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Adaptive limited feedback links for cooperative multi-antenna multicell networks

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Abstract

The overall performance of cooperative networks is quite sensitive to channel state information (CSI) of serving and interfering base stations (BSs) and affected strongly by quality of limited feedback links. In this paper, we propose two adaptive limited feedback strategies for intercell interference cancelation in multi-antenna multicell networks. The first proposed strategy is developed to improve average multicell capacity assuming a fixed rate feedback link. This algorithm is based on adaptation of the number of bits to quantize CSI of serving and interfering BSs according to transmitter power and location of the user in its own cell. The second proposed strategy is designed in a way to increase average capacity of cell-edge users assuming an adaptive rate feedback link. This algorithm is based on the idea of allocating more bits to quantize CSI of users at cell-edge regions while allocating less bits for users near the serving BS. We illustrate performance of the proposed feedback links for downlink cooperative multi-antenna multicell networks in wireless channels.

1 Introduction

The increasing demand for wireless multimedia and interactive Internet services incurs intensive research efforts on design of novel wireless communication systems for high-speed, reliable, and cost-effective transmission solutions. Upcoming cellular standards like the 3GPP LTE Advanced are targeting universal frequency reuse in a bid to increase peak data rates. This could, however, lead to high levels of intercell interference (ICI) due to simultaneous transmissions on the same frequency by neighboring base stations (BSs). The ICI can significantly reduce data rates and cause outages in cellular systems especially at cell edges. In order to solve this problem, cooperative multicell transmission has emerged as a promising technique to effectively reduce the ICI, enhance cell-edge throughput, and increase whole system throughput for cellular communication system [1,2].

While the multiple-input multiple-output (MIMO) system is now a key technology to improve performance and capacity of wireless communications over conventional single-antenna systems, the concept of cooperative communications has more recently emerged as a solution

to exploit potential MIMO gains on a distributed scale [3]. The use of multiple-antenna techniques in downlink wireless networks increases overall throughput by exploiting degrees of freedom in the spatial domain. It is possible to accommodate up to $N_t - 1$ interference signals in a cooperative multicell transmission when a BS is equipped with N_t antennas by performing linear transceiver processing techniques.

A full cooperative multicell transmission requires to exchange all users' channel state information (CSI) as well as their data. In order to reduce backhaul load, partial cooperative strategies have been considered where BSs share only users' CSIs [4]. In partial cooperative multicell networks, each BS designs its beamforming vector to communicate its own user by employing different transmission strategies such as maximum ratio combining (MRC) and partial zero-forcing (PZF) [5] by taking into account interference coming from other cells. It is important to develop cooperative techniques with limited feedback that maximize performance while keeping feedback load at a reasonable level. The limited feedback systems have been investigated from point-to-point MIMO channels to MIMO broadcast channels in the literature extensively [6,7].

The performance of cooperative multicell networks is highly dependent on the quality of feedback information of both serving and interfering BSs. The quality of

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quantized CSI is improved by employing efficient bit partitioning strategies to quantized CSI belonging to serving and interfering BSs while having a reduced rate feedback channel. In [8], a robust decentralizing framework has been presented by evaluating the effect of feedback errors under a digital feedback model. In [9], the adaptive ICI method where multiple BSs jointly select transmission strategies has been presented with carefully designed feedback strategies. In [10], at high signal-to-interference noise ratio (SINR), a feedback allocation strategy has been presented to reduce mean loss caused by the random vector quantizer (RVQ) in sum capacity. The adaptive bit partitioning for delayed limited feedback channels has been presented by allocating more bits to quantize stronger channels with smaller delays and fewer bits to weaker channels with larger delays in [11]. Adaptive feedback schemes for coordinated zero forcing have been investigated by minimizing expected quantization error to maintain optimal multiplexing gain in [12]. Limited feedback schemes with channel quantization for cooperative multicell processing (CoMP) have been examined in [13] including CoMP channel reconstruction, CoMP codebook generation, and per-cell codeword selection. A scalable two-stage feedback mechanism which includes a first stage of individual per-cell feedback to support single-cell multiuser MIMO and a second stage of multicell feedback to efficiently enable CoMP per-cell has been described in [14]. In [15], multiple-input single-output (MISO) joint processing systems with limited feedback where BSs exchange both CSI and their data via ideal backhaul links have been examined to maximize quantizated channel accuracy in the presence of path loss. For single-antenna cooperative multiuser multicell systems, a selective feedback which prevents to feed back CSI of the users whose channel quality does not exceed a given threshold has been presented in [16]. The best-M partial feedback strategy for orthogonal frequency division multiple access (OFDMA)-based heterogeneous multicell systems has been presented in [17] while maintaining fair scheduling among the users with different locations.

These limited feedback strategies assume that each user has a fixed number of bits to quantize its CSIs belonging to serving and interfering BSs to improve average capacity while providing poor performance for cell-edge users. It is possible to further improve capacity at cell edges by employing more quantization bits for cell-edge users. In [18,19], a precoding matrix index (PMI) restriction method has been examined by informing other BSs about the precoding vector which causes large interference to mitigate ICI for cell-edge users.

In this paper, we consider a single-user MISO multicell network by employing partial cooperative transmission. Each cell consists of one serving and two interfering BSs each having N_t transmit antennas. Each BS communicates

to one user with a single antenna. We assume that each user quantizes and feeds back its CSI regarding serving and interfering BSs to its serving BS, and then these quantized CSIs are shared among BSs through an ideal backhaul. Our main contributions are summarized as follows: Firstly, with a constraint on the total number of feedback bits per user, we propose a limited feedback link to maximize average multicell capacity depending on user location and power levels at cell edges. Secondly, we propose a limited feedback link to improve performance of cell-edge users while holding constraint on the average number of feedback bits in the cell. This proposed method is based on allocating more bits to quantize CSI of the users far from their serving BS to efficiently perform ICI cancelation while allocating less bits for the users near BSs.

This paper is organized as follows. In Section 2, the system model for multi-antenna multicell networks is described including transmission strategies and limited feedback issues. In Section 3, the proposed adaptive feedback links are given to improve average multicell capacity and to increase especially cell-edge capacity. In Sections 4 and 5, the performance results are illustrated for downlink cooperative single-user multi-antenna multicell networks in wireless channels and the concluding remarks are drawn, respectively.

2 System model

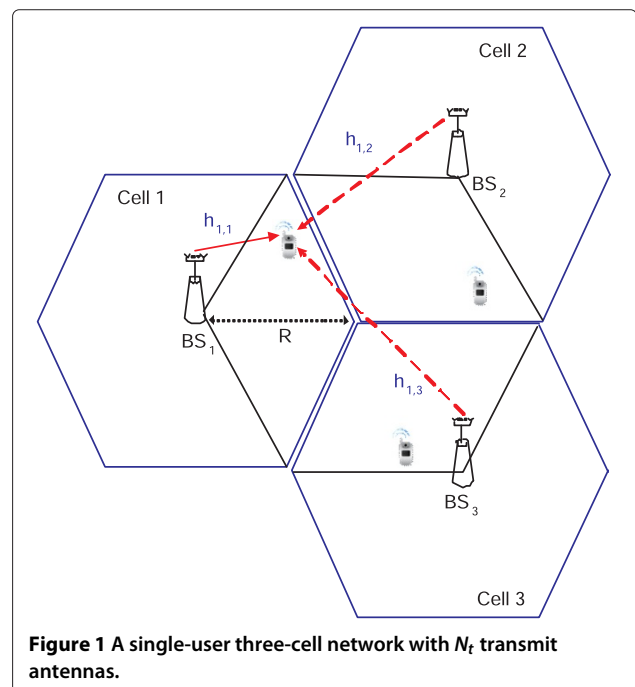As illustrated in Figure 1, we examine a downlink multicell network with three BSs where each of them has N_t

Figure 1 A single-user three-cell network with N_t transmit antennas.

transmit antennas and each user is equipped with one antenna.

