Low Computational Design of Large Transmit Array MIMO Using Flexible Subarray Grouping

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***Abstract*—This paper presents an improved version of low computational block diagonalization for Multiple Input Multiple Output (MIMO) multiuser telecommunication system equipped with a large array in transmitter side. While uniform subarray structure simply based on antenna index is adopted in previous work, this study investigates the effective flexible subarray grouping based on channel condition between antenna elements and receivers. In subarray grouping of large transmit array, all antenna elements are first sorted in the descent order of a certain metric, and then, they are grouped into subarrays according to a certain rule (in this paper, two metrics and two rules are considered). Through computer simulations, it is shown that this scheme is not effective for uniform subarray, but in nonuiform construction, it could achieve performance improvement under certain conditions.**

Keywords–Large array antenna; massive Multiple Input Multiple Output (MIMO); multiuser; subarray; zero-forcing.

I. INTRODUCTION

Multiple Input Multiple Output (MIMO) telecommunication system which utilizes array antenna in both of the transmitter and receiver sides has been established as a strategy which increases the data rate and/or reliability in the wireless communications [1]. To cope with the further increasing demand of the capacity, recently collecting attentions is so-called large or massive MIMO [2] which is equipped with large array one or both ends. It is actively studied also in industrial sector as given in [3]-[5]. In this system, the main topic is how to reduce the heavy computational load originated from a large number of antenna elements. For this aim, many approaches based on nonlinear processing [6] like suboptimal search method (for example, the application of tabu search in uplink for maximal likelihood detection [7], and in downlink for vector perturbation [8]) and belief propagation [9] have been proposed.

In the previous work [10], paying attentions to the fact that the linear processing approach which is popular in the conventional MIMO multiuser communication is not well investigated for the large array antenna model, we have proposed low computational version of block diagonalization for the MIMO system with large transmit array. This system first divide a large array into subarrays, and then, block diagonalization is applied to each of them: in [10], the subarrays are uniformly grouped simply based on antenna index not considering the state of the transmit antenna element to user connection. This study investigates the effect of more sophisticated grouping based on the channel condition between transmit antenna element to user, where two types of ordering metrics and two types of grouping rules are considered. Intuitively, subarray grouping based on the connection strength seems to bring performance improvement, but as shown later, this prediction does not consist in simple case like [10]. Then, when it is effective? How much is the improvement? The answers of those questions and features of flexible subarray grouping are shown in this paper.

The overall organization is as follows: Section II gives the system model of the multiuser MIMO considered in this study. Section III describes the low computational design method of the multiuser MIMO with large transit array utilizing the flexible subarray grouping. In Section IV, evaluation of the system performance is carried out through computer simulations based on the comparison with the conventional methods. Finally, in Section V, the conclusions of this study are described together with the future works.

II. SYSTEM MODEL

The model of MIMO multiuser system considered in this study is depicted in Figure 1, which consists of a transmitter Tx with N_t antennas and M receivers $\mathrm{Rx}_0, \cdots, \mathrm{Rx}_{M-1}$ with $N_{r,0}, \cdots, N_{r,M-1}$ antennas, respectively. Transmitter Tx transmits L_m data streams $\{s_{m,0}(t), \cdots, s_{m,L_m-1}(t)\}$ to receiver Rx_m using N_t-dimensional weight vectors $\boldsymbol{w}_{t,m,0}, \cdots, \boldsymbol{w}_{t,m,L_m-1}$. After passing propagation channel represented by $N_{r,m}$-by-N_t matrix H_m, a replica $\hat{s}_{m,\ell}(t)$ of data stream $s_{m,\ell}(t)$ is produced at Rx_m using $N_{r,m}$-dimensional weight vector $\boldsymbol{w}_{r,m,\ell}$. Here, the (n_r, m_t)-th element of H_m is the channel response between the n_t-th element of transmit array and the n_r-th element of receive array.

Though the picture of Figure 1 shows a typical MIMO multiuser downlink model, here, one assumption is added: the transmitter Tx has a large number of antenna elements (namely, N_t is a large number: in this study, $N_t = 128$) as shown in the simulation section (on the other hand, $N_{r,m}$ is assumed to be a small number: in this study, $N_{r,m} = 2$). Under this condition, generally, a heavy computational load is required for the design of the transmit weight, and the reduction of computation is an important topic in this kind of system. One solution is given in [10], and the next section suggests its improved version attempting better performance.

