LETTER

Unitary Beamforming Multi-User MIMO System with Efficient User Scheduling Algorithm*

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SUMMARY This letter proposes a new practical multiuser MIMO (MU-MIMO) scheme, which is an evolution of the well-known Per User Unitary beamforming Rate Control (PU^2RC) proposed for 3GPP-LTE and IEEE802.16m standards. The proposed scheme includes an efficient user scheduling algorithm which alleviates the major weakness of the conventional PU^2RC. Numerical results show that the proposed scheme provides notable performance improvement especially with small and medium user pool since it effectively exploits the benefit from large codebook size.
key words: *multi-user MIMO, unitary beamforming, PU^2RC, user scheduling, 3GPP-LTE, IEEE802.16m*

1. Introduction

In multiple input multiple output (MIMO) broadcast channel, multiuser MIMO (MU-MIMO) technique is the key solution for high throughput in recent wireless communication standards such as 3GPP-LTE and IEEE802.16m. It is well known that the dirty paper coding (DPC) is the optimal transmit strategy in terms of sum capacity [1]. However, practical near-capacity DPC has not been developed yet.

Zero forcing beamforming (ZFBF) [2]–[4] and Per User Unitary beamforming Rate Control (PU^2RC) [5]–[8] schemes have been proposed as practical MU-MIMO solutions in recent 3GPP-LTE and IEEE802.16m standards. ZFBF operation requires only linear computations, and the ZFBF scheme with greedy scheduling algorithm asymptotically achieves the optimum sum capacity as the number of users goes to infinity [2]. However, the drawback of the ZFBF scheme is that the performance is notably dominated by the inaccuracy of channel state information (CSI). On the contrary, the PU^2RC scheme which is a practical generalization of random beamforming [9] with the predefined sets of orthogonal codebooks is both simple and robust against CSI inaccuracy since the channel feedback, user scheduling and beamforming are jointly designed by its nature [5], [8]. Hence, the PU^2RC scheme has become one of the major candidates for limited-feedback MU-MIMO systems.

Recent numerical results in [8] have shown that the PU^2RC scheme outperforms the ZFBF scheme with large number of users, whereas the performance becomes poor with small number of users. Moreover, enlarging the codebook size rather degrades the performance in contrast to the case of the large number of users. This is the major weakness of the conventional PU^2RC scheme; the user scheduler in BS becomes inefficient especially when user pool is small. Hence, in this letter, we propose a new *Per User Unwasted Unitary beamforming Rate Control* (PU^3RC) scheme based on an efficient user scheduling algorithm, which alleviates the weakness of the conventional PU^2RC scheme.

2. System Model

We assume that base station (BS) has M transmit antennas and each user has a single receive antenna. Equal power allocation over M active users is considered. A time sample received at user-k is given by

$$y_k = \sqrt{\frac{P}{M}}(\mathbf{h}_k^H \mathbf{w}_k)x_k + \sqrt{\frac{P}{M}}\sum_{j\neq k}(\mathbf{h}_k^H \mathbf{w}_j)x_j + n_k,\ \ j,k \in \mathcal{A}, \tag{1}$$

where P is the total transmission power, x_k is an independent data symbol transmitted through M transmit antennas satisfying $E[|x_k|^2] = 1$, $\mathbf{h}_k^H$ is the MISO channel vector ($\mathbf{h}_k \in \mathbb{C}^{M\times 1}$), $\mathbf{w}_k$ is the linear precoding vector ($\mathbf{w}_k \in \mathbb{C}^{M\times 1}$), n_k is the complex Gaussian noise term with unit variance at user-k, and $\mathcal{A}$ is a set of the simultaneously scheduled users among the entire user set $\mathcal{S}$. The channel is assumed to be block fading where the channel remains static in each block. The channel state information (CSI) between BS and each receiver is perfectly known to the receiver (i.e. user) utilizing pilot broadcasting.

In practical MU-MIMO systems, only partial CSI feedback is allowed since it results in high signaling overhead in uplink control channel. One channel direction information (CDI) and one channel quality information (CQI) are agreed as a reasonable amount of channel feedback in the next generation communication systems [3], [6], [7]. Each

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user quantizes its channel direction using the predefined codebook, C, and feeds quantized CDI back to BS at every beginning of blocks via feedback channel [10], [11]. In unitary beamforming scheme such as PU^{2}RC, the precoding vectors of the simultaneously scheduled users are orthonormal. Let $\mathcal{W}^{(g)}$ $(g = 1, 2, \cdots, G)$ denote the g-th orthonormal set in the codebook, C. The precoding vector $\mathbf{w}_m^{(g)}$ $(m = 1, 2, \cdots, M)$ denotes the m-th member of $\mathcal{W}^{(g)}$. The number of feedback bits required for CDI feedback is $B = \log_2 |C| = \log_2 G + \log_2 M$. Here, it is assumed that CQI is perfectly known to BS without quantization as in [2], [5], [8].

