On the Fairness of the Multiuser Eigenmode Transmission System

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Received April 7, 2011; accepted May 9, 2011; published June 28, 2011

Abstract

The Multiuser Eigenmode Transmission (MET) has generated significant interests in literature due to its optimal performance in linear precoding systems. The MET can simultaneously transmit several spatial multiplexing eigenmodes to multiple users which significantly enhance the system performance. The maximum number of users that can be served simultaneously is limited due to the constraints on the number antennas, and thus an appropriate user selection is critical to the MET system. Various algorithms have been developed in previous works such as the enumerative search algorithm. However, the high complexities of these algorithms impede their applications in practice. In this paper, motivated by the necessity of an efficient and effective user selection algorithm, a low complexity recursive user selection algorithm is proposed for the MET system. In addition, the fairness of the MET system is improved by using the combination of the proposed user selection algorithm and the adaptive Proportional Fair Scheduling (PFS) algorithm. Extensive simulations are implemented to verify the efficiency and effectiveness of the proposed algorithm.

Keywords: Multiuser eigenmode transmission, user selection, fair scheduling, MIMO systems

This research was supported by research grants from National Science and Technology Major Projects of China's Government [2010ZX03005-001, Development of Ultra-high-speed Wireless LAN Radio Interface Technology] and [2010ZX03005-003, Research of Architecture and Key Technologies for Wireless Innovative Campus Area Networks].

DOI: 10.3837/tiis.2011.06.001

1. Introduction

In point-to-multipoint broadcasting channels, the Multiuser Eigenmode Transmission (MET) achieves the best performance in linear precoding systems [1]. In this paper, we will analyze the structure of MET and also provide a low complexity design scheme of the MET.

The MET consists of three parts, (i) the precoding based Block Diagonalization (BD) technique, (ii) the eigenmode user selection [2], and (iii) power allocation based on the eigenmode user selection [3]. The basic form of the BD technique is the zero-forcing (ZF) precoding in broadcast channel, where the granularity of the BD is in single user level. Similarly, the eigenmode is the granular in the MET (and multiple eigenmodes could be allocated to a single user). In the MET, the BD technique dramatically reduces the precoding at the transmitter and also the complexity of receiver. The maximum number of eigenmodes that can be transmitted in linear precoding equals the number of transmit antennas M. The eigenmode-user allocation that achieves the best MET performance will be select from all possible allocations through certain optimization algorithm. In [1], Boccardi and Huang propose to continually select an eigenmode and allocate it to a suitable user until all the M eigenmodes have been found or any additional eigenmode will decrease the system throughput. After the eigenmode-user selection, water-filling algorithm is applied to find the best power allocation.

We focus on the analysis of narrow-band system in this paper, and the wide-band system is beyond the scope of this paper and is for future research. Further, it is assumed that the transmitter has perfect knowledge of the Channel State Information (CSI), and also the synchronization and propagation error is negligible.

The rest of this paper is organized as follows. Section 2 provides the system model. In Section 3, the proposed user selection algorithm is presented along with the analysis of the system fairness. Simulation results are shown and analyzed in Section 4. Section 5 concludes the paper.

2. System Model

In the point-to-multipoint downlink channel between the base station and K users, the baseband channel [4][5][6] is

$$\begin{aligned} y_k &= p_k\, \mathrm{R}_k \cdot \mathrm{H}_k \cdot \sum_{k=1}^{K} \mathrm{T}_k \cdot x_k + \mathrm{R}_k \cdot n_k \\ &= p_k\, \mathrm{R}_k \cdot \mathrm{H}_k \cdot \mathrm{T}_k \cdot x_k + p_k\, \mathrm{R}_k \cdot \mathrm{H}_k \cdot \sum_{i=1, i\neq k}^{K} \mathrm{T}_i \cdot x_i + R_k \cdot n_k \end{aligned} \tag{1}$$