Using a narrow band flat-fading model, the baseband received signal of the user of cell u is given by

$$y_u = \sqrt{P_{u,u}}\mathbf{h}_{u,u}^H\mathbf{w}_u x_u + \sum_{v=1;v\neq u}^{U} \sqrt{P_{u,v}}\mathbf{h}_{u,v}^H\mathbf{w}_v x_v + n_u \quad (1)$$

where $P_{u,v}$ is the received power of user u from BS v, and $\mathbf{h}_{u,v}$ is the channel vector with $N_t \times 1$ from the BS v to the user of cell u. It is assumed that each component of $\mathbf{h}_{u,v}$ has independent identically distributed random variable with $\mathcal{CN}(0,1)$, and x_u is the transmitted symbol where $\mathbb{E}\{|x_u|^2\}$ is normalized to 1. $\mathbf{w}_u$ is the beamforming vector with $\mathbb{E}\{\|\mathbf{w}_u\|^2\} = 1$, and n_u is the complex additive white Gaussian noise with zero mean and $\mathbb{E}\{|n_u|^2\} = 1$ at cell u.

The associated capacity of the user of cell u is calculated as

$$R_u = \mathbb{E}[\log_2(1 + \gamma_u)] \quad (2)$$

where γ_u is the instantaneous SINR of the user of cell u:

$$\gamma_u = \frac{P_{u,u}|\mathbf{h}_{u,u}^H\mathbf{w}_u|^2}{1 + \sum_{v=1;v\neq u}^{U} P_{u,v}|\mathbf{h}_{u,v}^H\mathbf{w}_u|^2} \quad (3)$$

The received power from serving and interfering BSs is calculated considering the following path loss model:

$$P_{u,v} = P_0\left(\frac{d_{u,v}}{R}\right)^{-\alpha} \quad (4)$$

where R is the radius of the cell, P_0 is the received power at the cell edge, α is the path loss exponent, and $d_{u,v}$ is the distance between user of cell u and BS v.

2.1 Transmission strategies

In this work, two classical transmission strategies are considered to design the beamforming vectors: 1) maximum ratio combining (MRC) beamforming and 2) partial zero forcing (PZF) beamforming [5].

1) MRC beamforming

The interference coming from other cells can be ignored since the user is far from the interfering BSs. Therefore, the precoding vector is designed according to the channel direction of the user itself. The precoding vector is determined by

$$\mathbf{w}_u = \frac{\mathbf{h}_{u,u}}{\|\mathbf{h}_{u,u}\|} \quad (5)$$

For MRC, the distribution of the received power is $|\mathbf{h}_{u,u}^H\mathbf{w}_u|^2 \sim \chi^2_{2N_t}$ where χ^2_n denotes the chi-squared random variable with n degrees of freedom.

2) PZF beamforming

Some degrees of freedom are used for ICI cancelation where $N_t \geq U$ by satisfying the orthogonality criterion $\mathbf{h}_{i,u}^H\mathbf{w}_u = 0$ for $\forall i, i \neq u$ and maximizing $|\mathbf{h}_{u,u}^H\mathbf{w}_u|^2$. This corresponds to select $\mathbf{w}_u$ in the direction of the projection of the channel vector, $\mathbf{h}_{u,u}$, on the nullspace of $\mathbf{V}_u = [\mathbf{h}_{u,1}, \mathbf{h}_{u,2}, \ldots, \mathbf{h}_{u,u-1}, \mathbf{h}_{u,u+1}, \mathbf{h}_{u,U}]$ with the size of $N_t \times (U-1)$.

Then, the precoding vector is determined by

$$\mathbf{w}_u = (\mathbf{I} - \mathbf{P})\mathbf{h}_{u,u} \quad (6)$$

where the projection matrix on $\mathbf{V}_u$ is $\mathbf{P} = \mathbf{V}_u(\mathbf{V}_u^H\mathbf{V}_u)^{-1}\mathbf{V}_u^H$.

For PZF precoding, the distribution of the received power is $|\mathbf{h}_{u,u}^H\mathbf{w}_u|^2 \sim \chi^2_{2(N_t-(U-1))}$.

For three-cell network coordination, each BS has three different strategies. For BS_1 as an example, these strategies are described as follows: 1) MRC beamforming, denoted by $t_1 = \text{MRC}$; 2) PZF beamforming for user 2 or user 3, denoted by $t_1 = \text{PZF}(2 \text{ or } 3)$; and 3) PZF beamforming for both user 2 and user 3, denoted by $t_1 = \text{PZF}(2,3)$. The same kind of transmission strategies can be defined both for BS_2 and BS_3.

Then, the strategy sets can be defined for BS_1, BS_2, and BS_3, respectively,

$$\mathcal{T}_1 = \{\text{MRC}, \text{PZF}(2 \text{ or } 3), \text{PZF}(2,3)\},$$
$$\mathcal{T}_2 = \{\text{MRC}, \text{PZF}(1 \text{ or } 3), \text{PZF}(1,3)\},$$
$$\mathcal{T}_3 = \{\text{MRC}, \text{PZF}(1 \text{ or } 2), \text{PZF}(1,2)\}.$$

The strategies taken by BSs are $(t_1, t_2, t_3) \in \mathcal{T}_1 \times \mathcal{T}_2 \times \mathcal{T}_3$. Therefore, there are 3^3 different triples to be considered to reach the optimum solution.

When the CSI of the serving and interfering BSs for each user is known perfectly at the serving BS and shared among interfering BSs through perfect backhaul link, the objective is to select the transmission strategies $t_i; i = 1, 2, 3$ to maximize the average multicell capacity as

$$(t_1^*, t_2^*, t_3^*) = \arg\max_{t_1 \in \mathcal{T}_1, t_2 \in \mathcal{T}_2, t_3 \in \mathcal{T}_3} R_1 + R_2 + R_3 \quad (7)$$

The average user capacity in cell u is given by

$$R_1(t_1, t_2, t_3)$$
$$= \mathbb{E}\left(\log_2\left(1 + \frac{P_0(d_{1,1}/R)^{-\alpha}Z}{1 + aP_0(d_{1,2}/R)^{-\alpha}Y + bP_0(d_{1,3}/R)^{-\alpha}Y}\right)\right) \quad (8)$$

where the distribution of Z and Y is $\chi^2_{N_t-m_1}$ and χ^2_1, respectively. The value of m_1 is changing depending on the transmission strategy implemented by BS_1. It is set to $m_1 = 0$ for MRC, $m_1 = 1$ for PZF(2or3) and $m_1 = 2$ for PZF(2,3). The value of a is equal to 0 if the strategy of PZF(1) or PZF(1,3) is chosen by BS_2; otherwise, a is equal to 1. Similarly, the value of b is equal to 0 if the strategy of PZF(1) or PZF(1,2) is chosen by BS_3 and else $b = 1$ when the strategy of MRC is employed.

