Unified Optimal Power Allocation Strategy for MIMO Candidates in 3GPP HSDPA

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We compare the achievable throughput of time division multiple access (TDMA) multiple-input multiple-output (MIMO) schemes illustrated in the 3rd Generation Partnership Project (3GPP) MIMO technical report, versus the sum-rate capacity of space-time multiple access (STMA). These schemes have been proposed to improve the 3GPP high speed downlink packet access (HSDPA) channel by employing multiple antennas at both the base station and mobile stations. Our comparisons are performed in multi-user environments and are conducted using TDMA such as Qualcomm's High Data Rate and HSDPA, which is a simpler technique than STMA. Furthermore, we present the unified optimal power allocation strategy for HSDPA MIMO schemes by exploiting the similarity of multiple antenna systems and multi-user channel problems.

Keywords: Multi-input multi-output (MIMO), space-time multiple access (STMA), 3GPP standard.

I. Introduction

In third generation wireless mobile communications such as wideband code division multiple access (WCDMA), high data rate transmissions need to be supported for wireless multimedia services. High speed downlink packet access (HSDPA) is a promising technique to achieve a bit rate of 10 Mbps [1]. The HSDPA system employs various technologies such as adaptive modulation and coding, hybrid automatic repeat requests, fast cell selection, and multiple-input multiple-output (MIMO) antenna processing. Among them, MIMO techniques have been proven to boost up spectral efficiency much higher than using other technologies [2]-[4]. The industrial organizations have proposed their MIMO solutions for the 3rd Generation Partnership Project (3GPP) standard in which various multiple-antenna schemes combined with HSDPA are under active discussions [5].

There are various categorized MIMO schemes, depending on the target performance characteristics, which increase data rate as well as spectral efficiency [6], [7]. Beamforming is a good candidate for interference suppression and high capacity performance with a long history of research work [8]; for example, in [9] beamforming is explored in a MIMO context. A smart antenna exploits beamforming to increase system capacity and reduce the interference in cellular environments. Spatial multiplexing is the most recent MIMO scheme. Lucent developed the Bell Labs' layered space-time (BLAST) architecture, which has two major variants, namely vertical BLAST (V-BLAST) [10] and diagonal BLAST (D-BLAST) [7]. BLAST-based schemes achieve spatial multiplexing gain by transmitting simultaneously independent data streams on the different transmit branches and at the same spreading code. In V-BLAST, independent channel coding is applied to each sub-layer, that is, different data substreams are mapped to each transmit antenna.

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Most of the previous MIMO schemes are designed for point-to-point communications, which is referred to as single-user MIMO (SU-MIMO). For the evaluation of system performance, a multi-user environment needs to be considered, whereas SU-MIMO systems focus on link performance without any higher layer assumptions. In multi-user MIMO (MU-MIMO) systems, priority scheduling is applied for downlink transmission to serve multiple mobile stations [11], [12] so that, for performance evaluation, the system-level approach is preferable over the link-level one. In this paper, we compare the capacity performances of SU-MIMO with MU-MIMO.

It is well known that the optimal solution for MIMO systems is (singular value decomposition-based) full beamforming with a water-filling (WF) solution, which assumes perfect channel state information (CSI) at both the transmitter and receiver. When imperfect CSI is available at the transmitter, the non beamforming approach [13] or the partial beamforming approach [14] can be considered, resulting in suboptimal performance.

On the other hand, the problem of power allocation in MIMO with non/partial beamforming at the base station has not yet been solved in a unified way, to our best knowledge. Therefore, we investigate the unified power allocation method for such cases.

In our numerical results, it is shown that the partial beamforming approach with our unified method outperforms the non-beamforming approach, while both are upper bounded by the full beamforming approach. In our unified power allocation, we exploit a similarity between multiple antenna systems and multi-user channel problems.

The rest of the paper is organized as follows. Section II describes the channel model. In section III, we examine the achievable rate of SU-MIMO and MU-MIMO. Section IV observes the system characteristics of MIMO candidates in 3GPP. We propose the unified optimal power allocation strategy of the selected MIMO schemes in section V. Finally, we conclude in section VI.

Notation: The matrix norm of $\mathbf{H}$ is defined by $\|\mathbf{H}\| = \sqrt{\lambda_{\max}(\mathbf{H}^H\mathbf{H})}$.

II. System Model

In Fig. 1, a multi-user MIMO system in wireless mobile channels is illustrated, in which a radio base station communicates with K mobile stations. Each mobile station has M_r receive antennas, while the base station has M_t transmit antennas. Based on the CSI fed back from the mobile stations, the base station performs appropriate space-time processing such as multi-user scheduling, power and modulation adaptation, beamforming, and space-time coding.

