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Downlink performance of cell edge using cooperative BS for multicell cellular network

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Abstract

We consider the downlink of a multicell system comprised of base stations (BSs) and user terminals equipped with multiple antennas respectively on the condition that arbitrary BS cooperation and distance dependent propagation path loss are assumed. In this paper, we consider homogeneous networks for the rectangular coordinates and show the cell edge performance of cellular networks based on distance from their cell center, i.e., BS. We focus on the downlink capacity of edge users in the cellular networks and show that BS cooperation can improve the spectral efficiency. The BSs cooperate for their transmission to the cell edge users in order to improve their signal-to-interference-plus-noise ratio (SINR) for inter-cell interference (ICI) cancelation in downlink multicell systems. When fractional frequency reuse (FFR) is applied to the cell edge, it is conjectured that BS cooperation, or a coordinated multipoint (CoMP), will further improve the system performance. Simulation results show that the proposed scheme outperforms the reference schemes in terms of the cell edge SINR with a minimal impact on the path loss exponent in the networks.

Keywords: Multicell MIMO, Power constraint, Cell edge channel capacity, Inter-cell interference, Fractional frequency reuse

1 Introduction

In conventional cellular networks, a major degrading factor affecting the system performance is inter-cell interference (ICI). This is caused by neighboring cells using the same frequency band. The ICI can cause significant performance loss at user (mobile station (MS)) terminals, especially, at cell edge users located in the vicinity of cell boundaries. Various techniques have been recommended to mitigate ICI [1, 2]. Users close to the base station (BS) typically have a high mean signal-to-interference-plus-noise ratio (SINR), whereas, the users at cell intersections suffer from low SINR levels. Multi-input multi-output (MIMO) has emerged as a key method to achieve high spectrum and power efficiency in mobile communication [3, 4]. Though the capacity region of MIMO broadcast channel (BC) is an unsolved problem for lack of a general theory on non-degraded broadcast channels, an achievable region for MIMO broadcast channel was obtained by applying the dirty paper coding (DPC) [5] at the transmitter [6–8] which established the duality of achievable region and the capacity region of the MIMO. This makes the solution of sum capacity of MIMO BC possible, since the solution of sum capacity of MIMO BC is in general a non-convex optimization, while MIMO multiple access channel can be solved by convex optimization. In this paper, we consider a multicell network, where primary cell edge users suffer severe ICI due to their location on the cell boundary. As a solution, we explore the problem of ICI mitigation on the primary cell edge users by deploying cells at the borders of adjacent primary cells to serve primary cell edge users. The cell edge problem of this system is addressed. In [9–11], it is shown that with the optimal power control, such BS cooperation eliminates the inter-cell interference penalty. In other words, a network of interfering cells has the same per-cell capacity as a single, isolated cell.

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In order to further reduce the complexity of the joint cooperation and coordination strategies, the emerging distributed solutions to the intriguing multicell capacity maximization problem have drawn more and more attention, with only local information achievable [12–14]. Typically, the frequency reuse factor is much less than unity, so that the level of co-channel interference is low. Thus, interference is controlled by fixing the frequency reuse pattern and the maximum power spectral density levels of each base station. We analyze the cooperation scenario in a multicell environment where the other cell interference is significant. The capacity achieved through cooperation is shared equally among the cell edge users, i.e., resources are shared fairly among the cooperating users. The transmission rate to each user is determined based on the SINR. Cooperative transmission by three BSs can improve this SINR by transmitting jointly to one user at a time.

A recent study on the fractional frequency reuse (FFR) scheme with the BS cooperation/coordinated multipoint (CoMP) [15, 16] applies CoMP with BS joint transmission in FFR cell edge only for multiuser diversity, leaving the FFR cell center region not in cooperation [17, 18]. In [15], the authors analyze a cluster of three-cell cooperative MIMO base station with FFR scheme, showing that the scheme via antenna rearrangement can improve the spectral efficiency. Inter-cell interference coordination (ICIC) scheme that makes use of inter-cell coordination is investigated in a multicell environment with aggressive frequency reuse. In the recent years, the FFR scheme has attracted the attention of the researchers in different standardization bodies and forums. The behind FFR lies in the fact that mobile stations (MSs) in the central area of a cell are more robust against interference due to low path loss and hence they can tolerate higher reuse compared to those at the cell border suffering from high interference as well as high path losses [19, 20]. Therefore, it makes sense to use different degrees of reuse factor for MSs in the cell center and cell edge areas. A common example of FFR for a network with base BSs is a blend of reuse factor of 1, 3, and 7 in the cell center and cell edge areas, respectively. The performance of this scheme is compared with that of some reference schemes, for example, reuse of one, reuse of three, and reuse of seven schemes [21, 22]. Reuse 1 scheme represents the no coordination case, and the other two represent cases where coordination is used in a static manner. The main contributions of this paper are summarized as follows:

- ➢ We consider a new multicell structure for the downlink system. Multicell downlink is a cooperative technology which coordinates multiple separated cells. It improves the performance of cell edge for ICI cancelation in BS cooperative downlink systems.
- ➢ It is well known that a major drawback of this system is having strong interference since users located at cell edges may experience much interference from signal transmitted in adjacent cells.
- ➢ We try to quantify the cell edge performance of cellular systems with and without ICI according to the distance from their cell center.
- ➢ We consider 19 cells composed of two tiers. MSs in the cell edge determined by the polar and rectangular coordinates experience the interference.
- ➢ We note that at a path loss exponent of 3.6, we observe an approximately 13-dB improvement in cell edge SINR by using reuse of three relative to reuse of one based on FFR. A reuse of seven increases cell edge SINR by 8 dB.

The rest of this paper is organized as follows. The system model is described in Section 2. In Section 3, we discuss multicell cooperation scheme. In Section 4, we address inter-cell interference technique control. In Section 5, we are amenable to analysis for multicell cellular systems with ICI. In Section 6, we introduce power constraint for per base station and simulation results in Section 7. Finally, we conclude the paper in Section 8.

2 System model

In mobile cellular scenarios, the radio propagation can be characterized by three independent phenomena: path loss variation with distance, large-scale shadowing, and small-scale fading. A large-frequency reuse factor is assumed to isolate the cells, and the ICI is negligible by spectrum allocation carefully among coordinated BSs. We consider the cellular system has L coordinated cells, each with M antennas as shown in Fig. 1. Each cell has K users each with N antennas. Perfect CSI at the BSs is assumed, and we also consider each cell the same as each BS. The precoded transmit signal vector x_k of MS is given by

$$\boldsymbol{x}_k = \boldsymbol{T}_k \boldsymbol{s}_k \tag{1}$$

where $\boldsymbol{T}_k$ is the precoding matrix and $\boldsymbol{s}_k$ is the data for user k. Thus, the received signal vector at the user k can be expressed as

$$\begin{aligned}\boldsymbol{y}_k &= \underbrace{\boldsymbol{H}_{k,k}\boldsymbol{x}_k}_{\text{desired } signal} + \underbrace{\sum_{j=1,\, j\neq k}^{L} \boldsymbol{H}_{k,j}\boldsymbol{x}_j}_{ICI} + \boldsymbol{n}_k \\ &= \boldsymbol{H}_{k,k}\boldsymbol{T}_k\boldsymbol{s}_k + \sum_{j=1,\, j\neq k}^{L} \boldsymbol{H}_{k,j}\boldsymbol{T}_j\boldsymbol{s}_j + \boldsymbol{n}_k,\end{aligned} \tag{2}$$