Similarly, the average user capacity for cell 2 and cell 3 can be calculated for any transmission strategies as in Equation 8 by setting the parameters a, b and m_i. Then, the transmission set of $\left(t_1^*, t_2^*, t_3^*\right)$ which achieves the highest multicell capacity is chosen as an optimum solution of the problem defined in Equation 7.

2.2 Limited feedback link

When the CSI of the serving and interfering BSs for each user feeds back to the serving BS through a limited feedback link and shared among interfering BSs through perfect backhaul link, the objective is to select the bit partitioning to quantize CSI of the serving and interfering BSs for a given criterion. In this work, we assume that the channel direction information (CDI) is quantized using RVQ [20,21] before transmission over the limited feedback link. We also assume that each user has a perfect knowledge of the CSI belonging to serving and interfering BSs and the channel quality information (CQI) is perfectly available at all BSs. Then, the users only feed back their CDI to the serving BS associated to all these links after quantization using the codebook known by the users and the BSs. The quantized CDI required to perform PZF is exchanged between BSs using backhaul.

The CDI is obtained as

$$\mathbf{g}_{u,v} = \frac{\mathbf{h}_{u,v}}{\|\mathbf{h}_{u,v}\|} \quad \forall u, v \tag{9}$$

The codebook composed of N_t dimensional unit vectors is given by $\mathfrak{C}_{u,v} = \left\{\mathbf{c}^1_{u,v}, \mathbf{c}^2_{u,v}, \ldots, \mathbf{c}^{M_{u,v}}_{u,v}\right\}$ where $M_{u,v} = 2^{B_{u,v}}$ is the number of codewords and $B_{u,v}$ is the number of quantization bits.

By using the minimum chordal distance metric, the indices of quantized CDI are

$$n_{u,v} = \arg\min_{1 \le m \le M_{u,v}} 1 - \left|\left(\mathbf{c}^m_{u,v}\right)^H \mathbf{g}_{u,v}\right|^2 \quad \forall u, v \tag{10}$$

Then, the quantized CDI is obtained as

$$\hat{\mathbf{g}}_{u,v} = \mathbf{c}^{n_{u,v}}_{u,v} \quad \forall u, v \tag{11}$$

The expectation of the mismatch between the quantized and exact CDI over the channel realization is as follows[6]:

$$\mathbb{E}_{\mathbf{g},\mathbf{c}}[d^2(\mathbf{g}, \mathbf{c}^H)] = 2^{B_{u,v}} \beta\left(2^{B_{u,v}}, \frac{N_t}{N_t - 1}\right) < 2^{-\frac{B_{u,v}}{N_t - 1}} \tag{12}$$

When the CDI at the BS is obtained through limited feedback, the received power and interference power can be approximated as $\gamma_{u,u}Z$ and $\kappa_{u,v}Y$, respectively [9]. Then, the average user capacity defined for cell 1 in Equation 8 can be written for each cell under the quantized CDI as

$$R_u(B_{u,v})$$
$$= \mathbb{E}\left(\log_2\left(1 + \frac{P_0(d_{u,u}/R)^{-\alpha}\gamma_{u,u}Z}{1 + \sum_{v=1; v\neq u}^{U} P_0(d_{u,v}/R)^{-\alpha}\kappa_{u,v}Y}\right)\right) \tag{13}$$

where $\gamma_{u,u} = 1 - 2^{-\frac{B_{u,u}}{N_t-1}}; \forall u$ is the mismatch coefficient for a given $B_{u,u}$ which is the number of quantization bits for the serving BS and $\kappa_{u,v} = 2^{-\frac{B_{u,v}}{N_t-1}}; v \neq u$ is the quantization error coefficient for a given $B_{u,v}; v \neq u$ which is the number of quantization bits for interfering BSs.

3 The limited feedback design at fixed rate

In this section, our objective is to select the bit partitioning among the serving and interfering BSs to maximize the average multicell capacity under the constraint that the number of total feedback bits to quantize serving and interfering BSs is fixed for each user.

For a given position, $d_{u,u}$, the optimization problem is given by

$$\max_{B_{u,v}} R_T =$$
$$\max_{B_{u,v}} \sum_{u=1}^{U} \mathbb{E}\left(\log_2\left(1 + \frac{P_0(d_{u,u}/R)^{-\alpha}\gamma_{u,u}Z}{1 + P_0 \sum_{v=1; v\neq u}^{U} (d_{u,v}/R)^{-\alpha}\kappa_{u,v}Y}\right)\right) \tag{14}$$

The constraints are

$$\sum_{v=1}^{U} B_{u,v} = B_{\max}, \quad \forall u \tag{15}$$
$$B_{u,v} \ge 0, \quad \forall v, u; u \neq v$$
$$B_{u,u} > 0, \quad \forall u$$

In the multicell network, the cell area can be divided into two regions: 1) the non-cooperative region (NCR) that corresponds to the center of the cell and 2) the cooperative region (CR) that corresponds to the edge of the cell. If the user is in the NCR, MRC beamforming is performed

by the other BSs and the number of quantization bits of interfering BSs, $B_{u,v}$, is selected as zero. Otherwise, PZF beamforming is applied by all neighborhood cells or one of the neighborhood cell depending on the location of this user. In this case, the number of bits, $B_{u,v}$ is selected as higher than zero. Therefore, the selection of the number of quantization bits is also corresponding to the selection of transmission strategies.

The regions can be determined according to the power in the cell edge and the total number of quantization bits. For example, if the power in the cell edge is quite high for a given transmitter power and cell radius, only CR regions can be constructed for three-cell networks.

3.1 The proposed adaptive limited feedback to maximize multicell capacity

We consider the bit partitioning problem in Equation 14 for the high-SINR region where $\log_2(1 + x) \approx \log_2(x)$ by performing either MRC and/or PZF beamforming to satisfy this condition. Then, we have

$$R_T^h = \sum_{u=1}^{U} \mathbb{E}\left(\log_2\left(\frac{P_0(d_{u,u}/R)^{-\alpha}\gamma_{u,u}Z}{1 + P_0 \sum_{v=1;v\neq u}^{U}(d_{u,v}/R)^{-\alpha}\kappa_{u,v}Y}\right)\right) \quad (16)$$

where $R_T^h \approx R_T$ at the high-SINR region.