Assume that $\mathbf{H}_k$ is the $M_r \times M_t$ MIMO channel matrix from the base station to the k-th mobile station, x is the $M_t \times 1$ transmit symbol vector, n_k is the $M_r \times 1$ independent and identically distributed additive white Gaussian noise vector $\sim CN(0, \mathbf{I}_{M_r})$, and y is the $M_r \times 1$ receive symbol vector. In multi-user MIMO systems, the received signal for the k-th mobile station is then mathematically represented as

$$\mathbf{y}_k = \mathbf{H}_k\mathbf{x} + \mathbf{n}_k, \tag{1}$$

where $k = 1, \ldots, K$. The transmitter is subject to an average power constraint $\mathrm{Tr}(\Sigma_x) \le P$, where $\Sigma_x \triangleq E[\mathbf{x}\mathbf{x}^H]$ denotes the covariance matrix of the input signal. In our analysis, the channel matrix $\mathbf{H}_k$ is modeled as a single-path Rayleigh with independent and identically distributed entries $\sim CN(0, 1)$ and block fading.

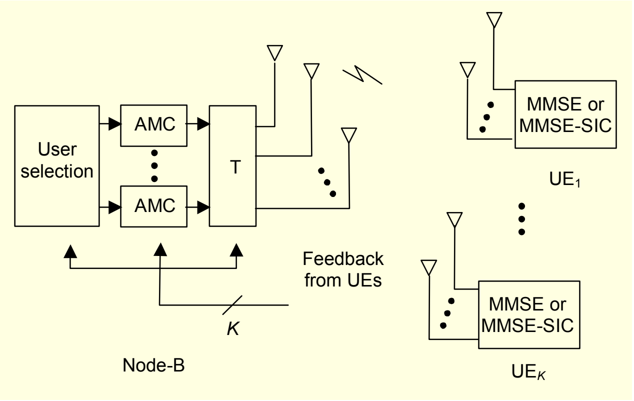

Fig. 1. A multi-user MIMO system.

III. MIMO Capacity Bound

MIMO schemes for the broadcast channel (BC) represented as in (1) can be brought into several scenarios, depending on the assumptions about the constraints put on transmit streams: the multiple access fashion and the knowledge of CSI at the transmitter.

First, we consider two methods of multiple access, which are time division multiple access (TDMA) MIMO and space-time multiple access (STMA) [15], as shown in Fig. 2. TDMA-MIMO is a point-to-point communication at a time in which the base station transmits to a single selected user so as to optimize the link performance, while STMA allows the base station to transmit to multiple users simultaneously, approaching the capacity limit of the multiple-antenna BC. Since the multiple-antenna BC has a rank-aware degraded1) nature [16], STMA can

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1) The multiple antenna BC is shown to have continually a non-degraded nature until the number of selected users K_s becomes equal to the certain number $K_{s,\max}$, where $M_t \le K_{s,\max} \le M_t(M_t+1)/2$; otherwise, the capacity is degraded.

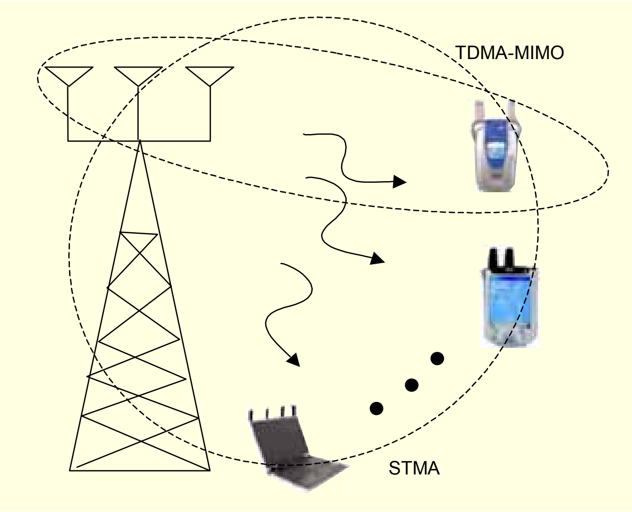

Fig. 2. system configuration of TDMA-MIMO and STMA.

outperform TDMA-MIMO at the cost of increased signaling traffic for CSI feedback. This issue will be described in detail in the following subsections.

Depending on the constraints applied to the transmit (antenna) streams, we categorize SU-MIMO systems into the uncoordinated downlink MIMO and the coordinated downlink MIMO. If transmit streams are independent like the streams generated by individual users, then (1) represents the uncoordinated downlink MIMO. Moreover, in the uncoordinated downlink MIMO the channel with a single user and a channel with multiple users are equivalent to a (multi-user) vector multiple access channel (MAC) and a vector interference channel, respectively, in which the modified power constraint, that is, the sum power constraint, is put on the transmit streams instead of separate power constraints. On the other hand, if they are not independent but allowed to cooperate, (1) represents the coordinated downlink MIMO, arising in D-BLAST with multi-dimensional coding. Hence, in MIMO applications the similarity between multiple antenna systems and the multi-user channel problems (see Lemma 1) is an effective tool to design the optimal transmit covariance matrix [17].

