Enhanced Multiuser Eigenmode Transmission for Joint Frequency-spatial Resource Allocation in OFDM-MIMO Downlink Systems

Fanglei Sun, Huan Sun, Mingli You, Tao Yang, and Jinhui Chen
Research and Innovation Center
Alcatel-Lucent Shanghai Bell Co., Ltd.
Shanghai, P. R.China
Email:{fanglei.a.sun, hua.a.sun, mingli.you, tao.a.yang, jinhui.chen}@alcatel-sbell.com.cn

***Abstract*— Orthogonal frequency-division multiplexing (OFDM) and multiple-input-multiple-output (MIMO) are two key technologies adopted in future wireless communication systems, such as LTE/LTE-A. There are many papers addressed the resource allocation problems for OFDM and MIMO systems independently. However few discussions targets on the joint frequency-spatial resource allocation problem, particularly on eigenmode scheduling level. In this paper, we try to propose novel resource allocation schemes on eigenmode selection level, with the joint consideration of precoding problem in spatial domain, eigenmode scheduling and power allocation cross spatial and frequency domains.**

I. Introduction

Multiple-input multiple-output (MIMO) technique has been acknowledged to be promising for the next generation of mobile communication systems [1]. By deploying multiple antennas at both transmitter and receiver, the space diversity can be exploited to maximize the system capacity in MIMO systems. Orthogonal frequency division multiplexing (OFDM) has also been considered as a key technique to efficiently utilize the bandwidth, which provides another degree of freedom for scheduling in frequency dimension. Combined MIMO and OFDM techniques, the wideband frequency selective MIMO changel can be separated into many flat fading MIMO channels, and thus the equalization data detection can be implemented very easily on the basis of subcarrier by subcarrier. Therefore, OFDM-MIMO system is an attractive solution for high-speed broadband wireless networks, such as long-term evolution (LTE) systems specified in 3GPP [2], and IEEE Worldwide Interoperability for Microwave Access (WiMAX) systems [3].

Considering the multiple-input multiple-output broadcast channel (MIMO-BC) where the transmitter equipped with M_t antennas sends distinct information to K users, each equipped with M_r antennas. It has been shown in [4] that the capacity region of the MIMO-BC can be achieved by means of a nonlinear transmission technique known as "dirty paper coding" (DPC) Linear precoding (beamforming) techniques with lower complexity have also been proposed in which the transmitted signal is a linear combination of the users' data signals. One typical of beamforming techniques for the case of a single-antenna receiver $(M_r = 1)$ is based on zero-forcing (ZF) [5] where each user receives only its desired signal with no interference. The most straightforward extensions of the zero-forcing technique to the case of $M_r > 1$ appear in [6]-[8], where multiple spatial streams (or eigenmodes) are transmitted to each user with no interuser interference, resulting in a block diagonal (BD) covariance matrix. Further improvements of the original schemes have been proposed in [9], and [10]. In [11], the author simplified a linear transmission technique based on the BD technique using joint coordinated transmit-receive processing, named multiuser eigenmode transmission (MET). As in [7], MET also use a receiver beamformer to select a subset of the eigenmodes of a given user, a transmitter beamformer in order to guarantee the orthogonality between the different users and uses a joint eigenmode-user selection scheme where the set of active users and active eigenmodes is selected in a greedy manner to maximize the sum-rate of the system.

MET could achieve good performance for MU-MIMO system. However, for a joint OFDM-MIMO systems, its resource allocation on spatial and frequency domain is independent. In detail, in frequency domain, the total power is allocation to subbands averagely and the transmissions among the subbands are orthogonal. For each subband, in spatial domain, a sub-optimal algorithm MET was proved to be a near optimal solution combined user/stream selection and linear procoding for best-effort (BE) traffics. The drawback of this solution lies in that it restricts the scheduling freedom among frequency and spatial domain, thus the performance improvement is limited. In this paper, we proposed an enhanced multiuser eigenmode transmission (EMET) algorithm providing optimal eigenmode scheduling, precoding, and power allocation cross frequency and spatial domain. In order to reduce the computational complexity, two simplified EMET algorithms are also presented for easy application.