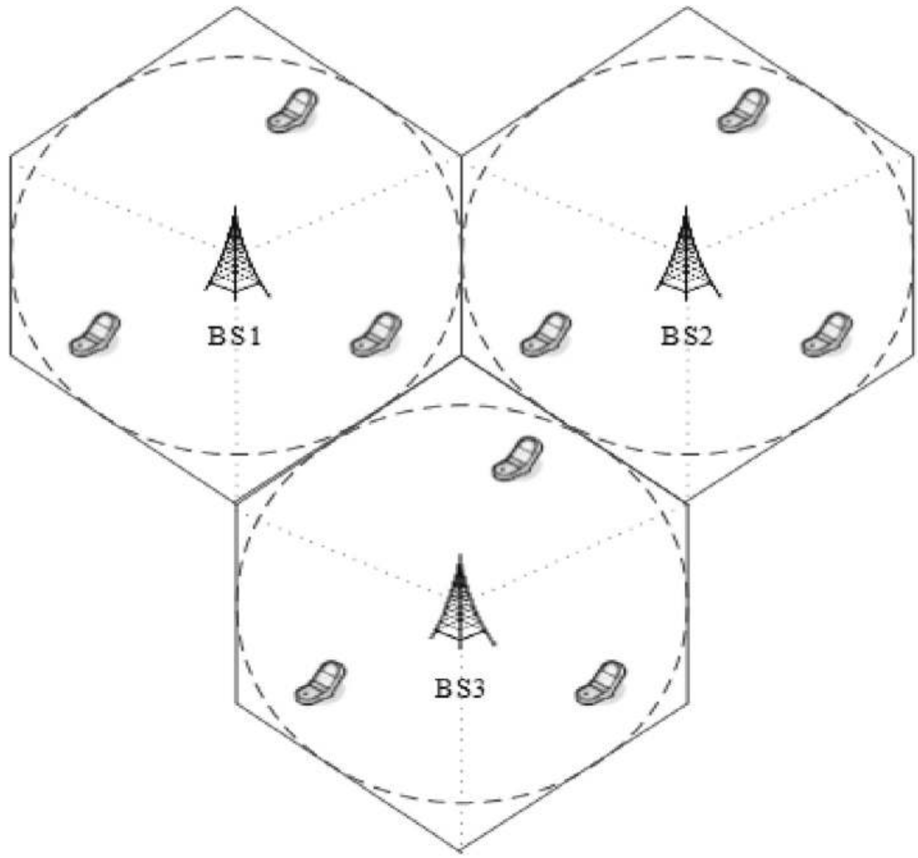

Fig. 1 Block diagram of multicell downlink system

where $\boldsymbol{n}_k$ is a vector of Gaussian noise with variance σ^2. Here, we assume channel *switching* system because all interference is eliminated. Furthermore, the per-cell power constraints are defined as $tr\{\boldsymbol{Q}_k\} \leq P_k$, where $\boldsymbol{Q}_k = \mathbb{E}[\boldsymbol{x}\boldsymbol{x}^H]$ is the covariance matrix of the transmission vector and P_k is the total transmission power. The fading coefficients remain quasi-static within some time interval (called a block) and change independently between blocks. Therefore, the channel from MS k to jth cell can be modeled as a $N \times M$ random matrix

$$\boldsymbol{H}_{k,j} = \sqrt{cd_{k,j}^{-\alpha} g_{k,j}} \boldsymbol{B}_{k,j}, \tag{3}$$

where $cd_{k,j}^{-\alpha}$ denotes the path loss, $d_{k,j}$ is the distance (in km) between MS-k and the *BS*; α is the path loss exponent, c is the median of the mean path loss at the reference distance of 1 km; $g_{k,j}$ is a log-normal distributed shadowing variable with variance, and $\boldsymbol{B}_{k,j} \in \mathbb{C}^{N \times M}$ represents the small-scale fading.

In a cell, each MS with a high SINR will be assigned spatially multiplexed data streams, based on the rank of the MIMO channel and the MIMO capacity. The low SINR cell boundary MSs which seek cooperation are always assigned a single stream of data. The SINR experienced by a user k is given by

$$\mathrm{SINR}_k = \frac{\boldsymbol{H}_{k,k}^H \boldsymbol{T}_k^H \boldsymbol{H}_{k,k} \boldsymbol{T}_k}{\sum\limits_{k=1, j \neq k}^{K} \sum\limits_{j=1}^{L} \boldsymbol{H}_{k,j}^H \boldsymbol{T}_{k,j}^H \boldsymbol{H}_{k,j} \boldsymbol{T}_{k,j} + \sigma^2 \boldsymbol{I}}. \tag{4}$$

Let (ς_j, ψ_j) represent the polar coordinate of the jth remote antenna unit (RAU) in cell, and (μ_k, ω_k) denote the polar coordinate of MS-k. The distance $d_{k,j}$ is noticed by the locations of the MS, BS, and RAU as shown in Fig. 2. Then, the BS-MS distance is given by

$$d_{k,j} = \sqrt{\mu_k^2 + \varsigma_j^2 - 2\mu_k \varsigma_j \cos\left(\omega_k - \psi_j\right)}. \tag{5}$$

To evaluate the cell edge performance, first define the location-specific downlink spectral efficiency [23]. In the multicell environment, the mutual information of the wireless channel can be expressed as