3. New PU^{3}RC Scheme

We propose a new MU-MIMO scheme which includes an efficient user scheduling algorithm to mitigate the major weakness of the conventional PU^{2}RC scheme that the user scheduler becomes inefficient with small number of users. The main idea of the proposed scheme is that BS estimates the SINR of the non-selected user based on its CDI and CQI reports and *additionally selects up to M users* to be served without wasting precoding vectors. Hence, the proposed scheme is referred to as Per User Unwasted Unitary beamforming Rate Control (PU^{3}RC) and is described as follows.

STEP 1 (Pilot broadcasting & Channel estimation): Each user estimates its channel, $\mathbf{h}_k$, based on pilot broadcasting.

STEP 2 (CDI & CQI feedback): Each user finds the codeword vector in the codebook, C, which has the minimum chordal distance from its channel vector as

$$\mathbf{w}_{m_k}^{(g_k)} = \arg\min_{\mathbf{v}\in C} \ \sin^2(\angle(\mathbf{v}, \mathbf{h}_k)). \tag{2}$$

The quantized channel direction is reported to BS using codeword vector indices, i.e., $\{\mathrm{CDI}_k\} = \{g_k, m_k\}$, where g_k denotes the index for orthonormal set in the codebook and m_k denotes the index for the precoding vector in the orthonormal set. The CQI feedback of user-k, $\{\mathrm{CQI}_k\}$, is calculated as

$$\mathrm{CQI}_k = \frac{\frac{P}{M}|\mathbf{h}_k^H \mathbf{w}_{m_k}^{(g_k)}|^2}{\frac{P}{M}\sum_{j\neq m_k}|\mathbf{h}_k^H \mathbf{w}_j^{(g_k)}|^2 + 1}. \tag{3}$$

STEP 3 (First user selection): Firstly, initialize $\mathcal{A}_1 = \mathcal{A}_2 = \emptyset$. We define a user set in which users report $\mathbf{w}_m^{(g)}$ as their CDI feedback as

$$\mathcal{U}_m^{(g)} = \left\{1 \le k \le K \;\middle|\; \mathbf{w}_{m_k}^{(g_k)} = \mathbf{w}_m^{(g)}\right\}. \tag{4}$$

Then, the index of the orthonormal subset in the codebook which maximizes the total throughput is

$$L = \arg\max_g \sum_{m=1}^{M} \log\left(1 + \max_{k\in\mathcal{U}_m^{(g)}} \mathrm{SINR}_k\right), \tag{5}$$

and the user set of the selected user is

$$\mathcal{A}_1 = \bigcup_{m=1}^{M}\left\{\pi \;\middle|\; \pi = \arg\max_{k\in\mathcal{U}_m^{(L)}} \mathrm{SINR}_k\right\}. \tag{6}$$

Note that the user scheduling in the conventional PU^{2}RC scheme terminates in STEP 3. If any precoding vector $\mathbf{w}_m^{(L)}$ in the selected orthonormal set $\mathcal{W}^{(L)}$ remains unallocated, i.e., $\mathcal{U}_m^{(L)} = \emptyset$, the precoding vector is *wasted*, which decreases system throughput.

STEP 4 (Additional user selection): This is the key step which prevents the proposed PU^{3}RC scheme from wasting any precoding vectors. For the unallocated (wasted) precoding vectors in the selected orthonormal set, BS can calculate the estimated SINR when it is allocated to any non-selected user. This is because CDI and CQI values of a user contain partial information of its channel. Based on SINR estimation of user-k, γ_k, which is computed in the next section, the most appropriate user for the unallocated precoding vector is selected as

$$\mathcal{A}_2 \leftarrow \mathcal{A}_2 \bigcup \left\{\pi \;\middle|\; \pi = \arg\max_{k\in(\mathcal{S}\cap\mathcal{A}_1^C\cap\mathcal{A}_2^C)} \gamma_k\right\}, \tag{7}$$

where $\mathcal{A}_2$ is the set of users which are additionally selected in the proposed PU^{3}RC scheme. STEP 4 is repeated until all unallocated precoding vectors in the selected orthonormal set $\mathcal{W}^{(L)}$ are matched with specific users.

