Impact of Channel Asymmetry on Base Station Cooperative Transmission with Limited Feedback

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***Abstract*—To exploit the full benefit of base station (BS) cooperative transmission, also known as coordinated multi-point (CoMP) transmission, large amount of feedback is required to gather the channel information. In this paper, we analyze the impact of channel asymmetry, which is inherent in CoMP systems, on downlink coherent BS cooperative transmission using zero-forcing beamforming with limited feedback. Per-cell quantization of multicell channels is considered, which quantizes the local channel and cross channels separately and is more feasible in practice. We analyze the per-user rate of limited feedback multi-user CoMP systems, and provide approximate expressions for both the inter-cell and intra-cell residual multi-user interference introduced by the quantization errors. When the desired user is at the cell center, the former is weak, but the latter is strong and depends not only on the signal to noise ratio but also on the location of its co-scheduled users. Simulation results validate our theoretical analysis.**

I. Introduction

Base station (BS) cooperative transmission, which is also known as coordinated multi-point (CoMP) transmission, is an effective strategy to mitigate inter-cell interference (ICI) in universal frequency reuse cellular systems. When both data and channel state information (CSI) are forwarded to a central unit (CU) via backhaul links, coherent cooperative transmission can significantly enhance the downlink spectrum efficiency by using multiuser (MU) multiple-input multiple-output (MIMO) precoding [1, 2].

In frequency division duplexing (FDD) MU-MIMO systems, the required CSI at transmitter is obtained through uplink feedback with limited number of bits. The impact of limited feedback on the performance of single cell MU-MIMO transmission has been extensively investigated [3–5], which showed that quantization error leads to severe throughput loss especially at high signal-to-noise ratio (SNR) level.

Despite that the considered CoMP system can be viewed as a large single-cell MIMO system with a "super BS", there are distinct differences between the channels of the two systems. The CoMP channel is an aggregation of multiple single-cell channels between each cooperative BS and each mobile station (MS), which implies that the channel is inherently *asymmetric*, i.e. that the average channel gains from different BSs to each MS are different. As a result, the transmit strategies designed for single-cell system perform differently in CoMP channel. This calls for the design of new strategies to accommodate the unique channel feature. By exploiting the channel asymmetry, the channel norm can be used for multi-user scheduling for CoMP transmission, which significantly reduces the feedback overhead [6]. Allocating the feedback bits among the per-cell channels with different channel gains was shown to perform better than equal bits allocation for CoMP systems in [7, 8]. Considering that the number of BSs in CoMP systems is dynamic, a scalable channel quantization scheme based on per-cell codebooks is proposed in [9].

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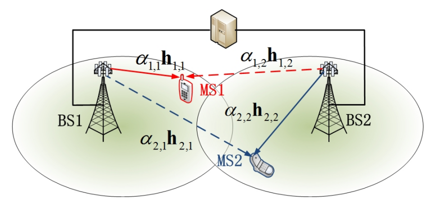

Fig. 1. An example of CoMP system. The solid lines denote the local channel while the dash lines represent the cross channels.

In this paper, we analyze the impact of channel asymmetry on coherent CoMP system using multicell zero-forcing beamforming (ZFBF) with limited feedback. We consider per-cell channel quantization since it is of practical importance [9]. The channel direction information (CDI) of the local channel, i.e., the channel between BS and MS in the same cell, and the CDIs of cross channels, i.e., the channel between BS and MS in different cells, are quantized separately. We will derive an approximate average per-user rate achieved by limited feedback MU-MIMO CoMP system. We will show that the average rate not only depends on the per-cell CDI quantization error, the number of transmit antennas and SNR, but also relies on the location of the co-scheduled MSs.

II. System Model

Consider a cooperative cluster with N cells, each cell containing one BS equipped with n_t antennas and one single-antenna MS. We assume that CSI from the cooperative N BSs to the N MSs are available at the CU via ideal backhaul links. ZFBF is used for coherent cooperative transmission. An example of CoMP system is shown in Fig. 1.

