Fair Allocation of Backhaul Resources in Multi-Cell MIMO Coordinated Beamforming

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***Abstract*—Coordinated beamforming in multipoint MIMO networks has been introduced to increase the overall capacity of wireless networks. In coordinated beamforming, the channel state information between the different MIMO access points/base stations in one hand, and the mobile stations on the other hand, needs to be shared among the MIMO nodes. A "backhaul" between different MIMO access points is used to transfer the channel state information. The channel state information of different links is quantized with different quantization steps according to a specific optimization criteria. This information is then shared through the backhaul. In this paper, we study the problem of allocating the backhaul bandwidth among users in coordinated beamforming MIMO multipoint networks. First, we prove through mathematical analysis, that there are many allocations that can provide "near maximum sum rate". These different allocations vary significantly in fairness between users. A "fair" allocation is an allocation that provides a small variance between the rates of different users. Motivated by this finding, we introduce two novel, low complexity, backhaul bandwidth distribution schemes that can achieve a very close to maximum sum rate, and at the same time, offer throughput fairness among users. Simulation results show that, for the same sum-rate, the proposed schemes can achieve more fairness among users when compared to the conventional scheme, which gives all users the same share of bandwidth. Moreover, we show that one of the proposed schemes, namely the Equal SIR scheme, can achieve zero variance among users in a wide range of backhaul bandwidths while keeping a very close to maximum sum rate.**

***Index Terms*—Beamforming, Network MIMO, Backhaul.**

I. Introduction

Interference is one of the key challenges that limits the capacity of wireless communication systems. The conventional approach to deal with interference is to limit the resources re-usability (time, frequency, code,...) to introduce some kind of orthogonality between users. Recently, other approaches have been introduced for either making use of interference, or at least coordinating users' transmissions [1]. For example, Multi-Cell MIMO (sometimes referred to as Network MIMO) is a new technology used by base-stations to mitigate the interference by coordinating base-stations transmission in cellular networks. 3GPP LTE-A and IEEE 802.16m have recently chosen Network MIMO as a means to increase the cell-edge and system throughput in their networks[2] [3].

A fundamental challenge in cooperative MIMO networks is the issue of limited backhaul bandwidth. For example, in multi-cell processing, full cooperation among base-stations requires the exchange of full channel state information (CSI) and user's data among all base-stations, which requires a very high-speed backhaul.

Several attempts to reduce backhaul requirements through distributed cooperation, statistical CSI exchange or clustered cooperation have been proposed [4] [5] [6]. Another approach to reduce backhaul load is to do cooperation only for a selected subset of users according to a criteria that selects only the deserving users [7] [8] [9]. Authors of these papers have mainly considered data sharing, focusing on sum-rate and not fairness. Adaptive feedback allocation methods are also a recent research topic. Another type of collaboration, called Interference Coordination [1], can be used when no high-speed backhaul is available. It requires the exchange of CSI only to perform some form of coordinated beamforming.

Distributing the backhaul link bandwidth among users is considered a resource allocation problem. In any resource allocation problem, there is always a trade-off between global performance, best represented by sum-rate, and fairness. Although fairness is usually studied in higher layers, the emerging cross-layer design concepts have encouraged the study of fairness in the physical layer. A comprehensive study of fairness in wireless communications, both in physical and MAC layers, was performed in [12]. The used criterion is to measure the mean versus variance among the users' throughputs. Note that the mean of the users' throughput reflects the sum-rate in the network, as the mean throughput is the sum-rate divided by the number of users. It was shown that most of the time whenever global performance, represented by the mean, is maximized, the fairness, represented by the variance, increases.

In this paper, we tackle the problem of distributing the backhaul bandwidth among different mobile stations to exchange the CSI in a cooperative beamforming MIMO network. We derive an analytical model for the interference in coordinated beamforming networks with backhauls that have limited bandwidth, assuming only quantized CSI is shared but no data sharing. Using this analytical model, we show that the condition for achieving a close to maximum sum-rate is trivial, and many allocations can be used to achieve a close to maximum sum-rate. We analytically show that the optimization of sum-rate provides insignificant performance improvement compared to the conventional scheme, which equally allocates backhaul bandwidth among users. Motivated by this important

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finding, we study the problem from the fairness perspective. We propose two low complexity schemes for distributing the backhaul bandwidth and achieve a fair rate distribution with close to maximum sum-rate. We show, through analysis and simulation, that these two approaches are able to provide the same sum-rate while ensuring fairness among users compared to the conventional scheme. These schemes are particularly important for networks with low bandwidth backhaul links, or when users are required to feed back their CSI through a limited bandwidth in the wireless uplink. In this case, efficient utilization of the backhaul bandwidth is mandatory.

