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Block Diagonalization with Multiuser Beamforming for Coordinated Multi-Point Transmission

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***Abstract* — Coordinated Multi-Point transmission and reception (CoMP) technique is mostly required to reduce the inter-cell interference (ICI). It also increases the cell edge user throughput and improves the coverage. We apply block diagonal beamforming to downlink transmission, and assume perfect knowledge of downlink channels and transmit messages at each transmit point. Two different power allocation schemes are investigated for SVD, ZF and BD based multicell transmission.The SVD scheme achieves a suboptimal performance, butat a reduced complexity.In this paper, we study the performance of multiuser beamforming for differently in various CoMP scenarios. The simulations results indicate that the proposed scheme offers much higher performance gain compared with the CoMP-JP mode and reduce the complexity in comparison with BD scheme.**

***Keywords* — Block Diagonalization (BD), Coordinated Beamforming, Joint Processing, CoMP, Zero-forcing.**

I. INTRODUCTION

A multiuser MIMO system typically consists of a base station equipped with multiple antennas and a number of mobile users, each possibly equipped with multiple receive antennas. The base station transmits data to these mobiles users [1]-[2]. To eliminate or reduce interference, the base station is required to employ orthogonalization techniques. These orthogonalization techniques distribute signals to mobile users among different dimensions of resources and thus obtain a minimum interference between them. In this approach, the base station transmits signals to multiple mobile users by applying orthogonal beamforming weights. As a result, each mobile user's beamforming weights lie in the null space of all other mobile users' channels. This is equivalent to having orthogonal channels between different mobile users. Zero-forcing (ZF) and BD [3] are alternative low complexity transmission techniques. BD scheme is an attractive orthogonalization scheme for its low complexity and acceptable sum capacity [4]. Attention has been focused on improving the performance of BD under realistic scenarios. Accurate CSIT is clearly important for MIMO broadcast systems in order to achieve maximum throughput. When the receiver knows the channel perfectly and instantaneously feeds this information back to the transmitter using a finite number of bits, we have quantified the rate loss and have shown that increasing the number of bits linearly with the system SNR is sufficient to maintain a constant SNR loss with respect to perfect CSIT [5]. Further, we have established the advantage of BD relative to ZF in terms of feedback load, and the advantage of using quantized feedback as opposed to using analog feedback.

In [6], the impact of mutual coupling on BD performance in terms of sum rate capacity is addressed on the performance of a multiuser MIMO system employing BD scheme in terms of sum rate capacity.

For the multiuser MIMO downlink, the interference due to signals transmitted to other users is known at the transmitter, and in principle, a precoder could be used to essentially undo its effects. The primary drawback of such schemes is that their use of nontraditional coding leads to increased complexity at both the transmitter and receiver. Numerical results for the system SNR, sum rate, and bit error-rate (BER) are shown in [7]. If zero-forcing beamforming (ZFBF) is used, the feedback rate must be scaled with the number of transmit antennas as well as SNR in order to achieve rates close to perfect CSIT systems [8]-[9]. In such a system the transmitter emits multiple beams and uses its channel knowledge to select beamforming vectors such that nulls are created at certain users. Inaccurate CSI leads to inaccurate nulling and thus translates directly into multi-user interference and reduced SINR/throughput. Similar to the results in [9], it was shown that scaling the number of feedback bits approximately linearly with the system SNR is sufficient to maintain the slope of the capacity vs. SNR curve and achieve a rate that is a constant gap from the throughput of BD with perfect CSIT. In [10], the authors have shown that zero-forcing beamforming can achieve sum capacity only when the number of users is large and a scheduler that selects spatially semi-orthogonal users is used. In [11], the BD technique with a minimum mean square error vector precoding for achieving further gain in performance with minimal computational overhead was combined. Moreover, due to the QR decomposition based block diagonalization, dimension of the system being processed is reduced. BD is a generalization of zero-forcing beamforming for multiple stream transmission to each user. The scaling factor for BD offers an advantage over ZF in terms of the number of bits required to achieve the same sum capacity. In this paper, we study the performance of multiuser beamforming for various CoMP scenarios.