where $k = 1, 2, \ldots, K$, the first term $p_k\, \mathrm{R}_k \cdot \mathrm{H}_k \cdot \mathrm{T}_k \cdot x_k$ is the desired signal, the second term $p_k\, \mathrm{R}_k \cdot \mathrm{H}_k \cdot \sum_{i=1, i\neq k}^{K} \mathrm{T}_i \cdot x_i$ are the signals from other users and the last term is the ambient noise. Equation (1) models a non-cooperative multiuser channel, which implies that the user can use the multipath technique to transmit the signal just as that in the standard MIMO system and all the signals from other users are treated as noise at the receiver. From this perspective, constructing an orthogonal precoding among multiple users is the best way to achieve the capacity of the broadcasting channel [7] .

- y_k is a vector of order N_k which denotes the result of left multiplying the original received signal by the receiver matrix R_k . In addition, N_k , is the number of data streams from the base station to the k-th user, which is less than or equal to the number of antennas of the receiver N_k'.
- The receiver matrix of the k-th user is R_k , which is N_k by N_k'. In the MET, the row vector of R_k consists of a subset of the left eigenvectors of the unitary transform of H_k , and the subsect corresponds to the eigenmodes selected by the k-th user. R_k is the matching matrix that matches the selected left eigenvectors of the original channel matrix H_k .
- The matrix of the wireless channel of the k-th user is H_k , which is N_k' by M. The singular value decomposition (SVD) of H_k can be written as $\mathrm{H}_k = \mathrm{U}_k \Lambda_k \mathrm{V}_k^H$.
- The precoding matrix of the transmitter of the k-th user is T_k , which is M by N_k . M is the number of transmit antennas of the base station (BS). In concern of the feature of broadcasting channel, the signals in the downlink channel of all the users are identical before multiplying the matching matrix. In the orthogonal downlink transmission, T_k can eliminate the righthand side eigenvectors of the eigenmodes of all the other users.
- x_k is a data symbol vector of length N_k .
- p_k is the normalized transmitting power under long term fading. Compared to users in the central part of the cell, users located at the edge of the cell have smaller p_k [8] [9].
- n_k is a N_k' dimensional ambient noise vector that follows a normal distribution, i.e., $n_k \sim \mathrm{N}_c(0, \delta^2 \mathrm{I})$.

By stacking equation (1) of all k, we can obtain

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \end{bmatrix} = \begin{bmatrix} p_1 \mathrm{R}_1 \cdot \mathrm{H}_1 \\ p_2 \mathrm{R}_2 \cdot \mathrm{H}_2 \\ \vdots \\ p_k \mathrm{R}_k \cdot \mathrm{H}_k \end{bmatrix} \begin{bmatrix} \mathrm{T}_1 & \mathrm{T}_2 & \cdots & \mathrm{T}_k \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_k \end{bmatrix} \tag{2}$$

where $n_k = \mathrm{R}_k n_k \sim \mathrm{N}_c(0, \delta^2 \mathrm{I})$. Assume that H has been normalized such that $\mathrm{Trace}(\mathrm{HH}^{\mathrm{H}}) = 1$, $p_k \mathrm{R}_k \cdot \mathrm{H}_k$ consists of the following information:

- Received power p_k
- Eigenvalue of the selected eigenmode $\mathrm{R}_k \mathrm{U}_k \Lambda_k$

- Righthand side eigenvector of the selected eigenmode (the *j-th* column vector of V_k^H)