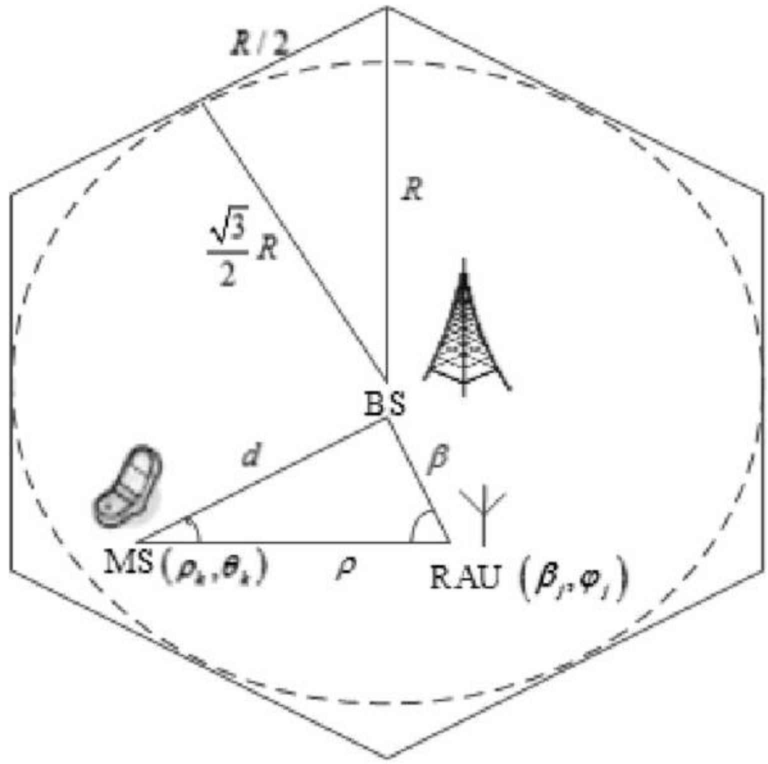

Fig. 2 System model: polar and rectangular coordinates

$$\begin{aligned} I &= \log_2 \det\left(\boldsymbol{I}_{LN} + \frac{P}{M}\boldsymbol{H}_{k,j}\boldsymbol{H}_{k,j}^H\right) = \log_2 \det\left(\boldsymbol{I}_M + \frac{P}{M}\boldsymbol{H}_{k,j}^H\boldsymbol{H}_{k,j}\right) \\ &= \log_2 \det\left(\boldsymbol{I}_M + \frac{Pc}{M}\sum_{j=1, j\neq k}^{L}\frac{g_{k,j}}{d_{k,j}^{\alpha}}\boldsymbol{B}_{k,j}^H\boldsymbol{B}_{k,j}\right) \end{aligned}, \tag{6}$$

which is a random variable depending on the fading condition. The location-specific spectral efficiency can be obtained by taking the mean of (6) with respect to shadowing and small-scale fading coefficients, i.e.

$$C(\mu_k, \omega_k) = E\left[\log_2 \det\left(\boldsymbol{I}_M + \frac{Pc}{M}\sum_{j=1, j\neq k}^{L}\frac{g_{k,j}}{d_{k,j}^{\alpha}}\boldsymbol{B}_{k,j}^H\boldsymbol{B}_{k,j}\right)\right]. \tag{7}$$

3 Multicell cooperation scheme

BS cooperation entails sharing control signals, transmit data, user propagation channel state information (CSI), and precoders via high-capacity wired backhaul links to coordinate transmissions. BS cooperation approach is feasible; the BSs are connected by a high-speed wired backbone that allows information to be reliably exchanged among them. Full cooperation leads to the highest sum rates at the cost of increased overhead due to global CSI requirements and the exchange of a greater amount of information among BSs, including CSI, transmit data, and precoding data. In the BS cooperation schemes, the CSI at the BSs plays an important role in maximizing the system performance. The BSs use this information to adapt their transmission strategies to the channel conditions. We analyze the cooperation scenario in a multicell environment where the other cell interference is significant. The capacity achieved through cooperation is shared equally among the cell edge users, i.e., resources are shared fairly among the cooperating users. The transmission rate to each user is determined based on the signal-to-interference-plus-noise ratio (SINR). Cooperative transmission by two base stations can improve this SINR by transmitting jointly to one user at a time. However, this improvement in terms of throughput may not always be enough to increase the throughput of each user. The signals from the serving BS and from the neighbor BS arrive at the terminal at the same time, i.e., received signals by the terminal from the two BSs are frame synchronized.