The simulation results will show that the proposed scheme outperforms zero-forcing precoding in CoMP-JP mode and is close to the optimal linear precoding in CoMP-JP. Recently, most research work focuses on CoMP-JP mode. In [12]-[13], conventional ZF precoding scheme is applied in DL CoMP-JP. A related scheme is BD [14]-[15], which requires a limitation of the number of receive antennas and the number of data streams. And the precoding scheme in [16] based on signal-to-leakage-plus noise ratio (SLNR) maximizes the sum of the achievable rate through minimizing the leakage to other UEs, which has no restriction as to the number of receive antennas per

UE. Therefore, linear precoding in CoMP-JP is an optimized solution with relatively lower complexity requirements at both the access points (Aps) and the UEs.

In terms of downlink CoMP, two different approaches are under consideration: Coordinated scheduling, or Coordinated Beamforming (CBF), and Joint Processing/Joint Transmission (JP/JT). In the first category, the transmission to a single UE is transmitted from the serving cell, exactly as in the case of non-CoMP transmission [17]-[18].

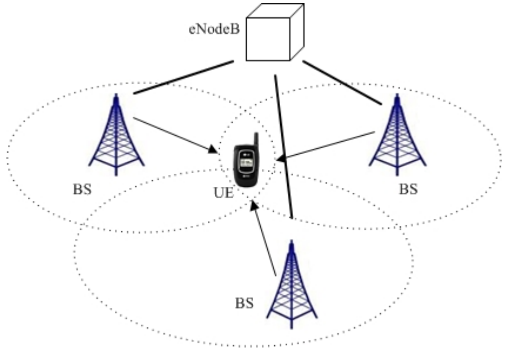

Fig.1. CoMP-Joint processing

In CoMP-JP mode as shown in Fig.1, the data information to the UE is simultaneously transmitted from all APs under the control of the same eNodeB. The UE's data is distributed and jointly processed across the APs and the channel state information (CSI) is required for all the AP-UE pairs. Although CoMP-JP mode is incurring large system overhead, it can coherently or non-coherently improve the received signal quality and cancel actively interference for the UEs. The CoMP-JP mode can be used for serving one UE (SU) or multiple UEs (MU) using the given time/frequency resources at the same time.

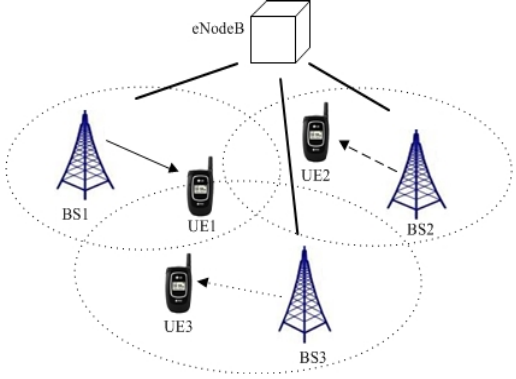

Fig.2. CoMP coordinated beamforming

In the category of coordinated scheduling/beamforming as shown in Fig. 2, the data information to the UE is transmitted from its serving cell only but the cells in the CoMP set coordinate their transmission so that inter-cell interference can be reduced. Meanwhile, it is not necessary to share the UE's data information across multiple APs, which alleviates the heavy overhead on the network. To achieve the coordination, the UE needs to feedback information about the CSIs of the serving cell and the other cells in the CoMP set. CoMP-CBF mode can also increase the cell edge user throughput via interference management.

This paper is organized as follows. Section II describes the system model. In Section III, presents coordinatedbeamforming of CoMP-JP. In Section IV, presents complexity analysis. Simulation results are presented in Section V and conclusions are delivered in Section VI.

Notation: $(\cdot)^T$ and $(\cdot)^H$ denote transpose and Hermitian transpose operations, respectively. | · | and || · || represent the absolute value and norm of a vector or matrix.