The global channel vector from all cooperative BSs to MS_k

is an aggregation of N single-cell channel vectors, i.e.,

$$\mathbf{g}_k = [\alpha_{k,1}\mathbf{h}_{k,1}, \ldots, \alpha_{k,N}\mathbf{h}_{k,N}], \quad (1)$$

where $\alpha_{k,b}$ and $\mathbf{h}_{k,b} \in \mathbb{C}^{1\times n_t}$ are respectively the large scale fading coefficient and the small scale fading channel vector between BS_b and MS_k, $\alpha_{k,b}$ includes both path loss and shadowing. We assume that the per-cell channels are uncorrelated and the entries in each $\mathbf{h}_{k,b}$ are independent and identically distributed (i.i.d), and $\mathbf{h}_{k,b} \sim \mathcal{CN}(0,1)$. For MS_k that located in the same cell as BS_b, we denote $\alpha_{k,k}\mathbf{h}_{k,k}$ as its local channel and $\alpha_{k,b}\mathbf{h}_{k,b}$, $b \neq k$, as the cross channels.

The data to be transmitted to all N MSs are $\mathbf{d} = [d_1, \ldots, d_N]^T$. Equal power allocation among MSs are considered. The receive signal at MS_k is

$$y_k = \sqrt{P}\mathbf{g}_k\mathbf{v}_k d_k + \sqrt{P}\sum\nolimits_{j=1,j\neq k}^{N}\mathbf{g}_k\mathbf{v}_j d_j + n_k, \quad (2)$$

where P is the transmit power for each MS, $\mathbf{v}_j \in \mathbb{C}^{Nn_t\times 1}$ represents a unitary precoding vector of all cooperative BSs for MS_j, and n_k is additive white Gaussian noise with zero mean and variance σ_n^2.

A. Finite Rate Feedback Model

We assume that the large scale fading coefficient $\alpha_{k,b}$, $b = 1, \ldots, N$, are perfectly known at BSs. We further assume that MS_k has perfect knowledge of all its per-cell channel vectors, $\mathbf{h}_{k,b}$, $b = 1, \ldots, N$. Considering that the number of cooperative BSs may be dynamic [9], we employ a *per-cell codebook* to quantize the per-cell channel vectors in $\mathbf{g}_k$.

Denote the instantaneous norm and direction of the channel between MS_k and BS_b as $\rho_{k,b} = \|\mathbf{h}_{k,b}\|$ and $\bar{\mathbf{h}}_{k,b} = \mathbf{h}_{k,b}/\|\mathbf{h}_{k,b}\|$. Denote the per-cell codebook for quantizing the CDI between MS_k and BS_b as $\mathcal{C}_{k,b}$. It consists of unit norm row vectors $\mathbf{c}_i$, $i = 1, \ldots, 2^{B_{k,b}}$, where $B_{b,k}$ is the number of bits used to quantize $\bar{\mathbf{h}}_{k,b}$. Then the quantized CDI $\hat{\mathbf{h}}_{k,b} = \mathbf{c}_{i_{k,b}}$, where the index $i_{k,b}$ is chosen as $i_{k,b} = \arg\max_{1\leq j\leq 2^{B_{k,b}}} |\bar{\mathbf{h}}_{k,b}\mathbf{c}_j^H|^2$.

After MS_k has quantized the CDI for both local and cross channels, it feeds back the indices $\{i_{k,1}, \ldots, i_{k,N}\}$ to its serving BS, i.e., BS_k, which requires $\sum_{b=1}^{N} B_{k,b}$ bits in total. As in [10], we ignore the instantaneous norm $\rho_{k,b}$, which induces minor performance loss. Then BS_k reconstructs the global channel of MS_k as $\hat{\mathbf{g}}_k = [\alpha_{k,1}\hat{\mathbf{h}}_{k,1}, \ldots, \alpha_{k,N}\hat{\mathbf{h}}_{k,N}]$.

B. Multicell Zero-forcing Beamforming

When all BSs obtain the reconstructed global channel vectors, they send the vectors to the CU via low latency and error free backhaul links. A multicell ZFBF matrix is obtained at the CU as $\mathbf{V} = \hat{\mathbf{G}}^H\left(\hat{\mathbf{G}}\hat{\mathbf{G}}^H\right)^{-1}$, where $\hat{\mathbf{G}} = \left[\hat{\mathbf{g}}_1^H, \ldots, \hat{\mathbf{g}}_N^H\right]^H$. Consider per-user power constraint as in [3], then the beamforming vector for MS_k is obtained by normalizing the kth column of $\mathbf{V}$ as $\mathbf{v}_k = \mathbf{V}(:,k)/\|\mathbf{V}(:,k)\|$.

