PAPER

On the Performance of Multiuser MIMO Systems in WCDMA/HSDPA: Beamforming, Feedback and User Diversity*

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SUMMARY   Several multiple-input multiple-output (MIMO) techniques have been proposed for 3GPP WCDMA/HSDPA systems and several performance evaluation for the comparison purpose are in progress. Most MIMO candidates in HSDPA have been generally designed for point-to-point communication, which means that a single-user throughput is of their major concern. However, multiple users and user scheduling need to be considered in wireless packet transmission, so as to maximize system throughput. In this paper we propose an effective user scheduling technique in both space and time domains that offers three main benefits, which are the spatial-beamforming, uplink feedback signaling, and advanced receivers. Furthermore, user scheduling is combined with modified successive interference cancellation (SIC) reception, which allocates all transmit antennas to the best user with SIC or each transmit antenna to different users with minimum mean squared-error (MMSE). Simulation results show that the proposed scheme has higher user diversity gain than other MIMO candidates in terms of achievable throughput.

key words: multiuser, MIMO, STMA, WCDMA, HSDPA

1.   Introduction

In third generation wireless mobile communications (e.g., wideband code division multiple access (WCDMA) [2]), high-rate data transmission need to be supported for wireless multimedia services. High speed downlink packet access (HSDPA) is a solution to achieve a bit rate of 10 Mbps. HSDPA systems utilize various technologies such as adaptive modulation and coding (AMC), hybrid automatic repeat request (H-ARQ), fast cell selection (FCS), and multiple-input multiple-output (MIMO) antenna processing [3]. In MIMO systems, multiple data streams are transmitted in parallel through multiple antennas, which increases reliability as well as spectral efficiency [4]. Space-time block coding (STBC) is one of the major techniques to achieve full transmit diversity and has a simple maximum-likelihood decoding algorithm at the receiver [5]. Beamforming is another method to improve link reliability by interference rejection and linear combining [6]. Transmit/receive diversity is a well-known technique to reduce the fluctuation of fad-

ing, resulting in diversity gain [7]. Spatial multiplexing is used to exploit multiplexing gain by transmitting different data symbols from multiple transmit antennas, simultaneously [8].

Recently, MIMO technology has been an active area as a working item in WCDMA/HSDPA standardizations by 3GPP [9]. The proposed schemes in 3GPP are based on the combination of various MIMO technologies such as beamforming, space-time block coding, transmit diversity, and/or multiplexing. One of the significant factors in 3GPP MIMO is the channel state information (CSI) signaling. Depending on the various types of transmission approaches, both the required types and the estimation algorithms for CSI can vary. Thus, the feedback signaling of CSI needs to be designed in an optimized way, especially when the transmitter has multiple transmit antennas, in which both AMC and precoding can be applied to maximize the link throughput and/or minimize the error rate. In radio communication systems with multiple access such as cellular systems, multiuser signaling is of important concern for system design. A scheduling criterion must be considered for sum rate improvement in a multiuser MIMO while a single-user MIMO is designed to improve a point-to-point link throughput.

In this paper, we propose a novel multiuser MIMO scheme which exploits user diversity for scheduling users and adapts the transmit beamforming based on the feedback information. We also investigate the scheduling schemes when combined together with advanced receiver structures. Furthermore, we compare the system performance of our proposed multiuser MIMO scheme with other schemes in 3GPP. The remainder of the paper is organized as follows. Section 3 gives an overview of 3GPP MIMO schemes. In Sects. 4 and 4.2, we propose an effective multiuser MIMO scheme and scheduling criteria with advanced receivers, respectively. Simulation results are presented in Sect. 5. Finally, we draw some conclusions in Sect. 6.

Notation: The notation $\mathbb{E}$ represents the expectation operator, and the superscripts ^{T} and ^{H} stand for transposition, conjugate transposition, respectively.

2.   System Model

In Fig. 1, a multiuser MIMO system in wireless MIMO broadcast channels is illustrated, in which a radio base sta-

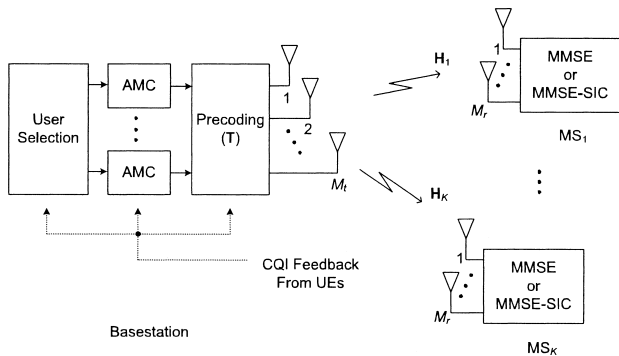---

Fig. 1　A multiuser MIMO system.

Fig. 2　Schematic of PARC transmitter.

tion (BS) communicates with K mobile stations (MSs) [10]. Each MS has the linear/non-linear reception entity and M_r receive antennas, while the BS has M_t transmit antennas. Based on the partial or full channel state information (CSI) fed back from MSs, BS performs appropriate space-time processing such as multiuser scheduling [11], power and modulation adaptation [12], beamforming [13], and space-time coding [5]. Here, CSI includes channel direction information (CDI) and channel quality information (CQI), which are used for determining the beamforming direction and the power allocation for each beam.

Assume that $\mathbf{H}_k$ is the $M_r \times M_t$ MIMO channel matrix from the BS to the kth MS, $\mathbf{x}_k$ is the $M_t \times 1$ transmitted symbol vector intended for the kth MS, and $\mathbf{y}_k$ is the $M_r \times 1$ received symbol vector at the kth MS. In addition, $\mathbf{n}_k$ is the $M_r \times 1$ independent and identically distributed (i.i.d.) additive white Gaussian noise (AWGN) vector $\sim \mathcal{CN}(0, \mathbf{I}_{M_r})$ where $\mathbf{I}_{M_r}$ denotes the $M_r \times M_r$ identity matrix. Then, the received signal for the kth MS in multiuser MIMO systems is mathematically described as

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

where $k = 1, \ldots, K$, and $\mathbf{x} = \sum_{k=1}^{K} \mathbf{x}_k$. The transmitter is subject to an average power constraint $\mathrm{Tr}(\boldsymbol{\Sigma}_x) \leq P$ where $\boldsymbol{\Sigma}_x \triangleq \mathbb{E}[\mathbf{x}\mathbf{x}^H]$ denotes the covariance matrix of the input signal. In our analysis, the mobile channel $\mathbf{H}_k$ is modeled as a single path Rayleigh with i.i.d. entries $\sim \mathcal{CN}(0, 1)$ and block fading.