The rest of the paper is organized as follows. Section II introduces the system model. Section III describes the problem formulation, solution and fairness discussion. Section IV shows the simulation results. Finally, Section V concludes the paper.

II. System Model

We consider a Wyner type [13], two base stations, N-user per cell MIMO downlink system, as shown in Fig. 1 for $N = 2$. Each base station has $M = 2N$ antennas, while users are each equipped with a single antenna. Channel is taken from the Zero-mean Circularly-symmetric Complex-Gaussian model $(ZMCSCG)$ [14]. This channel model is usually used in the coordinated beamforming MIMO networks [15]. We also take the simple, yet efficient, Zero-Forcing (ZF) precoder, its columns are normalized to obey maximum power limit condition. Hence the received signal may be expressed as

$$\mathbf{y} = \mathbf{L}_1\mathbf{H}_1\mathbf{W}_1\mathbf{x}_1 + \mathbf{L}_2\mathbf{H}_2\mathbf{W}_2\mathbf{x}_2 + \mathbf{n} \tag{1}$$

where $\mathbf{y}$ is the received signal vector with elements y_i representing the received signal at users i, $\mathbf{x}_k$ is the transmitted signal from base-station k. $\mathbf{L}_k$ is a diagonal matrix with diagonal elements representing the square root of the power path-loss, $(l_{ii,k})^2 = K\left(\frac{d_{k,i}}{d_o}\right)^{-\gamma}$, where $d_{k,i}$ is the distance between base-station k and user i, K is the loss at a reference distance d_o and γ is the path loss exponent [16]. $\mathbf{H}_k$ is the channel matrix between users and base-station k and $\mathbf{W}_k$ is the corresponding linear beamformer used at base-station k. $\mathbf{n}$ is the noise vector. Without loss of generality, we will focus on users in the first cell. For a user in the first cell, the first term represents the useful signal and the same cell interference, the second represents the other cell interference and the third is the noise term. Therefore the instantaneous received signal to interference and noise ratio $(SINR_i^t)$ for a general beamformer for user i in the first cell is

$$SINR_i^t = \frac{Pt_{1,i}\,(l_{ii,1})^2\,|\mathbf{h}_{1,i}\mathbf{w}_{1,i}|^2}{\sigma^2 + \sum\limits_{\substack{1\le j\le N, i\ne j \forall k=1\\ 1\le k\le 2}} Pt_{k,j}\,(l_{ii,k})^2\,|\mathbf{h}_{k,i}\mathbf{w}_{k,j}|^2} \tag{2}$$

where $\mathbf{h}_{k,i}$ is the channel vector between base-station k and user i, $\mathbf{w}_{k,i}$ is the beamforming vector between base-station k and user i. $Pt_{k,l}$ is the symbol power to be transmitted from base station k intended to user l, $\mathbf{x}_k^H\mathbf{x}_k = [Pt_{k,1}, Pt_{k,2}, ..., Pt_{k,M}]$, and σ^2 is the noise power. Let $P_{k,i,l} = Pt_{k,l} \times (l_{ii,k})^2$ denote the value of $Pt_{k,l}$ when received at user i. Then $(SINR_i^t)$ is written as

$$SINR_i^t = \frac{P_{1,i,i}\left|\mathbf{h}_{1,i}^H\mathbf{w}_{1,i}\right|^2}{\sigma^2 + \sum\limits_{\substack{1\le j\le N, i\ne j \forall k=1\\ 1\le k\le 2}} P_{k,i,j}\left|\mathbf{h}_{k,i}^H\mathbf{w}_{k,j}\right|^2} \tag{3}$$