III. Performance analysis of CoMP transmission

A. Approximation of the Average Per-user Rate

A widely employed performance metric to analyze the impact of limited feedback on MU-MIMO system is rate loss. The derivation of the rate loss in [3, 5] is based on the assumption of i.i.d. channels. Since CoMP channels are not i.i.d. any more, we can not apply their results. Since it is very hard to obtain an explicit expression of average per-user rate, we approximate the average rate of MS_k as in [11] and the references therein as follows,

$$\begin{aligned}\bar{R}_k &\approx \log_2\left(1 + \frac{\mathbb{E}\{P|\mathbf{g}_k\mathbf{v}_k|^2\}}{\sigma_n^2 + \mathbb{E}\{P\sum_{j=1,j\neq k}^{N}|\mathbf{g}_k\mathbf{v}_j|^2\}}\right)\\ &= \log_2\left(1 + \frac{\mathbb{E}\{\mathrm{S}_k\}}{\mathbb{E}\{\mathrm{I}_k\}}\right) = \log_2\left(1 + \widetilde{\gamma}_k\right), \end{aligned} \quad (3)$$

where $\widetilde{\gamma}_k = \mathbb{E}\{\mathrm{S}_k\}/\mathbb{E}\{\mathrm{I}_k\}$ is an approximate receive signal-to-interference plus noise ratio (SINR) at MS_k.

The derivation of the approximate SINR is still rather involved owing to the pseudo-inverse of the channel matrix in the ZFBF. For mathematical tractability, we assume that the selected MSs are mutually orthogonal in terms of their quantized global channels as in [12]. In practice, this is a reasonable approximation when the number of MSs is large enough. Although the assumption is strong, we will verify through simulations in Section IV that the following results are applicable also for realistic scenarios without this assumption.

Under the orthogonal scheduling assumption, the precoder vector for MS_j reduces to $\mathbf{v}_j = \hat{\mathbf{g}}_j^H/\|\hat{\mathbf{g}}_j\|$. Then the average signal power is

$$\begin{aligned}&\mathbb{E}\{\mathrm{S}_k\} = \mathbb{E}\left\{P\left|\mathbf{g}_k\frac{\hat{\mathbf{g}}_k^H}{\|\hat{\mathbf{g}}_k\|}\right|^2\right\}\\ =&\frac{P}{\sum_{n=1}^{N}\alpha_{k,n}^2}\mathbb{E}\left\{\left|\sum\nolimits_{b=1}^{N}\alpha_{k,b}^2\rho_{k,b}\bar{\mathbf{h}}_{k,b}\hat{\mathbf{h}}_{k,b}^H\right|^2\right\}\\ =&\frac{P}{\sum_{n=1}^{N}\alpha_{k,n}^2}\Big(\sum\nolimits_{b=1}^{N}\alpha_{k,b}^4\mathbb{E}\left\{\rho_{k,b}^2\left|\bar{\mathbf{h}}_{k,b}\hat{\mathbf{h}}_{k,b}^H\right|^2\right\}\\ &+\sum_{b=1}^{N}\sum_{a=1,a\neq b}^{N}\Re\left\{\mathbb{E}\left\{\rho_{k,b}\rho_{k,a}\bar{\mathbf{h}}_{k,b}\hat{\mathbf{h}}_{k,b}^H\hat{\mathbf{h}}_{k,a}\bar{\mathbf{h}}_{k,a}^H\right\}\right\}\Big). \end{aligned} \quad (4)$$

Define $\sin^2\theta_{k,b} = 1 - |\bar{\mathbf{h}}_{k,b}\hat{\mathbf{h}}_{k,b}^H|^2$ as the quantization error of $\bar{\mathbf{h}}_{k,b}$, then $\bar{\mathbf{h}}_{k,b}\hat{\mathbf{h}}_{k,b}^H = \cos\theta_{k,b}e^{j\phi_{k,b}}$, where $\phi_{k,b}$ is a phase ambiguity introduced by the per-cell channel quantization [13]. Denote the average quantization error of $\bar{\mathbf{h}}_{k,b}$ as $\delta_{k,b}^2 = \mathbb{E}\{\sin^2\theta_{k,b}\}$, which is upper-bounded by $2^{-\frac{B_{k,b}}{n_t-1}}$ when random vector quantization (RVQ) is considered [3]. Assume that $\cos\theta_{k,b}$ is independent of $\phi_{k,b}$, we have