Moreover, the maximizing system performance is also accompanied by the overhead cost for the CSI acquisition via channel training and feedback in frequency division duplex (FDD) systems. It needs to scale proportionally to the number of transmit and receive antennas as well as the number of users in the system in order to maintain a constant gap of the sum rate with respect to the full CSI case. The cooperative BSs via a wired backbone network brings about huge data traffic and information.

3.1 No cooperation

Under normal operation, there is no cooperative transmission, i.e., the signal is received only from home BS; the SINR in the downlink for MS is given by Eq. (4). The capacity for terminal MS in bits/s/Hz under no cooperation can be derived from the Shannon capacity given by

$$C_{\mathrm{nc}} = \log_2(1+\beta\mathrm{SINR}_{\mathrm{nc}}), \tag{8}$$

where β is determined by the SNR gap between the practical coding scheme and the theoretical limit.

3.2 Cooperation

When terminal MS is in cooperation with BSs, $\mathrm{SINR}_{\mathrm{coop}}$ and SINR of the downlink channel will depend on the type of cooperation scheme. Then, the capacity for terminal MS under cooperation in bits/s/Hz will be

$$C_{\mathrm{coop}} = \delta\log_2\left(1+\beta\mathrm{SINR}_{\mathrm{coop}}\right). \tag{9}$$

The factor δ in Eqs. (8)–(9) defines the proportion of resource sharing among the terminals under cooperation. In our system, considering resource fairness, the value for δ is 1/2.

The users in the serving cell and the neighbor cell who decided to cooperate for an SINR improvement will share the available resource between them equally. Therefore, the individual user throughput is 1/2 of the actual capacity of the cooperative transmission as in (9), considering $\beta = 1$ in the capacity expressions (8) and (9), for a low SINR regime, as $\log(1+x) \approx x$. The exact expression for the capacity for cooperative scheme with resource constraint to perform better than normal transmission, i.e., $C_{\mathrm{coop}} > C_{\mathrm{nc}}$, is shown below:

$$\begin{aligned}&\frac{1}{2}\log\left(1+\beta\mathrm{SINR}_{\mathrm{coop}}\right) > \log(1+\beta\mathrm{SINR}_{\mathrm{nc}})\\&\Rightarrow\log\left(1+\beta\mathrm{SINR}_{\mathrm{coop}}\right) > \log(1+\beta\mathrm{SINR}_{\mathrm{nc}})^2\\&\Rightarrow 1+\beta\mathrm{SINR}_{\mathrm{coop}} > 1+2\beta\mathrm{SINR}_{\mathrm{nc}}+(\beta\mathrm{SINR}_{\mathrm{nc}})^2\\&\Rightarrow\mathrm{SINR}_{\mathrm{coop}} > \beta\mathrm{SINR}_{\mathrm{nc}}^2+2\mathrm{SINR}_{\mathrm{nc}}\end{aligned} \tag{10}$$

Hence, it is worthwhile for the user to decide whether to perform cooperation in the downlink channel.

4 Inter-cell interference technique control

In this section, we provide the cell edge performance for rectangular coordinate. The performance of cell edge is usually either noise limited or interference limited [21]. In noise-limited situation which typically occurs in large cells in the rural areas, the performance can be usually be improved by providing a power gain.

4.1 Inter-cell interference: an example 2-cell case

The received signal strength goes down as the path loss increases with distance from the serving BS. The ICI goes up because when a MS moves away from one BS, it is generally getting closer to another BS as shown in Fig. 3. Furthermore, we assume a universal frequency reuse, which means that both BS1 and BS2 transmit on the same frequency resources. Here, we consider each BS has M antennas and each cell K users each with N antennas. Therefore, the signal transmitted from BS2 appears as interference to the MSs. From Eq. (5), we consider $\theta = 90°, \beta = 0$; then, we assume $d = \rho$ for the polar coordinate case. The SINR experienced by the MS at a distance d from BS2 can be written as similar way to (4) for the rectangular case:

$$\mathrm{SINR} = \frac{P_1 h_k d_k^{-\alpha}}{\sum\limits_{j\neq k} P_2 h_j (2R-d)_j^{-\alpha} + N_0}, \tag{11}$$

where α is the path loss exponent, N_0 is noise, and P_k is the transmit power for the kth BS. Also, R is the cell radius with $2R$ as the distance between BS1 and BS2. In

