Centralised and Decentralised Precoding Framework in Multi User-Mimo Wireless Communication

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ABSTRACT

In this paper, we propose a dual-branch Tomlinson-Harashima precoding (DB-THP) scheme that employs transmit processing and ordering strategy in order to mitigate the interference in MU-MIMO systems. THP is a nonlinear pre-equalization technique employed at the transmitter. We have investigated the performance of two variations of THP structure according to the positions of the diagonal weighted filter, i.e., decentralized at the receiver and centralized at the transmitter. Simulations results indicate that the use of DB-THP based precoder structure in downlink multiuser multiple-input-multiple-output (MU-MIMO) systems perform better in comparison to other precoding techniques namely, the linear ZF-THP and Block Diagonalization (BD) in terms of bit error rate (BER) performance and system capacity. Furthermore, it is also shown that the performance of THP depends on the ordering of precoding symbols.

INTRODUCTION

Next-Generation wireless communication systems aim to support high data rate services with high spectral efficiency and large system capacity. In modern communications systems one of the main strategy used to achieve high spectral efficiency is the multiple input-multiple output (MIMO) technique. Multi-user (MU) MIMO systems have the potential to combine the high capacity achievable with MIMO processing with the benefits of space division multiple access (SDMA). In the MU MIMO scenario, a base station (BS) or an access point (AP) is equipped with multiple antennas and is simultaneously communicating with a group of users. Each of these users is also equipped with multiple antennas. In a MU scenario, capacity becomes a multidimensional region defined by the set of all rate vectors \( \mathbf{R} = (R_1, \ldots, R_K) \) simultaneously achievable by all users. When channel state information (CSI) is available at the transmit side, precoding techniques can be employed at the base station (BS) to mitigate the Multiuser Interference (MUI). Efficient power allocation for multiple antennas with the help of precoding technique results in improved capacity and quality of service in wireless communication networks.

The function of precoding is to suppress the interference brought about by the non-orthogonality among user’s channels. Various linear precoding schemes like zero forcing (ZF) (Spencer et al., 2004) and block Diagonalization (BD) (Choi and Murch, 2004) based precoding techniques have been proposed for MU-MIMO systems. In ZF precoding channel vectors of each user are projected onto the subspace that is orthogonal to that spanned by the channel vectors of all other users. However, this precoding technique requires a high average transmit power. As a generalization of ZF precoding, block Diagonalization (BD) based precoding algorithms suffer a loss in performance at low signal to noise ratios (SNRs) when the noise is the dominant factor (Spencer et al., 2004).

Another kind of precoding technique is a non-linear technique that includes Dirty paper coding (DPC). DPC is not suitable for practical use due to the requirement of infinitely long code words and very high transmit power. In comparison, motivated by the information-theoretic consideration proposed in (Choi and Murch, 2004), Tomlinson-Harashima non linear precoding (THP) achieves more system capacity. Though THP was introduced for the pre-equalization of ISI in SISO channels (Tomilson, 1971), it has been extended to MU-
MIMO downlink channels (Windpassinger et al., 2004), (Windpassinger et al., 2003). In general, there are two basic THP structures, according to the positions of the diagonal weighted filter – decentralised at the receivers (Windpassinger et al., 2004) or centralised at the transmitter (Windpassinger, 2004) which are denoted as dTHP and cTHP respectively.

This paper is structured as follows. Section 1 describes the system model and basics of THP techniques. Section 2 describes about the proposed methodology and the results and discussion is given in section 3. The last section gives the conclusion.