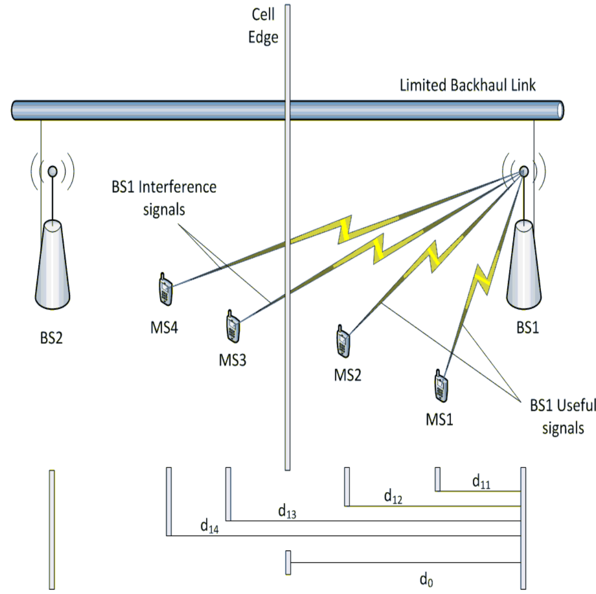

Fig. 1. System model for a 2 base station, 2 users per base station case.

Each base station is assumed to have perfect knowledge of its own users channels. A user in the first cell estimates the channel between himself and cell 2 basestation. The estimates are transferred to the basestation of the first cell, and then these channel estimates are conveyed through the backhaul to cell 2 base station to do coordinated beamforming. However, due to the limited backhaul bandwidth, only quantized versions of the channels may be exchanged between the coordinating base-stations. Uniform quantization is assumed. Each base station uses the perfectly known channels of its own users, and the quantized channels of the other cell users to design a beam-forming matrix $\mathbf{W}$. Even with coordinated ZF beamforming, the users whose channels were quantized will suffer from interference due to quantization. This quantization interference is what is left from the multi-cell interference and is still the major limit for the system performance.

Interference Model

Here, we derive an analytical expression for the average received $SINR_i$ using a beamformer based on the quantized-channel. It should be noted that the interference from the same cell users equals zero due to using ZF beamforming based on perfectly known channels. The received multi-cell interference

I_i at user i in the first cell is

$$I_i = \sum_{1\leq j\leq N} P_{2,i,j} \left|\mathbf{h}_{2,i}^H \mathbf{w}_{2,j}\right|^2 \tag{4}$$

the unquantized channel vector $\mathbf{h}_{2,i}$ may be written in terms of the quantized channel vector $\hat{\mathbf{h}}_{2,i}$ using the simple formula

$$\mathbf{h}_{2,i} = \hat{\mathbf{h}}_{2,i} + \hat{\mathbf{n}}_i \tag{5}$$

where $\hat{\mathbf{n}}_i$ is the quantization noise vector corresponding to user i channels. So

$$I_i = \sum_{1\leq j\leq N} P_{2,i,j} \left|(\hat{\mathbf{h}}_{2,i} + \hat{\mathbf{n}}_i)^H \mathbf{w}_{2,j}\right|^2$$

$$I_i = \sum_{1\leq j\leq N} P_{2,i,j} \Big[\left|\hat{\mathbf{h}}_{2,i}^H \mathbf{w}_{2,j}\right|^2 + \left|\hat{\mathbf{n}}_i^H \mathbf{w}_{2,j}\right|^2 + \left(\hat{\mathbf{h}}_{2,i}^H \mathbf{w}_{2,j}\right)^* \left(\hat{\mathbf{n}}_i^H \mathbf{w}_{2,j}\right) + \left(\hat{\mathbf{h}}_{2,i}^H \mathbf{w}_{2,j}\right)\left(\hat{\mathbf{n}}_i^H \mathbf{w}_{2,j}\right)^*\Big]$$

the first term $\left|\hat{\mathbf{h}}_{2,i}^H \mathbf{w}_{2,j}\right|^2$ is independent on the quantization noise and depends only on the beamformer type. It equals zero for the ZF beamformer we use throughout the paper. This is because the beamformer coefficients at cell 2 are chosen based on the quantized channel coefficients received through the backhaul. So the interference due to quantization only, I_{qi}, equals the total interference I_i and is given by