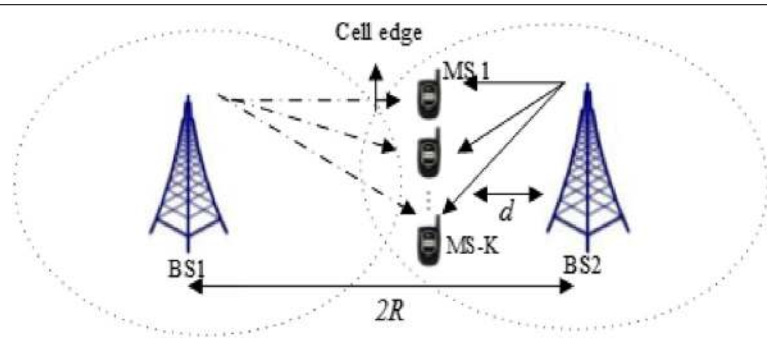

Fig. 3 An ICI broadcast channel based on the rectangular coordinate

general, all the BSs in a system use the same transmit power; and therefore, we will assume $P_1 = P_2$. In a severely interference-limited scenario, the background noise N_0 can be ignored.

The above Eq. (11) expression can be simplified as

$$\mathrm{SINR} = \frac{P_1 d^{-\alpha}}{N_0 + P_2(2R-d)^{-\alpha}} = \frac{P d^{-\alpha}}{P(2R-d)^{-\alpha}} = \frac{1}{\left(\frac{2R}{d}-1\right)^{-\alpha}} = \left(\frac{2R}{d}-1\right)^{-\alpha}. \quad (12)$$

We note that SINR degrades with increasing d. Also, for a given $d < R$, the SINR is higher for a larger path loss exponent α. This is because the interference travels a longer distance for $d < R$ and is attenuated more for larger α. We also note that the maximum SINR at the cell edge with $d = R$ is limited to 0 dB.

Let us assume the path loss model for desirer BS1

$$\mathrm{PL}_s = 128.1 + 37.6\log_{10}(d)\mathrm{dBs}. \quad (13)$$

The same path loss model is assumed for the interferer BS2.

$$\mathrm{PL}_i = 128.1 + 37.6\log_{10}(2R-d)\mathrm{dBs}. \quad (14)$$

The SINR experienced by the MS can be written as

$$\mathrm{SINR}_{\text{with-ICI}} = \frac{Ph_k\left(10^{\frac{\mathrm{PL}_s}{10}}\right)}{N_0 + Ph_j\left(10^{\frac{\mathrm{PL}_i}{10}}\right)}. \quad (15)$$

When the ICI is not present, the SINR experienced by the MS can be written as:

$$\mathrm{SINR}_{\text{without-ICI}} = \frac{Ph_k\left(10^{\frac{\mathrm{PL}_s}{10}}\right)}{N_0}. \quad (16)$$

However, in case of downlink using multiuser MIMO, it is possible that many users located at the cell edge are receiving to their corresponding cell (BS2) in the downlink as shown in Fig. 3. A user receiving in BS2 from the cell edge will see these multiple interferers transmitted at BS2 with approximately the same power as its own transmitted power at BS2. When the number of these interfering BS1 users is greater than 2, the SINR seen on the downlink can be lower than the uplink SINR in interference limited scenarios.

4.2 Multicell for frequency reuse case: cell edge performance

Let us consider a case of hexagonal cell layout, two tiers of interferers, and universal frequency reuse, i.e., reuse of one as shown in Fig. 4. A network consisting of 19 cells is shown in Fig. 4. Cell 1 is surrounding six neighboring cells from 2 to 7. Each cell is served by BS with