II. SYSTEM MODEL

Considering the downlink joint processing/reception comprised of L cells in intra-eNodeB scenario, it is assumed that there are K users equipped with N_R antennas and uniformly distributed at the edge of each cell. AP in each cell is configured with N_T antennas. For downlink CoMP, APs in different cells send the same signals which contain multiple data streams to multi-users. The APs belonging to the same eNodeB jointly receive the feedback information. In Fig. 3, we give an example of the downlink CoMP-JP MU comprised of three cells [22]-[23].

$$y_k = \mathbf{H}_k \mathbf{x}_k + \sum_{i=1}^{K} \mathbf{H}_i \mathbf{x}_i + \eta_k, \quad k = 1, \cdots K \tag{1}$$

where, the channel matrix H_i are denoted by

$$\mathbf{H}_k = diag\left[\mathbf{h}_{k1}\,\mathbf{h}_{k2} \cdots \mathbf{h}_{kL}\right] \tag{2}$$

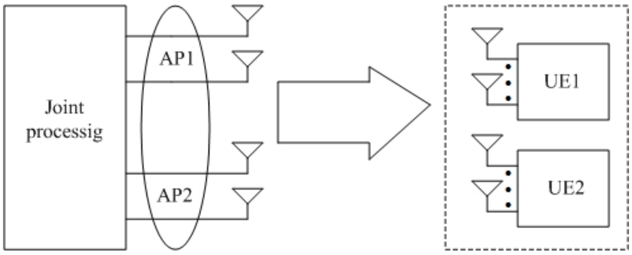

Fig.3. Block diagram of the multiuser system in CoMP

where $\mathbf{H}_k$ denote the $N_R \times LN_T$ channel matrix from the APs to the *k*-th UE, and $\mathbf{h}_{ki}$ represents the $N_R \times N_T$ channel gain from the *i*-th AP $(1 \le i \le L)$ to the *k*-th UE. η_k denotes the $N_R \times 1$ additive white Gaussian noise (AWGN) vector with zero mean and universal variance σ^2 The transmitted signals can be written as

$$\mathbf{x}_k = \mathbf{M}_i \mathbf{s}_i \tag{3}$$

The total power constraint is imposed by

$$E\left(\|\mathbf{x}\|^2\right) = P_t$$

III. COORDINATED BEAMFORMING OF COMP-JP

In this section, we represent a novel block diagonalization method for multiuser MIMO systems. The BD algorithm is an extension of zero-forcing method for multiuser MIMO systems where each user has multiple antennas.

A. Block Diagonalization

In this subsection, there is no need for complete diagonalization of the channel, and BD requires only block diagonalization where multiuser interference (MUI) is completely eliminated. The interference from other user signals is canceled in the process of precoding. CoMP gain depends much on the precoding scheme. BD based precoding is utilized when considering multiple receive antennas, and reasonable precoding complexity and performance gain compared with unitary precoding and ZF-BF precoding method. The received signal at the k-th MS, given as Eq. (1), is rewritten as

$$y_i(n) = \mathbf{H}_i \sum_{i=1}^{K} \mathbf{M}_k s_k(n) + \eta_i(n)$$

$$= \mathbf{H}_i \mathbf{M}_i s_i(n) + \mathbf{H}_i \sum_{i=1}^{K} \mathbf{M}_k s_k(n) + \eta_i(n) \qquad (4)$$

where the second term represents the CCI caused by the multiuser sharing the downlink resources. The principal idea of the block diagonalization is to find the beamforming vectors which can zero-force the CCI. The key idea of BD is to precoder each user's data $\mathbf{x}_k$ with precoding matrix $\mathbf{M}_k$, such that

$$\mathbf{H}_i \mathbf{M}_k = 0, \quad \text{for all} \quad i \neq j \text{ and } 1 \leq i, k \leq K \qquad (5)$$

which means all multi-user interference will be eliminated. With the beamforming vectors satisfying Eq. (5), the CCI is completely eliminated and thus the *k-th* MS observes a point-to-point MIMO link with the base station. With a sum power constraint, the achievable throughput for the resulting block-diagonal system is

$$C_{BD} = \max_{\mathrm{H}_i w_k = 0, i \neq k} \log_2 \left| \mathrm{I} + \frac{1}{\sigma^2} \mathbf{H}_i \mathbf{M}_i \mathbf{H}_i^* \mathbf{M}_i^* \right|$$

$$= \max_{\mathrm{H}_i w_k = 0, i \neq k} \sum_{k=1}^{K} \log_2 \left| \mathrm{I} + \frac{1}{\sigma^2} \mathbf{H}_k \mathbf{M}_k \mathbf{H}_k^* \mathbf{M}_k^* \right| \leq C_s \qquad (6)$$

where C_s represents the sum capacity of the system. $\tilde{\mathbf{H}}_k$ is defined as the channel matrix for all users other than user k.