Related work:
As shown in Fig.1, consider a MU-MIMO downlink model with basic THP structures. It has $N_t$ transmit antennas at the base station and $N_r$ receive antennas at $k$th user terminal. With ‘K’ users in the system, the total receive antennas are $N_r = \sum N_k$. The total data streams transmitted is denoted by $S$. Based on the complete knowledge of CSI, there are three filters used to implement THP algorithms: the feedback filter $B$, the feed forward filter $F$ and the scaling matrix $G$. The feedback filter $B$ is used to successively cancel the interference caused by the previous streams from the current stream. The feed forward filter $F$ is used to enforce the spatial causality and implemented at the transmit side for MU-MIMO systems. The scaling filter $G$ contains the corresponding weighted coefficient for each stream. $G$ is employed at the receiver end in case of dTHP and at the transmit end in case of cTHP. The quantity $x$ is the combined transmit signal vector after the feedback operation and $\tilde{x}$ is the combined transmit signal vector after precoding.

\[ H = L \cdot Q \]

where $L$ is a lower triangular matrix and $Q$ is a unitary matrix. The feedback, feed forward and scaling filters for the THP algorithm can be obtained as,

\[
F = Q^H
\]

\[
G = \text{diag} \left[ l_{1,i}, l_{2,i}, \ldots, l_{s,i} \right]^{-1}
\]

\[
B^{(dTHP)} = G \cdot L
\]

\[
B^{(cTHP)} = L \cdot G
\]

where $l_{i,j}$ is the $i$th diagonal element of the matrix $L$. In Tomilson-Harashima precoding, the transmitted symbols $x_i$ are successively generated as

\[
x_i = s_i - \sum_{j=1}^{p_i} b_{i,j} x_j, \quad i = 1, \ldots, S
\]

where $s_i$ is the transmitted data and $b_{i,j}$ are the elements of matrix $B$ in row $i$ and column $j$. To reduce the amplitude of the channel symbol $x_i$ to the boundary of the modulation alphabet, a modulo operation $M(.)$ should be employed which is defined element-wise as

\[ M(x) = \text{mod}(x, M) \]
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\[ M(x_i) = x_i - \frac{\text{Re}(x_i)}{\tau} + \frac{1}{2} \tau - j \frac{\text{Im}(x_i)}{\tau} + \frac{1}{2} \tau, \]

where the value of \( \tau \) depends on the chosen modulation scheme. The modulo processing is equivalent to adding a vector \( d \) to the transmit data \( s \), such that the modified data is \( v = s + d \). Thus the received signal for dTHP and cTHP respectively can be expressed as,

\[ r^{(\text{dTHP})} = v + G n, \]
\[ r^{(\text{cTHP})} = v + \beta n \]

where the quantity \( n = [n_1^T, n_2^T, ..., n_J^T]^T \) is the Gaussian noise vector with i.i.d entries of zero mean and variance \( \sigma^2 \) and the factor \( \beta \) is used to impose the power constraint which is approximately obtained as,

\[ \beta = \frac{E[F G_i]}{E[s]} \approx \sqrt{\sum_{j=1}^{K} (1/|\mathbf{I}_j|)} \]

Where \( || \) denotes norm of a vector and \( E(.) \) denotes the mean value.

**Proposed Method:**

In this section, the interference of two basic structures of THP is analysed and it is shown that ordering of precoded symbols plays a significant role in mitigating the interference problem in both the cases. Based on this analysis, the structures of DB- dTHP and DB-cTHP are proposed and illustrated. Finally, the MMSE filters for both the schemes are derived based on an extended system model. The proposed system involves

A. Design of Transmit Patterns
B. Derivation of DB-MMSE-THP filters
C. Sum-Rate Performance Analysis

**A. Design of Transmit Patterns:**

The ordering of the precoded symbols plays an important role in the performance of THP systems. However in (Joham and Utschick, 2005), (Wübben et al., 2003), (Liu and Krzymień, 2008), (Fung et al., 2007), various ordering methods were developed for either SU-MIMO or MU-MIMO with single receive antenna. In this work, DB-THP structure which is suited for the users with multiple antennas is proposed based on two basic TTHP structures. The design of the ordering transmit patterns is done in two steps.

1. Ordering patterns between multiple users is obtained (i.e., \( T_u^{(1)} \) for \( i = 1, 2, ..., K \)).
2. Ordering patterns between multiple streams for \( i^{th} \) user is obtained (i.e., \( T_h^{(j)} \) where \( j \) denotes the different ordering states).