3.　TDMA MIMO Schemes

3.1　Per-Antenna Rate Control (PARC)

Lucent initially proposed their multiple antenna solution, which is called the per-antenna rate control (PARC), in 3GPP MIMO TR [14]. The transmitter structure of PARC is shown in Fig. 2, in which separately encoded data streams are transmitted from each antenna with equal power but possibly with different data rates while 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 number of spreading codes. The post-decoding signal-to-interference-plus-noise
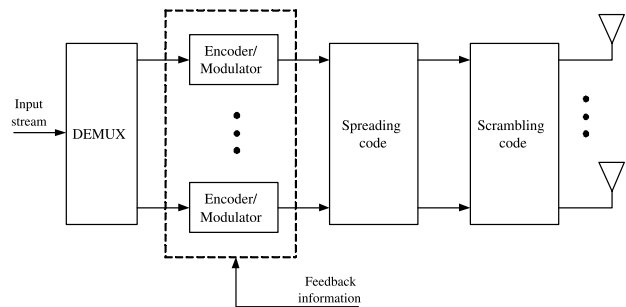
ratio (SINR) of each transmit antenna is estimated at the receiver and then fed back to the transmitter, which is used to determine the data rate on each antenna. The vector signaling with more feedback overhead over the scalar signaling in conventional systems is required for link adaptation.

The minimum mean squared-error (MMSE) filtering and successive interference cancellation (SIC) are applied to the receiver, i.e., MMSE-SIC reception, or V-BLAST detection, [15] is applied. In MMSE-SIC reception, there are the two key aspects in detection of any substream:

i) Interference nulling: interference from yet to be detected substreams is projected out
ii) Interference canceling: interference from already detected substreams is subtracted out

where Aspect i and Aspect ii. are performed by MMSE filtering and SIC, respectively. Consider the received SINR for PARC, in which each stream is transmitted out of a different antenna. The transmit symbol vector is $\mathbf{x} = \mathbf{s}$, where $\mathbf{s} = [s_1, s_2, \cdots, s_{M_t}]^T$ is the $M_t \times 1$ transmitted symbol vector and s_m is the transmit symbol at transmit antenna m. The received SINR of the mth stream, or s_m, for MMSE-SIC reception becomes [16]

$$\gamma_{\mathrm{S},k,m} = \mathbf{h}_{k,m}^H \left(\sum_{n=m+1}^{M_t} \mathbf{h}_{k,n}\mathbf{h}_{k,n}^H + \frac{M_t}{P}\mathbf{I} \right)^{-1} \mathbf{h}_{k,m} \tag{2}$$

where $\mathbf{h}_{k,m}$ is the mth column vector of $\mathbf{H}_k$. The achievable rate is then given by

$$C_k = \sum_{m=1}^{M_t} c_f(\gamma_{\mathrm{S},k,m}) \tag{3}$$

where $c_f(\gamma) = \log(1 + \gamma)$. On the other hand, the achievable rate for MMSE reception can be derived by replacing $\sum_{n=m+1}^{M_t} \mathbf{h}_{k,n}\mathbf{h}_{k,n}^H$ with $\sum_{n \neq m}^{M_t} \mathbf{h}_{k,n}\mathbf{h}_{k,n}^H$ in the received SINR of (2), which is given by

$$\gamma_{\mathrm{M},k,m} = \mathbf{h}_{k,m}^H \left(\sum_{n=1, n \neq m}^{M_t} \mathbf{h}_{k,n}\mathbf{h}_{k,n}^H + \frac{M_t}{P}\mathbf{I} \right)^{-1} \mathbf{h}_{k,m}. \tag{4}$$

where the replacement has been taken because of non employing interference cancellation in MMSE reception. It is obvious that $\gamma_{\mathrm{S},k,m}$ is larger than or equal to $\gamma_{\mathrm{M},k,m}$ where the equality holds if and only if $\sum_{n=1}^{m-1} \mathbf{h}_{k,n}\mathbf{h}_{k,n}^H = 0$ for each k and m.

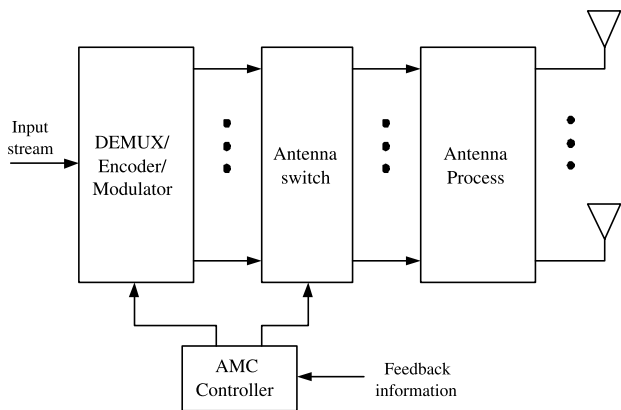**Fig. 3** Schematic of SPARC transmitter.

Fig. 4 Schematic of PU^{2}RC transmitter.

3.2   Selective PARC

The selective PARC (SPARC) has been proposed by Ericsson, which is conceptually based on PARC scheme in the previous subsection [17]. Recent results have shown that PARC can achieve the full open-loop capacity of the flat fading MIMO channel [14] when the receiver uses MMSE-SIC decoding. However, there is a significant gap between the open-loop capacity and the closed-loop capacity, when signal-to-noise ratio (SNR) is low and/or the number of receive antennas is less than the number of transmit antennas. An approach to achieve the near-capacity of the closed-loop MIMO is SPARC, which compensates for the capacity loss by the gain of antenna selection. In Fig. 3, the AMC controller handles the adaptive mode of antenna, modulation, and coding. The appropriate power balancing from all transmit antennas is achieved in the antenna processor before transmission. For example, if the number of the selected antennas is limited to one, SPARC will operate as a single stream transmit diversity (with partial feedback in Sect. 4.3).