Exploring the linear space, we found that the righthand side eigenvectors of all the *K* users are of importance. The matrix *H* consists of random channel parameters and $\sum_{k=1}^{K} N_k \le M$. It is almost assured that *H* is row full rank, though in some special cases a singular *H* may appear. In the MET, a singular *H* will degrade the throughput of the system, and thus one of the key points in eigenmode-user selection is to ensure that *H* is always full rank. The objective of orthogonal transmission is to find a precoding matrix such that $\mathrm{H} \cdot \mathrm{T} = \mathrm{D}$, where *D* is block diagonalized matrix whose subblock is of size $N_k \times N_k$ for $k = 1, \ldots, K$. Only the design of sub-optimal T matrix will be discussed here since the design of optimal *T* is challenging. We are going to modify the *M* by $\sum_{k=1}^{K} N_k$ precoding matrix into a $\sum_{k=1}^{K} N_k$ pseudo inverse of the channel matrix,

$$\mathrm{T} = \left\|\mathrm{H}^{+}\right\|_{\mathrm{F}}^{-1} \mathrm{H}^{+} \tag{3}$$

where + denotes the pseudo inverse and *F* denotes the Frobenius norm. According the matrix theory, $\mathrm{X} = \mathrm{H}^{+}$ has the smallest Frobenius norm among all the matrices that satisfy $\mathrm{AX} = \mathrm{I}$, and it is also the one that maximizes the system throughput. Note that the precoding matrices in equation (1) and equation (3) are identical, and also $\left\|\mathrm{H}^{+}\right\|_{\mathrm{F}}^{-1}$ is used to normalize the transmitting power. Since the size of the precoding matrix is constrained to be $\sum_{k=1}^{K} N_k \le M$, the orthogonality of the pseudo inverse matrix could be expressed as

$$\mathrm{H} \cdot \mathrm{T} = \left\|\mathrm{H}^{+}\right\|_{\mathrm{F}}^{-1} \cdot \mathrm{H} \cdot \mathrm{H}^{+} = \left\|\mathrm{H}^{+}\right\|_{\mathrm{F}}^{-1} \cdot \mathrm{I} \tag{4}$$

By substituting equation (4) into equation (2), we have

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \end{bmatrix} = \left\|\mathrm{H}^{+}\right\|_{\mathrm{F}}^{-1} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_k \end{bmatrix} \tag{5}$$

It can be observed that the MET constructs a virtual parallel communication channel for all $\sum_{k=1}^{K} N_k$ eigenmodes of the users with channel gain $\left\|\mathrm{H}^{+}\right\|_{\mathrm{F}}^{-1}$. No interference exists among the eigenmodes, and also the precoding at transmitting side will not increase the noise at the receiver.

The mutual information [10] in equation (5) is

$$\log\left[\det\left(\mathrm{I}+\frac{1}{\left\|\mathrm{H}^{+}\right\|_{\mathrm{F}}^{2}\sigma^{2}}\mathrm{I}\right)\right]=\sum_{k=1}^{K}N_{k}\cdot\log\left(1+\frac{1}{\left\|\mathrm{H}^{+}\right\|_{\mathrm{F}}^{2}\sigma^{2}}\right) \quad (6)$$

The similarity between the MET and the ZF precoding scheme, which is also a kind of BD technique, can be observed from equation (6). Better performance is achieved by the MET through avoiding to allocate the power on worse eigenmodes.

3. Multiuser Scheduling

If the total number of antennas of all the users is less than or equal to M, the precoding scheme is simple because all the users will be served. However, in practice, the number of users usually exceeds the maximum number of users that the system can serve. Thus, the user selection and scheduling is one of the critical part in the MET. In the rest part, maximum throughput scheduling, proportional fairness scheduling and modified proportional fairnessscheduling will be discussed.

In conventional enumeration algorithm, the eigenmode set is empty initially. In each loop, the eigenmode whichprovides the maximum system throughput increment is selected until all the M eigenmodes have been found or any additional eigenmode will decrease the system capacity. However, the high complexity of this enumerationalgorithm impedes its application in practice. In the rest of this paper, a low complexity implementation of the MET is developed.