$$\tilde{\mathbf{H}}_k = \left[\mathbf{H}_1^T, \cdots, \mathbf{H}_{k-1}^T, \mathbf{H}_{k+1}^T, \cdots, \mathbf{H}_K^T \right]^T \qquad (7)$$

The zero inter-user interference constraint forces $\mathbf{M}_k$ to lie in the null space of $\tilde{\mathbf{H}}_k$. The constraint of Eq. (4) can be rewritten as

$$\tilde{\mathbf{H}}_k \mathbf{M}_k = 0 \qquad (8)$$

Eq. (8) indicates that the beamforming vectors for the *k-th* mobile user should lie in the null space of Eq. (7). By applying singular value decomposition (SVD), the following is obtained

$$\tilde{\mathbf{H}}_k = \mathbf{U}_k \begin{bmatrix} \mathbf{\Sigma}_k & 0 \\ 0 & 0 \end{bmatrix} \left[\mathbf{V}_k^{(1)} \quad \mathbf{V}_k^{(0)} \right]^H \qquad (9)$$

where $\mathbf{\Sigma}_k$ is the diagonal matrix with all non-negative singular values $\tilde{\mathbf{H}}_k$ to be its diagonal elements with a dimension equals to the rank of $\tilde{\mathbf{H}}_k$. $\mathbf{V}_k^{(0)}$ contains vectors corresponding to the zero singular values and $\mathbf{v}_k^{(1)}$ consists of the singular vectors corresponding to non-zero singular values. Thus, $\mathbf{V}_k^{(0)}$ is an orthogonal basis for the null space of $\tilde{\mathbf{H}}_k . \mathbf{V}_k^{(0)}$ represented by $\tilde{\mathbf{V}}_k^{(0)}$ as the block diagonalization precoding matrix $\mathbf{M}_k$ for the user k. So, the precoding matrix can be denoted as

$$\mathbf{M}_k = \left[\tilde{\mathbf{V}}_1^{(0)} \mathbf{V}_1^{(1)} \quad \tilde{\mathbf{V}}_2^{(0)} \mathbf{V}_2^{(1)} \quad \cdots \quad \tilde{\mathbf{V}}_K^{(0)} \mathbf{V}_K^{(1)} \right]^{1/2} \qquad (10)$$

where $\mathbf{\Lambda}$ is a diagonal matrix whose element scale λ_i the power transmitted into each of columns of $\mathbf{M}_k$. The capacity of the BD [7] is

$$C_{BD} = \max_{\Lambda} \log_2 \left| \mathbf{I} + \frac{\mathbf{\Sigma}^2}{\sigma^2} \right| \qquad (11)$$

With the precoding matrix $\mathbf{M}_k$, the effective channel $\mathbf{HM}$ is block diagonal, which means all inter-user interference other than intra-user interference is eliminated. They form an orthogonal basis for the space of Eq. (7). The columns are the candidate beamforming vectors. To maximize the sun rate, the optimal power loading matrix should be applied using the water-filling method.

B. Zero-forcing Beamforming Algorithm

In this subsection, we design zero-forcing beamforming. The eNodeB selects the two UEs, the concatenated quantized channel vectors are $\mathbf{H}_k = \left[\mathbf{H}_1^T \; \mathbf{H}_2^T \right]^T$. Then the ZF matrix is

$$\mathbf{M}_k = \mathbf{H}_k^H \left(\mathbf{H}_k \mathbf{H}_k^H \right)^{-1} \mathrm{diag}(\mathbf{p})^{1/2}$$
$$= \mathbf{G}_k \, \mathrm{diag}(\mathbf{p})^{1/2} \qquad (12)$$

where $\mathbf{p}_k = (p_1 \;\; p_2)^T$ is the vector of power normalization coefficients. For equal power allocation

$$p_k = \frac{P_t}{2} \frac{1}{\left\| g_k \right\|^2}, \qquad (13)$$

where g_k denotes the k-th column of $\mathbf{G}_k$. The SINR of k-th UE is given by

$$\mathrm{SINR}_k = \frac{p_k \left| \mathbf{H}_k g_k^H \right|^2}{N_0 + \sum_{i \neq k} p_i \left| \mathbf{H}_k g_k^H \right|^2} \qquad (14)$$

where N_0 denotes the power of noise.