By applying Jensen's inequality, we obtain the upper bound for R_T^h as

$$R_T^h \leq \sum_{u=1}^{U} \log_2\left(\mathbb{E}\left(\frac{P_0(d_{u,u}/R)^{-\alpha}\gamma_{u,u}Z}{1 + P_0 \sum_{v=1;v\neq u}^{U}(d_{u,v}/R)^{-\alpha}\kappa_{u,v}Y}\right)\right) \quad (17)$$

Since Y and Z are independently distributed random variables, it can be rewritten as

$$R_T^h \leq \sum_{u=1}^{U} \log_2\left[\mathbb{E}\left(P_0(d_{u,u}/R)^{-\alpha}\gamma_{u,u}Z\right)\right.$$
$$\left.\times \mathbb{E}\left(\frac{1}{1 + P_0 \sum_{v=1;v\neq u}^{U}(d_{u,v}/R)^{-\alpha}\kappa_{u,v}Y}\right)\right] \quad (18)$$

With the definition of $c = P_0 \sum_{v=1;v\neq u}^{U}(d_{u,v}/R)^{-\alpha}\kappa_{u,v}$ which is an interference term, the second term written as $\frac{1}{1+cY}$ can be expressed by $\sum_{n=0}^{\infty}(-1)^n(cY)^n = 1 - cY + (cY)^2 - (cY)^3 + \dots$ By holding the assumption that $\kappa_{u,v}$ are sufficiently small by allocating enough bits for CSI of interfering BSs, we set $\frac{1}{1+cY} \approx 1 - cY$.

Then, Equation 17 can be re-expressed as

$$R_T^h \leq \sum_{u=1}^{U} \log_2\left[\left(P_0(d_{u,u}/R)^{-\alpha}\gamma_{u,u}\right)\right.$$
$$\left.\times \mathbb{E}(Z)\left(1 - \left(P_0 \sum_{v=1;v\neq u}^{U}(d_{u,v}/R)^{-\alpha}\kappa_{u,v}\right)\mathbb{E}(Y)\right)\right] \quad (19)$$

Replacing $\mathbb{E}[Z] = (N_t - m_u)$ and $\mathbb{E}[Y] = 1$ and using Equation 12, R_T^h can be rewritten as

$$R_T^h = \sum_{u=1}^{U} R_u^h \leq \sum_{u=1}^{U}\left(\log_2\left(P_0(d_{u,u}/R)^{-\alpha}\right) + \log_2\left(1 - 2^{-\frac{B_{u,u}}{N_t-1}}\right)\right.$$
$$+ \log_2(N_t - m_u)$$
$$+ \log_2\left(1 - P_0 \sum_{v=1;v\neq u}^{U}(d_{u,v}/R)^{-\alpha}2^{-\frac{B_{u,v}}{N_t-1}}\right)$$
$$\left.+ \log_2(N_t)\right) \quad (20)$$

Since it is very complex to solve the optimization problem given in Equation 20, we propose to maximize R_u^h at each cell separately.

In a three-cell network, the optimization problem for a user in cell 1 is written as follows:

$$\max_{B_{1,1},B_{1,2},B_{1,3}} R_1^h = \log_2\left(P_0(d_{1,1}/R)^{-\alpha}\right) + \log_2\left(1 - 2^{-\frac{B_{1,1}}{N_t-1}}\right)$$
$$+ \log_2(N_t - m_1)$$
$$+ \log_2\left(1 - P_{1,2}2^{-\frac{B_{1,2}}{N_t-1}} - P_{1,3}2^{-\frac{B_{1,3}}{N_t-1}}\right) \quad (21)$$

where $P_{1,2} = P_0(d_{1,2}/R)^{-\alpha}$ and $P_{1,3} = P_0(d_{1,3}/R)^{-\alpha}$.

Since $d_{1,1}$ and m_1 do not depend on $B_{1,1}$, $B_{1,2}$, and $B_{1,3}$, we can express the optimization problem as

$$\max_{B_{1,1},B_{1,2},B_{1,3}} R_1^h = \log_2\left(1 - 2^{-\frac{B_{1,1}}{N_t-1}}\right)$$
$$+ \log_2\left(1 - P_{1,2}2^{-\frac{B_{1,2}}{N_t-1}} - P_{1,3}2^{-\frac{B_{1,3}}{N_t-1}}\right) \quad (22)$$

subject to

$$B_{1,1} + B_{1,2} + B_{1,3} = B_{\max} \quad (23)$$
$$B_{1,1} > 0$$
$$B_{1,2} \geq 0$$
$$B_{1,3} \geq 0$$

The values of $B_{1,1}$, $B_{1,2}$, and $B_{1,3}$ that maximize the bound of capacity of cell 1 are obtained by using the method of Lagrange multipliers which is one of the classical approach for solving constrained optimization problems.

$$L(B_{1,1}, B_{1,2}, B_{1,3}, \lambda) = R_1^h + \lambda(B_{1,1} + B_{1,2} + B_{1,3} - B_{\max})$$

Then, we have

$$\frac{\partial L}{\partial B_{1,1}} = \frac{1}{(N_t - 1)} \frac{2^{-B_{1,1}/(N_t-1)}}{\left[1 - 2^{-B_{1,1}/(N_t-1)}\right]} + \lambda = 0$$

$$\frac{\partial L}{\partial B_{1,2}} =$$
$$\frac{1}{(N_t - 1)} \frac{P_{1,2}2^{-B_{1,2}/(N_t-1)}}{\left[1 - P_{1,2}2^{-B_{1,2}/(N_t-1)} - P_{1,3}2^{-B_{1,3}/(N_t-1)}\right]} + \lambda = 0$$

$$\frac{\partial L}{\partial B_{1,3}} =$$
$$\frac{1}{(N_t - 1)} \frac{P_{1,3}2^{-B_{1,3}/(N_t-1)}}{\left[1 - P_{1,2}2^{-B_{1,2}/(N_t-1)} - P_{1,3}2^{-B_{1,3}/(N_t-1)}\right]} + \lambda = 0$$

$$(24)$$

By solving the equations, we obtain

$$B_{1,1} = -(N_t - 1)\log_2\left(\frac{-\lambda(N_t - 1)}{1 - \lambda(N_t - 1)}\right) \qquad (25)$$

$$B_{1,2} = -(N_t - 1)\log_2\left(\frac{-\lambda(N_t - 1)}{P_{1,2}(1 - 2\lambda(N_t - 1))}\right)$$

$$B_{1,3} = -(N_t - 1)\log_2\left(\frac{-\lambda(N_t - 1)}{P_{1,3}(1 - 2\lambda(N_t - 1))}\right)$$

For a given $B_{\max}$ and N_t, λ can be calculated at any location of the user in the cell by solving the following equation:

$$\frac{-(\lambda(N_t - 1))^3}{(1 - \lambda(N_t - 1))(1 - 2\lambda(N_t - 1))^2} = P_{1,2}P_{1,3}2^{-\frac{B_{\max}}{(N_t-1)}}$$

$$(26)$$

Then, since the obtained values $B_{1,1}$, $B_{1,2}$, and $B_{1,3}$ are positive real numbers, a round operation is applied to get integer values for codebook design.

In order to calculate the number of bits for serving and interfering CDI for BS_2 and BS_3, the same derivation can be obtained for cell 2 and cell 3 separately as in Equation 25.

4 The limited feedback design at adaptive rate

Compared to the previous section where the number of feedback bits per user is fixed, in this section, we relax this constraint by fixing an average number of feedbacks bits per cell. By focusing on each cell separately, our objective is to select the bit partitioning among the serving and interfering BSs to maximize the average cell-edge user capacity under the constraint that the number of

total feedback bits is averagely fixed in each cell. The solution for the Wyner model including only two cells has been examined in [22]. In this paper, we propose an adaptive bit partitioning solution for a multicell network to improve average cell-edge user capacity by allocating more quantization bits in the cell-edge users.