The major objective is to design effective and simple transmit patterns. Drawing upon previous design methods (Lamare and Sampaio-Neto, 2008) and considering the nature of distributed users in MU-MIMO scenarios, the design of transmit patterns is developed in three steps. In the first step, the different ordering pattern between multiple users is obtained as,

\[ T_u^{(1)} = I_K, \]
\[ T_u^{(i)} = \begin{bmatrix} I_p & 0_{p,K-p} \\ 0_{K-p,p} & \Pi_{K-p} \end{bmatrix}, \quad 2 \leq i \leq K \]

where \( p = (i - 2) \) and \( \Pi_{K-p} \) denotes the exchange matrix of size \((K - p) \times (K - p)\) with ones on the reverse diagonal. Next, the streams for each user are shuffled. The ordering patterns for \( i^{th} \) user equipped with \( N_i \) antennas is given by

\[ T_u^{(i)} = I_{N_i}, \]
\[ T_h^{(j)} = \begin{bmatrix} I_q & 0_{q,N_i-q} \\ 0_{N_i-q,q} & \Pi_{N_i-q} \end{bmatrix}, \quad 2 \leq j \leq J \]

where \( q = (j - 2) \) and \( J \) is the maximum number of ordering states.

Finally, the above two \( T \) matrices are combined and \( T^{(i)} \) is generated. The combining scheme is that for ordering pattern \( T_u^{(i)} \), the ordering state \( j \) is incremented by one while \( j \leq J \). Inside each \( (T_u^{(i)}, T_h^{(j)}) \) combining process, in order to put \( T_h^{(j)} \) in the right position, the row indices of the nonzero entries is located in \( T_u^{(i)} \). Then, the ordering pattern \( T_h^{(j)} \) is arranged to its corresponding nonzero element in the matrix \( T_u^{(i)} \) and preserve the original pattern.

In case if the users equipped with the same number of receive antennas, then the combining strategy is simply the Kronecker product between \( T_u^{(i)} \) and \( T_h^{(j)} \).
The equivalent channel matrix for a chosen transmit pattern is obtained as $H^{(l)} = T^{(l)} H$. Since the DB strategy employs diversity branches, the BER performance of the proposed DB-THP algorithms will stay the same or have a better performance than the conventional THP algorithms.

B. Derivation of DB-MMSE-THP filters:

It is known that MMSE based precoding algorithms is always better than the ZF based ones (Joham and Utschick, 2005). The filters for MMSE-cTHP (Joham and Utschick, 2005), results in high computational complexity since multiple matrix inverses are used. Orthogonality based filters for MMSE-dTHP were derived in (Liu and Krzymień, 2008). Based on the work proposed in (Keke et al., 2014) the feedback, feed forward and scaling filters of DB-MMSE-cTHP and DB-MMSE-dTHP from the extended matrix and their corresponding receive models are described.

The extended channel matrix $H$ of size $N_r \times (N_r + N_t)$ for DB-MMSE-TH precoding scheme is defined as,

$$H^{(l)} = [H^{(l)}, \sigma_n I_{N_t}]$$

On LQ decomposition, the extended channel matrix is given by,

$$H^{(l)} = L^{(l)} Q^{(l)} = L^{(l)} [Q_1^{(l)}, Q_2^{(l)}],$$

where $L^{(l)}$ is a $N_r \times N_r$ lower triangular matrix and $Q^{(l)}$ is a $N_r \times (N_r + N_t)$ matrix that can be partitioned to matrix $Q_1^{(l)}$ and $Q_2^{(l)}$. Thus the filters for the proposed schemes can be obtained as

$$F^{(l)} = Q^{(l)} H^{(l)}.$$
Fig. 2: Dual Branch-THP structure with diversity (a) DB- dTHP (b) DB- cTHP

Fig. 2 shows the proposed dual branch THP structures with receive diversity. The derived transmit patterns and MMSE filters (feedback, feed forward and scaling filters) are used in the structure.