1. SU-MIMO Capacity

Before establishing the sum capacity of TDMA-MIMO and STMA in multi-user environments, we first formally define the capacity of SU-MIMO. In SU-MIMO systems, the channel capacity obtained by the optimal MIMO transceiver is given by

$$C(\mathbf{H}_k) = \sum_{m=1}^{M_t} \log(1 + p_m \lambda_m(\mathbf{H}_k)), \tag{2}$$

where $\lambda_m(\mathbf{A})$ is the m-th eigenvalue of $\mathbf{AA}^{\mathrm{H}}$. The power distribution factor p_m is set to P/M_t for the open-loop (OL) MIMO case, whereas the WF is applied with the power constraint $\sum_m p_m \leq P$ for the optimum distribution in the closed-loop (CL) MIMO case. It is shown in [18] that the ergodic capacity for OL-MIMO with, as an example, $M_r = M_t$, can be precisely approximated as

$$\begin{aligned}
&\overline{C}_{M_t,M_t}(P) \\
&\cong \overline{C}_{1,1}(P) + (M_t - 1)\cdot \lim_{n\to\infty} \frac{\overline{C}_{n,n}(P)}{n} \\
&= e^{1/P}\log_2(e)E_1(1/P) \\
&\quad + (M_t - 1)\cdot \left\{ \frac{2\log_2(1+\sqrt{4P+1})}{x} \right. \\
&\qquad\qquad \left. - \frac{\log_2(e)}{4P}(\sqrt{4P+1}-1)^2 - 2 \right\},
\end{aligned} \tag{3}$$

where $\overline{\mathrm{C}}_{1,1}$ is the average capacity of a single-input single-output (SISO) Rayleigh channel, and the other part is the capacity of both the number of transmit and receive antennas approaching infinity divided by the number of antennas.

2. MU-MIMO Capacity

For the evaluation of MU-MIMO capacity, we consider TDMA-MIMO and STMA, in which STMA can achieve the sum capacity of MU-MIMO, whereas TDMA-MIMO results in a gap from the optimal sum-rate [19].

A. The Sum-Rate of TDMA-MIMO

Consider the sum-rate capacity of TDMA-MIMO, in which the base station transmits only to the user with the largest capacity at a time, and hence the sum-rate capacity is given as

$$C_{TDMA}(\mathbf{H}_1,\ldots,\mathbf{H}_K) = \max_{k=1,\ldots,K} C(\mathbf{H}_k), \tag{4}$$

where we have used the definition stating that the maximum sum-rate of TDMA-MIMO is the largest single user capacity of K users. That is, the maximum sum-rate is achieved by selecting the user with the largest channel capacity for transmission, namely, max C/I scheduling, while the random user selection is called round-robin scheduling [19].

B. The Sum-Rate of STMA

It has been known that the sum capacity of STMA is achieved by using dirty paper coding (DPC) to simultaneously transmit to not only one user but also several users optimally selected [11]. Intuitively speaking, DPC processing for BC can be seen like the successive interference cancellation (SIC) with minimum mean-square error (MMSE) QR decomposition at the transmitter side.

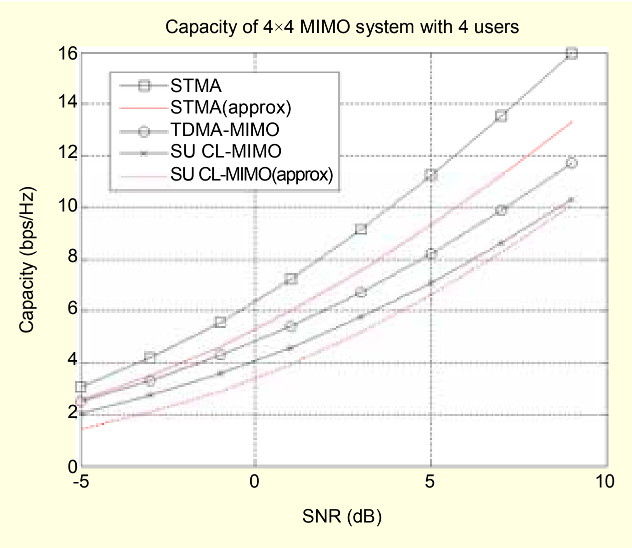

Fig. 3. Sum capacities of STMA and TDMA-MIMO for the 4-user, M_t=M_r=4BC channel.