$$\begin{aligned}\mathbb{E}\{\mathrm{S}_k\} =& \frac{Pn_t}{\sum_{n=1}^{N}\alpha_{k,n}^2}\sum\nolimits_{b=1}^{N}\alpha_{k,b}^4\Big(\mathbb{E}\{\cos^2\theta_{k,b}\}\\ &+\sum_{b=1}^{N}\sum_{a=1,a\neq b}^{N}\mathbb{E}\{\rho_{k,b}\rho_{k,a}\cos\theta_{k,b}\cos\theta_{k,a}\cos(\phi_{k,b}-\phi_{k,a})\}\Big)\\ =& Pn_t\sum\nolimits_{b=1}^{N}\alpha_{k,b}^2\frac{\alpha_{k,b}^2}{\sum_{n=1}^{N}\alpha_{k,n}^2}(1-\delta_{k,b}^2), \end{aligned} \quad (5)$$

where the last step comes from the fact that the phase ambiguity is uniformly distributed between 0 and 2π [13].

The averaged interference power is

$$\mathbb{E}\{\mathrm{I}_k\} = P\mathbb{E}\{\sum_{j=1,j\neq k}^{K} \frac{1}{\|\hat{\mathbf{g}}_j\|^2}|\mathbf{g}_k\hat{\mathbf{g}}_j^H|^2\}$$
$$= \frac{P}{\sum_{n=1}^{N}\alpha_{j,n}^2}\sum_{j=1,j\neq k}^{N}\mathbb{E}\{|\mathbf{g}_k\hat{\mathbf{g}}_j^H|^2\}. \quad (6)$$

According to [3], $\bar{\mathbf{h}}_{k,b}$ can be expressed as $\bar{\mathbf{h}}_{k,b} = \cos\theta_{k,b}\hat{\mathbf{h}}_{k,b} + \sin\theta_{k,b}\mathbf{s}_{k,b}$, where $\mathbf{s}_{k,b}$ is a unit-norm vector isotropically distributed in the nullspace of $\hat{\mathbf{h}}_{k,b}$. Then we have

$$\begin{aligned}\mathbb{E}\{|\mathbf{g}_k\hat{\mathbf{g}}_j^H|^2\} =& \mathbb{E}\{\sum_{b=1}^{N}\alpha_{k,b}^2\alpha_{j,b}^2\cos^2\theta_{k,b}|\hat{\mathbf{h}}_{k,b}\hat{\mathbf{h}}_{j,b}^H|^2\}\\ &+\mathbb{E}\{\sum_{b=1}^{N}\alpha_{k,b}^2\alpha_{j,b}^2\sin^2\theta_{k,b}|\mathbf{s}_{k,b}\hat{\mathbf{h}}_{j,b}^H|^2\}\\ <&\mathbb{E}\{\sum_{b=1}^{N}\alpha_{k,b}^2\alpha_{j,b}^2|\hat{\mathbf{h}}_{k,b}\hat{\mathbf{h}}_{j,b}^H|^2\}\\ &+\mathbb{E}\{\sum_{b=1}^{N}\alpha_{k,b}^2\alpha_{j,b}^2\sin^2\theta_{k,b}|\mathbf{s}_{k,b}\hat{\mathbf{h}}_{j,b}^H|^2\}. \quad (7)\end{aligned}$$

Since we assume that the scheduled MSs are mutually orthogonal in terms of the quantized global channel, we have $\hat{\mathbf{g}}_k\hat{\mathbf{g}}_j^H = \sum_{b=1}^{N}\alpha_{k,b}\alpha_{j,b}\hat{\mathbf{h}}_{k,b}\hat{\mathbf{h}}_{j,b}^H = 0$. By assuming that the quantization of channels from one BS to multiple MSs are independent, we have

$$\mathbb{E}\{|\hat{\mathbf{g}}_k\hat{\mathbf{g}}_j^H|^2\} = \sum_{b=1}^{N}\mathbb{E}\{\alpha_{k,b}^2\alpha_{j,b}^2|\hat{\mathbf{h}}_{k,b}\hat{\mathbf{h}}_{j,b}^H|^2\} = 0. \quad (8)$$

Substituting (8) into (7) we have

$$\begin{aligned}\mathbb{E}\{|\mathbf{g}_k\hat{\mathbf{g}}_j^H|^2\} &< \sum_{b=1}^{N}\alpha_{k,b}^2\alpha_{j,b}^2\mathbb{E}\{\sin^2\theta_{k,b}\}\mathbb{E}\{|\mathbf{s}_{k,b}\hat{\mathbf{h}}_{j,b}^H|^2\}\\ &= \frac{1}{n_t-1}\sum_{b=1}^{N}\alpha_{k,b}^2\alpha_{j,b}^2\delta_{k,b}^2, \quad (9)\end{aligned}$$

where $\mathbb{E}\{|\mathbf{s}_{k,b}\hat{\mathbf{h}}_{j,b}^H|^2\} = \frac{1}{n_t-1}$ is obtained according to [3].