And the UE rate is as follows

$$R_k = \log(1 + \mathrm{SINR}_k)$$

$$= \log \left(1 + \frac{p_k \left| \mathbf{H}_k g_k^H \right|^2}{N_0 + \sum_{i \neq k} p_i \left| \mathbf{H}_k g_k^H \right|^2} \right). \qquad (15)$$

C. Minimum Mean Squared Error (MMSE)

In this case the beamforming vectors are obtained in order to maximize the overall SINR at the receiver. The beamforming matrix $\mathbf{M}_k$ is then

$$\mathbf{M}_k = \mathbf{H}_k^H \left(\mathbf{H}_k \mathbf{H}_k^H + \frac{1}{\rho} I_N \right)^{-1} \qquad (16)$$

where ρ is the signal-to-noise ratio (SNR), defined as the ratio between the maximum available power and noise power σ_n^2. By denoting with $\mathbf{A} = \mathbf{H}_k \mathbf{M}_k$, we can express the SINR for each user's signal at the receiver output as

$$SINR_k = \frac{\left|\mathbf{A}_{i,i}\right|^2 P_i}{\sum_{k \neq i} \left|\mathbf{A}_{i,j}\right|^2 P_i + \sigma_n^2}. \qquad (17)$$

IV. COMPLEXITY ANALYSIS

In this Section, we discuss the complexity of the generalized zero forcing-Gram Schmidt Orthogonalization (GZF-GSO) algorithm and compare with the conventional BD scheme. For the sake of simplicity, all users are assumed to have the same number of the receive antennas N_k and $KN_k \le N_T$. The complexities of the alternative methods are usually compared by the number of floating point operations (flops). A flop is defined as real floating operations, e.g. a real addition, multiplication, division and so on. One complex addition and multiplication involve 2 and 6 flops respectively. Other complex operations, e.g. division, are roughly regarded as complex multiplications.

For a $m \times n$ complex-valued matrix **A** with $m \le n$, its multiplication with another $n \times p$ complex-valued matrix **B** requires 8*mnp* flops. But when **B** has a special form the complexity reduces. For instance, when**B** is a diagonal or block diagonal matrix, the complexity reduces to $4mn(m+1)$ flops. By treatingall operations as multiplications, the SVD operation on **A** takes about $24mn^2 + 48m^2n + 54m^3$ flops,the GSO on **A** takes $8m^2n - 2mn$, the inversion operation onan $m \times m$ triangular complex-valued matrix takes about $4m^2(m+1)$, the QR decomposition on**A** takes $12m^2n$ flops. The water filling operation is always done in the real-valued domain but itdoes not have a fixed complexity. But in worst case, it takes up to at most $2m^2 + 6m$ flop forwater filling over m eigenvalues [24].

The complexity computation of water-filling power allocation is

$$\delta_1 = 2K^2 N_k^2 + 6KN_k \qquad (18)$$

The complexity computation of QR-BD is given by [24]

$$\delta_2 = KN_k + 2kN_k^2 + 8KN_T\left(N_T - \left(K-1\right)N_k\right)N_k. \qquad (19)$$

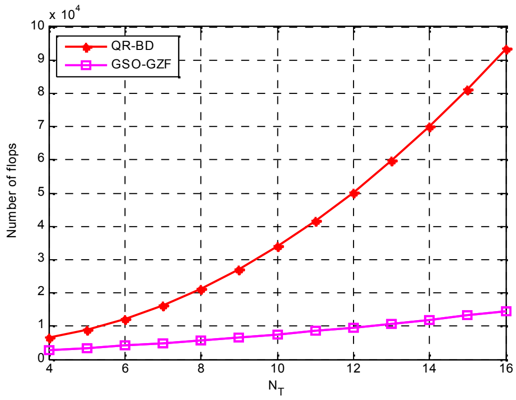

Fig.4. Comparison of the required flops versus the number of transmit antennas, N_T