This paper is organized as follows. Section II introduces the system model of a multiuser OFDM-MIMO system and basic idea of MET algorithm. Section III presents the details of our proposed EMET algorithm and its simplified variations. In Section IV, the simulation results and analyses are given.

Section VI draws the conclusions of this paper.

II. System Model an Introduction of MET

A. System Model

In this section, we describe the MIMO-OFDM system model with M_t transmit antennas, M_r receive antennas and N orthogonal OFDM subcarriers considered in this paper. We also assume the number of users is K. As many paper addressed, the resource allocation problems for OFDM-MIMO system is usually separated to spatial and frequency domains. Due to the orthogonality of OFDM subcarriers, the problem is simplified to performance optimization of MU-MIMO under condition that equal power allocation on subcarriers. For a DL MU-MIMO system, ZF or BD based precoding could cancel the multi-stream/multi-user interference. However, it is because of the nullification conditions, the number of users that ZF/BD can support simultaneously is limited. We denote the maximum number of simultaneous users as K'. When $K > K'$, it is necessary to restrict BD to a suitably selected group of users, thereby motivating the need of scheduling algorithms. Shen et. al. have studied the user selection with BD in [12]. However, their work in [12] does not consider the optimization of receiver, i.e., a passive receiver identity matrix is applied. In general, it is more challenging to jointly optimize receiver bemfroming and transmitter precoding with the scheduling consideration.

B. Introduction of MET

Based on BD precoding, a linear precoding technique, called MET is proposed, which addresses the shortcomings of previous ZF-based beamformers by transmitting to each user on one or more eigenmodes chosen using a greedy algorithm.

The singular value decomposition (SVD) of H_k can be expressed as $\mathbf{U}_k\Lambda_k\mathbf{V}_k^H$, where the singular values are indexed in descending order : $\sqrt{\lambda_{k_1}} \geq \sqrt{\lambda_{k_2}} \cdots \sqrt{\lambda_{k_i}}$. Let u_k^j and v_k^j be the j-th column of $\mathbf{U}_k$ and $\mathbf{V}_k$, respectively. We denote the j-th eigenmode of user k as $\mathbf{h}_k^j = \lambda_{k_j}(\mathbf{v}_k^j)^H$. In contrast to the capacity-based user selection algorithm (BD-U) proposed in [11], MET selects a suitable subset of eigenmodes, instead of selecting users directly. The receive matrix $\mathbf{R}_k$ consists of the conjugate transposes of the columns of $\mathbf{U}_k$ corresponding to the selected eigenmodes of user k. For example, if the j_a-th $(a = 1, \cdots, L_k)$ eigenmode of user k is selected by the scheduling algorithm, then we have $\mathbf{R}_k = [(\mathbf{u}_k^{j_1})^H \cdots (\mathbf{u}_k^{j_{L_k}})^H]$ and we have.

$$\hat{\mathbf{H}}_k = \mathbf{R}_k\mathbf{H}_k = [(\mathbf{h}_k^{j_1})^H \cdots (\mathbf{h}_k^{j_{L_k}})^H]^H \tag{1}$$

Let Φ_i be a subset of eigenmodes, whose element (k, j) corresponds to $\mathbf{h}_k^j$. The cardinality of Φ_i is smaller than or equal to M_t. We construct the subset Ψ_i of users, corresponding to Φ_i, such that if $k \in \Psi_i$, then at least one of the eigenmodes in Φ_i belongs to user k. Apply ZF/BD precoding for the users in Ψ_i. According to the nullification conditions, we have

$$\hat{\mathbf{H}}_k\mathbf{T}_j = 0 \ for\ all\ j \neq k\ and\ j, k \in \Psi_i \tag{2}$$