Substituting (9) into (6), we obtain the upper bound of the average interference power as

$$\mathbb{E}\{\mathrm{I}_k\} < \underbrace{\frac{P}{n_t-1}\alpha_{k,k}^2\beta_{k,k}\delta_{k,k}^2}_{\mathrm{I}_k^{\mathrm{intra}}} + \underbrace{\frac{P}{n_t-1}\sum_{b=1,b\neq k}^{N}\alpha_{k,b}^2\beta_{k,b}\delta_{k,b}^2}_{\mathrm{I}_k^{\mathrm{inter}}},$$
$$\triangleq \mathbb{E}\{\mathrm{I}_k\}^{\mathrm{UB}}, \quad (10)$$

where $\beta_{k,b} = \sum_{j=1,j\neq k}^{N}\frac{\alpha_{j,b}^2}{\sum_{n=1}^{N}\alpha_{j,n}^2}$ is called as impact coefficient, which reflects the contribution of each per-cell quantization error to the residual interference and depends on the large scale fading gains of the co-scheduled MSs.

Then we obtain a lower bound of $\widetilde{\gamma}_k$ in (3) as

$$\widetilde{\gamma}_k > \frac{n_t\sum_{b=1}^{N}\alpha_{k,b}^2\frac{\alpha_{k,b}^2}{\sum_{n=1}^{N}\alpha_{k,n}^2}(1-\delta_{k,b}^2)}{\frac{1}{n_t-1}\sum_{b=1}^{N}\alpha_{k,b}^2\beta_{k,b}\delta_{k,b}^2 + \frac{\sigma_n^2}{P}} \triangleq \widetilde{\gamma}_k^{\mathrm{LB}}. \quad (11)$$

It is well-known that coherent cooperative transmission can convert ICI into desired signal. This is in fact the sum of the numerator of (11) except the term of $b = k$, i.e., $\sum_{b=1,b\neq k}^{N}\alpha_{k,b}^2\frac{\alpha_{k,b}^2}{\sum_{n=1}^{N}\alpha_{k,n}^2}(1-\delta_{k,b}^2)$, where $1-\delta_{k,b}^2$ reflects the signal energy loss introduced by the quantization error. It is also well-known that residual inter-user interference exists when the CSI is not perfect at the BSs. This multi-user interference can be divided into two parts in the CoMP system, inter-cell interference and intra-cell interference as shown in (10). The inter-cell interference to MS_k is caused by the signal transmitted from all BSs other than BS_k to all MSs except MS_k, and the intra-cell interference to MS_k is induced by the signal transmitted from BS_k to MSs in other cells.[1] These two parts of the inter-user interference have different contributions to the performance of CoMP transmission due to the asymmetric channel.

B. Impact of Channel Asymmetry

We can see from (11) that the impact of channel asymmetry on $\widetilde{\gamma}_k^{\mathrm{LB}}$ lies in two aspects, which include both the channel asymmetry of the desired MS, i.e., MS_k, and that of its co-scheduled MSs, i.e., the MSs who share the same time-frequency resources with MS_k. In the following, we separately analyze these two aspects.

1) Channel Asymmetry of the Desired MS: When MS_k moves from cell edge to cell center, the large scale fading gain of its local channel $\alpha_{k,k}^2$ will increase while those of its cross channels $\alpha_{k,b}^2$, $b \neq k$, will decrease. In this case, the inter-cell interference $\mathrm{I}_k^{\mathrm{inter}}$ will reduce but the intra-cell interference $\mathrm{I}_k^{\mathrm{intra}}$ will grow. When MS_k is located at cell center, its performance will be primarily limited by $\mathrm{I}_k^{\mathrm{intra}}$. The value of $\mathrm{I}_k^{\mathrm{intra}}$ largely depends on the quantization error of local CDI $\delta_{k,k}^2$ and the impact coefficient $\beta_{k,k}$, which is related to the large scale fading gains of the co-scheduled MSs of MS_k.