By defining a normalized threshold distance between the BS and user as d_{th}, we determine NCR and CR as illustrated in Figure 2. The NCR, K^X, is the region for which the normalized distance $d_{u,u}/R$ is between 0 and d_{th}, while the CR, K^Y, is the region for which the normalized distance $d_{u,u}/R$ is from d_{th} and 1.

If the user is situated in the region K^X, the average capacity is calculated as

$$R_u^X = \mathbb{E}\left(\log_2\left(1 + \frac{P_0(d_{u,u}/R)^{-\alpha}\gamma'_{u,u}Z}{1 + \sum_{v=1;v\neq u}^{U} P_0(d_{u,v}/R)^{-\alpha}Y}\right)\right)$$

$$(27)$$

where $\gamma'_{u,u} = 1 - 2^{-B'_{u,u}/(N_t-1)}$ with $B'_{u,u}$ is the number of bits to quantize CDI of the serving BS when the user is in the NCR where interference cancelation is not performed and bit allocation to quantize CDI of interfering BSs is not required.

If the user is situated in the region K^Y, the average capacity is calculated as

$$R_u^Y = \mathbb{E}\left(\log_2\left(1 + \frac{P_0(d_{u,u}/R)^{-\alpha}\gamma''_{u,u}Z}{1 + \sum_{v=1;v\neq u}^{U} P_0(d_{u,v}/R)^{-\alpha}\kappa''_{u,v}Y}\right)\right)$$
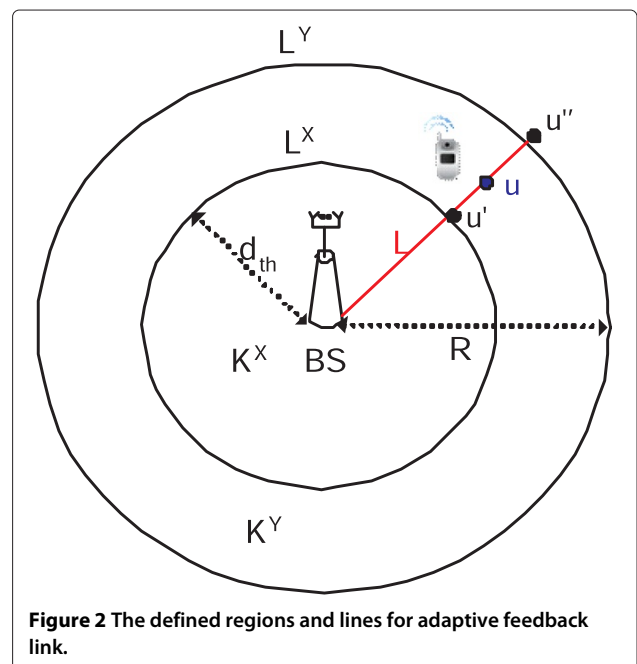
$$(28)$$

Figure 2 The defined regions and lines for adaptive feedback link.

where $\gamma''_{u,u} = 1 - 2^{-B''_{u,u}/(N_t-1)}$ with $B''_{u,u}$ is the number of bits to quantize CDI of the serving BS and $\kappa''_{u,v} = 2^{-B''_{v,u}/(N_t-1)}$ with $B''_{v,u}; v \neq u$ is the number of bits to quantize CDI of interfering BSs when the user is in the CR.

We define one circle L^X of radius d_{th} associated to region K^X and another circle of L^Y of radius 1 associated to region K^Y.

The average capacity of a user u' situated on the circle L^X is

$$R_{u'} = \mathbb{E}\left[\log_2\left(1 + \frac{P_0 d_{th}^{-\alpha} \gamma'_{u,u} Z}{1 + \sum_{v=1; v\neq u}^{U} P'_{u,v} Y}\right)\right] \quad (29)$$

where $P'_{u,v} = P_0(d_{u',v}/R)$.

The average capacity of the user u'' situated on the circle L^Y is

$$R_{u''} = \mathbb{E}\left[\log_2\left(1 + \frac{P_0 \gamma''_{u,u} Z}{1 + \sum_{v=1; v\neq u}^{U} P''_{u,v} \kappa''_{u,v} Y}\right)\right] \quad (30)$$

where $P''_{u,v} = P_0(d_{u'',v}/R)$.

4.1 The proposed bit partitioning for cell-edge users

Our criterion is based on the maximization of sum capacity of the users located on the circles L^X and L^Y to improve the capacity of users in the cell-edge region under the constraint that the average number of feedback bits within each cell is fixed. For an arbitrary user u, we draw a line L crossing the position of the associated BS and the position of considering user as shown in Figure 2. As a result, we then introduce two virtual users u' and u'' located at the intersection of the line L with circles L^X and L^Y, respectively. Any user can be situated either L_X or L_Y depending on its location in the cell. Since our target is to maximize the overall capacity, we apply a bit allocation to maximize rates at these representative circles.

Then, the determination of the bit partitioning for any user u situated on a line L can be described according to the following optimization problem:

$$\max_{B'_{u,u}, B''_{u,u}, B''_{u,v}} R_u^W = R_{u'} + R_{u''} \quad (31)$$

The constraints are

$$k_1 B'_{u,u} + k_2\left(B''_{u,u} + \sum_{v=1; v\neq u}^{U} B''_{u,v}\right) = B_{avg}$$
$$B'_{u,u} > 0; \forall u$$
$$B''_{u,v} > 0; \forall u, v \quad (32)$$

where $k_1 = d_{th}^2$ and $k_2 = (1 - d_{th}^2)$.

The first constraint means that the average number of feedback bits in the cell remains fixed in multicell networks. The remaining constraints imply that CDI for each serving and interfering BSs is quantized by using at least one bit.

In a three-cell network, the optimization problem for the user in cell 1 can be solved in the following:

$$R_1^W = \mathbb{E}\log_2\left(1 + \frac{\gamma'_{1,1} P_0 d_{th}^{-\alpha} Z}{1 + (P'_{1,2} + P'_{1,3}) Y}\right)$$
$$+ \mathbb{E}\log_2\left(1 + \frac{\gamma''_{1,1} P_0 Z}{1 + (\kappa''_{1,2} P''_{1,2} + \kappa''_{1,3} P''_{1,3}) Y}\right) \quad (33)$$

For high SINR values where $\log_2(1 + x) \approx \log_2(x)$, we have

$$R_1^{Wh} = \mathbb{E}\log_2\left(\frac{\gamma'_{1,1} P_0 d_{th}^{-\alpha} Z}{1 + (P'_{1,2} + P'_{1,3}) Y}\right)$$
$$+ \mathbb{E}\log_2\left(\frac{\gamma''_{1,1} P_0 Z}{1 + (\kappa''_{1,2} P''_{1,2} + \kappa''_{1,3} P''_{1,3}) Y}\right) \quad (34)$$

where R_1^{Wh} is the rate belonging to cell 1 at high SINR values.

