Efficient combination of MU-MIMO THP and user scheduling to achieve both high system capacity and fairness

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Abstract: This letter proposes an efficient method for combining MU-MIMO Tomlinson Harashima precoding (THP) with user scheduling techniques to realize fairness among users as well as high system capacity. The concept of the proposed approach is to first adopt semiorthogonal user selection (SUS) for throughput maximization and then apply proportional fairness (PF) to the remaining users, which regains fairness lowered by using SUS for throughput maximization. Moreover, considering that THP adopted as a precoder for PF requires the calculation of ordering and precoding for each user combination, the proposed method adopts linear precoding (LP) instead of THP to relax the computational effort during operation of PF. This approach is inspired by the fact that LP achieves almost the same system capacity as THP with ordering when conducting PF. The effectiveness of the proposed method is demonstrated by comparing it to MU-MIMO THP with SUS or PF in terms of system capacity and fairness among users, by means of computer simulations.

Keywords: MU-MIMO THP, semiorthogonal user selection (SUS), proportional fairness (PF), system capacity, fairness index (FI)

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1 Introduction

In recent years, MU-MIMO has become a promising technique for achieving high system capacity over broadband wireless communications [1, 2]. In order to realize MU-MIMO systems, precoding techniques are essential and are categorized into two approaches: linear precoding (LP) and nonlinear precoding. In particular, nonlinear precoding provides better system capacity than LP because of the reduction effect of the noise enhancement [3, 4, 5, 6], which has emerged as a promising technique to realize next-generation (5G) mobile broadband systems [7]. Among various nonlinear precoding schemes, Tomlinson Harashima precoding (THP) is considered a realistic approach because the perturbation vector can be generated by the simple modulo operation [5, 6].

On the other hand, the combination of MU-MIMO with user scheduling needs to be considered from a system-level viewpoint. This is because the capacity of the entire system depends strongly on how simultaneous users are selected from existing users within a certain cell. Thus far, we have proposed an efficient method
for combining MU-MIMO THP with semiorthogonal user selection (SUS) [8] to maximize the system capacity without any ordering calculation [6]. However, since SUS is originally utilized for throughput maximization, this method has a problem in that the users with high CNR tend to be selected, which leads to unfairness among users. Moreover, although the combination of MU-MIMO and scheduling techniques has been investigated so far [6, 9, 10, 11], the objectives of the previous work are limited to a specific scheduling technique such as SUS or PF, which does not aim to achieve both high system capacity and fairness.

In this letter, we propose an efficient method for combining MU-MIMO THP with user scheduling techniques to improve fairness among users while retaining the merit of high system capacity. The concept of the proposed approach is to first adopt SUS for throughput maximization within the users with relatively higher CNR and then conduct PF among the remaining users to achieve fairness for those users with relatively lower CNR, which regains fairness lowered by using SUS. Moreover, considering that THP with PF requires the calculation of ordering and precoding for all possible user combination, the proposed method adopts LP instead of THP in operation of PF to relax its calculation cost. The motivation behind this approach comes from the fact that LP provides almost the same system capacity as THP in application to PF. Moreover, the effectiveness of the proposed method is demonstrated by comparing it to MU-MIMO THP with SUS or PF in terms of system capacity and fairness among users.

2 Proposed method

2.1 System concept

From the viewpoint of system-level performance, it is important to consider how to effectively combine MU-MIMO THP with user scheduling techniques. In the proposed method, we aim to first achieve throughput maximization by means of SUS, which is known as a practical approach to realize Greedy-based user scheduling. Fig. 1 shows the system concept and configuration of the proposed method. As shown in Fig. 1(a), when combining THP with SUS, the results of the ordering of SUS are fully reused for the ordering of THP in order to exploit the space diversity benefit without any ordering calculation of THP [6]. However, SUS has the problem of starving the users in relatively bad channel conditions, which leads to providing little resources for the users at the edge of a cell. To cope with this problem, the proposed method applies PF to the remaining users. As shown in Fig. 1(b), the proposed method first conducts SUS for throughput maximization, and then PF is applied to the remaining users for the period of the PF use ratio \( \beta \) in order to regain fairness lowered by using SUS, which makes it possible to simultaneously realize both high system capacity and fairness. Moreover, considering that PF requires a heavy computational load for ordering and precoding at each user combination, we adopt LP instead of THP during operation of PF. As shown in Fig. 1(c)-(i),(ii), comparing the traditional THP with ordering and LP, the adoption of LP makes precoding simpler and eliminates the ordering calculation, whose effort is proportional to the fourth power of the number of antennas [12].

The motivation behind this approach stems from the fact that LP provides almost
the same system capacity as THP in operation of PF. Fig. 1(c)-(iii) shows the performance comparison, in terms of system capacity versus fairness index (FI), between THP and LP in application to two contrasting user scheduling techniques, where $4 \times 4$ and $6 \times 6$ are assumed as MIMO configurations and the number of existing users $K = 24$. It can be seen from Fig. 1(c)-(iii) that PF ($\beta = 1.0$) significantly reduces the advantage of THP over LP, and SUS ($\beta = 0.0$) provides high system capacity in combination with THP.