4.   Proposed STMA MIMO Scheme

In this section, we present the practical method of space-time multiple access (STMA) MIMO, which utilizes transmit beamforming and user diversity using the matched filter[†] based unitary precoding for multiuser MIMO transmission. The proposed scheme has two main features: the closed-loop MIMO and the downlink user diversity. The transmit array gain is achieved by exploiting feedback, resulting in the link throughput/error rate improvement. Using user diversity in space-time domain the system throughput (represented by the sum rate of vector channels to all users) is improved.

4.1   Per-User Unitary Beamforming and Rate Control

We propose the multiuser MIMO scheme using the unitary basis transformation, which is called the per-user unitary beamforming and rate control (PU^{2}RC). The transmit-
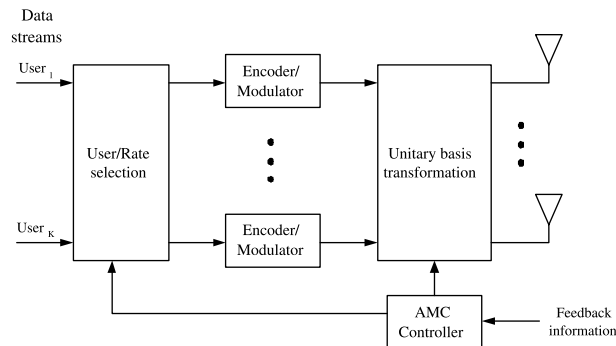
ter structure of the proposed system is shown in Fig. 4. Using (1), the received signal vector for the kth user is written as

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{W} \mathbf{s} + \mathbf{n}_k \tag{5}$$

where transmit signal is beamformed by employing the precoding matrix $\mathbf{W} = [\mathbf{w}_1 \cdots \mathbf{w}_{M_t}]$. That is, $\mathbf{x} = \mathbf{W}\mathbf{s} = \sum_{m=1}^{M_t} \mathbf{w}_m s_m$ where $\mathbf{w}_m$ is the $M_t \times 1$ beamforming vector and $\mathbf{s} = [s_1, s_2, \cdots, s_{M_t}]^T$ is the $M_t \times 1$ transmitted symbol vector. Note that since PU^{2}RC is a STMA scheme, BS is allowed to allocate each s_m to users independently, i.e., each s_m can be associated to the different user.

As one of the main features of the proposed scheme, we use the matched filter based unitary precoding (MFUP), i.e., the constraint $\mathbf{W}^H \mathbf{W} = \mathbf{I}_{M_t}$ is applied to (5). The constraint $\mathbf{W}^H \mathbf{W} = \mathbf{I}_{M_t}$ is achieved by the scheduler at BS, which finds the set of beams that are orthogonal each other amongst candidate beams. The scheduling operation as the spatial domain user diversity significantly increases the sum rate throughput obtained by the matched filter beamforming since the operation searches the high received SINR users. Although the matched filter beamforming increases the received signal power by matching the transmit beam to the user channel, the interference between users still remains. The spatial domain user diversity, hence, is applied to reduce interference between users by selecting the set of user channels that are close to orthogonal each other. Furthermore, MFUP is a much simpler scheme to implement than other transmit precoding schemes such as dirty-paper coding (DPC) [18], while the sum rate of both MFUP and DPC scales as $M_t \log \log K M_r$ when K is large [6], [19]. Note that DPC is known to be optimal to achieve the capacity region of the multiuser MIMO (downlink) channel [20].

The scheduling criterion for spatial domain user diversity in MFUP is derived from the following criterion:

$$\{(\mathbf{v}_m^*, k_m^*)\}_{m=1}^{M_t}$$

[†]We use here the terminology of *matched filter* to notice that the filtering weights delivered from users are applied to transmit streams without any change, i.e., feedback information, which represents CSI, is used as it is at the transmitter, which is slightly different from the conventional use of the terminology.

$$= \arg \max_{\mathbf{v}_m : \mathbf{v}_m^H \mathbf{v}_n^* = 0, m \neq n} \sum_{m=1}^{M_t} c_f \left(\frac{P}{M_t} \lambda_{k_m}(\mathbf{v}_m) \right) \quad (6)$$

where $\mathbf{v}_m \in \{\mathbf{v}_{k,l}\}$, $\mathbf{v}_{k,l}$ is the lth eigenvector of $(\mathbf{H}_k^H \mathbf{H}_k)$ and $\lambda_k(\mathbf{v}_m)$ is the eigenvalue corresponding to $\mathbf{v}_m$ for the kth user. Also, $\mathbf{v}_m^*$ and k_m^* are the selected eigenvector and user, respectively, for the mth stream. If $\mathbf{v}_m^H \mathbf{v}_n = 0, m \neq n$ is assumed for all m and n, the criterion of (6) finds the M_t largest eigenvalues, of which the sum rate is larger than or equal to that of the eigenvalues of any one user. However, since the exact orthogonality between two random vectors in continuous domain is not possible, the probability of finding the eigenvectors satisfying $\mathbf{v}_{k_1,m_1}^H \mathbf{v}_{k_2,m_2} = 0$ for $k_1 \neq k_2$ is zero.