3.1 Recursive User Selections

In this subsection, we will present how to select the ideal user through recursively calculating the LQ decomposition of H. In closed-loop, the original MET uses linear search algorithm, and at each step it decides whether a new user-eigenmode pair is to be added to the channel matrix H as an additional row. Compared to the method of re-computing the precoding matrix at every time, using the Gram-Schmidt Orthogonalization is more efficient to recursively compute the LQ decomposition. Starting from the first row, the orthogonality of each row of H is evaluated cursively through the LQ decomposition, and each row of H represents the right-hand side eigenvector of the selected eigenmode. The LQ decomposition can be written as $\mathrm{H}=\mathrm{LQ}$, where L is a lower triangular matrix of size $\sum_{k=1}^{K}N_k\times\sum_{k=1}^{K}N_k$ and Q is a matrix of size $\sum_{k=1}^{K}N_k\times M$ with orthogonal rows. Therefore, we have $\mathrm{H}^{+}=\mathrm{Q}^{H}\,\mathrm{L}^{-1}$. Assume that the LQ decomposition of n-th order H is available, then the LQ decomposition of (n+1)-th order H is

$$\mathrm{H}_{(n+1)}=[H_{n}^{H}\mid h_{(n+1)}^{H}]^{H} \quad (7)$$

where the subscript n denotes the n-th loop. Then

$$\mathrm{q} = \mathrm{h}_{(\mathrm{n}+1)}(\mathrm{I} - \mathrm{Q}^{\mathrm{H}}_{(\mathrm{n})}\mathrm{Q}_{(\mathrm{n})}) \tag{8}$$

$$\mathrm{Q}_{(\mathrm{n}+1)} = \begin{bmatrix} \mathrm{Q}_{(\mathrm{n})} \\ \dfrac{\mathrm{q}}{\|\mathrm{q}\|_{\mathrm{F}}} \end{bmatrix} \tag{9}$$

$$\mathrm{L}^{-1}_{(\mathrm{n}+1)} = \begin{bmatrix} L^{-1}_{(\mathrm{n})} & 0 \\ -\dfrac{\|\mathrm{q}\|_{\mathrm{F}}}{h_{(n+1)}q^{H}} h_{(N+1)} \mathrm{Q}^{H}_{(n)} L^{-1}_{(n)} & \dfrac{\|\mathrm{q}\|_{\mathrm{F}}}{h_{(n+1)}q^{H}} \end{bmatrix} \tag{10}$$

Now, assume that the LQ decomposition of $\mathrm{H}_{(\mathrm{n}+1)}$ is obtained. In order to remove the last column of $\mathrm{H}_{(\mathrm{n}+1)}$, which is the LQ decomposition of $\mathrm{H}_{(\mathrm{n})}$, we can just remove the last row of $\mathrm{Q}_{(\mathrm{n}+1)}$ and the last column of $\mathrm{L}^{-1}_{(\mathrm{n}+1)}$.

According to equations (8) ~ (10), we define

$$\begin{aligned} \Delta^{2}_{(\mathrm{n}+1)} @ \left\|\mathrm{H}^{+}_{(\mathrm{n}+1)}\right\|^{2}_{F} - \left\|\mathrm{H}^{+}_{(\mathrm{n})}\right\|^{2}_{F} &= \left\|\mathrm{L}^{-1}_{(\mathrm{n}+1)}\right\|^{2}_{\mathrm{F}} - \left\|\mathrm{L}^{-1}_{(\mathrm{n})}\right\|^{2}_{\mathrm{F}} \\ &= \frac{1}{\left\|\mathrm{h}_{(\mathrm{n}+1)}\right\|^{2}_{F}} \left(1 + \mathrm{h}_{(n+1)} \mathrm{Q}^{H}_{(n)} \mathrm{L}^{-1}_{(n)} \left(\mathrm{L}^{-1}_{(n)}\right)^{H} \mathrm{Q}_{(n)} \mathrm{h}^{H}_{(h+1)}\right) \\ &= \frac{1}{\left\|\mathrm{h}_{(\mathrm{n}+1)}\right\|^{2}_{F}} \left(1 + \mathrm{h}_{(n+1)} \mathrm{H}^{+}_{(\mathrm{n})} \left(\mathrm{H}^{+}_{(\mathrm{n})}\right)^{H} \mathrm{h}^{H}_{(h+1)}\right) \end{aligned} \tag{11}$$