III. SYSTEM DESIGN

In the previous work in [10], we have presented a low computational design method of MIMO downlink system with a large transmit array, based on block diagonalization [6], which is a popular linear processing technique of multiuser MIMO. This section describes an improved version with flexible subarray grouping taking into account the channel condition.

First, a large transmit antenna is divided into S subarrays $\mathrm{Tx}_0, \cdots, \mathrm{Tx}_{S-1}$. Subarray Tx_s consists of antennas with index set $\mathcal{N}_t^{(s)} = \{n_{t,s,0}, \cdots, n_{t,s,N_{t,s}-1}\}$, where any

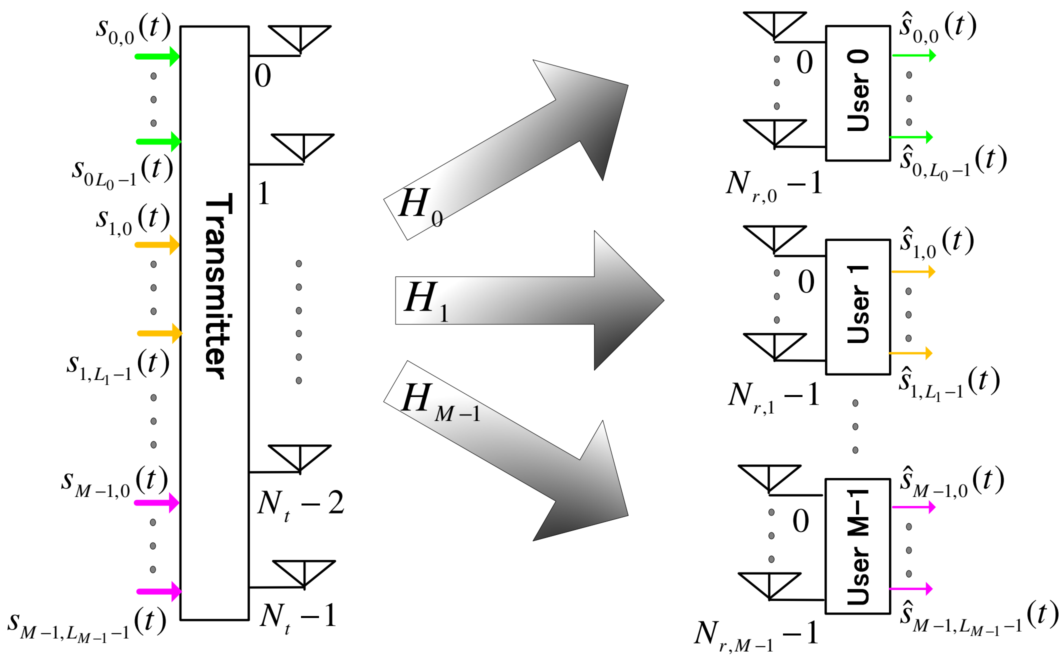

Fig. 1 Model of MIMO multiuser system (downlink).

antenna element belongs to only one of S subarrays (therefore, $N_t = \sum N_{s,k}$ consists). Here, the problem is how to construct those subarrays. Though uniform subarrays are constructed simply in the order antenna index regardless of the channel state in [10], namely, $\mathcal{N}_t^{(s)} = sN_{t,0} + \{0, \cdots, N_{t,0} - 1\}$ (remark that $N_{t,s} = N_{t,0}$ for any s), in this study, we consider flexible subarray grouping. The whole procedure of flexible subarray grouping is depicted in Figure 2.

In the first step, one of the following two metrics based on the channel condition between the n_t-th transmit antenna element and the m-th receiver end is calculated:

(M-1) *Norm Metric*: This metric is defined by $f_{n_t} = \|\boldsymbol{h}_{m,n_t}\|$, where $\boldsymbol{h}_{m,n_t}$ is a Single Input Multiple Output (SIMO) channel defined by $\boldsymbol{h}_{m,n_t} = [H_{m,0,n_t}, \cdots, H_{m,N_{r,m}-1,n_t}]^T$, and H_{m,n_r,n_t} is a scalar which shows response between the n_t-th antenna element of Tx and the n_r-th antenna element of Rx_m.