Next, we clarify the effectiveness of adopting LP during operation of PF in terms of the computational effort. The computational effort is composed of the calculation of scheduling technique and precoding, whose complexity depends on the number of receive antennas and existing users. First, we calculate the total computational cost in the case of applying THP to both SUS and PF by

$$C_T = (1 - \beta) \times (S_N + T_N) + \beta \times K - N_S \times C_N, \quad (O_N + T_N),$$  

where $K$, $N_S$, and $N_r$ are the number of existing users, SUS users, and receive antennas, respectively. Moreover, $S_N$, $T_N$, $L_N$ and $O_N$ denote the number of complex multiplications for SUS, THP, LP, and ordering of THP, respectively.

Fig. 1. System concept and configuration of the proposed method.
On the other hand, the total computational cost in the case of adopting LP instead of THP during operation of PF is calculated as

\[ C_P = (1 - \beta) \times (S_N + T_N) + \beta \times K \times N_S \times C_N \times L_N. \]  

From Eqs. (1) and (2), it can be seen that the application of LP to PF relaxes the computational effort for PF, while the computational effort for SUS is unchanged.

Suppose that the effectiveness of the proposed method is defined as

\[ R_{PF} = \frac{C_P}{C_T} \simeq \frac{L_N}{O_N + T_N}, \]

then its effectiveness \( R_{PF} \) for the MIMO configuration of \( 4 \times 4 \) and \( 6 \times 6 \) is calculated as

\[ R_{PF} = \begin{cases} 0.219 & (N_t = N_r = 4) \\ 0.153 & (N_t = N_r = 6) \end{cases}, \]

where \( N_t \) is the number of transmit antennas. From Eq. (3), it can be said that the proposed method can dramatically reduce the calculation cost by adopting LP instead of THP during operation of PF and that its effectiveness is enhanced with an increase in the MIMO configuration.

### 3 Numerical results

In this section, we describe a demonstration of the effectiveness of the proposed method in comparison with MU-MIMO THP using SUS or PF in terms of channel capacity and fairness among users. In this performance evaluation, existing users are assumed to be uniformly distributed in a single cell, where the attenuation coefficient \( a = 3.5 \), and the average CNR at the cell edge was set to be 15.0 dB. It should be noted that the number of users for SUS \( N_S \) was the same as the number of transmit antennas, and the fairness among users was measured by using the FI which is defined as [13]

\[ FI = \left[ \sum_{i=0}^{K-1} \frac{1}{T_{ave}} \sum_{t=0}^{T_{ave}-1} C_i(t) \right]^2 \]

\[ K \sum_{i=0}^{K-1} \left( \frac{1}{T_{ave}} \sum_{t=0}^{T_{ave}-1} C_i(t) \right)^2, \]

where \( C_i(t) \) is the channel capacity of the \( i \)-th user at time slot \( t \) and \( T_{ave} \) is the observation time for the average system capacity.

Fig. 2 shows the relationship between average FI and system capacity with a parameter of the PF use ratio \( \beta \), where \( 4 \times 4 \) and \( 6 \times 6 \) were assumed as MIMO configurations and \( K = 24 \). In Fig. 2, the performance of the method using only THP or LP with both SUS and PF is also shown for reference. From Fig. 2, it can be seen that the proposed method using both THP and LP improves fairness by increasing the PF use ratio \( \beta \) while reducing the system capacity. Moreover, the proposed method provides almost the same system capacity and fairness as the method using only THP regardless of \( \beta \), which implies that the system capacity and fairness can be retained even by adopting LP during operation of PF while dramatically reducing the computational effort.
Fig. 3 shows the impact of the existing users on the system capacity with a parameter of the MIMO configuration. From Fig. 3, it can be seen that the increase in the existing users $K$ makes the proposed method approach the method using only THP with both SUS and PF regardless of the MIMO configuration because of the enhancement of the multiuser diversity benefit.

4 Conclusion

In this letter, we have proposed an efficient method for combining MU-MIMO THP with two different user scheduling techniques to realize fairness as well as high system capacity. The feature of the proposed approach is to apply PF to the users except for the SUS users, which can provide resources for the users in bad channels. Moreover, taking advantage of the fact that LP provides almost the same system capacity as THP in application to PF, LP is adopted instead of THP during operation of PF in order to reduce the computational effort. Numerical results showed that the proposed method can control the degree of fairness among users by changing the PF use rate, and can dramatically reduce the computational cost while providing the same system capacity and fairness as the method using only THP with both SUS and PF.

Fig. 3 shows the impact of the existing users on the system capacity with a parameter of the MIMO configuration. From Fig. 3, it can be seen that the increase in the existing users $K$ makes the proposed method approach the method using only THP with both SUS and PF regardless of the MIMO configuration because of the enhancement of the multiuser diversity benefit.

In our future work, we will investigate the impact of the non-uniform user distribution on the performance of the proposed method. This is because the non-uniform user distribution reduces the spread of the CNR, which would enhance fairness even by the traditional SUS method.