Perform SVD

$$\hat{\mathbf{H}}_k\mathbf{T}_k = \bar{\mathbf{U}}_k\bar{\Lambda}_k\bar{\mathbf{V}}_k^H \tag{3}$$

Then the sum rate achieved is

$$R_{\Phi_i} = max_{\Psi_i \in \Phi_i} \sum_{j \in \Psi_i} \log(1 + (\bar{\sigma}_j^k)^2 w_j^k) \tag{4}$$

where $\bar{\sigma}_j^k$ is the j-th diagonal element of $\bar{\Lambda}_k$ and w_j^k is the power allocated on the j-th eigenmode of user k, the sum power of w_j^k is less or equal to the total transmit power P.

For the eigenmode selection, the computational complexity of the brute-force exhaustive search of finding the optimal subset of eigenmodes that achieves the maximum sum rate is very high, therefore the author of MET proposed to adopt greedy eigenmode selection. The algorithm first chooses the eigenmode with highest gain. Then, from the remaining unselected eigenmodes, it selects the one which can obtain the highest sum rate jointly with the selected eigenmodes. The algorithm terminates when M_t eigenmodes are selected or when the sum rate drops if more eigenmodes are selected.

III. Algorithm Description of Enhanced MTE

A. Optimal Joint Frequency-Spatial Resource Allocation

For the joint frequency-spatial resource allocation problem, the objective function could be formulated by

$$R = \max \sum_{n=1}^{N} \sum_{k=1}^{K} \sum_{j=1}^{|S_{k,n}|} r_{k,n}^j \tag{5}$$

$$s.t. \quad \sum_{n=1}^{N} \sum_{k=1}^{K} \sum_{j=1}^{|S_{k,n}|} p_{k,n}^j \leq P_{Total} \tag{6}$$

$$p_{k,n}^j \geq 0 \tag{7}$$

where $|S_{k,n}|$ is the numberof streams of user k on subband n, $p_{k,n}^j$ is the power allocated for stream j of user k on subband n, $r_{k,n}^j$ is the capacity achieved by stream j of user k on subband n, and P_{Total} is the total downlink power at eNB.

B. Description of EMET

MET originally proposed for MU-MIMO considers the eigenmode selection on different subband independently, which only exploits the spatial multiplexing gain. For joint frequency-spatial resource allocation, our EMET extends the eigenmode candidate pool to the eigenmodes spreading on all subbands, as show in Fig. 1. Our eigenmode scheduling algorithm exploits the spatial multiplexing gain and frequency diversity gain simultaneously, and improves the scheduling flexibility, thus prospective performance gain can be analyzed. In the following section, we will introduce the basic idea of EMET algorithm and its simplified algorithms.

Fig. 1 shows the eigenmode list cross frequency-spatial domain by SVD decomposition for each user k. EMET attempts to extend the eignmode candidate pool from only

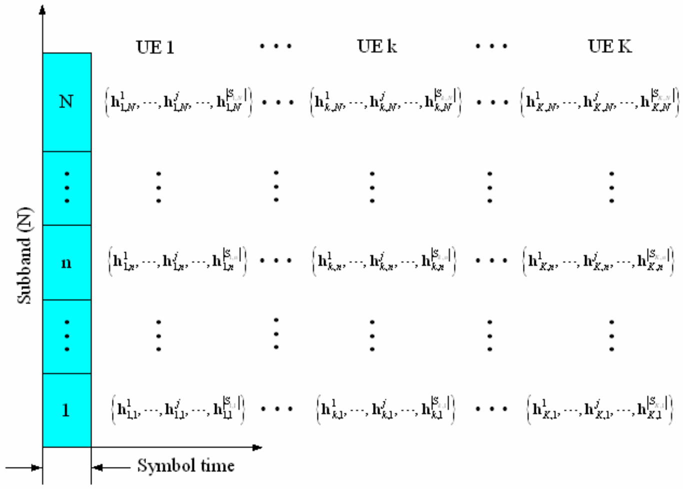

Fig. 1. Eigenmodes cross frequency and spatial domains .