In the sequel, we present a precoding based approach where the orthogonality between eigenvectors can be achieved by considering the limited feedback of CSI. A precoder using limited feedback approaches developed in [13] is presented, because the quantized encoding is essential for limited feedback systems, e.g., frequency division duplex (FDD) cellular systems. Limited feedback precoders use predefined codebooks, $\mathcal{W}$, which are finite sets of vectors using, e.g., Grassmannian subspace packing [13]. These codebooks are stored at both the BS and MSs. By modifying (6), the scheduling criterion for the limited feedback system is presented as follows:

$$\{(\mathbf{w}_m^*, k_m^*)\}_{m=1}^{M_t}$$

$$= \arg \max_{\mathbf{w}_m : \mathbf{w}_m^H \mathbf{w}_n^* = 0, m \neq n} \sum_{m=1}^{M_t} c_f(\gamma_{k_m}(\mathbf{w}_m)) \quad (7)$$

where $\mathbf{w}_m \in \mathcal{W}$, $\mathbf{w}_m^*$ and k_m^* are the selected beam and user for the mth stream, respectively, and $\gamma_k(\mathbf{w}_m)$ is the received SINR corresponding to $\mathbf{w}_m$ for the kth user. The function (7) corresponds to finding the optimal precoding matrix from a limited feedback codebook $\mathcal{W}$. As shown in (7), the scheduling operation is performed at BS based on CQI, i.e., $\{\gamma_k(\mathbf{w}_m)\}$, and CDI, i.e., $\{\mathbf{w}_m\}$, which are fed back from MSs for all $k = 1, \ldots, K$ and each MS calculates and feeds back $\{\gamma_k(\mathbf{w}_m)\}$ and $\{\mathbf{w}_m\}$ for all $\mathbf{w}_m \in \mathcal{W}$.

The kth MS calculates a received SINR $\gamma_k(\mathbf{w}_m)$ as a function of $\mathbf{w}_m$, which is mathematically represented as

$$\gamma_k(\mathbf{w}_m) = \frac{|\mathbf{b}^H \mathbf{H}_k \mathbf{w}_m|^2}{\sum_{l=1, l \neq m}^{M_t} |\mathbf{b}^H \mathbf{H}_k \mathbf{w}_l|^2 + \frac{M_t}{P} \|\mathbf{b}\|^2} \quad (8)$$

$$= \frac{|\mathbf{b}^H \mathbf{H}_k \mathbf{w}_m|^2}{\|\mathbf{b}^H \mathbf{H}_k\|^2 - |\mathbf{b}^H \mathbf{H}_k \mathbf{w}_m|^2 + \frac{M_t}{P} \|\mathbf{b}\|^2} \quad (9)$$

where $\mathbf{b}$ is the receive beamforming vector. For example, $\mathbf{b}$ can be obtained by MMSE criterion. It is noteworthy that in (9) the other beamforming vectors $\{\mathbf{w}_m\}_{m \neq l}$ existed in (8) are removed, which are not necessary in MFUP because of the unitary property of $\mathbf{W} = [\mathbf{w}_1^*, \mathbf{w}_1^*, \ldots, \mathbf{w}_{M_t}^*]$. That is, if $\mathbf{W}$ is not a unitary matrix, as seen in (8) MS must know the other transmit beamforming vectors in order to obtain $\gamma_k(\mathbf{w}_l)$ before scheduling. However, prior knowledge of $\{\mathbf{w}_m\}_{m \neq l}$ at

MS is not available since there is no way for BS to deliver them to MS before the scheduler determines them.

Theorem 1: Assume that the number of the transmitted data streams L is equal to M_t. In MFUP, to obtain the received SINR with respect to $\mathbf{w}_m$ at the kth MS, the other beamforming vectors, i.e., $\{\mathbf{w}_m\}_{m \neq l}$, are not necessary to be known at the kth MS.

Proof: The proof of Theorem 1 is found in (8) and (9). □

The number of the transmitted data streams L is smaller than or equal to M_t so as to increase the transmit power for each stream. By replacing M_t with L in (9), the SINR becomes a lower-bound of the received SINR. In a system which allows for BS to transmit less than M_t streams a MS has to be taken into account by being more conservative in determining CQI per each stream. To reduce the loss in performance due to the conservativeness of the SINR prediction, an incremental H-ARQ mechanism can be employed for the repetition-coded multiple packets.

Theorem 2: If the number of the transmitted data streams L is less than or equal to M_t, $\gamma_{k_m}(\mathbf{w}_m)$ is a lower-bound of the actual received SINR with respect to $\mathbf{w}_m$ and L. The received SINR $\gamma_{k_m}(\mathbf{w}_m)$ is described in (9) wherein $\{\mathbf{w}_m\}_{m \neq l}$ are not included.

Proof: The proof is straightforward from the fact that $\|\mathbf{b}^H \mathbf{H}_k\|^2 - |\mathbf{b}^H \mathbf{H}_k \mathbf{w}_l|^2 + \frac{M_t}{P} \|\mathbf{b}\|^2$ is an upper-bound of the total interference and noise power when $L \leq M_t$. The actual SINR is lower bounded by

$$\gamma_k(\mathbf{w}_m, L) = \frac{|\mathbf{b}^H \mathbf{H}_k \mathbf{w}_m|^2}{\sum_{l \neq m, l \in A_L} |\mathbf{b}^H \mathbf{H}_k \mathbf{w}_l|^2 + \frac{L}{P} \|\mathbf{b}\|^2}$$

$$\geq \frac{|\mathbf{b}^H \mathbf{H}_k \mathbf{w}_m|^2}{\|\mathbf{b}^H \mathbf{H}_k\|^2 - |\mathbf{b}^H \mathbf{H}_k \mathbf{w}_m|^2 + \frac{M_t}{P} \|\mathbf{b}\|^2}$$

$$= \gamma_k(\mathbf{w}_m) \quad (10)$$

where $A_L \subset \{1, 2, \ldots, M_t\}$ includes the indices of the selected substreams including index m and has L elements. In (10), we apply the fact that when L is less than or equal to M_t, the total interference and noise power is

$$\sum_{l \neq m, l \in A_L} |\mathbf{b}^H \mathbf{H}_k \mathbf{w}_l|^2 + \frac{L}{P} \|\mathbf{b}\|^2$$

$$\leq \sum_{l=1, l \neq m}^{M_t} |\mathbf{b}^H \mathbf{H}_k \mathbf{w}_l|^2 + \frac{M_t}{P} \|\mathbf{b}\|^2. \quad (11)$$

□

The perfect determination of the optimal value of L that maximizes the system throughput is not possible because only the limited CSI is available at BS. Therefore, we may use suboptimal approaches, one of which is to determine L with respect to the lower bound of the average interference SINR $\bar{\gamma}_{k_m}(\mathbf{w}_m) \geq \frac{M_t}{L} \gamma_{k_m}(\mathbf{w}_m)$ (cf. Theorem 3), that is

$$(L, A_l) = \arg \max_{l=1, \ldots, M_t, A_l \subset \{1, \ldots, M_t\}, |A_l|=l}$$

$$\sum_{m \in A_l} c_f(\frac{M_t}{l}\gamma_{k_m}(\mathbf{w}_m)) \tag{12}$$

where γ_{k_m} and $\mathbf{w}_m$) for $m = 1, \ldots, M_t$ are determined by (7). The average interference SINR $\bar{\gamma}_{k_m}(\mathbf{w}_m)$ is defined in Theorem 3 to represent the signal-to-average-interference-plus-noise ratio.