$$I_{qi} = \sum_{1\leq j\leq N} P_{2,i,j} \Big[\left|\hat{\mathbf{n}}_i^H \mathbf{w}_{2,j}\right|^2 + \left(\hat{\mathbf{h}}_{2,i}^H \mathbf{w}_{2,j}\right)^* \left(\hat{\mathbf{n}}_i^H \mathbf{w}_{2,j}\right) + \left(\hat{\mathbf{h}}_{2,i}^H \mathbf{w}_{2,j}\right)\left(\hat{\mathbf{n}}_i^H \mathbf{w}_{2,j}\right)^*\Big] \tag{6}$$

For a sufficient number of quantization bits, the quantization noise elements are independent and uniformly distributed with zero mean [17]. Taking the mean over different channel realizations

$$\mathbf{E}\left\{I_{qi}\right\} = \mathbf{E}\left\{\sum_{1\leq j\leq N} P_{2,i,j} \left(\left|\hat{\mathbf{n}}_i^H \mathbf{w}_{2,j}\right|^2\right)\right\} \tag{7}$$

as the terms

$$\mathbf{E}\left\{\left(\hat{\mathbf{h}}_{2,i}^H \mathbf{w}_{2,j}\right)^* \left(\hat{\mathbf{n}}_i^H \mathbf{w}_{2,j}\right) + \left(\hat{\mathbf{h}}_{2,i}^H \mathbf{w}_{2,j}\right)\left(\hat{\mathbf{n}}_i^H \mathbf{w}_{2,j}\right)^*\right\} = 0 \tag{8}$$

Hence

$$\mathbf{E}\{I_{qi}\} = \sum_{1\leq j\leq N} P_{2,i,j} \mathbf{E}\left\{\left|\sum_{1\leq k\leq M} \hat{n}_{i,k} w_{2,j,k}\right|^2\right\} \tag{9}$$

where $\hat{n}_{i,k}$,$w_{2,j,k}$ are the k^{th} elements of $\hat{\mathbf{n}}_i$ and $\mathbf{w}_{2,j}$ respectively. Since quantization noise elements are zero-mean and independent on the beamforming vectors, the above expression reduces to

$$\mathbf{E}\{I_{qi}\} = \sum_{1\leq j\leq N} P_{2,i,j} \sum_{1\leq k\leq M} \mathbf{E}\{|\hat{n}_{i,k} w_{2,j,k}|^2\}$$

$$\mathbf{E}\{I_{qi}\} = \sum_{1\leq j\leq N} P_{2,i,j} \sum_{1<k<M} \mathbf{E}\{|\hat{n}_{i,k}|^2\}\mathbf{E}\{|w_{2,j,k}|^2\}$$

$$\mathbf{E}\{I_{qi}\} = \sum_{1\leq j\leq N} P_{2,i,j}\, Q_i \sum_{1\leq k\leq M} |w_{2,j,k}|^2$$

and as we assumed before that beamformer vectors are normalized $\left(\sum_{1\leq k\leq M} |w_{2,j,k}|^2 = 1\right)$, then

$$\mathbf{E}\{I_{qi}\} = \sum_{1\leq j\leq N} P_{2,i,j} \times Q_i \tag{10}$$

where Q_i is the quantization noise and is given by [17]

$$Q_i = \mathbf{E}\{|\hat{n}_{i,k}|^2\} = \frac{\mathrm{C}}{2^{2\times l_i}} \tag{11}$$

where $C = \frac{2}{3}$ [17] and l_i is the number of quantization bits per channel given to user i.

From (3) and (10), the channel average $SINR_i$ may be written as [18]

$$SINR_i = \frac{P_{1,i,i}\mathbf{E}\{|\mathbf{h}_{1,i}\mathbf{w}_{1,i}|^2\}}{\mathbf{E}\left\{\sigma^2 + I_i\right\}} = \frac{P_{1,i,i}}{\sigma^2 + \sum\limits_{1\leq j\leq N} P_{2,i,j} \times Q_i} \tag{12}$$