Correspondingly, the sum capacity of STMA is given by

$$C_{STMA}(\mathbf{H}_1,\ldots,\mathbf{H}_K) = C_{DPC}(\mathbf{H}_1,\ldots,\mathbf{H}_K)$$
$$= \max_{\{\sum_{k=1}^{K} \mathbf{Tr}(\mathbf{Q}_k) \le P\}} \log\left|\mathbf{I} + \sum_{k=1}^{K} \mathbf{H}_k^H \mathbf{Q}_k \mathbf{H}_k\right|, \quad (5)$$

where $\mathbf{Q}_k \geq 0$ is a constraint, and the duality of the multiple antenna BC and MAC is employed for simple description.

For easier understanding of its performance, we present an approximation of the ergodic STMA capacity with K users in a fading channel as follows

$$\overline{C}_{M_t,M_t,K}(P) = \overline{C}_{M_t,M_t}\left(P\sum_{k=1}^{K} 1/k\right), \quad (6)$$

where the number of transmit and receive antennas are both M_t. The detailed derivation of (6) is omitted due to space constraints but is easily extended from the result of (3).

C. Comparison

In Fig. 3, the STMA and TDMA-MIMO sum capacities, $C_{STMA}(\mathbf{H}_1, \ldots, \mathbf{H}_K)$ and $C_{TDMA}(\mathbf{H}_1, \ldots, \boldsymbol{H}_K)$, respectively, and the SU CL-MIMO capacity are plotted for the four-user, $M_t = M_r = 4$ BC channel, along with their approximations.

STMA is shown in Fig. 3 to achieve a gain of around 1.5 times higher than TDMA-MIMO at all signal-to-noise ratio regimes.

IV. HSDPA MIMO Candidates

We now examine the system architecture of each candidate. We see that for performance improvement, the candidate solutions are designed exploiting a mixture of basic MIMO algorithms such as multiplexing, antenna selection, beamforming, and so on. Regarding the beamforming capability that depends on the available rate for the feedback signaling, MIMO proposals are specified into three transmission approaches: non beamforming, full beamforming, and partial beamforming.

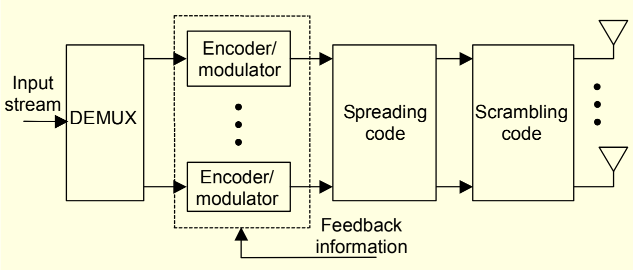

Fig. 4. Schematic of PARC transmitter.

1. Nonbeamforming Approach

A. Per-antenna Rate Control (PARC)

Lucent initially proposed this multiple antenna solution [13]. The transmitter structure of PARC is shown in Fig. 4, in which separately encoded data streams are transmitted from each antenna with equal power, but possibly with different data rates, while the spreading code is reused through all streams. The data rates for each antenna are controlled by adaptively allocating transmit resources such as modulation order, code rate, and the number of spreading codes. The post-decoding signal-to-interference plus noise ratio (SINR) of each transmit antenna is estimated at the receiver and then fed back to the transmitter, which is used to determine the data rate on each antenna. The vector signaling with more feedback overhead over the scalar signaling used in conventional systems is required for link adaptation.

MMSE filtering with SIC is applied to the receiver, in other words, SIC reception. Let

$$\mathbf{G}_{k,m} = (\mathbf{H}_{k,\overline{m}}^H \mathbf{H}_{k,\overline{m}} + (1/P)\mathbf{I}_{M_t-m})^{-1}, \quad (7)$$

where $\mathbf{I}_{M_t\text{-}m}$ is the M_t-m dimension square identity matrix and $\mathbf{H}_{k,\overline{m}}$ is a deflated version of $\mathbf{H}_k$ in which columns 1, 2, ... , m have been zeroed. The received SINR of the m-th stream becomes

$$\gamma_{S,K,M} = \frac{P/M_t}{[\mathbf{G}_{k,m}]_{mm}} - 1. \quad (8)$$

The capacity is then

$$C_k = \sum_{m=1}^{M_t} c_f(\gamma_{S,K,M}), \quad (9)$$

where $c_f(\gamma) = \log(1+\gamma)$. On the other hand, by replacing $\mathbf{H}_{k,\overline{m}}$