Theorem 3: We define the average interference power as the interference power averaged over all possible set of interference signal powers such that $I_{avg} = E_{A_L}[\sum_{l \neq m, l \in A_L} |\mathbf{b}^H\mathbf{H}_k\mathbf{w}_l|^2]$. The average interference SINR is then lower bounded by $\frac{M_t}{L}\gamma_{k_m}(\mathbf{w}_m)$. Here, $A_L \subset \{1, 2, \ldots, M_t\}$ is a possible set of the indices of L selected substreams including index m.

Proof: The average interference SINR is lower bounded by

$$\bar{\gamma}_k(\mathbf{w}_m)$$
$$= \frac{|\mathbf{b}^H\mathbf{H}_k\mathbf{w}_m|^2}{E_{A_L}[\sum_{l \neq m, l \in A_L} |\mathbf{b}^H\mathbf{H}_k\mathbf{w}_l|^2] + \frac{L}{P}\|\mathbf{b}\|^2}$$
$$= \frac{M_t}{L} \frac{|\mathbf{b}^H\mathbf{H}_k\mathbf{w}_m|^2}{\frac{M_t}{L}E_{A_L}[\sum_{l \neq m, l \in A_L} |\mathbf{b}^H\mathbf{H}_k\mathbf{w}_l|^2] + \frac{M_t}{P}\|\mathbf{b}\|^2}$$
$$\geq \frac{M_t}{L} \frac{|\mathbf{b}^H\mathbf{H}_k\mathbf{w}_m|^2}{\|\mathbf{b}^H\mathbf{H}_k\|^2 - |\mathbf{b}^H\mathbf{H}_k\mathbf{w}_m|^2 + \frac{M_t}{P}\|\mathbf{b}\|^2}$$
$$= \frac{M_t}{L}\gamma_k(\mathbf{w}_m) \tag{13}$$

where $A \subset \{1, 2, \ldots, M_t\}$ includes the indices of the selected substreams and has L elements. In (13), we use

$$E_{A_L}\left[\sum_{l \neq m, l \in A_L} |\mathbf{b}^H\mathbf{H}_k\mathbf{w}_l|^2\right]$$
$$= \frac{(L-1)\binom{M_t-1}{L-1}}{(M_t-1)\binom{M_t-1}{L-1}}(\|\mathbf{b}^H\mathbf{H}_k\|^2 - |\mathbf{b}^H\mathbf{H}_k\mathbf{w}_m|^2)$$
$$= \frac{L-1}{M_t-1}(\|\mathbf{b}^H\mathbf{H}_k\|^2 - |\mathbf{b}^H\mathbf{H}_k\mathbf{w}_m|^2). \tag{14}$$

□

In summary, PU^{2}RC incorporating MFUP at the transmitter offers the following two advantages: user diversity gain in the space domain and effective measurement of received SINRs.

4.2 Opportunistic Scheduling for Advanced Receivers

In this subsection, we explore scheduling criteria for the MIMO system with advanced receivers and propose an effective hybrid scheduling criteria for this case, where the advanced receiver utilizes the SIC reception. In the previous sections, all MIMO solutions except PU^{2}RC are designed based on a single-user environment and hence, they are not able to fully utilize the capacity of multiuser channels. That

is, only in PU^{2}RC the advantages of multiuser channels are properly exploited.

The multiuser scheduling methodology is needed when all users cannot be served at the same time due to the limited resources (e.g., the number of antennas, transmit power, etc.). In [10], two channel-aware opportunistic scheduling methods have been considered. One of them is a method that all the transmit antennas are assigned to a single selected user, where the single user data streams are spatially multiplexed at the transmitter. The maximum rate achieved by the corresponding scheduler is expressed as [10], [21]

$$C_{A,1} = \max_k \sum_m c_f(\gamma_{S,k,m}) \tag{15}$$

$$C_{A,2} = \max_k \sum_m c_f(\gamma_{M,k,m}) \tag{16}$$

for the (full) SIC reception and the linear reception, respectively, where $\gamma_{S,k,m}$ and $\gamma_{M,k,m}$ are defined in Sect. 3.1. In the other scheduling method, all users compete independently for each transmit antenna, where BS assigns the selected user streams to each antenna. This scheduling method can be applied to the proposed STMA MIMO scheme. The maximum rates using this scheduling method heavily depend on a particular receiver structure, which are given by

$$C_{B,1} = \max_Q \sum_{m=1}^{M_t} \min_{k \in Q_m} c_f(\gamma_{S,k,m}), \tag{17}$$

$$C_{B,2} = \sum_{m=1}^{M_t} \max_k c_f(\gamma_{M,k,m}), \tag{18}$$

for the SIC reception, and the linear reception, respectively, where $Q = [k_1, k_2, \ldots, k_{M_t}]$ is a user index vector selected from all K users (multiple selection is allowed), $Q_m = [k_1, k_2, \ldots, k_{M_t-m+1}]$ is the deflated version of Q where k_n for $n = M_t - m, \ldots, M_t$ are deleted from Q. Note that (17) follows from the fact that the interfering signal can be decoded as long as the transmission rate is less than the capacity of the interfering link [22].

Theorem 4: The SIC reception subtracts out the interfering signals from all upper layer substreams regardless of its ownership, i.e., although all upper layer substreams are not indented for the corresponding user. The throughput performance of (17) is, then, equal to that of (15), i.e., $C_{B,1} = C_{A,1}$. Hence, we can use the scheduler (15) instead of (17) to reduce the scheduling complexity.