(M-2) *Absolute Sum Metric*: This metric is defined by equation $f_{n_t} = \sum_{n_r} |H_{m,n_r,n_t}|$, which does not require any multiplication operation. It is more preferable choice compared with norm metric from the viewpoint of the computational cost (remark that since the calculation of metric is carried out user by user, advantage of this simplicity becomes large).

In the following, the transmit antenna elements are renumbered in descent order, namely, indices $\{n_{t,0}\, n_{t,1} \cdots, n_{t,N_t-1}\}$ such that $f_{n_{t,0}} \geq f_{n_{t,1}} \geq \cdots \geq f_{n_{t,N_t-1}}$ are replaced by new indices $\{0, 1, \cdots, N_t - 1\}$ (after this operation, $f_0 \geq f_1 \geq \cdots \geq f_{N_t-1}$ consists). The conventional approach in [10] can be regarded as a scheme adopting random number as metric f_{n_t} because of the i.i.d. (independent and identically distributed) statistics of the fading.

In the second step, based on the above ordering, subarray grouping is carried out according to one of the following two rules:

(R-1) *Even Grouping*: Antenna $0, 1, 2, \cdots$ are grouped into $\mathcal{N}_t^{(0)}, \mathcal{N}_t^{(1)}, \mathcal{N}_t^{(2)}, \cdots$ in the order of the antenna index after the renumbering. If it reached to $s = S - 1$ (namely, $\mathcal{N}_t^{(S-1)} = \{S - 1\}$), then the subarray index return to 0, like $\mathcal{N}_t^{(0)} = \mathcal{N}_t^{(0)} \cup \{S\}, \mathcal{N}_t^{(1)} = \mathcal{N}_t^{(1)} \cup \{S + 1\}, \cdots$. If the number of elements in $\mathcal{N}_t^{(s)}$ has reached to $N_{t,s}$, this subarray is excluded from the above circulation. This operation attempts to keep the average metric of all the subarrays equal as possible.

(R-2) *Uneven Grouping*: Transmit antennas are grouped like $\mathcal{N}_t^{(s)} = \sum_{k=0}^{s-1} N_{t,k} + \{0, \cdots, N_{t,s}\}$, namely, $N_{t,0}$ antennas with the strongest metric are grouped into the first subarray, and those with the next strongest $N_{t,1}$ are distributed to the second subarray. This operation is repeated all the N_t elements are grouped into one of subarrays.

As a consequence of the above subarray grouping, subchannel between subarray Tx_s and receiver Rx_m is derived as $H_m^{(s)} = [\boldsymbol{h}_{m,n_{t,s,0}}, \cdots, \boldsymbol{h}_{m,n_{t,s,N_{t,s}-1}}]$.

After subarray construction, the conventional block diagonalization is applied to each subarray. Since the optimal receiver weight is different subarray by subarray, two methods – Method 1 (Tx and Rx simultaneous design) and Method 2 (Rx first Tx second design) – are considered to determine it uniquely (for the detail, see [10]).

(i) *Method 1*: Subarray weight vector $\boldsymbol{w}_{t,m}^{(s)} = V_m^{(s)} \boldsymbol{v}_m^{(s)}$ is calculated by block diagonalization of $H_m^{(s)}$, where the columns of $V_m^{(s)}$ span the kernel of $H_{-m}^{(s)} = [H_0^{(s)T}, \cdots, H_{m-1}^{(s)T}, H_{m+1}^{(s)T}, \cdots, H_{M-1}^{(s)T}]$, and $\boldsymbol{v}_m^{(s)}$ is the right singular value vector of $H_m^{(s)} V_m^{(s)}$ corresponding to the largest singular value. Then, virtual channel $H_{v,m} = [H_m^{(0)} \boldsymbol{w}_{t,m}^{(0)}, \cdots, H_m^{(S-1)} \boldsymbol{w}_{t,m}^{(S-1)}]$ is cal-