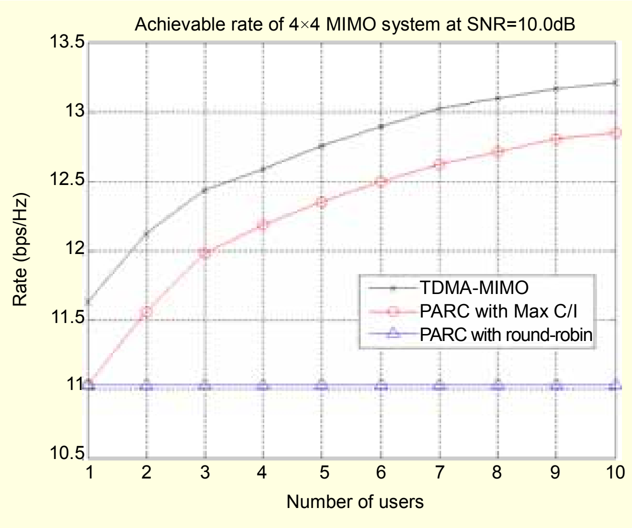

Fig. 5. Achievable rate of PARC with respect to the number of MSs, for $M_t=M_r=4$ and SNR=10 dB.

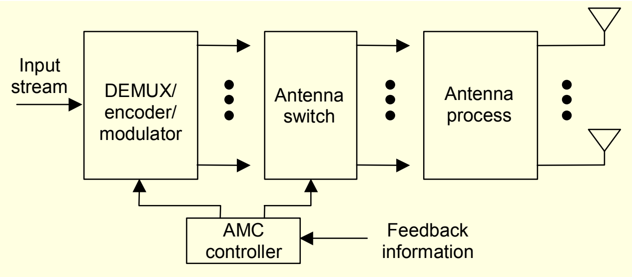

Fig. 6. Schematic of SPARC transmitter.

by $\mathbf{H}_k$ in (4), the received SINR, denoted as $\gamma_{M,k,m}$, and the capacity can be derived for MMSE reception.

Figure 5 shows the maximum achievable rate of PARC for comparison when $M_t = M_r = 4$, in which PARC with max C/I scheduler performs only 0.5 BPS/Hz lower than TDMA-MIMO in terms of sum-rate, while PARC with a round-robin scheduler gets no gain as the number of users increases.

B. PARC with Antenna Selection

Recent results have shown that PARC without power allocation achieves the full OL capacity of the flat fading MIMO channel. However, there is a significant gap between the OL capacity and the CL capacity when SINR is low and/or the number of receive antennas is less than the number of transmit antennas. An alternative way is by antenna selection, which overcomes the performance gap by the gain of (simplified form of) power allocation.

In employing antenna selection for PARC, there can be two different approaches: the mobile station decision approach and mobile station suggestion approach. In the mobile station decision approach as in [13], the mobile station feeds back the selected rate set including antenna selection information. However, in the mobile station suggestion approach, as in selective PARC (SPARC) [20], the mobile station sends back the antenna ordering information and the SINR values of each antenna to let the base station decide the antenna and rate selection.

Thus, additional amounts of feedback are required for SPARC, resulting in higher flexibility of antenna selection at the base station. More specifically, SPARC adaptively selects the number of antennas, which represents the transmission mode, and the best subset of antennas for the selected mode, of which will be described in detail in section V.1. Interestingly, SPARC becomes equivalent to a single stream transmit diversity scheme with transmit antenna selection if the number of selected antennas is limited to one at the base station.

2. Full Beamforming Approach

To enhance the performance of PARC, the unitary precoding-based spatial multiplexing scheme has been proposed, which is the combined technique of PARC and transmit adaptive array (TxAA), called the per-stream rate control (PSRC) [21], [22]. For example, the unitary rotation matrix at the transmitter used in PSRC can be given by

$$\mathbf{W} = \begin{bmatrix} A & -\sqrt{1-A^2}\exp(-j\phi) \\ \sqrt{1-A^2}\exp(j\phi) & A \end{bmatrix}, \qquad (10)$$

where $0 \le \phi < 2\pi$ and $0 \le A \le 1$. The rotation matrix $\mathbf{W}$ is chosen at the receiver from a finite predetermined set. Given a precoding matrix, the modulation size and code rate are selected to maximize the total throughput.

3. Partial Beamforming Approach

Another proposal, a double TxAA (DTxAA), has been contributed in [14]. In DTxAA, if, for example, four transmit antennas ($M_t = 4$) are employed at the base station, the transmit antennas are divided into two sub-groups, and each sub-group transmits independent data streams with a TxAA operation of a pair of transmit antennas. The diagram of a general partial beamforming system is depicted in Fig. 7.

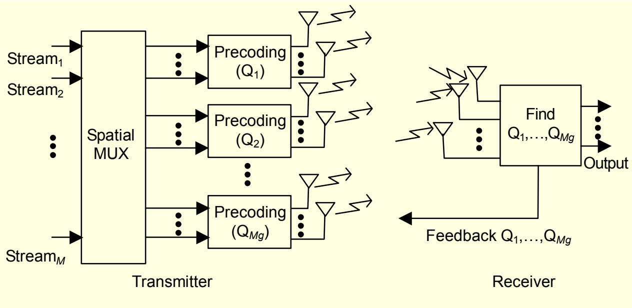

Fig. 7. Block diagram of a general partial beamforming system.