2) Channel Asymmetry of the Co-scheduled MSs: If the desired MS, i.e., MS_k, is located at a specific position where $\alpha_{k,1}^2 = \cdots = \alpha_{k,N}^2 = \alpha_k^2$ and the bits used to quantize different per-cell CDIs are identical, i.e., $\delta_{k,1}^2 = \cdots = \delta_{k,B}^2 = \delta_k^2$, the interference at MS_k will not depend on the large scale fading gains of its co-scheduled MSs because $\mathbb{E}\{\mathrm{I}_k\}^{\mathrm{UB}} = \frac{P}{n_t-1}\alpha_k^2\delta_k^2\sum_{b=1}^{N}\sum_{j=1,j\neq k}^{N}\frac{\alpha_{j,b}^2}{\sum_{n=1}^{N}\alpha_{j,n}^2} = \frac{P}{n_t-1}\alpha_k^2\delta_k^2(N-1)$. Since the MSs are randomly distributed in cells, the probability of a MS located at the specific position is extremely small in reality. This implies that the performance of the desired MS will largely depend on the location of its co-scheduled users, even though we have assumed orthogonal scheduling.

When MS_k is located at any other positions, the intra-cell interference $\mathrm{I}_k^{\mathrm{intra}}$ depends on the impact coefficient $\beta_{k,k} = \sum_{j=1,j\neq k}^{N}\beta_{k,k}(j)$, where $\beta_{k,k}(j) \triangleq \frac{\alpha_{j,k}^2}{\sum_{n=1}^{N}\alpha_{j,n}^2}$ is determined by the location of MS_j. For MS_j, $\alpha_{j,j}^2$ represents its local channel power and $\alpha_{j,k}^2$, $k \neq j$, represents its cross channel power. Considering that $\alpha_{j,k}^2 \leq \alpha_{j,j}^2$, the minimal and maximal values of $\beta_{k,k}(j)$ are achieved when $\alpha_{j,k}^2 = 0$ and $\alpha_{j,k}^2 = \alpha_{j,j}^2$.

[1]Note that intra-cell interference is typically referred as the interference caused by the signal transmitted to multiple users within the same cell. Here we borrow this notation to emphasize that the interference comes from the same BS of the desired MS in the coherent CoMP system.

When the value of all $\beta_{k,k}(j)$, $j = 1,\ldots,N, j \neq k$, approach 0, so does $\beta_{k,k}$, which leads to a small value of $\mathrm{I}_k^{\mathrm{intra}}$. This is a scenario where all the co-scheduled MSs are located far from BS_k. In this case, BS_k transmits to all MSs in other cells with very low power. It is not hard to understand that little interference are generated from BS_k to MS_k.

When the value of all $\beta_{k,k}(j)$, $j = 1,\ldots,N, j \neq k$, reach their maximal value under the case of $\alpha_{j,k}^2 = \alpha_{j,j}^2$, $k \neq j$, the value of $\beta_{k,k}$ is maximized, which results in the largest value of $\mathrm{I}_k^{\mathrm{intra}}$. This corresponds to a scenario where all the co-scheduled MSs are located at the edge of cell k. Then the signal power transmitted from BS_k to MS_j will achieve the maximal allowable value, which results in the maximal intra-cell interference to MS_k.

Observation 1: Due to the asymmetric feature of CoMP channels, the impact of quantization error on the per-user rate of MU-MIMO transmission depends not only on the large scale fading gains of the local and cross channels of the desired MS, but also on those of its co-scheduled MSs. This distinguishes CoMP MU-MIMO transmission from single-cell MU-MIMO transmission, whose performance dependence on channel quality is roughly the same for the cases when user selection is considered or not considered [3–5].

Observation 2: Imperfect CDI leads to severe intra-cell interference for cell-center MS. This is especially true when its co-scheduled users are located near the cell edge.

IV. Simulation and Numerical Results

In this section, we verify our analysis through simulations. Although our earlier analysis apply for multiple BSs, in this section we consider a simple but fundamental scenario where two BSs each with four antennas cooperatively serve two single-antenna MSs, to provide a more clear picture.

In the simulations, the small scale fading channels between BSs and MSs are i.i.d Rayleigh fading channels. The per-cell codebook for quantizing the per-cell CDI is obtained by RVQ, considering that the per-cell channels are i.i.d., though the global channel is asymmetric. The number of bits used for quantizing each per-cell CDI is all set to be 4 unless otherwise specified. The per-user throughput is calculated with $R_k = \mathbb{E}\left\{\log_2\left(1+\frac{P|\mathbf{g}_k\mathbf{v}_k|^2}{\sigma_n^2+P\sum_{j=1,j\neq k}^{N}|\mathbf{g}_k\mathbf{v}_j|^2}\right)\right\}$ by averaging over 5000 realizations of the small scale fading channels. In order to demonstrate that our analysis still holds when the assumption of orthogonal user selection is not satisfied, MS_2 is always served simultaneously with MS_1 no matter if their quantized global channels are orthogonal or not.