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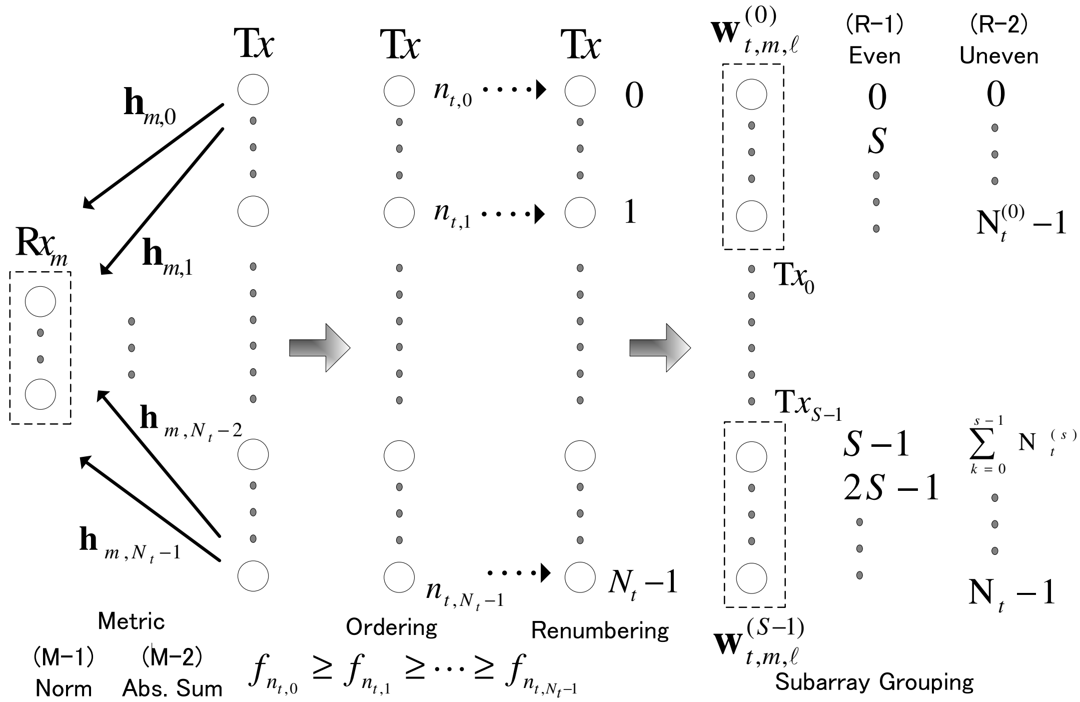

Fig. 2 Procedure of flexible subarray grouping.

culated, and transmitter and receiver weights $\boldsymbol{w}_{t,m,\ell} = [c^{(0)}_{m,\ell}\boldsymbol{w}^{(0)T}_{t,m},\ \cdots,\ c^{(S-1)}_{m,\ell}\boldsymbol{w}^{(S-1)T}_{t,m}]^T$ and $\boldsymbol{w}_{r,m,\ell}$ are derived, where $\boldsymbol{w}_{r,m,\ell}$ and $\boldsymbol{c}_{m,\ell} = [c^{(0)}_{m,\ell},\ \cdots,\ c^{(S-1)}_{m,\ell}]^T$ are the left and right singular value vectors of $H_{v,m}$ corresponding to the ℓ-th largest singular value (it is defined as $\ell = 0$ for the largest one).

(ii) *Method 2*: Receiver weight $\boldsymbol{w}_{r,m,\ell}$ is derived as the left singular value vector of H_m, and then, channel $\tilde{H}_m = [H^T_m\boldsymbol{w}^*_{r,m,0},\ \cdots,\ H^T_m\boldsymbol{w}^*_{r,m,L_m-1}]^T$. After the calculation of $\boldsymbol{w}^{(s)}_{t,m}$ and $H_{v,m}$ is carried out in a similar manner as Method 1 but using $\tilde{H}_m$ instead of H_m, vector $\boldsymbol{c}_{m,\ell} = \boldsymbol{h}_{m,\ell}$ is derived from $H_{v,m} = [\boldsymbol{h}^T_{m,0},\ \cdots,\ \boldsymbol{h}^T_{m,L_m-1}]^T$.