Since the Frobenius norm is invariant under unitary transform, $\Delta^{2}_{(\mathrm{n}+1)}$ achieves its minimum $\dfrac{1}{\left\|\mathrm{h}_{(\mathrm{n}+1)}\right\|^{2}_{F}}$ when $\mathrm{h}_{(n+1)} \mathrm{H}^{+}_{(n)} = 0$ and $\mathrm{h}_{(n+1)} \neq 0$.

According to equation (6), the variation in the channel mutual information (i.e., the channel capacity [11][12]) of adding a new user is

$$\delta R_{(n+1)} = \sum_{k=1}^{n+1} N_k \cdot \log\left(1+\frac{1}{\left\|\mathrm{H}^{+}_{(n+1)}\right\|_{\mathrm{F}}^{2}\sigma^2}\right) - \sum_{k=1}^{n} N_k \cdot \log\left(1+\frac{1}{\left\|\mathrm{H}^{+}_{(n)}\right\|_{\mathrm{F}}^{2}\sigma^2}\right)$$

$$= N_{(n)} \log\left(1+\frac{1}{\left\|\mathrm{H}^{+}_{(n)}\right\|_{\mathrm{F}}^{2} + \Delta^2_{(\mathrm{n}+1)}\sigma^2}\right) + \tag{12}$$

$$\sum_{k=1}^{n} N_k \cdot \log\left(1-\frac{\Delta^2_{(\mathrm{n}+1)}}{\left(\left\|\mathrm{H}^{+}_{(n)}\right\|_{\mathrm{F}}^{2}\sigma^2+1\right)\left(\left\|\mathrm{H}^{+}_{(n)}\right\|_{\mathrm{F}}^{2}+\Delta^2_{(\mathrm{n}+1)}\right)}\right)$$

In the first term, we compute the mutual information of eigenmodes of all the (n+1) users including the eigenmode of the new one. The second term represents the total loss of all the former users when the new user is added to the system. Note that the summation is decreasing function of $\Delta^2_{(\mathrm{n}+1)}$. Therefore, the user that generates the smallest $\Delta^2_{(\mathrm{n}+1)}$ should be selected if the objective is to maximize the system capacity. In this way, the complexity is drastically reduced because only the computation and comparison of $\Delta^2_{(\mathrm{n}+1)}$ is required instead of the resource consuming singular decomposition.

3.2 Fairness

Although the objective of the MET is to enhance the capacity of point-to-multipoint broadcasting channel, the fairness should also be taken into account in the eigenmode-user selection. In this paper, we embed the Proportional Fair Scheduling (PFS) algorithm and the adaptive proportional fairness scheduling algorithm into the MET to improve the fairness of the system so that the starvation situation of user can be avoided and the user's satisfaction index is increased.

4. Simulation and Analysis

In this section, simulations are implemented to justify the multiuser scheduling algorithm in MET systems. The simulation scenario is defined as follows. In the MIMO broadcasting channel, the SNR is $SNR = P/\sigma^2$, $n_t = 4,\ n_r = 2,\ \hat{K} = 2$ and the update time of the time window is $t_c = 100$. The states of user channels are independent and uniformly divided into three parts which follow $CN(0,1)$, $CN(0,1/2)$ and $CN(0,1/4)$ distributions, respectively. We simulated the MET, MET with PFS and MET with adaptive PFS. In the adaptive PFS algorithm, the parameter α is set to two typical values 2 and 4, respectively.