STEP 5 (Unitary beamforming transmission): The final unitary beamforming matrix and scheduled user set are $\mathcal{W}^{(L)}$ and $\mathcal{A} = \mathcal{A}_1 \bigcup \mathcal{A}_2$, respectively. The system throughput of the proposed PU^{3}RC scheme is calculated as

$$R_{\mathrm{PU^3RC}} = \sum_{k\in\mathcal{A}_1}\log(1+\mathrm{CQI}_k) + \sum_{k\in\mathcal{A}_2}\log(1+\gamma_k). \tag{8}$$

4. Estimated SINR Computation for Additional User Selection (STEP 4)

For user-k which is not selected in the first user selection, i.e., $k \in (\mathcal{S}\cap\mathcal{A}_1^C\cap\mathcal{A}_2^C)$, the channel vector of user-k is expressed as

$$\mathbf{h}_k = \|\mathbf{h}_k\|\,\tilde{\mathbf{h}}_k = \|\mathbf{h}_k\|\,(\mathbf{w}_{m_k}^{(g_k)} + \mathbf{e}_k), \tag{10}$$

where $\tilde{\mathbf{h}}_k$ is a unit direction vector and $\mathbf{e}_k$ is the error vector between the real channel direction $\tilde{\mathbf{h}}_k$ and the quantized channel direction $\mathbf{w}_{m_k}^{(g_k)}$. We define an angle of the quantization error as

$$\theta_k = \angle(\tilde{\mathbf{h}}_k, \mathbf{w}_{m_k}^{(g_k)}). \tag{11}$$

The reported CQI of user-k is expressed using (10) in (3) as

$$\mathrm{CQI}_k = \frac{\frac{P}{M}\|\mathbf{h}_k\|^2\,|(\mathbf{w}_{m_k}^{(g_k)})^H\mathbf{w}_{m_k}^{(g_k)} + \mathbf{e}_k^H\mathbf{w}_{m_k}^{(g_k)}|^2}{\frac{P}{M}\|\mathbf{h}_k\|^2\sum_{j\neq m_k}|(\mathbf{w}_{m_k}^{(g_k)})^H\mathbf{w}_j^{(g_k)} + \mathbf{e}_k^H\mathbf{w}_j^{(g_k)}|^2 + 1}. \tag{12}$$

Rearranging the equation with respect to $\|\mathbf{h}_k\|^2$ gives

$$\begin{aligned}\mathrm{SINR}_k &= \frac{\frac{P}{M}|\mathbf{h}_k^H \mathbf{w}_n^{(L)}|^2}{\frac{P}{M}\sum_{i\neq n}|\mathbf{h}_k^H \mathbf{w}_i^{(L)}|^2 + 1} \\ &= \frac{\mathrm{CQI}_k|(\mathbf{w}_{m_k}^{(g_k)})^H \mathbf{w}_n^{(L)} + \mathbf{e}_k^H \mathbf{w}_n^{(L)}|^2}{\mathrm{CQI}_k \sum_{i\neq n}|(\mathbf{w}_{m_k}^{(g_k)})^H \mathbf{w}_i^{(L)} + \mathbf{e}_k^H \mathbf{w}_i^{(L)}|^2 + |1+\mathbf{e}_k^H \mathbf{w}_{m_k}^{(g_k)}|^2 - \mathrm{CQI}_k \sum_{j\neq m_k}|\mathbf{e}_k^H \mathbf{w}_j^{(g_k)}|^2}\end{aligned} \tag{9}$$

$$||\mathbf{h}_k||^2 = \frac{\mathrm{CQI}_k \cdot \frac{M}{P}}{|1+\mathbf{e}_k^H \mathbf{w}_{m_k}^{(g_k)}|^2 - \mathrm{CQI}_k \sum_{j\neq m_k}|\mathbf{e}_k^H \mathbf{w}_j^{(g_k)}|^2}. \tag{13}$$

Then, we calculate the SINR of user-k using (10) and (13) assuming that the unallocated precoding vector $\mathbf{w}_n^{(L)}$ is allocated for its transmission as (9).

