser MIMO broadcast channels

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ABSTRACT

The sum rate maximization in multiuser MIMO broadcast channels is investigated in this paper. We first propose an approach under a total power constraint. Compared with the most related methods in the literature, the proposed method can be easily adapted to a more realistic per-antenna power constraint. Since the power of each antenna is limited individually by the linearity of its power amplifier in practice, the per-antenna power constraint is more practical. Secondly, we propose a novel beamforming method under the per-antenna power constraint, a better sum rate performance is achieved compared with the methods in the literature. Moreover, the proposed method works even if the number of total receive antennas is larger than that of transmit antennas.

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 the systems [1] and [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 (ZF) [3] and block diagonalization (BD) [4] techniques are proposed. In [5] and [6], ZF-DPC method and successive BD-DPC (SBD-DPC) method are proposed respectively to further improve the global throughput by adopting DPC principle. Successive allocation DPC (SA-DPC) method proposed in [7] finds the transmit beamforming and receive combining vectors of one data stream at each step for the user who brings the largest throughput increase. This technique is very attractive since it does not impose any constraint on the number of receive antennas and that of users, the interference can also be removed completely. It is shown that the sum rates offered by these methods are close to the sum capacity, and they are easy to implement. But in these methods, the transmit beamforming vectors are designed under the assumption of a total power constraint. Moreover, the application scenarios of the methods mentioned above (except SA-DPC method) are limited to the situations where the number of total receive antennas is not more than that of transmit antennas. In [8], the zero-forcing interference constraint is relaxed, and a low complexity linear beamforming design method is proposed to maximize the minimum rate.

In practice, the power amplifier of each antenna is limited individually by its linearity. Especially in an orthogonal frequency division multiplexing (OFDM) system, where the peak-to-average power ratio (PAPR) is high [9]. Thus, a power constraint imposed on each transmit

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antenna is more realistic. These practical problems should be considered for new transmit beamforming vectors design in MU-MIMO broadcast channels. In MIMO channels, equal gain precoding is substantially investigated in [9–11]. It not only overcomes the linearity problem of power amplifiers, but also reduces the feedback overhead, since only the phase information is feedbacked. In MU-MIMO broadcast channels, per-antenna power constraint beamforming techniques are studied in [12–15]. [12] and [13] investigate the scenario where each user is equipped with a single antenna under the constraint of zero-forcing precoding. In [14], this constraint is relaxed and DPC technique is used to further improve the performance. In [15], authors analyze the case where each user is equipped with multiple antennas via block diagonalization, and DPC is used under the assumption of a preset user order. However, the method proposed in [15] (PBD-DPC method) assigns to a certain user a number of data streams depending on the rank of its channel matrix. This is suboptimal if, for instance, some of the subchannels are weak. In that case, the contribution of these subchannels to the sum rate might be negligible while they may impose severe constraints on the subchannels of subsequent users [7].

In the first part of this paper, we propose an alternative approach to SA-DPC method under the total power constraint. In SA-DPC method, the transmit beamforming vector is selected as the right singular vector corresponding to the largest singular value of the projected channel matrix, it is shown that the per-antenna power constraint is hard to be introduced by this way. In the proposed method, instead of obtaining the transmit beamforming vector directly, we first find the subspace where the transmit beamforming vector should lie in, then the transmit beamforming vector is selected in the above subspace to optimize the global throughput. The proposed method performs identically as SA-DPC method when the total power constraint is imposed, even though they are derived from different ways. Moreover, it is shown that the proposed method can be easily modified to the more realistic per-antenna power constraint. In the second part of this paper, a beamforming method under the per-antenna power constraint is proposed. Since the optimal solution to the original problem is difficult to obtain, in the proposed method, this problem is divided into two classical optimization problems, which can be solved with existing standard algorithms. We alternatively solve each subproblem under the assumption that another one is fixed, the convergence can be achieved within a small number of iterations. Similar to SA-DPC method and the first proposed method, one data stream is allocated to the user who brings the largest global throughput increase at each step. The noncausally known interference is pre-subtracted through DPC technique before transmission, and the remaining interference is eliminated by the transmit beamforming and receive combining vectors.

The main contributions of this paper are summarized as follows.

- An alternative approach to SA-DPC method is proposed. SA-DPC method calculates the transmit beamforming vector directly. In the proposed method, we first find the subspace where the transmit beamforming vector should lie in, then the one that maximizes the global throughput is selected. It is shown that the proposed method can be easily adapted to the scenario where the per-antenna power constraint is imposed.
- A new greedy data stream allocation method in multiuser MIMO broadcast channels under the per-antenna power constraint is proposed. Since the spatial diversity in multiuser MIMO broadcast channels is fully exploited, compared with PBD-DPC method in [15], a better sum rate performance is achieved by the proposed method.
- In the proposed method, receive combining technique is adopted, and the data streams are assigned to users successively, compared with PBD-DPC method in [15], the number of total receive antennas may be larger than that of transmit antennas.

The rest of the paper is organized as follows. Section 2 presents MU-MIMO broadcast channels and DPC principle, then SA-DPC method and PBD-DPC method are reviewed in Section 3. In Section 4, we describe the proposed beamforming method under the total power constraint. The proposed method under the per-antenna power constraint is presented in Section 5. Numerical simulation results are provided in Section 6, followed by concluding remarks in Section 7.

Notation: Standard notations are used in this paper. Bold lower and upper letters describe vectors and matrices, respectively; $\boldsymbol{A}^H$ and $\boldsymbol{A}^T$ represent Hermitian transpose and transpose of matrix $\boldsymbol{A}$, respectively; diag ($\boldsymbol{A}$), rank ($\boldsymbol{A}$) and tr ($\boldsymbol{A}$) denote the vector containing the diagonal elements, the rank 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; $\boldsymbol{A} \geq 0$ indicates that $\boldsymbol{A}$ is positive semi-definite; $\boldsymbol{I}_i$ is the $i \times i$ identity matrix; $\|\boldsymbol{x}\|$ is the Euclidean norm of $\boldsymbol{x}$; $\boldsymbol{0}$ is the zero vector in which every element is zero.

2. System model and DPC principle

2.1. System model

Consider 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. The channel state information (CSI) is supposed to be perfectly known at the base station. Since the channel gains vary with different users [16,17], an optimal L_k $(0 \leq L_k \leq N_{r,k})$ for the kth $(\forall k)$ user should be found to maximize the global throughput. In this paper, we propose a novel beamforming design method under the total power constraint, then we adopt this method to the more realistic per-antenna power constraint case to optimize the global throughput.

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

$$\boldsymbol{y}_k = \boldsymbol{U}_k^H \boldsymbol{H}_k \boldsymbol{V}_k \boldsymbol{x}_k + \boldsymbol{U}_k^H \boldsymbol{H}_k \sum_{l=1, l \neq k}^{K} \boldsymbol{V}_l \boldsymbol{x}_l + \boldsymbol{U}_k^H \boldsymbol{n}_k \tag{1}$$

where $\boldsymbol{H}_k \in \mathbb{C}^{N_{r,k} \times N_t}$ denotes the channel between the transmitter and the kth user; $\boldsymbol{x}_k \in \mathbb{C}^{L_k \times 1}$ is the transmit