C. Sum-Rate Performance Analysis:

The MU-MIMO channel is decomposed into parallel AWGN channels in the THP systems. Therefore, the $i^{\text{th}}$ SNR for the $l^{\text{th}}$ branch transmit signal of DB-ZF-THP is given by (Tse and Viswanath, 2005), (Huang et al., 2008),

$$\gamma_i^{(l)\text{DB-ZF-thp}} = \frac{\sigma_s^2}{\sigma_n^2 (1/h_{il})^2},$$

$$\gamma_i^{(l)\text{DB-ZF-thp}} = \frac{\sigma_s^2}{\sigma_n^2 \sum_{i=1}^S (1/h_{il})^2}$$

Then, the achievable sum rates for the $l^{\text{th}}$ branch of DB-ZF-dTHP and DB-ZF-cTHP are respectively given by

$$C_{(l)\text{DB-ZF-dTHP}} = \sum_{i=1}^S \log(1 + \frac{\sigma_s^2}{\sigma_n^2 h_{il}^2}),$$

$$C_{(l)\text{DB-ZF-cTHP}} = S \log \left(1 + \frac{\sigma_s^2}{\sigma_n^2 \sum_{i=1}^S (1/h_{il})^2} \right).$$

The achievable sum rates of DB-MMSE-dTHP and DB-MMSE-cTHP can be expressed, respectively, as follows

$$C_{(l)\text{DB-ZF-dTHP}} = \sum_{i=1}^S \log(1 + \frac{\sigma_s^2}{\sigma_n^2 h_{il}^2}),$$

$$C_{(l)\text{DB-ZF-cTHP}} = S \log \left(1 + \frac{\sigma_s^2}{\sigma_n^2 (1/h_{il})^2} \right)$$

where $\sigma_s^2 = E\|s\|^2$, $\sigma_v^2 = E\|\nu\|^2$.

RESULTS AND DISCUSSIONS

In this section, we assess the performance of the proposed DB-THP algorithms. A system with $N_t = 8$ transmit antennas and $K = 4$ users each equipped with $N_r = 2$ receive antennas is considered; this scenario is
denoted as the (2, 2, 2, 2) × 8 case. BPSK and QPSK modulation schemes are employed in the simulations. The channel matrix $H$ is assumed to be a complex i.i.d. Gaussian matrix with zero mean and unit variance. The number of simulation trials carried is $10^5$ and the packet length is $10^5$ symbols.

As illustrated in Fig. 3a, it is seen that the BER performance of the BD precoding algorithm is worse than that of the THP algorithms in a Perfect Channel State Information Scenario. For the THP algorithms, a better BER performance is offered by ZF-THP. However, a much better BER performance is achieved by MMSE-THP schemes. Also MMSE-cTHP achieves better performance compared to MMSE-dTHP. Much more improved performance is achieved by using the dual branch scheme. From Fig. 3a, the proposed DB-MMSE-cTHP has a gain of more than 3 dB as compared to the conventional MMSE-cTHP and DB-MMSE-dTHP has a gain of more than 2.5 dB as compared to the conventional MMSE-dTHP. The same phenomenon is also observed for the two types of THP with QPSK in Fig. 3b.

The transmit diversity of the proposed DB-MMSE-cTHP and DB-MMSE-dTHP algorithms is better than the conventional MMSE-THP algorithms because two branches are constructed and the ordering algorithms are used. It is worth noting that, with two branches, MMSE-cTHP and MMSE-dTHP achieves an improved performance and the BER performances are better with increased number of branches. Fig. 4 displays the sum-rate performance of the proposed DB-MMSE-cTHP and DB-MMSE-dTHP algorithms, respectively. It is also observed that DB-MMSE-dTHP offers a good performance compared to that of DB-MMSE-cTHP.
Fig. 4: Sum-rate performance of DB-THP, (2 2.2,2) × 8 MIMO, QPSK.

Conclusion:

In this paper, we presented DB-MMSE-cTHP and DB-MMSE-dTHP algorithms for MU-MIMO systems with multiple receive antennas. Traditional design of Tomlinson-Harashima Precoding does not contain any ordering algorithm and transmit pattern at the transmitter. The required computational complexity is still reasonable with the use of ordering algorithms and the filters that are derived based on LQ decomposition. A comprehensive comparative analysis has been carried out to show the effectiveness of ordering algorithms with existing precoding algorithms, including the BD, ZF-THP algorithms.

REFERENCES