Denoting α as the angle between any two neighboring codeword vector in the codebook C, the angle of the quantization error satisfies $\theta_k \leq \frac{1}{2}\alpha$ and

$$0 \leq |\mathbf{e}_k^H \mathbf{v}| \leq \sqrt{2\left(1-\cos\frac{\alpha}{2}\right)} \overset{\Delta}{=} \epsilon, \tag{14}$$

where $\mathbf{v}$ is any unit vector. Using (14) in (9), SINR_k is bounded as

$$\mathrm{SINR}_k \geq \frac{\mathrm{CQI}_k\left\{\max\left(|(\mathbf{w}_{m_k}^{(g_k)})^H \mathbf{w}_n^{(L)}| - \epsilon, 0\right)\right\}^2}{\mathrm{CQI}_k \sum_{i\neq n}\left\{|(\mathbf{w}_{m_k}^{(g_k)})^H \mathbf{w}_i^{(L)}| + \epsilon\right\}^2 + (1+\epsilon)^2} \overset{\Delta}{=} \gamma_k. \tag{15}$$

We consider γ_k as the worst-case estimated SINR. Hence, throughput computation using γ_k in (8) guarantees the minimum performance of the proposed $\mathrm{PU^3RC}$ scheme.

5. Numerical Results

We consider $M = 4$ transmit antennas and SNR = 20 dB. The size of codebook varies with the number of feedback bits, B. We assume no delay and errors in the feedback channel.

Figure 1 shows how the system throughput of the conventional $\mathrm{PU^2RC}$ scheme varies with the number of users according to the different codebook sizes. Generally, larger codebook provides higher beamforming gain due to precise channel feedback and beamforming. However, the system throughput increases only when the number of feedback bits increases from $B = 2$ to $B = 4$. Otherwise, the system throughput rather decreases as the codebook size increases ($4 < B$). The reason is that some precoding vectors in the selected orthonormal set remain unallocated (wasted) without large user pool†. In the small and medium user ranges ($1 \leq K \leq 30$), the resulting waste of the precoding vectors dominates the performance degradation over increased beamforming gain. Thus, the benefit from the larger codebook vanishes unless user pool is large enough.

Figure 2 compares the throughput performance of the proposed $\mathrm{PU^3RC}$ and conventional $\mathrm{PU^2RC}$ schemes. The

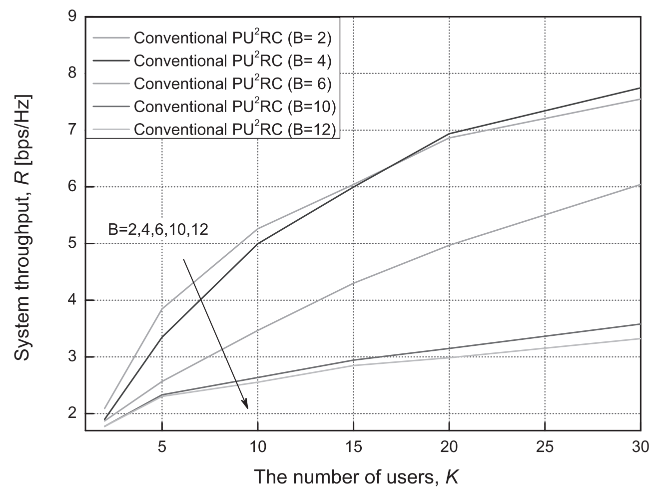

Fig. 1 System throughput of the conventional $\mathrm{PU^2RC}$ versus the number of users with various codebook sizes, where $M = 4$, and SNR = 20 dB.

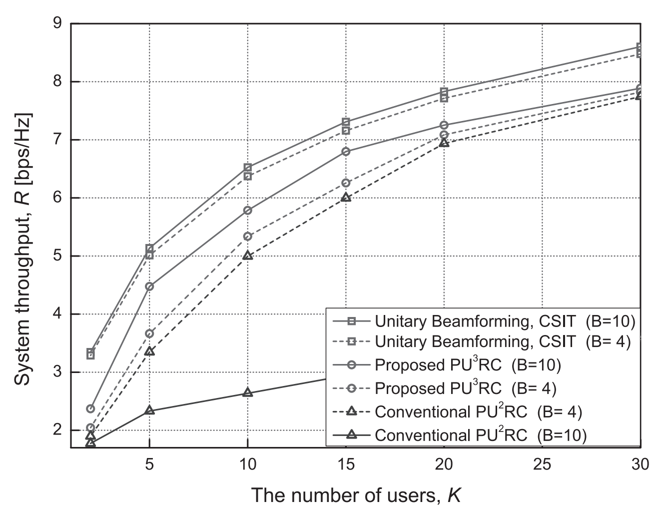

Fig. 2 Comparison of system throughput of the conventional $\mathrm{PU^2RC}$ and proposed $\mathrm{PU^3RC}$, where $M = 4$, and SNR = 20 dB.