Then, by applying Jensen's inequality, we obtain the upper bound for R_1^{Wh} as

$$R_1^{Wh} \leq \log_2 \mathbb{E}\left(\frac{\gamma'_{1,1} P_0 d_{th}^{-\alpha} Z}{1 + (P'_{1,2} + P'_{1,3}) Y}\right)$$
$$+ \log_2 \mathbb{E}\left(\frac{\gamma''_{1,1} P_0 Z}{1 + (\kappa''_{1,2} P''_{1,2} + \kappa''_{1,3} P''_{1,3}) Y}\right) \quad (35)$$

Using the same approach described in the previous section, we can rewrite Equation 35 as

$$R_1^{Wh} \leq \log_2(\gamma'_{1,1}) + \log_2(P_0 d_{th}^{-\alpha}) + \log_2(\mathbb{E}[Z])$$
$$+ \log_2(1 - (P'_{1,2} + P'_{1,3}) \mathbb{E}[Y])$$
$$+ \log_2(\gamma''_{1,1}) + \log_2(P_0 \mathbb{E}[Z])$$
$$+ \log_2(1 - (P''_{1,2} \kappa''_{1,2} + P''_{1,3} \kappa''_{1,3}) \mathbb{E}[Y]) \quad (36)$$

By suppressing the terms which are independent from the variables $B'_{1,1}, B''_{1,1}, B''_{1,2}$, and $B''_{1,3}$ and writing $\mathbb{E}[Y] = 1$, we have

$$R_1^{Wh} = \log_2\left(1 - 2^{-\frac{B'_{1,1}}{N_t-1}}\right) + \log_2\left(1 - 2^{-\frac{B''_{1,1}}{N_t-1}}\right)$$
$$+ \log_2\left(1 - P''_{1,2} 2^{-\frac{B''_{1,2}}{N_t-1}} - P''_{1,3} 2^{-\frac{B''_{1,3}}{N_t-1}}\right) \quad (37)$$

Then, the values of $B'_{1,1}$, $B''_{1,1}$, $B''_{1,2}$, and $B''_{1,3}$ that maximize Equation 37 are obtained using Lagrange multipliers.

$$L\left(B'_{1,1}, B''_{1,1}, B''_{1,2}, B''_{1,3}, \lambda\right) = R_1^{Wh} + \lambda k_1 B'_{1,1}$$
$$+ \lambda k_2\left(B''_{1,1} + B''_{1,2} + B''_{1,3}\right) - \lambda B_{\text{avg}}$$

(38)

Then, we have

$$\frac{\partial L}{\partial B'_{1,1}} = \frac{1}{(N_t - 1)} \frac{2^{-B'_{1,1}/(N_t-1)}}{\left[1 - 2^{-B'_{1,1}/(N_t-1)}\right]} + \lambda k_1 = 0$$

$$\frac{\partial L}{\partial B''_{1,1}} = \frac{1}{(N_t - 1)} \frac{2^{-B''_{1,1}/(N_t-1)}}{\left[1 - 2^{-B''_{1,1}/(N_t-1)}\right]} + \lambda k_2 = 0$$

$$\frac{\partial L}{\partial B''_{1,2}} =$$

$$\frac{P''_{1,2}}{(N_t - 1)} \frac{2^{-B''_{1,2}/(N_t-1)}}{\left[1 - P''_{1,2} 2^{-B''_{1,2}/(N_t-1)} - P''_{1,3} 2^{-B''_{1,3}/(N_t-1)}\right]} + \lambda k_2 = 0$$

$$\frac{\partial L}{\partial B''_{1,3}} =$$

$$\frac{P''_{1,3}}{(N_t - 1)} \frac{2^{-B''_{1,3}/(N_t-1)}}{\left[1 - P''_{1,2} 2^{-B''_{1,2}/(N_t-1)} - P''_{1,3} 2^{-B''_{1,3}/(N_t-1)}\right]} + \lambda k_2 = 0$$

(39)

By solving the equations, we obtain

$$B'_{1,1} = -A \log_2\left(\frac{-\lambda k_1 A}{1 - \lambda k_1 A}\right)$$ (40)

$$B''_{1,1} = -A \log_2\left(\frac{-\lambda k_2 A}{1 - \lambda k_2 A}\right)$$

$$B''_{1,2} = -A \log_2\left(\frac{-\lambda k_2 A}{P''_{1,2}(1 - 2\lambda k_2 A)}\right)$$

$$B''_{1,3} = -A \log_2\left(\frac{-\lambda k_2 A}{P''_{1,3}(1 - 2\lambda k_2 A)}\right)$$

where $A = (N_t - 1)$.

λ can be calculated for a given d_{th}, P_0, B_{avg}, and N_t by solving the following equation:

$$\left(\frac{-\lambda k_1 A}{1 - \lambda k_1 A}\right)^{k_1/k_2} \left(\frac{(-\lambda k_2 A)^3}{(1 - \lambda k_2 A)(1 - 2\lambda k_2 A)^2}\right) = P''_{1,2} P''_{1,3} 2^{-\frac{B_{\text{avg}}}{k_2 A}}$$

Since these bit partitioning values are positive real numbers, a round operation is performed to obtain integer values for codebook design.

While the proposed bit partitioning computes $B'_{1,1}$, $B''_{1,2}$, $B''_{1,3}$, and $B''_{1,1}$, depending on the position of the user, only some of these values will be used to quantize the CDI. If the user is in the NCR, $B'_{1,1}$ bits are allocated to quantize

the CDI of the serving BS. When the user is in the CR, $B''_{1,2}$, $B''_{1,3}$, and $B''_{1,1}$ bits are allocated to quantize the CDI of interfering BSs and serving BS, respectively. In practice, the bit partitioning can be precalculated for each user's position and a lookup table can be used to select the number of quantization bits depending on the position of the user.

5 Performance results

We illustrate the performance results to show the benefits of the proposed strategies in cooperative multicell networks. For the simulations, the parameters are chosen as $N_t = 4$, $R = 1$ km, and $\alpha = 3.7$. The performance results of the proposed bit partitioning schemes are compared with the performance of equal sharing PZF (PZF-EQ), MRC beamforming, and the bit partitioning algorithm in [12]. The PZF-EQ beamforming shares the quantized bits among serving and interfering BSs equally and always performs ICI, while MRC beamforming allocates all bits to quantize CQI of the serving BS and does not perform ICI. The bit partitioning for PZF-EQ and MRC is chosen respectively as $B_{u,u} = B_{u,v} = B_{\text{max}}/3; u, v = 1, 2, 3$ and $B_{u,u} = B_{\text{max}}; u = 1, 2, 3$ and $B_{u,v} = 0; u \neq v$; $u, v = 1, 2, 3$.