V. Unified Power Allocation Strategy

In this section, the optimal power allocation strategies for different MIMO candidates in 3GPP are investigated. We formulate and solve the general optimization problems of partial beamforming MIMO using the similarity between multiple antenna systems and multi-user channel problems.

Note that previous optimization works have treated power allocation for only a few special cases.

1. Using Multi-user Diversity

We now introduce the operation procedures of SPARC. It performs the antenna selection based on a subset property, by which selections at the prior mode are considered in order to reduce the amount of feedback [20]. Because of the similarity, the subset property based antenna selection process is equivalent to the greedy MMSE DPC (see Appendix A), which is a multi-user diversity approach for a MU-MISO system. A schematic of the transmitter is illustrated in Fig. 6, where the adaptive modulation and coding controller handles the adaptive mode of the antenna, modulation, and coding. Also, in the antenna processor the appropriate power balancing from all transmit antennas is achieved before transmission.

2. Using Iterative Water-Filling

The antenna selection as in SPARC is suboptimal for non beamforming systems, so we present a method to find the optimal power allocation for this system. We then present a more generalized method to be applicable also for the partial beamforming system. For the PARC system where transmit power is allocated to each transmit antenna, we propose to explore the similarity property that enables iterative WF [23] to be used for the optimal power allocation. From the similarity of PARC and MAC [17], the objective of such a problem in SU-MIMO channels can be represented by the simplified form of (5), which is given by

$$C_{SPARC}(\mathbf{H}) = \max_{p_m} \log \left| \mathbf{I} + \sum_{m=1}^{M_t} p_k \mathbf{h}_m \mathbf{h}_m^H \right|, \qquad (11)$$
$$\text{subject to } \; p_m \geq 0, \;\; \sum_{m=1}^{M_t} p_m \leq P$$

where $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_{M_t}]$. Note that substantial progress for the optimization of (5) has recently been made in [19] and [23], and is not yet completely answered because of its implication of the sum-power constraint, that is, $\Sigma_{m=1}^{M_t} p_m \leq P$.

Lemma 1. There is similarity between multiple antenna systems and multi-user channel problems. Therefore, a non beamforming scheme such as PARC can achieve the same capacity to the equivalent multi-user multiple-input multiple-output (MU-MISO) system so its power allocation can be optimized by the same way of the equivalent multi-user system. For the partial beamforming scheme, the equivalent MU-MIMO system is used to find its capacity and power allocation policy. Mathematically, if the partial beamforming system has M_t transmit antennas, M_r receiver antennas, and M_g antenna sub-groups, then it is equivalent to the MU-MIMO system consisting of a base station with M_r transmit antennas and M_g MSs each with (M_t/M_g) receive antennas.

Proof. The proof of Lemma 1 is given in Appendix II, and is derived by extending from the MU-MISO case in [17] to the MU-MIMO case. □

Previous works have not considered the general optimization of power allocation for various types of beamforming MIMO systems, while a few special cases were discussed. Thus, we formulate and solve the general optimization problem for this scheme as a function of the transmit covariance matrices, $\mathbf{Q}_1$ and $\mathbf{Q}_2$ in (12) (see Appendix B). The optimization is performed based on the techniques used for non beamforming (for example, PARC) in section V.1, that is, either the iterative WF or subset property. In the special case of $M_t = 4$ in SU-MIMO, iterative WF with the sum power constraint leads to the maximum throughput, which is given by

$$C_{\text{DTxAA}}(\mathbf{H}_1, \mathbf{H}_2) = \max_{\{\mathbf{Q_m}\}} \log \left| \mathbf{I} + \sum_{m=1}^{2} \mathbf{H}_m \mathbf{Q}_m \mathbf{H}_m^H \right|, \qquad (12)$$
$$\text{subject to } \; \mathbf{Q}_m \geq 0, \sum_{m=1}^{2} \text{Tr}(\mathbf{Q}_m) \leq P$$

where $\mathbf{H}_1 = [\mathbf{h}_1, \mathbf{h}_2]$, $\mathbf{H}_2 = [\mathbf{h}_3, \mathbf{h}_4]$ denote the first and second sub-group channel matrices, respectively. The capacity of DTxAA is larger than that of SPARC but smaller than that of the optimal CL-MIMO, which can be easily observed in (12).

Theorem 1. The optimal transmit covariance matrix for partial beamforming can be found using iterative WF (especially with the sum-power constraint), which has been shown as an effective optimization tool to design a transmit covariance for the downlink MU-MIMO system.