Proof: To prove Theorem 4, we first consider one instance of Q, i.e., $Q' = [k_1, k_2, \ldots, k_{M_t}]$. Some simple algebra yields the simplification of the throughput of Q' in (17):

$$R_{B,1}(Q') = \sum_{m=1}^{M_t} \min_{k \in Q'_m} c_f(\gamma_{S,k,m})$$
$$\leq \sum_{m=1}^{M_t} c_f(\gamma_{S,k_1,m}) \tag{19}$$
$$= R_{B,1}([k_1, k_1, \ldots, k_1])$$

$$= R_{A,1}(k_1) \qquad (20)$$

where $R_{A,1}(k_1) = \sum_{m=1}^{M_t} c_f(\gamma_{S,k_1,m}(Q'_m))$ is the term located inside of the maximization function of (15). The equality of (19) holds when $k_1 = k_2 = \ldots = k_{M_t}$. From (20), we conclude that when SIC is applied, the achievable rate of the multiuser selection is smaller than or equal to that of the single user selection. Hence, $C_{B,1} = C_{A,1}$ is valid, which completes the proof. □

To achieve the maximum throughput using advanced receivers, hybrid schedulers can be considered. One of hybrid schedulers, suggested in [21], is given by

$$C_{H,1} = \max\{C_{A,1}, C_{B,2}\}, \qquad (21)$$

in which both $C_{A,1}$ and $C_{B,2}$ are used to select the best user. It is seen in [21] that given the threshold point determined by the number of scheduled users, only one metric is sufficient for the hybrid scheduling criterion (21) where the scheduling policy is to switch between $C_{A,1}$ and $C_{B,2}$. In practice, it is desirable to choose the switching point K_{sw} satisfying $\mathcal{E}\{C_{A,1}\} = \mathcal{E}\{C_{B,2}\}$, so that the rule of (21) becomes

$$C_{H,2} = \begin{cases} C_{A,1}, & K \le K_{sw} \\ C_{B,2}, & K > K_{sw} \end{cases}. \qquad (22)$$

The hybrid scheduling criterion in (22) exploits multiuser diversity whereas the switching point is determined depending on the number of scheduled users. However, it is difficult to accurately know how many users are to be scheduled before the activation of the scheduling method, which is required to estimate K_{sw}. Hence, we propose the novel scheduling criterion in which the reception mode is to be constrained as *single user SIC (SU-SIC)*, which is given by (cf. Theorem 5)

$$C_{H,3} = \max_{\{S_j\}} \sum_j \max_k \sum_{m=1}^{|S_j|} c_f(\gamma_{su,k,m}(S_j)) \qquad (23)$$

where

$$\gamma_{su,k,m}(S_j) = \mathbf{h}_{k,s_{j,m}}^H \left(\sum_{n=1}^{M_t} \mathbf{h}_{k,s_{j,n}} \mathbf{h}_{k,s_{j,n}}^H \right.$$

$$\left. - \sum_{n=1}^m \mathbf{h}_{k,s_{j,n}} \mathbf{h}_{k,s_{j,n}}^H + \frac{M_t}{P} \mathbf{I} \right)^{-1} \mathbf{h}_{k,s_{j,m}} \qquad (24)$$

is the SINR when SIC is performed inside the substreams of S_j. Also, $S_j = [s_{j,1}, s_{j,2}, \ldots, s_{j,|S_j|}]$ is the jth sub-group of indices of transmit substreams with constraints $\bigcup_j S_j = \{1, 2, ..., M_t\}$, $\bigcap_j S_j = \phi$ and $s_{j,1} \le s_{j,2} \le \ldots \le s_{j,|S_j|}$, and $S_{j,m} = [s_{j,1}, s_{j,2}, \ldots, s_{j,|S_j|-m+1}]$ is the deflated version of S_j. It is defined that SU-SIC cancels out only self-interference, not interferences intended to other users, while SIC used in (17) attempts to remove all interferences associated with the upper layer substreams.

Theorem 5: Consider the STMA based scheduling criterion for the partial SIC reception, where SIC is operated within each sub-group of transmit substreams. By extension of (17), the scheduling criterion for partial SIC is given by

$$C_C = \sum_j \max_{Q_j} \sum_{m=1}^{|Q_j|} \min_{k \in Q_{j,m}} c_f(\gamma_{su,k,s_{j,m}}(S_j)), \qquad (25)$$

subject to $\sum_j |Q_j| = M_t$.

Here, $Q_j = [q_{j,1}, q_{j,2}, \ldots, q_{j,|Q_j|}]$ is a subvector of Q (the ordering is preserved) and $Q_{j,m} = [q_{j,1}, q_{j,2}, \ldots, q_{j,|Q_j|-m+1}]$ is a deflated version of Q_j where $q_{j,m}$ is the $s_{j,m}$th element of Q and $S_j = [s_{j,1}, s_{j,2}, \ldots, s_{j,|Q_j|}]$. Then, the performance of the scheduling criterion (25) is better than those of (17) and (18), i.e., $C_C \le C_{B,1}$ and $C_C \le C_{B,2}$, and moreover, is equivalent to that of (23), i.e., $C_C = C_{H,3}$. Hence, the SU-SIC reception is the optimal strategy for STMA based scheduling with SIC receivers in terms of the achievable sum rate.

Proof: The scheduling criteria of (17) and (18) are the special cases of (25) when $|Q_1| = |Q|$ and $|Q_j| = 1$ for all $j = 1, \ldots, M_t$, respectively, which proves $C_C \le C_{B,1}$ and $C_C \le C_{B,2}$. Considering $Q'_j = [k_1, k_2, \ldots, k_{|Q'_j|}]$, by the similar procedure in (19) and (20) we have

$$C_C(Q'_j) = \sum_{m=1}^{|Q'_j|} \min_{k \in Q'_{j,m}} c_f(\gamma_{su,k,s_{j,m}}(S'_j))$$

$$\le \sum_{m=1}^{|S'_j|} c_f(\gamma_{su,k'_1,s_{j,m}}(S'_j)) \qquad (26)$$

where S'_j and k'_1 are the modified versions of S_j and k_1 for Q'. Without loss of generality, $\sum_j \max_{Q'_j} C_C(Q'_j)$ in (25) becomes equivalent to $C_{H,3}$. As expected, in user selection the degree of freedom of (23), which is equivalent to (25), is larger than or equal to those of (17) and (18) so that we conclude that (23) is the optimal strategy for this case. The equality of the degree of freedom holds only when $K = 1$. This completes the proof of Theorem 5. □

So far, we considered three types of hybrid scheduling schemes: (21), (22) and (23). From a network point of view, the scheduling of (23), i.e., the SU-SIC based hybrid scheduler, is the most effective scheme among them because of its higher degree of freedom in scheduling as shown in Theorem 5. Using (23), in the subsequent section we will present an effective feedback protocol which allows transmitter to adaptively choose between (15) and (18). Moreover, the proposed protocol achieves the near maximum throughput of (23) without increasing the CQI feedback overhead compared to that required for (15).