as $\mathbf{E}\{|\mathbf{h}_{1,i}\mathbf{w}_{1,i}|^2\} = M - 2N + 1$ from [12] for the ZF beamformer. This value is the same for all users and is omitted for convenience. For the case of uniform power allocation in the second base-station we omit the third index in $P_{1,i,i}$ and $P_{2,i,j}$, therefore

$$SINR_i = \frac{P_{1,i}}{\sigma^2 + I_{qi}} \tag{13}$$

$$SINR_i = \frac{P_{1,i}}{\sigma^2 + P_{2,i} \times N \times Q_i} \tag{14}$$

Assuming each user has a rate r_i (in bits/symbol/Hz)[1], we may write user rates as a function of the average SINR as

$$r_i = \log_2\left(1 + SINR_i\right) \tag{15}$$

the sum-rate for N-users in each cell is given by

$$\sum_{1<i<N} r_i = \sum_{1\leq i\leq N} \log_2\left(1 + SINR_i\right) \tag{16}$$

The simulated interference and our derived analytical expression for interference are shown in Fig. 2. The figure shows that our analytical expression is matching with the simulated one. Note that $P_{2,i}$ is the value of the power received at user i in the first cell when transmitted from the second base-station intended to its users. The values of $P_{1,i}$ and $P_{2,i}$ vary greatly according to the user position due to the path loss. The main goal of this paper is to allocate bits among users according to their position.

[1]It can be shown that the expectation of the instantaneous rate is the logarithm of the expected SINR. The proof is not provided here due to space limitations and depends mainly on modeling the equivalent channel of the ZF precoder as a Chi-square random variable as in [12].

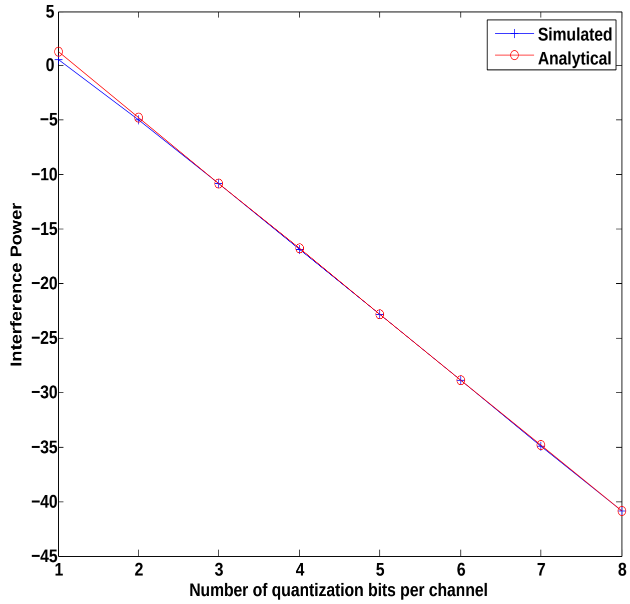

Fig. 2. Simulated and Analytically found interference versus number of quantization bits $\{P_{1,i} = P_{2,i} = 10 \;\; \forall i = 1:N, N = 8\}$ free of path-loss

III. Sum-Rate versus Fairness Analysis

In this section, we study how to allocate quantization bits in the backhaul among users. We tackle the problem from two perspectives , sum-rate and fairness. Most existing work in the literature assumed that different users get the same share of backhaul bandwidth. This scheme is referred to as the conventional scheme in our context.

A. Sum-Rate

The sum-rate maximization problem is formulated as

$$\begin{aligned} \max \quad & \sum_{1\le i\le N} r_i \\ \text{s.t.} \quad & \sum_{1\le i\le N} l_i = D \end{aligned} \tag{17}$$

The goal is to find the distribution of the bit budget D in the backhaul among the different users l_i's .The Lagrange multiplier formulation of the above problem is

$$\mathbf{J} = \sum_{1\le i\le N} \log_2\left(1 + SINR_i\right) + \mu \left(D - \sum_{1\le i\le N} l_i \right) \tag{18}$$

where D is the total number of backhaul bits and μ is the Lagrange multiplier, differentiating and equating with zero yields the following condition

$$\frac{I_{qi} \times P_{1,i}}{(I_{qi} + \sigma^2) \times (P_{1,i} + I_{qi} + \sigma^2)} = \mathbf{A} \tag{19}$$

where $\mathbf{A}$ is some constant. Any bit allocation that satisfies (19) achieves the maximum sum-rate. Special cases of the system operation are:

1) Region 1:

$$\sigma^2 \ll I_{qi} \ll P_{1,i}, \quad \forall i = 1:N \tag{20}$$

In region 1, a good approximation for (19) may be as follows

$$\frac{I_{qi} \times P_{1,i}}{I_{qi} \times P_{1,i}} = 1 = \mathbf{A}'' \tag{21}$$

this result clearly shows that the condition for sum-rate maximization is trivial and can be easily achieved with any scheme that gives reasonable number of bits to the edge users which represents the lowest $SINR$ or the largest interference. Examples for these schemes are the conventional scheme or the more fair schemes proposed later in this section.

2) Region 2:

$$\sigma^2 \approx I_{qi} \ll P_{1,i}, \quad \forall i = 1:N \tag{22}$$

A good approximation here is

$$\frac{I_{qi} \times P_{1,i}}{(I_{qi} + \sigma^2) \times P_{1,i}} = \mathbf{A} \tag{23}$$

or

$$I_{qi} = \mathbf{A}''' \tag{24}$$

which means equal interference for all users. However in region 2, similar to the famous power water-filling problem where the water-filling and the uniform power allocation are the same for high SNR [17], we argue that in region 2 the number of bits is large enough to make all schemes, the conventional scheme and the two water-filling like schemes proposed next, approach each other as will be shown from the simulation results.

As a conclusion, for high interference level as in region 1, any bit distribution will satisfy the max sum-rate condition in (19). In low interference levels as in region 2, there is no strict need to satisfy the equal interference condition to reach the max sum-rate. Hence, in all cases, the condition to satisfy the maximum sum-rate is relaxed.

B. Fairness

As mentioned in the introduction and in [12], global performance is usually penalized whenever we want better fairness. However, our important contribution in this paper is that in some cases, where the conditions for global performance is relaxed as we showed before, clever allocation of the backhaul bandwidth can be utilized to provide a much better fair performance while keeping the global performance, the sum-rate, almost the same. These schemes are (*Equal SIR*) and *(Equal Interference)*. These two fair schemes provide better fair conditions while preserving the global performance as well.

1) Equal Signal-to-Interference-ratio (SIR): in order to provide equal SIR for all users, we solve the following problem

$$\begin{aligned} \max \min \quad & \frac{P_{1,i}}{I_{qi}} \\ \text{s.t.} \quad & \sum_{1\le i\le N} l_i = D \end{aligned} \tag{25}$$

from (11) and (14), the solution for (25) is a water-filling like equation for allocating bits among users as follows

$$l_i = a + 0.5 \times \log_2 \left(\frac{P_{2,i}}{P_{1,i}} \right) \tag{26}$$

where a is a constant depending on the total number of bits and can be found by solving the equation

$$\sum_{1\le i\le N} l_i = \sum_{1\le i\le N} \left(a + 0.5 \times \log_2 \left(\frac{P_{2,i}}{P_{1,i}} \right) \right) = D \tag{27}$$

where D is the total number of bits available in the backhaul.

2) Equal Interference: inspired by in (24), we propose a scheme that provides equal inteference for all users. The bit distribution is obtained by solving the following maximization problem

$$\begin{aligned} \max \min \quad & I_{qi} \\ \text{s.t.} \quad & \sum_{1\le i\le N} l_i = D \end{aligned} \tag{28}$$

from (11), (14) and (24), the solution for (28) is a water-filling like equation for allocating bits among users as follows

$$l_i = a + 0.5 \times \log_2 (P_{2,i}) \tag{29}$$

a can be found similar to (27).