Table 1 summarizes the fairness performances of the three above mentioned systems with $\mathrm{SNR} = 0\mathrm{dB},\ K{=}60,\ t_c{=}100$. As shown by the simulation result, the proposed adaptive PFS algorithm outperforms the other algorithms in terms of fairness. Also it has been shown that the larger α is, the better fairness is obtained. The fairness factor is computed by

$$F(K)=\frac{(\sum_{k=1}^{K}x_k)^2}{K\sum_{k=1}^{K}x_k^2} \tag{13}$$

where x_k represents the average simulated transmission rate of the *k-th* user. A higher $F(k)$ value implies a better fairness. In the best situation where the resource is equally allocated to all users, $F(k)$ = 1. **Fig. 1** shows that the increase in α will decrease the system capacity. The scheme that allows the users transmitting at their best channel state can effectively enhance the fairness, especially when the distributions of user channel conditions are different. For a user with worse channel condition, even if he transmits at his best channel state, the transmission rate may still even lower than the transmission rate of a user who transmits at its average channel state but with a better channel condition. In this situation, the selection of user with worse channel implies a decrease of the total transmission rate of the system. The proposed adaptive PFS algorithm not only takes into account the history of channel information of the user itself but also gives more weight to the fairness by using exponential parameter so that the system has a better fairness performance. The increase in $R_k(t)/\overline{R_k(t)}$ shows that the user's channel condition is improved compared with its average in previous time, and the system will correspondingly increase the probability of transmission for this user. In contrast, if $R_k(t)/\overline{R_k(t)}$ decreases, which means that the user's channel condition is worse than the average in previous time, the system will decrease its probability of transmission. In addition, we use the parameter α to adjust the weight of user's current state in the decision compared to itself. In the normalized case, if α increases then $\overline{R_k(t)}^{\alpha}$ will decrease, which in term results in larger $R_k(t)/\overline{R_k(t)}^{\alpha}$. Accordingly, the closer the channel state of a user to its peak, the more weight is obtained in the scheduling decision. Systems with larger α tend to have better fairness performance and systems with smaller α tend to provide larger capacity. The proposed adaptive PFS algorithm maintains a good trade-off between the system fairness and the system capacity. **Fig. 2** presents the difference of user's throughput under different scheduling algorithms.

Table 1. Comparison of fairness factors (SNR = 20dB, K = 20)

Scheduling algorithms	MET	PFS	Adaptive PFS ($\alpha=2$)	Adaptive PFS ($\alpha=4$)
Fairness factors	0.36403	0.79941	0.83176	0.98239