The additional computational cost introduced by the proposed method is generally small. Once the metric is given, that for the distribution to groups is almost negligible. For the calculation of metrics, $N_t \sum N_{r,m}$ multiplications should be performed under the use of norm metric, but if the absolute sum metric with no multiplication suggested in this paper (the performance degradation from the norm metric is very small) is used, the complexity is only slightly increased, and not so much different compared with that of BD.

IV. Computer Simulations

In this section, computer simulations are carried out to verify the effectiveness and features of the proposed method described in Section III. The default simulation conditions are summarized in Table I.

The performance is evaluated using sum capacity represented by $C_m = \sum_{\ell} \log_2(1 + \text{SINR}_{m,\ell})$ for the m-th user, where $\text{SINR}_{m,\ell}$ is the Signal to Interference plus Noise Ratio (SINR) of the output signal $\hat{s}_{m,\ell}(t)$ of the ℓ-th stream of the m-th user (it is calculated by using 200 samples of fading channels). On the other hand, Signal to Noise Ratio (SNR) is defined by $\text{SNR}_m = P_{s.m}/P_{n,m}$, where $P_{s,m} = 1$ and $P_{n,m}$ are the total energy of the transmitted signal and the receiver noise.

The number of users is $M = 4$ and each of them is equipped with $N_{r,m} = 2$ antennas, and two data streams are send to Rx_m (hence $L_m = 2$) using $N_t = 128$ antennas from transmitter Tx based on the energy allocation by the

TABLE I. Simulation Conditions

Number of Receivers (Number of Users)	$M = 4$
Number of Transmit Antennas	$N_t = 128$
Number of Receive Antennas	$N_{r,m} = 2$
Number of Streams per User	$L_m = 2$
Subarrays (uniform)	$S = 16$ $N_{t,s} = 8$ $\mathcal{N}^{(s)}_t = 8s + \{0,\ \cdots,\ 7\}$ $s = 0,\ \cdots, S-1$
Subarrays (nonuniform)	$S = 12$ $N_{t,s=0\sim3} = 16$ $\mathcal{N}^{(s=0\sim3)}_t = 16s$ $+\{0,\ \cdots,\ 15\}$ $N_{t,s=4\sim S-1} = 8$ $\mathcal{N}^{(s=4\sim S-1)}_t = 8(s-4)$ $+\{0,\ \cdots,\ 7\} + 64$
Grouping Metric	Absolute Sum
Grouping Rule	Uneven Grouping
Energy Constraint	$P_m = 1$
SNR	$\text{SNR}_m = 20\text{dB}$
Channel Statistics	i.i.d. Rayleigh Fading with unit variance

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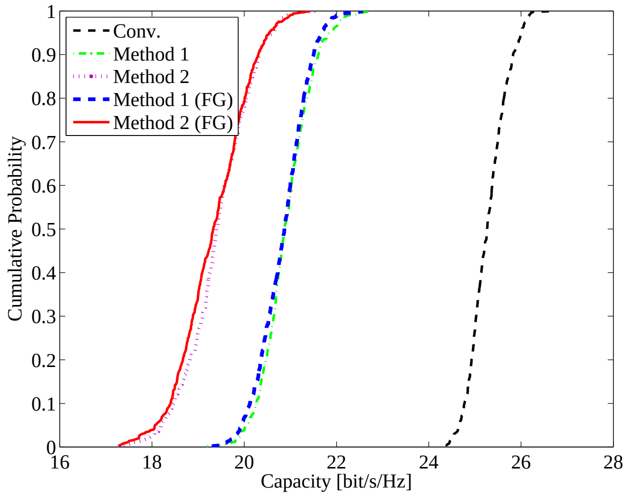
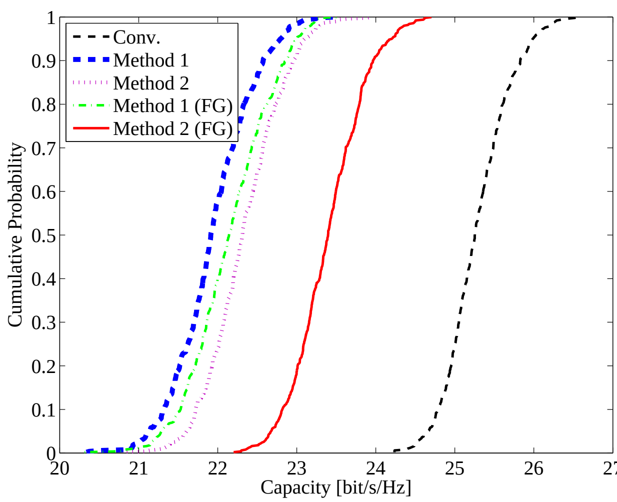


(a) Uniform subarray grouping.