The receive SNR of the cell-edge MS, γ_{edge}, is set to be 10 dB. The distance between two BSs are 500 m and the two MSs are located on the line connecting the two BSs. Shadowing are not considered in the simulation, then the distance between MS_1 and BS_1 can reflect the path loss of both local and cross channels of MS_1. The path loss factor ϵ is set as 3.76. We take the performance of MS_1 as an example to analyze. Define the receive SNR of the local channel of MS_1 as $\gamma_{1,1} = \frac{P\alpha_{1,1}^2}{\sigma_n^2}$.

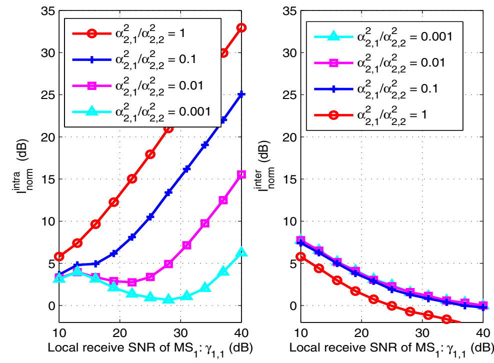

Fig. 2. Normalized average intra-cell and inter-cell interference to MS_1 versus the local receive SNR of MS_1. The y-axis $\mathrm{I}_{\mathrm{norm}}^{\mathrm{intra}}$ and $\mathrm{I}_{\mathrm{norm}}^{\mathrm{intra}}$ are the normalized intra-cell and inter-cell interference, respectively.

Given γ_{edge} and $\gamma_{1,1}$, the ratio of local and cross channel gain of MS_1 can be calculated according to the geometric relationship: $\frac{\alpha_{1,1}^2}{\alpha_{1,2}^2} = (2*10^{\frac{\gamma_{1,1}-\gamma_{\mathrm{edge}}}{10\epsilon}}-1)^{\epsilon}$. Different values of $\alpha_{2,1}^2/\alpha_{2,2}^2$ reflect different locations of MS_2 and determine the impact coefficient $\beta_{1,2}$. The decrease of $\alpha_{2,1}^2/\alpha_{2,2}^2$ reflects the movement of MS_2 from cell center to cell edge. When $\alpha_{2,1}^2/\alpha_{2,2}^2 = 1$, MS_2 is located at the exact cell edge.

We first observe the impact of channel asymmetry on the value of average intra-cell and inter-cell interference. To see whether the system is interference limited or not, we define a normalized interference as $\mathrm{I}_{\mathrm{norm}} = \mathrm{I}/\frac{\sigma_n^2}{P\alpha_{1,1}^2}$. When it exceeds 0 dB, the performance of MS_1 becomes interference limited. Fig. 2 presents the normalized average intra-cell interference and inter-cell interference power at MS_1 for various $\alpha_{2,1}^2/\alpha_{2,2}^2$. It is shown that when the value of $\gamma_{1,1}$ increase, i.e., MS_1 moves from cell edge to cell center, the intra-cell interference increases and the inter-cell interference decreases. When MS_1 is located at cell center, the value of intra-cell interference is much larger than that of inter-cell interference. Furthermore, the value of intra-cell interference depends heavily on the position of MS_2. A cell-edge MS_2 will lead to much more severe intra-cell interference to MS_1 than a cell-center MS_2.

Figure 3 shows the simulated average throughput of MS_1 for various $\alpha_{2,1}^2/\alpha_{2,2}^2$ as well as the average throughput lower bound which is obtained from (11) and (3). It is shown that the approximate average throughput is close to the simulation results when the local SNR of MS_1 is low. We can observe that when MS_2 is located at cell edge, i.e., $\alpha_{2,1}^2/\alpha_{2,2}^2 = 1$, the average rate of MS_1 will arrive at a ceiling when its local SNR is high. When the value of $\alpha_{2,1}^2/\alpha_{2,2}^2$ decreases, the ceiling effect is gradually alleviated. This validates our observations in last section as well as in Fig. 2 that the intra-cell interference of MS_1, whose value heavily depends on the location of MS_2, dominates the performance especially when MS_1 is located at cell center.