5.1 Fixed rate limited feedback channel

In order to verify the feasibility of the fixed rate limited feedback link, we compare the distribution of capacity values of the proposed solution given in Equation 21 to the optimum solution defined in Equation 14 which is obtained by searching the best in all combination of bit partitioning. According to average multicell capacity results illustrated in Figure 3, the proposed bit partitioning solution gives quite good approximation
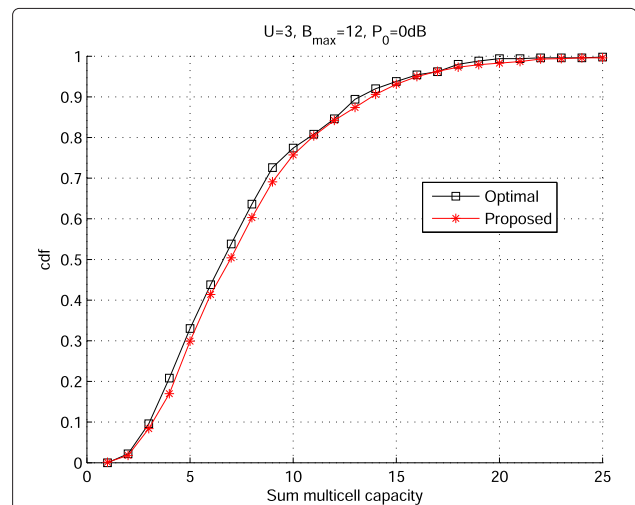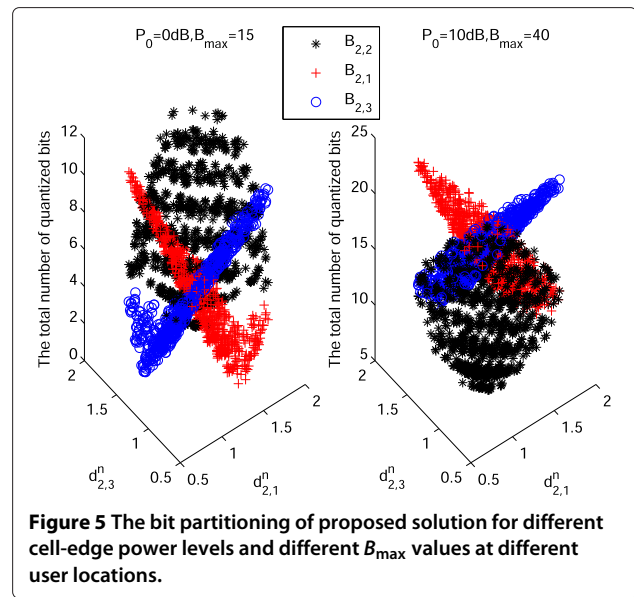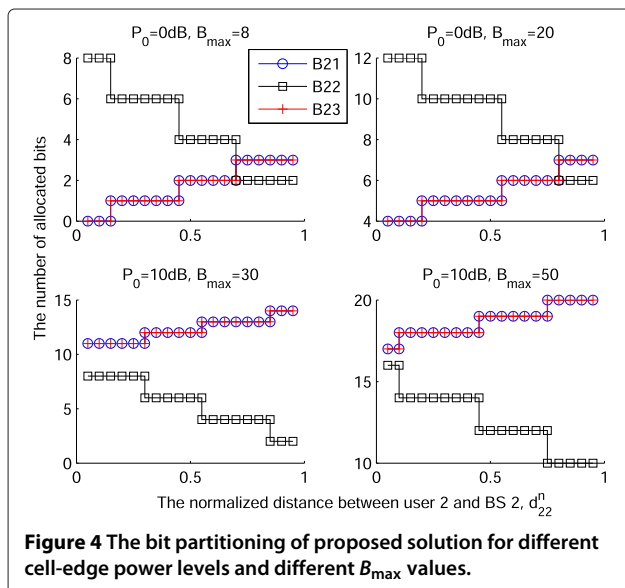

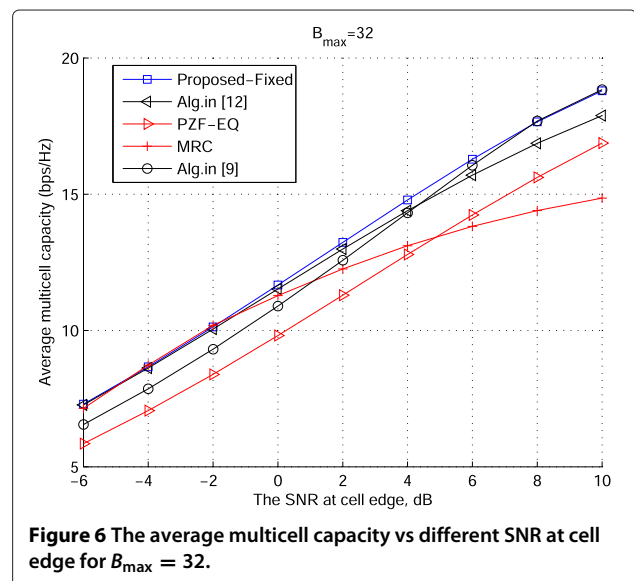**Figure 3 The comparison results of multicell capacity for the optimum and the proposed solution.**

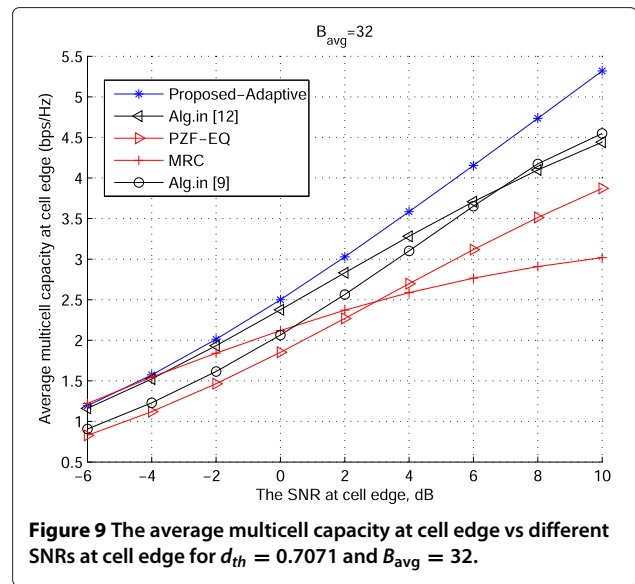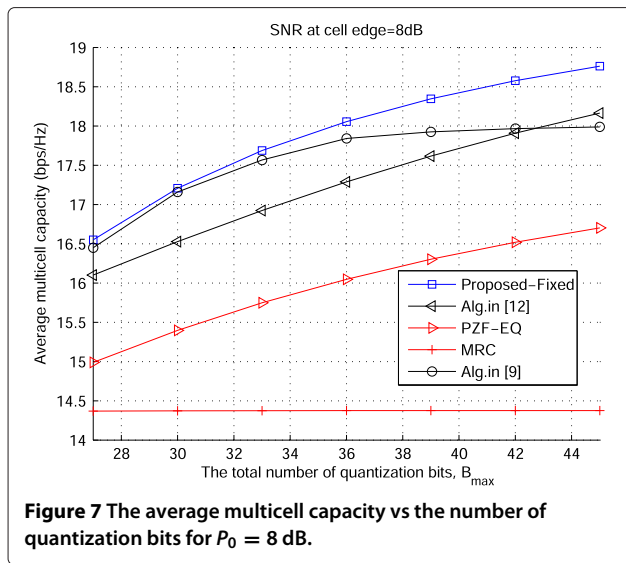to the optimum solution while having much lower complexity.