spatial domain considered in MET to a two-dimension space, namely joint frequency-spatial domain. $\mathbf{H}_{k,n}$ represents the channel of user k on subband n. The SVD of $\mathbf{H}_{k,n}$ can be expressed as $\mathbf{U}_{k,n}\Lambda_{k,n}\mathbf{V}_{k,n}$, where the singular value are indexed in descending order: $\sqrt{\lambda_{k,n}^1} \geq \sqrt{\lambda_{k,n}^2} \geq \cdots \geq \sqrt{\lambda_{k,n}^{|S_{k,n}|}}$. Let $\mathbf{u}_{k,n}^j$ and $\mathbf{v}_{k,n}^j$ be the j-th column of $\mathbf{U}_{k,n}$ and $\mathbf{V}_{k,n}$, respectively. We denote the j-th eigenmode of user k on subband n as $\mathbf{h}_{k,n}^j = \sqrt{\lambda_{k,n}^j}(\mathbf{v}_{k,n}^j)^H$. Instead of scheduling based on UE level, our scheme focuses on selection of a suitable subset of eigenmodes. The receive matrix $\mathbf{F}_{k,n}$ consists of the conjugate transposes of the columns of $\mathbf{U}_{k,n}$ corresponding to the selected eigenmodes of user k on subband n. For example, if the j_a-th, $(a = 1, \cdots, |S_{k,n}|)$ eigenmode of user k on subband n is selected by the scheduling algorithm, then we have $\mathbf{F}_{k,n} = [\mathbf{u}_{k,n}^1, \cdots, \mathbf{u}_{k,n}^{|S_{k,n}|}]$ and

$$\hat{\mathbf{H}}_{k,n} = \mathbf{F}_{(k,n)}\mathbf{H}_{k,n} = [(\mathbf{h}_{k,n}^{j_1})^H, \cdots, (\mathbf{h}_{k,n}^{j_{|S_{k,n}|}})^H] \quad (8)$$

Assume Ω_i is a subset of eigenmodes, whose elements (k, n, j) corresponds to $\mathbf{h}_{k,n}^j$. Sice the transmission on subbands are orthogonal, Ω_i consists of N non-overlapped subsets, $\Upsilon_n, n = 1, \cdots, N$. For each subset Υ_n, we construct the subset Θ_j^n of users, such that if user $k \in \Theta_j^n$, then at least one of the eigenmodes in Υ_n belonges to user k. We apply the BD algorithm for the users in Θ_j^n. There exists a precoding matrix which have

$$\hat{\mathbf{H}}_{k,n}\mathbf{T}_{j,n} = 0 \ for \ all \ j \neq k \ and \ j, k \in \Upsilon_n \quad (9)$$

Perform SVD of the effective channel after precoding for user $k \in \Upsilon_n$.

$$\hat{\mathbf{H}}_{k,n}\mathbf{T}_{k,n} = \mathbf{U}_{k,n} \begin{bmatrix} \Sigma_{k,n} & 0 \\ 0 & 0 \end{bmatrix} [\mathbf{V}_{k,n}^{(1)} \ \mathbf{V}_{k,n}^{(0)}]^H \quad (10)$$