To ensure that the performance of MS_1 is not interference limited, the number of bits used to quantize the per-cell channel should be adjusted according to the location of both MS_1 and its co-scheduled MS. Fig. 4 shows the number

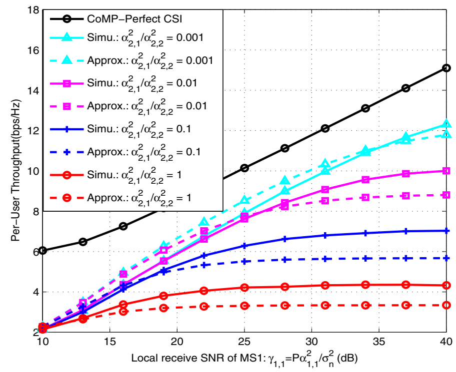

Fig. 3. Throughput of MS_1 versus the local SNR of MS_1.

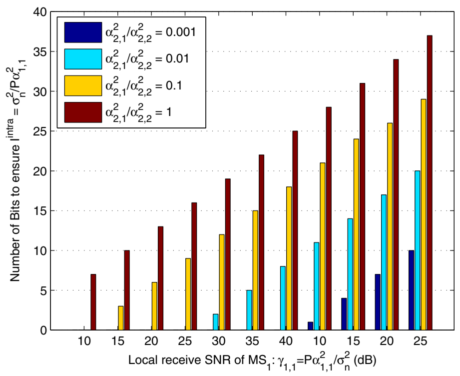

Fig. 4. Number of bits required to ensure that the value of the average intra-cell interference is the same as $\sigma_n^2/P\alpha_{1,1}^2$.

of bits for the feedback of local channel, which ensures the value of the average intra-cell interference to be equal to $\sigma_n^2/P\alpha_{1,1}^2$, i.e, $\mathrm{I}_1^{\mathrm{intra}} = \frac{P}{n_t-1}\alpha_{1,1}^2\beta_{1,1}\delta_{1,1}^2 = \sigma_n^2/P\alpha_{1,1}^2$. The quantization error of per-cell CDI is approximated as $\delta_{1,1}^2 \approx 2^{\frac{-B}{n_t-1}}$, which is an upper bound when RVQ is used. Then the number of required bits can be obtained as $B = (n_t-1)\log_2\left(\frac{\gamma_{1,1}\alpha_{1,1}^2\alpha_{2,1}^2 P}{(n_t-1)(\alpha_{2,1}^2+\alpha_{2,2}^2)}\right)$. This shows that the required number of feedback bits increases with the local SNR, and the position of the co-scheduled MSs has significant impact on the feedback bits. When the co-scheduled MS is located at the cell edge, the number of required bits is very high for MS_1 to reduce the intra-cell interference to the same level as the reciprocal of the SNR.

Figure 5 shows the performance of MS_1 when the bit allocation is adjusted according to the results in Fig. 4. No ceiling effect exists for the throughput of MS_1. The performance under large value of $\alpha_{2,1}^2/\alpha_{2,2}^2$ is even better than that under small value of $\alpha_{2,1}^2/\alpha_{2,2}^2$. This is because the large number of bits used to reduce the intra-cell interference can increase the signal power at the same time.

V. Conclusion

In this paper, we investigated the impact of channel asymmetry on CoMP MU-MIMO systems with limited feedback

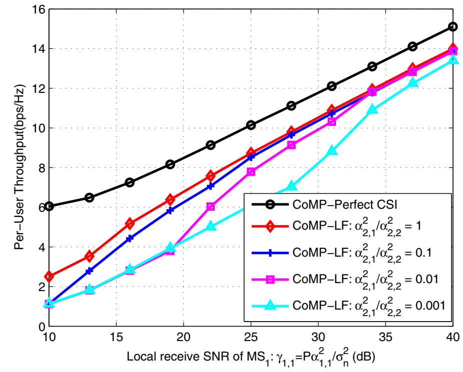

Fig. 5. Throughput of MS_1 when the bit allocation changes according to that shown in Fig. 4.

based on per-cell quantization. Our analysis shows that approximately, the average per-user rate depends on the SNR, the number of transmit antennas, the quantization error, as well as the location of the MSs. As in single cell systems, a cell-center MS is interference limited, but the resulting ceiling effect is severe only when its co-scheduled MSs in other cells are located in the cell edge. If bit allocation is allowed for per-cell channels to control the interference, the per-user rate will be improved significantly but the required feedback overhead increases accordingly.

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