system throughput of the ideal unitary beamforming scheme is also plotted as a reference of performance upper bound. In the ideal unitary beamforming scheme, BS is assumed to have all CQI values for all precoding vectors (entire codebook); the scheduler at BS always finds the appropriate users for all orthonormal sets without wasting any precoding

†With large user pool, i.e., $100 \leq K$, larger codebook, of course, provides higher throughput due to precise beamforming as presented in [8].

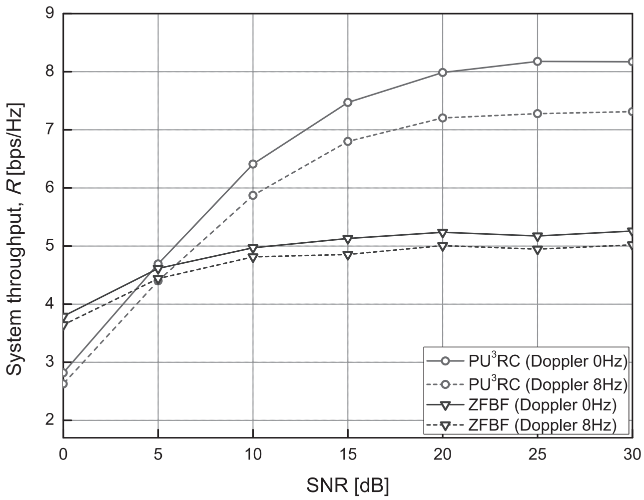

Fig. 3 Comparison of system throughput of the conventional ZFBF and proposed $\mathrm{PU}^3\mathrm{RC}$, where $M = 4$, and $K = 30$.

vectors. When codebook size is large, i.e., $B = 10$, the proposed $\mathrm{PU}^3\mathrm{RC}$ scheme provides huge throughput improvement over the conventional $\mathrm{PU}^2\mathrm{RC}$. This is because the proposed $\mathrm{PU}^3\mathrm{RC}$ scheme effectively exploits the benefit from large codebook size without wasting precoding vectors even with the small and medium number of users. When codebook size is small, i.e., $B = 4$, the performance gap between the proposed $\mathrm{PU}^3\mathrm{RC}$ and conventional $\mathrm{PU}^2\mathrm{RC}$ schemes reduces since SINR estimation and additional user selection process in the proposed $\mathrm{PU}^3\mathrm{RC}$ scheme (STEP 4) become inaccurate. Nevertheless, the proposed $\mathrm{PU}^3\mathrm{RC}$ scheme still outperforms the conventional $\mathrm{PU}^2\mathrm{RC}$ scheme.

Figure 3 compares the throughput performance of the proposed $\mathrm{PU}^3\mathrm{RC}$ and conventional ZFBF schemes considering channel feedback delay. The throughput performance gradually improves with SNR and saturates in high-SNR region due to interference. The proposed $\mathrm{PU}^3\mathrm{RC}$ outperforms the conventional ZFBF except at low SNR. Simulation results of more practical scenario with Doppler frequency which is resulted from user mobility is also presented†. The throughput performance of both schemes degrades with the Doppler frequency since channel feedback information becomes out-dated. The proposed $\mathrm{PU}^3\mathrm{RC}$ scheme still outperforms the ZFBF schemes regardless of the Doppler frequency.

†The user mobility for Doppler frequency of 8 Hz is approximately 4 km/H assuming carrier frequency of 2 GHz.

6. Conclusions

In this letter, we have proposed a new *Per User Unwasted Unitary beamforming Rate Control* ($\mathrm{PU}^3\mathrm{RC}$) scheme based on an efficient user scheduling algorithm. The proposed $\mathrm{PU}^3\mathrm{RC}$ scheme is an evolution of the conventional $\mathrm{PU}^2\mathrm{RC}$ scheme, which alleviates the issue that the user scheduling becomes inefficient without the large number of users. Numerical results show that the proposed $\mathrm{PU}^3\mathrm{RC}$ scheme considerably improves the system throughput especially in the small and medium number of user ranges.

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