(b) Nonuniform subarray grouping.

Fig. 3 Distribution function of capacity.

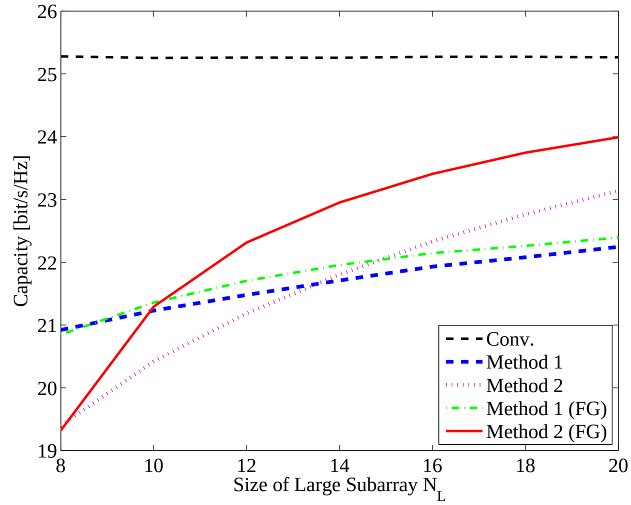


Fig. 4 Large subarray size versus capacity.

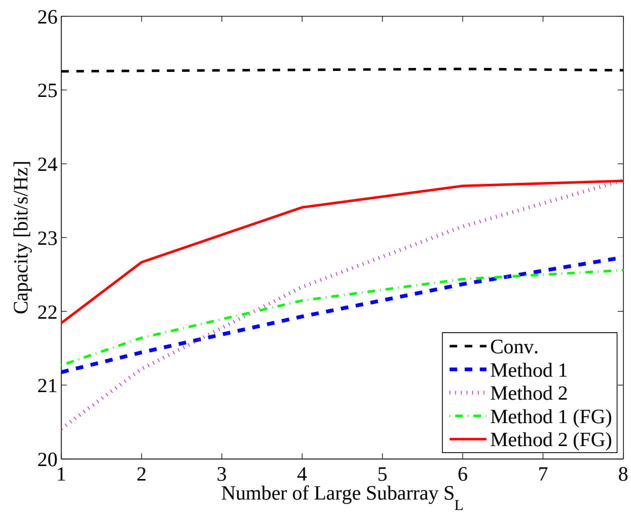


Fig. 5 Number of large subarray versus capacity.

water filling. Under this condition, default size and number of subarray are $N_{t,s} = 8$ and $S = 16$ for uniform case, and $N_{t,s=0\sim3} = 16$, $N_{t,s=4\sim S-1} = 8$ and $S = 12$ for nonuniform case.

Figure 3 depicts the distribution functions of capacity (since the curves of all users are almost same because of the symmetry of fading statistics in channels, it is drawn only for one user) for the case of the absolute sum metric and uneven grouping. Five curves respectively shows the results of the conventional block diagonalization (Conv.), Method 1 and Method 2 in [10], and those with flexible subarray grouping in Section III (Method 1 (FG) and Method 2 (FG)). In subplot (a) for uniform subarray grouping, the curves of Method 1 (FG) and Method 2 (FG) are overlapped with those of Method 1 and Method 2, which means flexible grouping is *not effective*. On the contrary, in nonuniform subarray grouping in subplot (b), the performance of Method 1 (FG) and Method 2 (FG) is better than that of Method 1 and Method 2, which means flexible grouping is *effective* (in this subplot, the position of the curves of Method 2 and its FG version is moved to the right of those of Method 1 and its FG version, since the increased degrees of freedom in a large subarray brings advantage to Method 2 [10]). From those results, it is considered that the proposed flexible grouping approach is a better choice when nonuniform array is adopted and antennas with the strong connection to the user is grouped into large subarrays. Another important point is that the performance improvement between Method 2 and Method 2 (FG) is larger than that of Method 1 and Method 1 (FG).