Then we can get the sum capacity achieved on subband n by

$$R_{\Upsilon_n} = \max \sum_{k \in \Theta_j^n} \sum_{j=1}^{|L_{k,n}|} \log(1 + p_{k,n}^j(\tilde{\lambda}_{k,n}^j)^2) \quad (11)$$

where $|L_{k,n}|$ is the number of scheduled eigenmodes of user k on subband n, and $\tilde{\lambda}_{k,n}^j$ is the j-th eigen value of $\Sigma_{k,n}$. Accordingly, the capacity achieved on all subbands is obtained by

$$R_{\Omega} = \max \sum_{n=1}^{N} \sum_{k \in \Theta_j^n} \sum_{j=1}^{|L_{k,n}|} \log(1 + p_{k,n}^j(\tilde{\lambda}_{k,n}^j)^2) \quad (12)$$

$$s.t. \ \sum_{n=1}^{N} \sum_{k \in \Theta_j^n} \sum_{j=1}^{|L_{k,n}|} p_{k,n}^j \leq P_{Total} \quad (13)$$

Since the transmissions on different subbands are orthogonal and the streams on the same subband are also orthogonal by BD and SVD processing, the above problem can be solved by cross frequency-spatial water-filling. The detailed cross subband eigenmode selection and power allocation of EMET is shown as the following.

Power allocation

i) Total power is allocated for all scheduled eigenmodes by the water-filling algorithm in each iteration.

Eigenmode selection

i) Initially, the eigenmode which achieves maximum $r_{k,n}^j$ supported by the total power at eNB, denoted by P_{Total}, is selected.

ii) For each iteration, assumming each eigenmode (on frequency domain, or by MET on spatial domain if the number of the scheduled eigenmodes is less than the number of transmit antenna, denoted by M_t) from the unselected eigenmode sets is added to the selected eigenmode sets and the corresponding capacity variations are obtained. Finally, the eigenmode which achieves the maximum capacity improvement is moved to the selected eigenmode set.

iii) The scheduling processing is terminated if the number of selected eigenmode reaches the downlink antenna freedom on each subbands or no more capacity gain is obtained.

Let Ω denote the candidate set of eigenmodes and Υ be the selected eigenmodes. The detailed proposed EMET algorithm is given by Fig. 2.

To balance the performance gain and computational complexity, two simplified EMET schemes are proposed. Fig. 3 shows that detailed algorithm description of the proposed two simplified schemes.

Scheme I:

Power allocation

i) Power allocation for each iteration is greedily increased by: $\triangle P = P_{Total}/Q$, Q, Q is the power iterative number.

Eigenmode selection

i) Initially, assuming $\triangle P$ is allocated on each subband, perform MTE, calculate the capacity achieved on each subband

Basic enhanced multiuser eigenmode selection (EMET) algorithm

1) Initially, let $\Omega = \left\{(k,n,j) \middle| k=1,...,K, n=1,...,N, j=1,...,\left|S_{k,n}\right|\right\}$, and $\Upsilon = \varnothing$. Calculate $\lambda_{k,n}^{j}$, and $\mathbf{h}_{k,n}^{j}$ by SVD.

2) Let $(u_1, v_1, s_1) = \arg\max_{(k,n,j)\in\Omega} \lambda_{k,n}^{j}$, $\Omega = \Omega - (u_1, v_1, s_1)$ and $\Upsilon = \Upsilon + (u_1, v_1, s_1)$. Set $R_{temp} = \log(1 + P_{Total}\lambda_{u_1,v_1}^{s_1})$.

3) For $i = 2 : N * N_T$

   a) For every $(k,n,j) \in \Omega$, only if the number of the selected eigenmodes on subcarrier n is less than N_T

      i) Let $\overline{\Upsilon}_{k,n,j} = \Upsilon + (k,n,j)$. Its corresponding user subset on different subbands is denoted as $\overline{\Im}_i^n$;

      ii) Determine $\mathbf{T}_{k,n}$ by SVD and calculate the effective channels on N subbands;

      iii) Perform SVD of $\hat{\mathbf{H}}_{k,n}\mathbf{T}_{k,n}$ $\left(k \in \overline{\Im}_i^n\right)$ on N subbands to obtain their singular values $\left\{\sqrt{\tilde{\lambda}_{k,n}^{j}}\right\}$.

      iv) Calculate $R_{k,n,j}$ by water-filling over $\tilde{\lambda}_{k,n}^{j}$.

   b) Let $(u_i, v_i, s_i) = \arg\max_{(k,n,j)\in\Omega} R_{k,n,j}$

   c) If $\max_{(k,n,j)\in\Omega} R_{k,n,j} < R_{temp}$

      The algorithm terminates.

   else Let $\Omega = \Omega - (u_i, v_i, s_i)$, $\Upsilon = \Upsilon + (u_i, v_i, s_i)$, and $R_{temp} = \max_{(k,n,j)\in\Omega} R_{k,n,j}$.