4.3 Feedback Signaling Protocols

We now design feedback signaling protocols in PU²RC. Two kinds of channel information, which are the beamforming vectors, CDI, and the corresponding channel qualities, CQI, are fed back to the transmitter. More specifically,

the beamforming vectors and the channel qualities are the quantized eigenvectors of each user, i.e., $\{\mathbf{v}_{k,m}\}_m$, and the received SINRs, i.e., $\{\rho_k(\mathbf{v}_{k,m})\}_m$, respectively, as described in Sect. 4.1. We consider quantized vectors from the set predefined by subspace packing [13], where the beam selection approach, i.e, the function in (7), is preferable to the eigen-decomposition approach, i.e., the function in (6), which is practically difficult to implement. In general, the set of selected vectors corresponds to the maximum sum rate at the receiver and the selected vectors are additionally constrained to be orthonormal to each other. In the following, feedback protocols for MMSE receivers and SIC receivers are subsequently discussed.

For MMSE receiver, we take into account two feedback protocols: full feedback and partial feedback. In full feedback, the information of the kth user may be given by

$$F_{A,k} = \{g_k, \{\gamma_{M,k,m}\}_{m=1,\dots,M_t}\} \qquad (27)$$

where g_k is the index of the matrix consisted of the selected vectors, $\mathbf{W} = [\mathbf{w}_1^*, \mathbf{w}_1^*, \dots, \mathbf{w}_{M_t}^*]$, and $\{\gamma_{M,k,m}\}_m$ are the received SINRs estimated at the receiver corresponding to g_k. All $\{\gamma_{M,k,m}\}_m$ denote the received SINRs using the MMSE reception and hence, $\gamma_{M,k,m}$ in (27) is calculated by (4) by replacing $\mathbf{H}_k$ with $\mathbf{H}_k\mathbf{W}$ as in (8).

When the number of the scheduling users are large, feeding back of the full CQI is no more necessary because of multiuser diversity. Note that as the number of users goes to infinity, only maximum received SINR is required at the transmitter (see Fig. 6). Considering such property, the partial feedback protocol is given by

$$F_{B,k} = \{g_k, m_S, \gamma_{M,k,m_S}\} \qquad (28)$$

where γ_{M,k,m_S} is the maximum received SINR and m_S is the index of the corresponding vector, instead of delivering SINRs for all vectors in (27), in which

$$\gamma_{M,k,m_S} = \max_{m=1,\dots,M_t} \gamma_{M,k,m}. \qquad (29)$$

In the SU-SIC based hybrid scheduling scheme, the complexity of feedback signalling in terms of its amount is significantly high because all self-interferences for each user must be canceled whenever the combinations of transmit substreams (or transmit antennas) assigned to users vary. Furthermore, the advantage of SIC over MMSE is sufficiently exploited with only a few users, while its gain diminishes quickly as the number of users increases. Instead of generating and delivering SNRs corresponding to all combinations of transmit substream assignment, we propose the feedback protocol combination of two specific cases such as (27) with SIC and (28) with MMSE, as follows:

$$F_{C,k} = \{g_k, m_S, \gamma_{M,k,m_S}, \{\gamma_{S,k,m}\}_{m \neq m_S}\} \qquad (30)$$

where SINRs are included for both MMSE and SIC receiver structures (i.e., γ_{M,k,m_S} and $\{\gamma_{S,k,m}\}$, respectively), while the number of SINRs in (30) is constrained equal to that in (27). Note that $\gamma_{S,k,m}$ in (30) is calculated by (2) by replacing

$\mathbf{H}_k$ with $\mathbf{H}_k\mathbf{W}$. In (30), the scheduler allocates either all transmit substreams to the best user with SIC or each transmit substream to different users with MMSE, depending on the CQIs delivered from users. That is, for a single user the combinations of allocating more than one transmit substream (but less than all transmit substreams) are excluded, which might have little impact on the sum rate as long as the number of transmit antennas is not large (cf. numerical results in the following section).

5. Numerical Results

This section shows the results of computer simulations conducted for the performance evaluations with the schemes described in the previous sections. In the following simulations, we assume that with $M_t = M_r = 4$, the linear MMSE receiver is used for PU²RC, PARC with MMSE linear receiver (PARC-MMSE) and SPARC with MMSE linear receiver (SPARC-MMSE) whereas the MMSE-SIC receiver is used for PARC-SIC. PU²RC with no beamforming represents PU²RC operated with a precoding codebook $\mathcal{W} = \{\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_{M_t}\}$ where the mth orthonormal basis vector $\mathbf{e}_m$ is mapped to the mth transmit antenna, while PU²RC with beamforming means PU²RC with a precoding codebook of which the size is more than M_t. Scheduling algorithms are applied to aforementioned MIMO schemes such that PARC and PU²RC use TDMA scheduling in (16) and STMA scheduling in (18) except that PARC-MMSE (round-robin) in Fig. 5 and PU²RC with hybrid scheduling in Fig. 7 use round-robin scheduling and the scheduling algorithm in (23), respectively.