Here, though the graph is not shown, the results of the norm and absolute sum metrics have only slight difference, hence we adopt absolute sum metric with much smaller computation in the rest of the simulation. We have also verified that the even grouping does not bring the performance improvement regardless of subarray construction. The reason is considered as follows: because of the randomness of the fading channel, even without antenna ordering, the average metric becomes almost same among subarrays.

To investigate the influence of the subarray size in the proposed approach, Figure 4 plots the large subarray size N_L

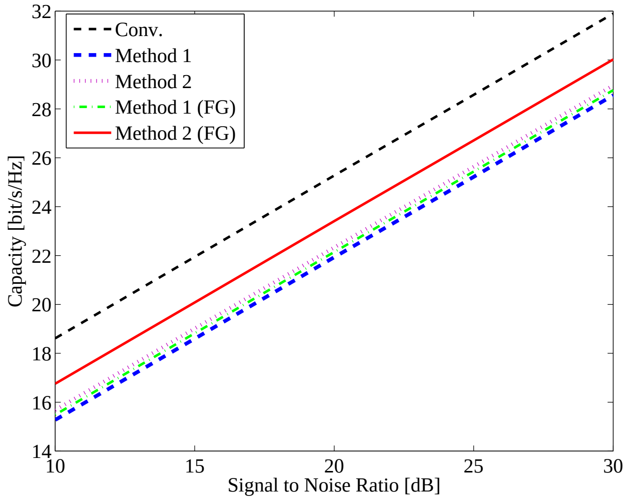


Fig. 6 SNR versus capacity.

versus capacity relation for nonuniform subarray construction. Among S subarrays, four subarrays $\mathrm{Tx}_{s=0\sim 3}$ have large size $N_L = N_{t,s=0\sim 3} \in \{8,\ 10,\ 12,\ 14,\ 16,\ 18,\ 20\}$, and other $S-4$ subarrays have short size $N_S = N_{t,s=4\sim S-1} = 8$. According to the uneven grouping rules, the antennas with strong connection to the target receiver are gathered into large subarrays. From this figure, it can be verified that the performance improvement by the proposed method becomes larger as the large subarray size in nonuniform scheme is increased. In this figure, Method 2 (FG) has better performance than the conventional methods in [10] except the uniform case of $N_S = N_L = 8$. It is also shown that the advantage of Method 2 (FG) against Method 1 (FG) is large under the large subarray size.

Figure 5 depicts the number of large subarray S_L versus capacity curves. Among S subarrays, $\mathrm{Tx}_{s=0\sim S_L-1}$ have large size $N_L = N_{t,s=0\sim S_L-1} = 16$, and other $S_S = S - S_L$ subarray have short size $N_S = N_{t,s=S_L\sim S-1} = 8$. What can be observed from this picture is that the performance improvement by the proposed method compared with the conventional approach [10] becomes small as the number of large subarray increases. This result shows the proposed method is advantageous when the uniformity of the subarray construction is small.

The relation between SNR and per-user capacity is drawn in Figure 6. From this figure, it can be seen that the relation among five methods does not depend on SNR.

V. Conclusions and Future Works

This paper has investigated on flexible subarray grouping in low computational block diagonalization for MIMO multiuser system adopting a large array in the transmitter side. All transmit antenna elements are first sorted in the descent order of one of two metrics (norm and absolute sum), and then, they are grouped into one of subarrays according to one of two rules (even and uneven grouping). Computer simulations have demonstrated that the proposed approach is useless for uniform subarray construction, but as the nonuiformity of subarray increases, one of two rules, uneven strategy invokes its effectiveness under certain conditions, and the performance improvement compared with the conventional approach in [10] becomes larger, where also shown is the simple absolute sum metric is sufficient.

A future work is the investigation on the subarray processing based on Minimum Mean Square Error (MMSE) criterion. Utilization of the subarray strategy for the signal detection in the large array is another attractive topic of study.

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