Fig. 2. Algorithm description of EMET.

Simplified EMET Scheme I

1) Initially, assuming ΔP, ($\Delta P = P/Q$, Q is the predefined iteration number) is allocated on each subband n, $P_n = \Delta P, \left(n = 1, \cdots, N\right)$, perform the MTE algorithm with allocated P_n and calculate R_n on subband $n \left(n = 1, \cdots, N\right)$. Allocated ΔP to the subband $j = \arg\max_n R_n$

2) For $i = 2 : Q$

   a) For the processed subband j in the previous iteration, allocate additional ΔP, thus $P_j = P_j + \Delta P$.

   b) Recalculate $R_j^{'}$ on subband j by MET, and update $R_j = R_j^{'} - R_j$

   c) Allocate ΔP to the subband $j = \arg\max_n R_n$

3) The algorithm terminates when P_{Total} is assigned up.

(a) Algorithm description of Scheme I

Simplified EMET Scheme II

1) P_{Total} is initially equally allocated on N subbands, and perform MET on each subband.

2) For the selected eigenmode on N subbands in the pervious step, perform water-filling.

(b) Algorithm description of Scheme II

Fig. 3. Algorithm description of the simplified schemes .

R_n, $n = 1, \cdots, N$, select the eigenmodes on sumbarrier $i = arg\max_n R_n$.

ii) For each iteration, assuming additional $\triangle P$ is allocated on the processed subband in the previous step, repeat MET with updated assigned power, update the capacity R_n by the capacity variation achieved by the additional $\triangle P$ on subband n, finally we also select the eigenmode on subband $i = arg\max_n R_n$.

iii) The iteration terminates till the P_{Total} is assigned up.

Scheme II:

i) The total power is initially equally allocated on N subbands, and perform MET with water-filling power allocation on each subcband.

ii) For all scheduled eigenmodes obtained in the above step, perform water filling power allocation cross the frequency and spatial domain.

IV. Simulation Results

In our simulations, we consider an ideal single cell scenario, and assume the total system bandwidth is 20 MHz, which is divided into 1200 subcarreirs, and 1200 is further grouped to 100 subbands. There are $K = 10$ mobile users in a cell. The number of antennas at each mobile user is $M_r = 2$, and the number of antennas at a base station is $N_t = 4$. The average SNR for downlink transmissions is varied from 0 dB to 20 dB. For the generation of channel model, We consider the ITU Umi channel model [13], which is widely use for LTE performance evaluation in 3GPP RAN1 discussions. The transmission data is assumed to be enough at each user's buffer. The simulation time is 100 TTI. Our simulation tool is Matlab V7.0. In order to reduce the computational complexity and speed up the run time of simulations, we assume each user only transmit one stream, namely, the principle eigenmode of each user participates the eigenmode selection cross frequency-spatial domains. It is proved that if the number of user is large enough, the performance achieved by priciple eignmode transmission approximates that achieved by multiple eignmode transmission. In this paper, we compare our proposed algorithm with the two types of algorithms. The first type algorithm is based on MTE but with different power allocation schemes. In MET-1, the total power is allocated to each subcarrier equally, then for each subcarrier, the power is further allocated on steams equally. For MET-2, the total power is allocated to each subcarrier equally, then for each subcarrier, however, the power is allocated to subcarriers by waterfilling. The second type of algorithm compared is based on zero-frocing (ZF) precoding. Due to the transmissions are based on principle eigenmode, the BD algorithm is reduced to ZF for MU-MIMO precoding. The differences between ZF-1 and ZF-2 on power allocation are the same with MET-1 and MET-2. Greedy stream selection is also utilized in ZF based MU-MIMO algorithms. Fig. 4 shows the sum capacity of these algorithms. It could be found that for the ZF based precoding algorithms, the performance is very poor, while the optimal power allocation on each subcarrier could greatly increase