Proof. From Lemma 1, any partial beamforming system has its equivalent MU-MIMO channel, and hence its beamforming vectors and powers can be optimized using the equivalent MU-MIMO channel. Since iterative WF is a tool for MU-MIMO channel optimization, it can be seen as a tool for partial beamforming optimization, of which the fact completes the proof. □

Figure 8 shows the achievable capacity of partial beamforming with the iterative WF-based unified power allocation algorithm (see Appendix C). Partial beamforming (DTxAA) outperforms non beamforming (PARC) and the

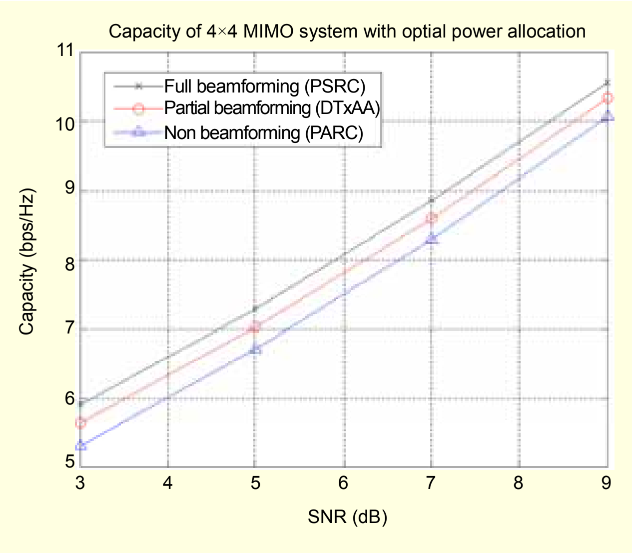

Fig. 8. Achievable capacity with the proposed unified power allocation, for M_t=4 and M_r=4.

capacity of partial beamforming is close to the full beamforming capacity bound. Note that the gain over PARC comes at the expense of additional feedback information for transmit beamforming inside the sub-group antennas, noting that additional information is less than that required for full beamforming.

Corollary 1. The achievable capacity of the partial beamforming system with the proposed unified power allocation, which is optimal for this system by Theorem 1, is larger than or equal to the capacity of the non-beamforming system.

The proof of Corollary 1 is not given here, but is obvious because of Theorem 1. That is, since partial beamforming has a higher degree of freedom to design the transmit covariance matrix than non-beamforming, the former is never worse than the latter.

VI. Conclusion

We first examined the sum-rate capacity of STMA (obtainable with the iterative WF algorithm), along with achievable throughput of TDMA-MIMO. In addition, utilizing the similarity of multiple antenna systems and multi-user channel problems, we have proposed a unified optimal power allocation strategy for TDMA-MIMO schemes in 3GPP HSDPA, that is, for PARC and DTxAA. An immediate area of future work would be to also investigate the efficient resource allocations such as transmit power and antennas for STMA.

Appendix A. Greedy MMSE DPC for MIMO

In this appendix, we present the algorithm of greedy MMSE DPC for MIMO, which is the updated version of greedy zero forcing-DP for MISO in [24], so as to consider MMSE filtering and receivers equipped with multiple receive antennas.

The algorithm for this case is outlined as follows. In greedy MMSE DPC, the base station selects the index pairs made up of a user and its antenna, $\{k_j, i_j\}_j$, on the basis of the downlink channel matrices $\{\mathbf{H}_k\}_{k=1}^{K}$ where $\{\mathbf{H}_k^T=[\mathbf{h}_{k,1},\ldots,\mathbf{h}_{k,Mr}]\}$. Before starting the procedure, we take as the initial value $m=0$.

Algorithm description: Let $m = m + 1$. If $m > K$, stop the procedure; otherwise, the base station calculates the received SINR for all (k, i) as

$$\gamma_{k,i}(m)=\mathbf{h}_{k,i}^H\left(\sum_{j=1}^{m-1}\mathbf{h}_{k_j,i_j}\mathbf{h}_{k_j,i_j}^H+mP^{-1}\mathrm{I}\right)^{-1}\mathbf{h}_{k,i}, \tag{13}$$

determines the index pair of user and antenna as the m-th selected index pair as

$$(k_m,i_m)=\arg\max_{k\in 1,\ldots,K,\, j\in 1,\ldots,M_r}\gamma_{k,i}(m), \tag{14}$$

and calculates the sum-rate achievable with $\gamma_{k_1,i_1},\ldots,\gamma_{k_m,i_m}$ as

$$R_m=\sum_{j=1}^{m}\log_2(1+\gamma_{k_j,i_j}(m)). \tag{15}$$

Repeat the algorithm until $R_m \le R_{m-1}$. Note that the total throughput of this scheme is given by R_m.