Figure 5 shows that PU²RC outperforms PARC-MMSE, where the number of users is assumed to be $K = 10$. Scheduling algorithms PU²RC has about 2 dB gain of transmit beamforming with a 4-bit feedback precoding codebook over PU²RC with no beamforming, and achieves additional user diversity gain over PARC-MMSE and PARC-MMSE (round-robin) by about 3.5 dB and 7 dB, respectively. The gain of PU²RC over PARC-MMSE comes from spatial user selection diversity.
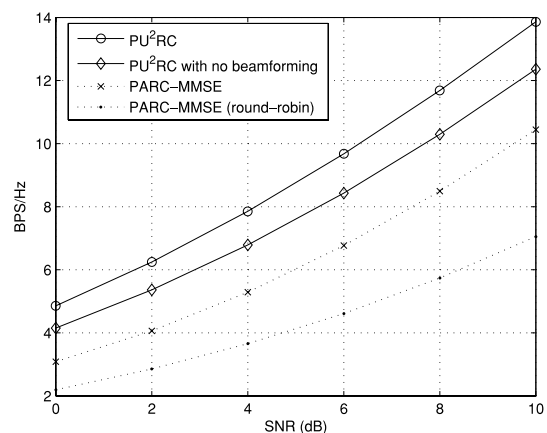

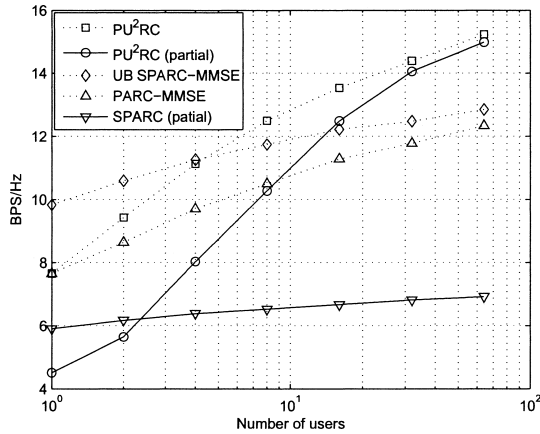**Fig. 5** Throughput comparison of PU²RC and PARC-MMSE.

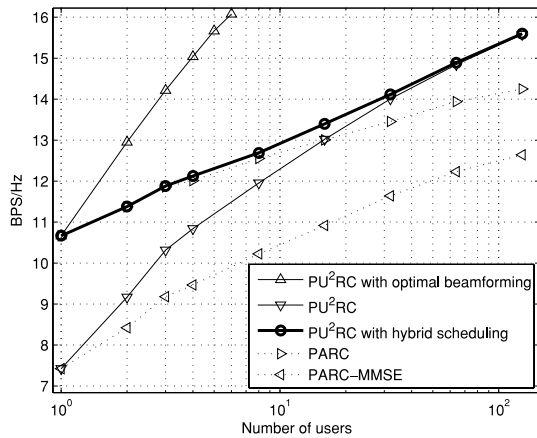**Fig. 6** Throughput comparison of PU^{2}RC, PARC-MMSE, and SPARC.

Fig. 7 Throughput performance of PU^{2}RC with hybrid scheduling over other schemes.

In Figs. 6 and 7, we illustrate numerical results in terms of the number of users at average SNR = 10 dB, and no beamforming is used for PU^{2}RC. Figure 6 shows the performance of PU^{2}RC with partial feedback. PU^{2}RC outperforms PARC-MMSE when feedback information for all transmit antennas are sent from MSs back to BS. With the assumption of partial feedback, i.e., the SINR of the selected substream (or antenna), PU^{2}RC still has significant gain over SPARC. This is because with partial feedback SPARC exploits only one transmit antenna, which results in a limited throughput gain over the number of users, while PU^{2}RC can transmit as many data streams as the number of transmit antennas at its maximum. The crossing point in PU^{2}RC and SPARC is due to the fact that the interference power is not included in the first CQI value measured in SPARC. The performances of PARC based schemes are upper bounded by the upper bound performance of SPARC (UB SPARC-MMSE), which, however, requires a significant number of CQIs that is given by [17]

$$O(M_t) = \sum_{m=1}^{M_t} m \binom{M_t}{m}. \qquad (31)$$

In Fig. 7, the throughput performance of PU^{2}RC with SU-SIC based hybrid scheduling is examined. It shows that when the number of users is less than 7, the performance of PARC using SIC receivers is better than that of PU^{2}RC using linear receiver, but rather surprisingly, vice versa for higher number of users. As expected from this result, the hybrid scheduling scheme with SU-SIC between PU^{2}RC and PARC performs better than both schemes, independent of the number of users. The performances of all schemes are upper bounded by PU^{2}RC with the block MMSE, not unitary, beamforming (BM-BF) in which the precoding matrix is obtained by the block MMSE algorithm with full CSI at the transmitter [23]. The block MMSE algorithm yields the near-optimal precoding matrix, which is given by

$$\mathbf{w}_m = \frac{\hat{\mathbf{w}}_m}{\|\hat{\mathbf{w}}_m\|}, \quad \hat{\mathbf{w}}_m = \left(\sum_{l=1, l \neq m}^{M_t} \mathbf{f}_l \mathbf{f}_l^H + \frac{M_t}{P} \mathbf{I} \right) \mathbf{f}_m \qquad (32)$$

where $\mathbf{f}_m = \lambda_{k_m^*}(\mathbf{v}_m^*)\mathbf{v}_m^*$ for $m = 1, 2, \ldots, M_t$ and $\{(\mathbf{v}_m^*, k_m^*)\}_{m=1}^{M_t}$ is the set of the selected users and eigenvectors that maximize the system throughput. In summary, the gain achieved in the proposed scheme results from the multiuser and beamforming gain in the space domain, where the space-time user diversity and transmit unitary beamforming are exploited.

6. Conclusions

We examined the throughput performance of TDMA-based MIMO candidates in WCDMA/HSDPA. Then, a framework for STMA-based MIMO design, i.e., PU^{2}RC, using multiuser diversity and multiplexing transmission was proposed. In particular, PU^{2}RC is designed to obtain the multiuser scheduling gain in proportion to the number of users and to achieve the beamforming gain by using the unitary basis transformation at the transmitter. Furthermore, user scheduling is combined together with the modified SIC reception, represented as SU-SIC. The proposed hybrid scheduler for SU-SIC allocates all transmit antennas to the best user with SIC or each transmit antenna to different users with MMSE, depending on the CQIs delivered from each MS. In this case, the sum rate performance is observed to approach the optimal throughput, assuming that the optimality is defined such that for each user the combinations of allocating two or more multiple transmit antennas are flexibly allowed.

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