IV. Simulation Results

The simulation is done for a two-base stations, 4 users per cell. Each basestation is equipped with 8 antennas. Backhaul bandwidth ranges from 1 to 40 bits on average per user. The reference distance d_o is assumed to be 1600m and is also considered the cell radius. Path loss exponent is 3.8. Users per cell are allocated every 400m starting from 400m to 1600m. We see this as the most general scenario for users allocation. If users are at the same distance, then any allocation scheme will treat all users equally. While if users are clustered, then we may consider every group of adjacent users as one super user and we have a special case of the uniform-distance allocation case. Base station power equals to 10 watt. Two important parameters are used to measure system performance: rate mean, which is defined as the average rate over all users rates, and rate variance, which is the variance among different rates of the users. As mentioned earlier, less variance for the same mean indicates better fairness. Fig. 3 plots the rate mean versus average number of available bits per user per channel. It is clear from the figure that all three schemes achieve the same mean, the explanation for this result was partially given in Section III. Moreover, simulations show that even when $I_{q,i} \approx P_{1,i}$, the sum rate is still almost the same. Fig. 4 is the combined plot of the mean versus variance which shows that our proposed schemes can achieve a much less variance while preserving the same mean. Also in Fig. 4 we can clearly see the two regions of operation of the system explained in III-A. The first region representing moderate interference ranges from $3 \sim 25$ bits and this is where our schemes perform at their best from the fairness point of view. The second region ranges from 26 bits onward and this is where the three schemes converge. The second region ends with all schemes approaching each other and this can be considered as the infinite backhaul point. Other simulation results for user groups clustered in different locations within the cells support the same conclusions. Finally two notes need to be highlighted. First note is that the Equal SIR scheme can achieve the lowest possible value for variance which is zero. Second note is that asymptotically, when we approach the infinite backhaul point, no scheme can achieve zero rate variance. In this region, all users suffer from no interference because channels are transmitted through the backhaul with no quantization. Consequently, because different users are located at different distances from the base stations, they will receive different powers. Hence, the rates of different users will not be the same, and the rate variance will no longer equals zero.

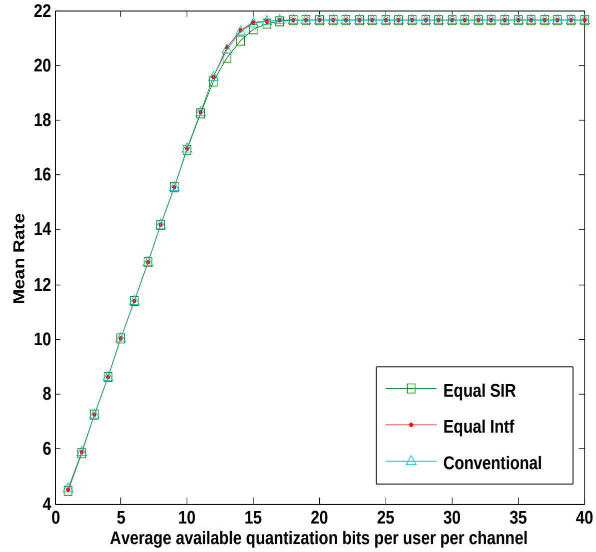

Fig. 3. Rate Mean versus number of quantization bits

V. Conclusion

In this paper we studied the problem of how to best allocate the backhaul bandwidth among users in a multi-cell MIMO coordinated beamforming system. The first approach was to maximize the network sum-rate, where we showed that the

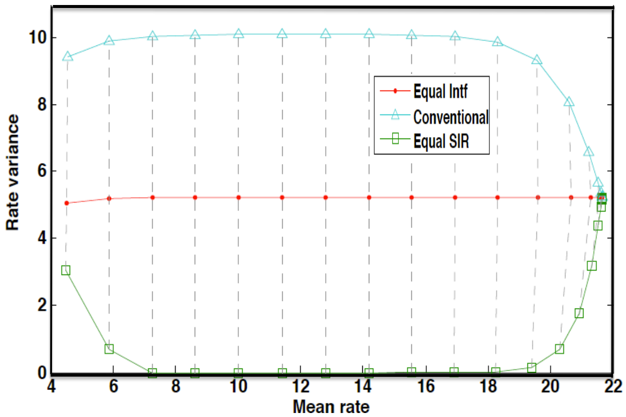

Fig. 4. Rate variance vs. Rate mean with vertical lines representing constant number of quantization bits

conditions for its optimization are very relaxed. We then turned our attention towards fairness, where we proposed two schemes: the Equal SIR and Equal Intereference. We showed through simulations that the proposed schemes achieve much less variances compared to the conventional scheme, which gives the same share of backhaul bandwidth to all users, without sacrificing the sum-rate performance.

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