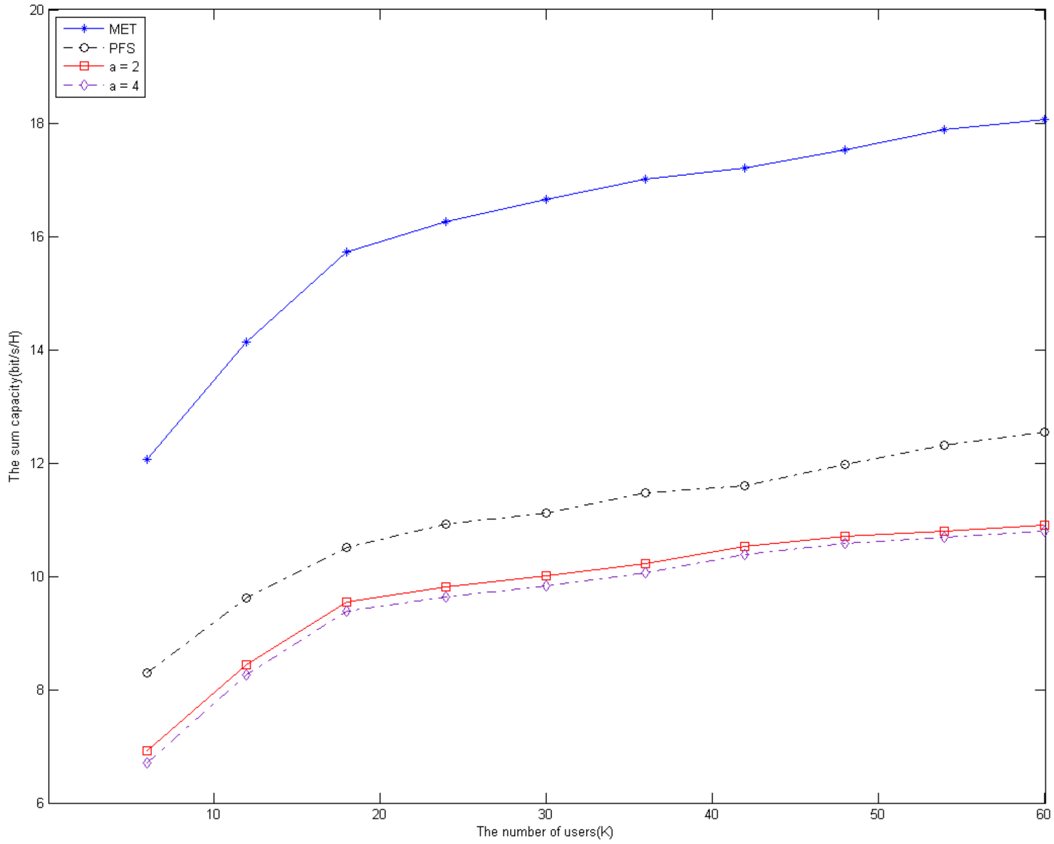

Fig. 1. Comparison of system sum capacities with different number of users.

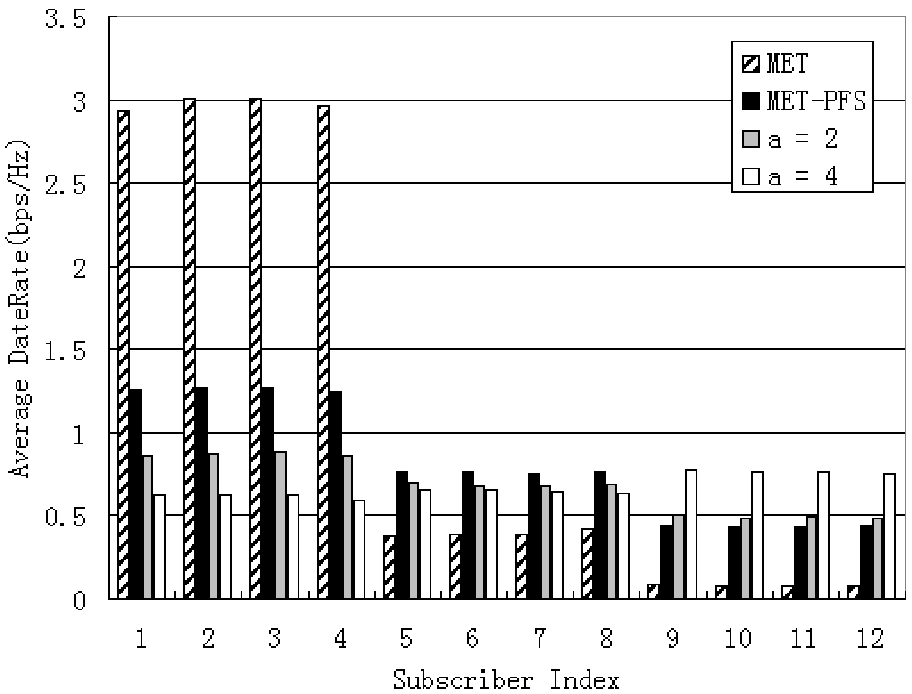

Fig. 2. Comparison of average data rates of users (SNR = 0dB, nt = 4, nr = 2).