The complexity of these two steps will be obtained as

$$\delta = \delta_1 + \delta_2 \qquad (20)$$

When $KN_k < N_T$, $\left(\mathbf{H}_k \mathbf{H}_k^*\right)^{-1}$ is multiplied by the block diagonal matrix, and then multiplied by $\mathbf{H}_k^*$. However when $KN_k = N_T$, the $\mathbf{H}_k^*\left(\mathbf{H}_k \mathbf{H}_k^*\right)^{-1}$ reduces to $\mathbf{H}_k^{-1}$ so that only one matrix multiplication is enough.

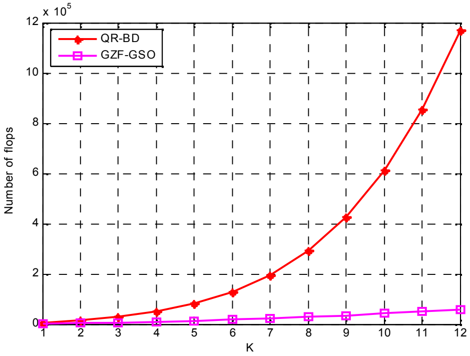

Fig.5. Comparison of the required flops versus the number of users, K

In Fig. 4, we fix $n = 2$ and $k = 2$ while express the number of flops as a function of N_T . In the Fig. 5, we fix $m = 24$ and $n = 2$, the number of flops is expressed a function of K. From Fig. 4 and Fig. 5, it obvious that GZF-GSO get a large advantage compared with BD. The larger N_T or K, we can get the more significant difference. From Fig 5, we consider $K = 10$ and the number of flops 6, then the complexity reduce $= \frac{6}{10} \times 100 = 60\%$.

V. SIMULATIONS RESULTS

In this section, we present the simulation results to illustrate the performance of proposed scheme. A multi-user MIMO system is simulated to evaluate the performance of the proposed multi-user beamforming scheme comparison to the conventional single user beamforming scheme. Fig. 6 shows BER performance of a multiuser MIMO system.

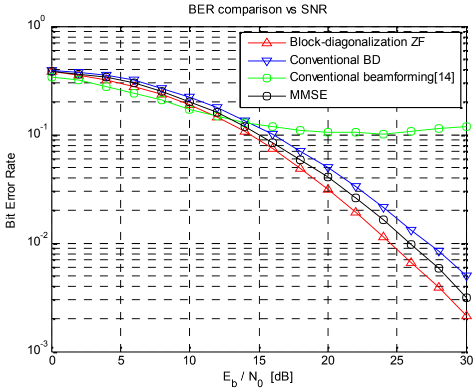

Fig.6. BER performance of a multiuser MIMO system with $N = 4$ transmit antennas, $K = 2$ users and $M_i = 2$ receive antennas.

While the conventional single-user beamforming fails in a multi-user environment in terms of BER the proposed scheme provides an acceptable BER in the presence of 2 users. The BD method is taken for both users while employing a zero-forcing detection at receiver and can be used to improve the BER performance.

Fig.7 shows the cumulative distribution function results of the sum system capacity. We give the non-CoMP scheme that means there is no coordination among APs and each UE will suffer from severe interference from other cells. The CoMP-JP scheme uses ZF or SVD precoding transmitting two data streams to a single UE with equal power allocation, which is across two APs' coordination under the control of the same eNodeB.