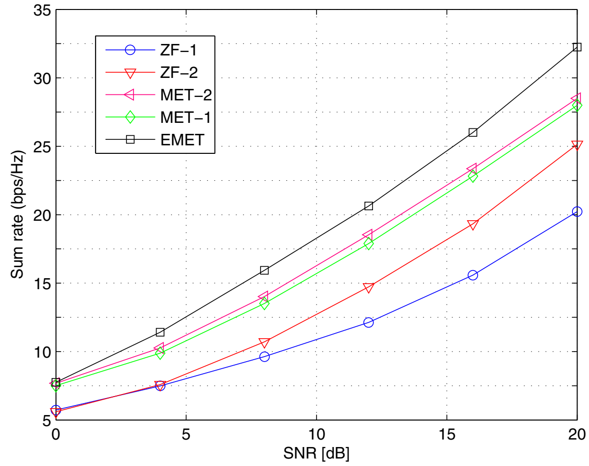

Fig. 4. Capacity comparison for OFDM-MIMO downlink systems.

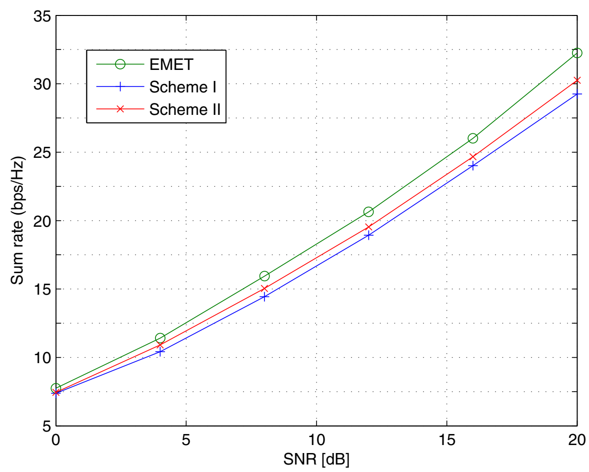

Fig. 5. Performance comparison of EMET and simplified schemes .

the performance. The MET based precoding algorithm could significantly increase performance compared with ZF based precoding, as presented in original paper. However, we found that the waterfiling power allocation on each subcarrier could only achieve limited improvement compared with the equal power allocation on streams. Finally, it is observed that the performance of EMET has distinct enhancement compared with MTE based algorithms. EMET exploit more frequency diversity gain then the compared algorithms, thus a nearly optimal performance gain with greedy resource allocation is obtained. For clearance, Fig. 5 shows the performance of our proposed EMET and the simplified versions. It is a trade-off between the performance and computational complexity.

V. Conclusions

In this paper, the joint frequency-spatial resource allocation is studied. We proposed an enhanced multi-user eigenmod selection on joint frequency and spatial domains, namely EMET, which jointly consider the precoding, eigenmode selection and optimal power allocation for OFDM-MIMO system. The simulation results shows that the performance of EMET could achieve a near optimal performance with greedy resource allocation on eigenmode level, and achieve significant gain compared with MET based or ZF based algorithms. To balance the performance gain and computational complexity, two simplified EMET schemes are proposed, which provided multiple choices for real implementation, such as the hotly discussed LTE-A system. In summary, all the proposed algorithms jointly consider the resource allocation in frequency and spatial domains simultaneously, their performances outperform the current adopted scheme in OFDM-MIMO systems.

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