5. Conclusions

In this paper, the MET is explored in multiuser downlink MIMO channel. The performance of the MET in linear precoding systems is the best and is almost the same as that of using dirty paper coding system. The MET can simultaneously transmit several spatial multiplexing eigenmodes to multiple users which significantly enhance the system performance. However, the maximum number of users that can be served simultaneously is limited due to the constraints on the number of base station's transmit antennas and the number of user's receive antennas. The high complexity of the previously developed enumerative search algorithm impedes its application in practice. A recursive user selection algorithm with low complexity is proposed in this paper. In addition, the fairness of the MET system is analyzed and is improved by using the combination of the low complexity scheduling algorithm and the PFS algorithm and also the adaptive PFS algorithm. Simulation results show that the proposed adaptive PFS algorithm provides a good system fairness performance while the high efficiency of the system is maintained.

References

[1] Boccardi, F., and Huang, H., "A near-optimum technique using linear precoding for the MIMO broadcast channel," in *Proc. of IEEE International Conference on Acoustics, Speech and Signal Processing*, vol. 3, pp. 17-20, Apr. 15-20, 2007. Article (CrossRef Link).

[2] Hu, H., Weckerle, M., and Luo, J., "Adaptive transmission mode selection scheme for distributed

wireless communication systems," *IEEE Communications Letters*, vol. 10, no. 7, pp. 573-575, 2006. Article (CrossRef Link).

[3] Schubert, M., and Boche, H., "Solution of the multiuser downlink beamforming problem with individual SINR constraints," *IEEE Transactions on Vehicular Technology*, vol. 53, no. 1, pp. 18-28, 2004. Article (CrossRef Link).

[4] Dai, L., Zhou, S., and Yao, Y., "Capacity analysis in CDMA distributed antenna systems," *IEEE Transactions on Wireless Communications*, vol. 4, no. 6, pp. 2613-2620, 2005. Article (CrossRef Link).

[5] Xiao, L., Dai, L., Zhuang, H., Zhou, S., and Yao, Y., "Information-theoretic capacity analysis in MIMO distributed antenna systems," in *Proc. of Vehicular Technology Conference*, vol. 1, pp. 779-782, Apr. 22-25, 2003. Article (CrossRef Link).

[6] Ni, Z., and Li, D., "Effect of fading correlation on capacity of distributed MIMO," in *Proc. of* 15th *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 3, pp. 1637-1641, Sep. 8-8, 2004. Article (CrossRef Link).

[7] Han, S., Zhou, S., Wang, J., Li, V. O. K., and Park, K., "Suboptimal transmission of orthogonal space–time block codes over correlated distributed antennas," *IEEE Signal Processing Letters*, vol. 14, no. 2, pp. 89-92, 2007. Article (CrossRef Link).

[8] Boal, A., Soares, A., Silva, J. C., and Correia, A., "Distributed antenna cellular system for transmission of broadcast/multicast services," in *Proc. of* 65th *Vehicular Technology Conference*, pp. 1307-1311, Apr. 22-25, 2007. Article (CrossRef Link).

[9] Shen, Y., Tang, Y., Kong, T., and Shao, S., "Optimal antenna location for STBC-OFDM downlink with distributed transmit antennas in linear cells," *IEEE Communications Letters*, vol. 11, no. 5, pp. 387–389, 2007. Article (CrossRef Link).

[10] Viswanath, P., and Tse, D. N. C., "Sum capacity of the vector Gaussian broadcast channel and uplink-downlink duality," *IEEE Transactions on Information Theory*, vol. 49, no. 8, pp. 1912-1921, 2003. Article (CrossRef Link).

[11] Roh, W., and Paulraj, A., "MIMO channel capacity for the distributed antenna," in *Proc. of* 56th *Vehicular Technology Conference*, vol. 2, pp. 706-709, Sep. 24-28, 2002. Article (CrossRef Link).

[12] Roh, W., and Paulraj, A., "Performance of the distributed antenna systems in a multi-cell environment," in *Proc. of* 57th *Vehicular Technology Conference*, vol. 1, pp. 587-591, Apr. 22-25, 2003. Article (CrossRef Link).

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