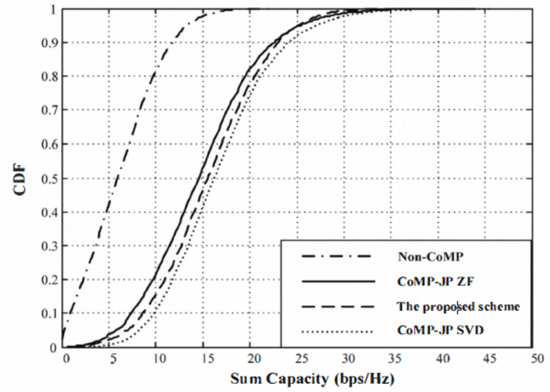

Fig.7. CDF of system sum capacity

From the Fig. 7, we have shown that the CoMP-JP mode or the CoMP-CBF mode both are better than Non-CoMP scheme, which confirms that the CoMP technique is a very promising scheme to improve the cell edge capacity [17]. The proposed scheme outperforms the CoMP-JP ZF scheme and it is close to the CoMP-JP SVD scheme. In CoMP-JP mode, all APs coordinates together to serve the UE, so the interference from other cell in the CoMP set turns into the desired useful signal.

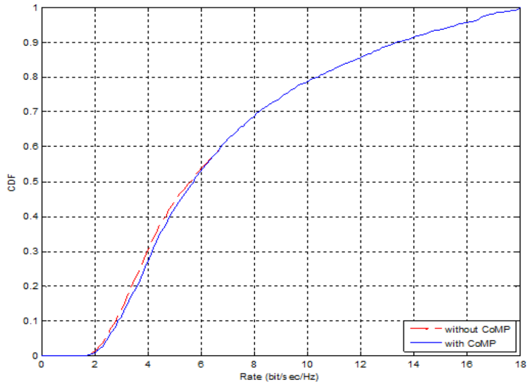

Fig.8. 4×4 Configuration case

Fig. 8 compares the rate geometries with and without CoMP transmissions for 4×4 antennas. As it can be seen, there is slight improvement in the cell average throughput. However, more improvement is observed for the 5% cell throughput.

The multi-user beamforming algorithm [1] of cell, which is based on SLNR, can be easily extended to the multicell system as described below:

$$SLNR_k = \frac{\left\|\mathbf{H}_k\mathbf{M}_k\right\|_F^2}{N_0\sigma_n^2 + \sum_{i \neq k}^{K}\left\|\mathbf{H}_i\mathbf{M}_k\right\|_F^2}$$

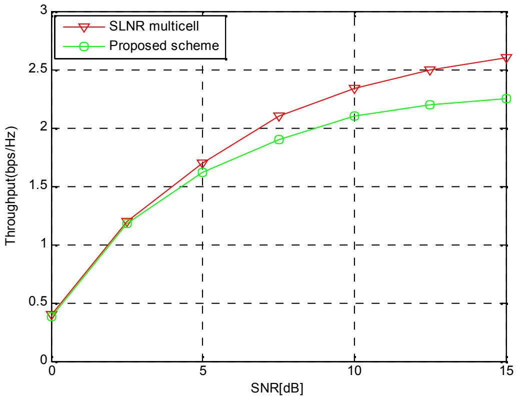

Fig.9. Throughput comparison between SLNR multicell and proposed scheme.

Fig.9 compares between SLNR multicell and proposed scheme. From Fig. 9, the proposed scheme doesn't improve average throughput distinctly at the low SNRs, its throughput is much higher than SLNR-multicell at the high SNRs, because the BSs choose the better quality channels for users, so the channels, which leak the least signal power into the other users difficultly, offer high quality service to target user when SNR increase.

VI. CONCLUSION

In this paper, we proposed an enhancement to block diagonalization that uses information about the CCI covariance matrix for each user to improve the sum rate. Numerical examples verified that the proposed MIMO-BD provides the better sum rate performance than the conventional BD [20]. The optimal BD precoding vectors for each user are shown to be in general non-orthogonal, which differs from the conventional orthogonal precoder design for the sum-power constraint case. The simulation results have shown that the proposed scheme shows a much higher performance gain even outperforms zero-forcing scheme in CoMP-JP mode. The CoMP-CBF mode has started to attract much attention for future research work because of the low overhead and good performance. We also shown the downlink coordinated beamforming of CoMP and proposed scheme based on SLNR & SNR to choose the optimal beamforming vector from codebook [21]. The analysis results also show that QR decomposition algorithm reduces the complexity to 60% of the conventional BD method.

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