Firstly, the number of quantization bits, $B_{u,v}$, determined by the proposed bit partitioning is illustrated in Figure 4, where the user location is changing only through the x-axis and the distance between the user and the interfering BSs are equal, and Figure 5, where the user location is changing both in the x-axis and y-axis, and consequently, the distance between the user and the interfering BSs are not the same. As shown in the figures, the CR and NCR are determined according to the power levels at cell edge and the total number of bits available for quantization. When both the power at cell edges and the number of bits are low, the NCR is large compared to CR. However, when the number of quantization bits is increased even if the power at the cell edge is low, the CR becomes larger. For the high power values at cell edge, there is no NCR anymore since the interference is quite high and must be eliminated. Besides, depending on the user location at the cell, the bit partitioning on the interfering BSs is also changed such as when the user is getting far from BS_1, then the number of quantization bits to cancel interference caused by BS_1 is also decreased.

The average multicell capacity is illustrated for different power levels at the cell edge for $B_{max} = 32$ in Figure 6. According to the performance results, when the cell-edge power is high and ICI cancelation is required, the multicell capacity of the proposed partitioning is quite high compared to PZF-EQ, while MRC beamforming gives very poor performance. When the cell-edge power is low and depending on the location of the users in the cell, either MRC or PZF beamforming can be

Figure 5 The bit partitioning of proposed solution for different cell-edge power levels and different B_{max} values at different user locations.

applied at the BSs, the proposed fixed bit partitioning achieves higher performance than MRC beamforming, while PZF-EQ has quite poor performance. The average multicell capacity for different total numbers of quantization bits per user for $P_0 = 8$ dB is illustrated in Figure 7. It is shown that the proposed fixed bit partitioning scheme outperforms both MRC and PZF-EQ beamforming strategies. Furthermore, the performance gain increases when the interference power coming from other cells increases. As illustrated in Figures 6 and 7, the proposed fixed bit partitioning outperforms the algorithm in [9] when the number of quantization bits increases and gives better performance than the algorithm in [12]

Figure 4 The bit partitioning of proposed solution for different cell-edge power levels and different B_{max} values.

Figure 6 The average multicell capacity vs different SNR at cell edge for $B_{max} = 32$.

Figure 7 The average multicell capacity vs the number of quantization bits for $P_0 = 8$ dB.

Figure 9 The average multicell capacity at cell edge vs different SNRs at cell edge for $d_{th} = 0.7071$ and $B_{avg} = 32$.

for higher cell-edge power levels and any number of quantization bits.

As a result, the superiority of the proposed fixed bit partitioning through the limited feedback link which adjusts the number of the quantization bits for serving and interfering BSs adaptively to maximize multicell capacity by taking into account the distance between the user itself and BSs has been demonstrated for any cell-edge power level and any number of total feedback bits per user.
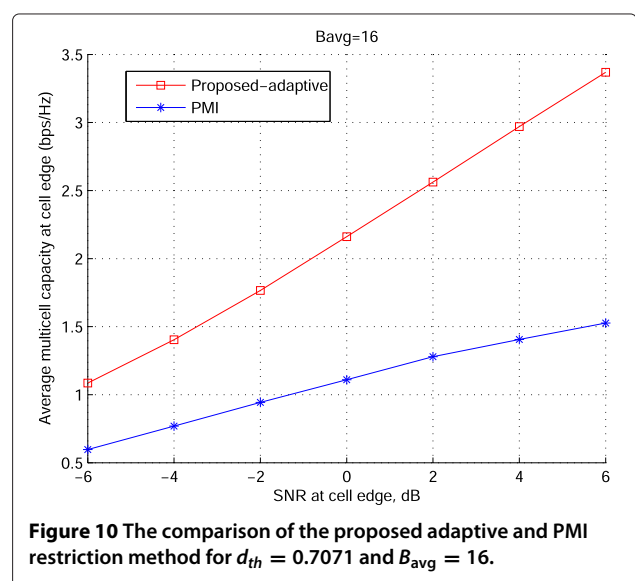
5.2 Adaptive rate limited feedback channel
The cell-edge capacity for different numbers of quantization bits is drawn in Figure 8 for $d_{th} = 0.7071$ where the users are equally distributed in the NRC and CR in the cell.
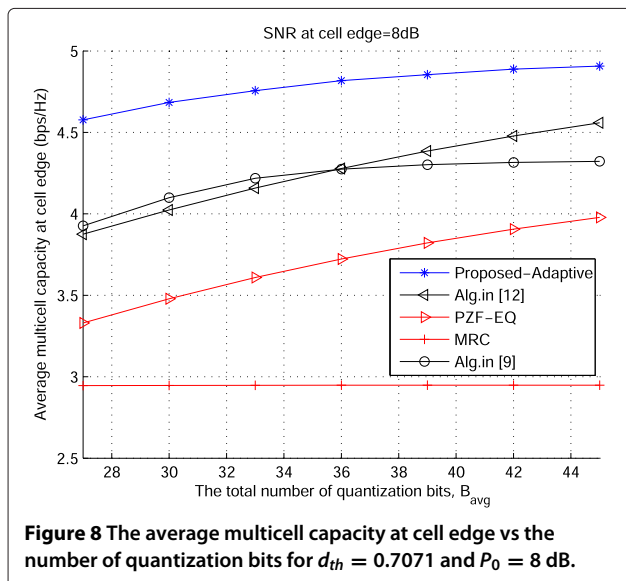
The proposed adaptive algorithm improves the capacity of the users at the cell edge significantly compared to PZF-EQ while keeping the same average feedback load. In Figure 9, the multicell capacity at cell edge is drawn for different cell-edge power levels for $B_{avg} = 32$, and it is verified that the proposed scheme achieves much higher gain compared to the PZF-EQ scheme when the interference power increases. It is also demonstrated that the proposed adaptive bit partitioning algorithm has better cell-edge capacity performance than the algorithms presented in [9] and [12].

Furthermore, the performance of the proposed bit partitioning is compared with the PMI restriction scheme for $d_{th} = 0.7071$ and $B_{avg} = 16$. In order to obtain the same

Figure 8 The average multicell capacity at cell edge vs the number of quantization bits for $d_{th} = 0.7071$ and $P_0 = 8$ dB.

Figure 10 The comparison of the proposed adaptive and PMI restriction method for $d_{th} = 0.7071$ and $B_{avg} = 16$.

average feedback link, the number of quantization bits is chosen as $B'_{u,u} = B_{u,u} = B_{u,v} = 8; u, v = 1, 2, 3$ for the PMI restriction method. According to Monte Carlo simulation results shown in Figure 10, the proposed bit partitioning scheme outperforms the PMI restriction method especially at high power levels for the same feedback load.

6 Conclusions

In this paper, we have considered intercell interference cancelation strategies in cooperative downlink multicell systems with limited feedback link. With the usage of the proposed bit partitioning, the bit partitioning at each cell is chosen adaptively based on the received power of the user to improve the average multicell capacity. We have also focused on the cell-edge capacity rather than the average multicell capacity. The cell-edge capacity has been improved by quantizing the channel state information of serving and interfering BSs for the users in the CR precisely to reduce the interference effect due to the other cells. The analytical derivations have been presented for the proposed bit partitioning scheme under the constraint that the average feedback rate is constant. It has been illustrated that the proposed strategy improves the cell-edge users' capacity significantly and achieves better performance than the PMI restriction scheme at the cell-edge region while keeping the same feedback rate.

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