Appendix B. Similarity between the Multi-antenna and Multi-user Problems

In this appendix, we show the (general) similarity between the multi-antenna system and multi-user channel problems, so as to present the optimal power allocation policy for the selected HSDPA MIMO schemes. The proof in this appendix is investigated based on the similarity described in [17], where per-antenna-based systems are considered. We assume that $M_t = 4$ and $K = 2$ as in (12). Nevertheless, the proof can be easily extended to the scenario where the base station and each mobile station have a different number of antennas. In order to prove the similarity, we show that the achievable throughput of the single-user MIMO system with limited transmit beamforming such as DTxAA is equivalently represented as the sum-rate capacity of the corresponding Gaussian MIMO BC, which is given by

$$C_{BC}(\mathbf{H}_1^H,\mathbf{H}_2^H)=\max_{\{\Sigma_m\}}\log\left|\mathbf{I}+\mathbf{H}_1^H\Sigma_1\mathbf{H}_1\right|+\log\frac{\left|\mathbf{I}+\mathbf{H}_2^H(\Sigma_1+\Sigma_2)\mathbf{H}_2\right|}{\left|\mathbf{I}+\mathbf{H}_2^H\Sigma_1\mathbf{H}_2\right|},$$

$$\text{subject to }\ \Sigma_m\ge 0,\ \sum_{m=1}^{2}\mathrm{Tr}(\Sigma_m)\le P. \tag{16}$$

The original formula representing the capacity of DTxAA is expressed as

$$C_{\mathrm{DTxAA}}(\mathbf{H}) = \max_{\mathbf{Q}:\mathbf{Q}\geq 0, \mathrm{Tr}(\mathbf{Q})<P} \log\left|\mathbf{I}+\mathbf{H}\mathbf{Q}\mathbf{H}^{H}\right|$$
$$= \max_{\{\mathbf{Q}_m\}} \log\left|\mathbf{I}+\mathbf{H}_1\mathbf{Q}_1\mathbf{H}_1^{\mathrm{H}}+\mathbf{H}_2\mathbf{Q}_2\mathbf{H}_2^{\mathrm{H}}\right|, \qquad (17)$$

where $\mathbf{Q} = \mathrm{diag}(\mathbf{Q}_1,\mathbf{Q}_2)$ and $\mathbf{H} = [\mathbf{H}_1,\mathbf{H}_2]$. Using the duality of BC and MAC [25], (17) can be rewritten as (16). This completes the proof.

Appendix C. Iterative WF-Based Unified Power Allocation Algorithm

In this appendix, we show how to solve multi-antenna problems using the iterative WF-based unified power allocation algorithm. The algorithm is based on the sum-power iterative WF in [26], where it is used to solve multi-user problems.

For simplicity, we solve the problem (12), with $M_t = M_r = 4$ and $M_g = 2$. The algorithm is described by the following:

Step 1. Initialize each covariance matrix $\mathbf{Q}_1^{(1)}$ by water-filling over $\mathbf{H}_i$ with total power P/M_g for i = 1, 2. The m-th iteration of the algorithm is covered in steps 2 and 3.

Step 2. Generate effective channels

$$\mathbf{G}_i^{(m)} = \left(\mathbf{I}+\sum_{j\neq i}\mathbf{H}_j\mathbf{Q}_j^{(m-1)}\mathbf{H}_j^{H}\right)^{-1/2}\mathbf{H}_i \quad \text{for } i=1,2. \qquad (18)$$

Step 3. Treating these effective channels as parallel channels, obtain the new covariance matrices $\{\mathbf{Q}_j^{(m-1)}\}_{i=1}^{2}$ by water-filling over $\mathbf{G}_i^{(m)}$ with total power P:

$$\mathbf{Q}_j^{(m)} = \mathbf{V}_i\mathbf{\Lambda}_i\mathbf{V}_i^{H}, \qquad (19)$$

where $\mathbf{V}_i$ is calculated by singular decomposition such as $\mathbf{G}_i^{(m)H}\mathbf{G}_i^{(m)}=\mathbf{V}_i\mathbf{D}_i\mathbf{V}_i^{H}$ and $\mathbf{\Lambda}_i=[\mu\mathbf{I}-(\mathbf{D}_i)^{-1}]^{+}$. The operation $[\mathbf{A}]^{+}$ denotes a component-wise maximum with zero, and the water-filling level μ is chosen such that $\Sigma_{i=1}^{2}\,\mathrm{Tr}(\mathbf{\Lambda}_i) = P$.

Note that as seen in (19), the covariance matrix $\mathbf{Q}_i^{(m)}$ consists of the beamforming matrix $\mathbf{V}_i$ and the diagonal power matrix $\mathbf{\Lambda}_i$.

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