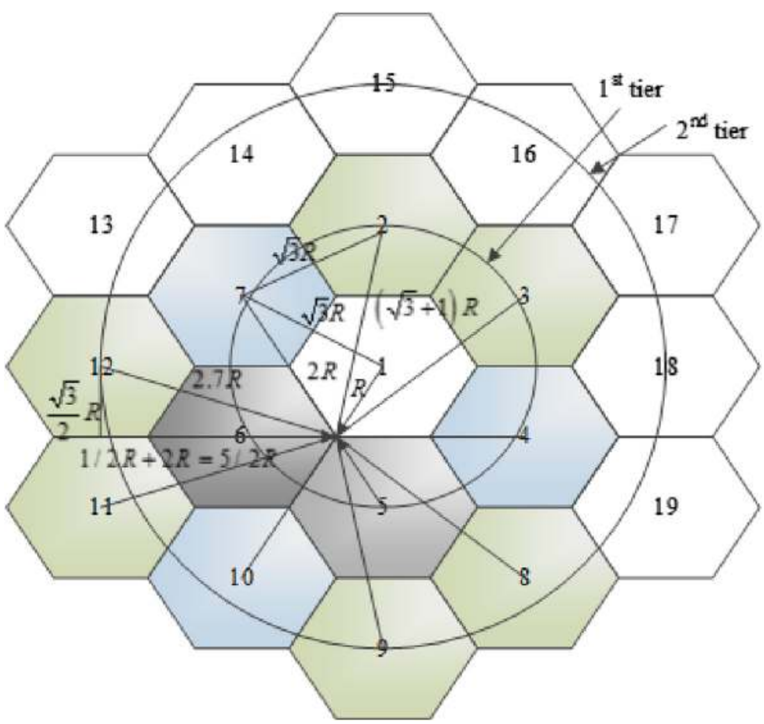

Fig. 4 An interference experienced by a cell edge MS based on the rectangular coordinate

M transit antennas and K users in the cell have N receive antennas. Each cell has radius R, and an additional cell parameter called the inter-cell coordination distance is defined in Fig. 4. The distance defines the boundary between the cell interior and the cell edge users.

We apply frequency reuse, so the users at the cell edge may suffer a high degree of interference from neighboring cells. Multiple neighboring cells have channel information of edge users, and they coordinate for the data transmission: one of these cells is selected to act as the home cell to transmit data to such a user, and other neighboring cells will take this user into consideration when designing precoding matrices. With pre-cancelation of intra-cell interference provided by the home cell and pre-cancelation of ICI at other neighboring cells, there will be no interference for this edge user from those cells.

With such a coordination strategy, the interference for both cell interior and cell edge users is efficiently mitigated. FFR is another technique for interference management where BSs cooperatively schedule users in different downlink bandwidths. However, FFR is a frequency domain interference management technique. This technique coordination strategy is a spatial domain technology that can be implemented with a universal frequency reuse.

The main idea of inter-cell coordination is to do interference pre-cancelation at all the neighboring cells for the active edge user and select one cell to transmit information data to this user. The precoding technique used for inter-cell coordination is multicell MIMO, the same as for intra-cell coordination. Each edge user selects a cell based on the channel state, denoted as the home cell, while the other neighboring cells act as helpers for the data transmission. The remaining cells are interferer cells.

4.2.1 Case I: reuse-1

In this case, a MS at the cell edge experiences interference from 11 cells with two interferers at distance R (cells 5, 6), three interferers at distance $2R$ (cells 4, 7, 10), and six interferers at a distance of $2.7R$ (cells 2, 3, 8, 9, 11, 12) where R is the cell radius. From Eq. (5), $\cos\left(\rho_k - \phi_j\right) = \cos\left(\frac{\pi}{2}\right) = 0$, then, $d_{k,j} = \sqrt{\rho_k^2 + \beta_j^2}$. In Fig. 4, we can calculate the distance of six interferers as

$$\begin{aligned} d &= \sqrt{\left(\frac{1}{2}R + 2R\right)^2 + \left(\frac{\sqrt{3}}{2}R\right)^2} \\ &= \sqrt{\left(\frac{5}{2}R\right)^2 + \left(\frac{\sqrt{3}}{2}R\right)^2} = \sqrt{\frac{25}{4}R^2 + \frac{3}{4}R^2} \\ &= 2.7R. \end{aligned} \tag{17}$$

In this case, 2 cells = R, 3 cells = $2R$, and 6 cells = $2.7R$. In the worst-case SINR,

$$\begin{aligned} \mathrm{SINR}_{\text{reuse-1}} &= \frac{R^{-\alpha}}{2 \times R^{-\alpha} + 3 \times (2R)^{-\alpha} + 6 \times [2.7R]^{-\alpha}} \\ &= \frac{1}{2 + 3 \times (2)^{-\alpha} + 6 \times (2.7)^{-\alpha}}, \end{aligned} \tag{18}$$

where α is the path loss exponent. If we ignore the six interferers at a distance of $2.7R(6 \times (2.7)^{-\alpha} = 0)$, the worst-case SINR is given as

$$\begin{aligned} \mathrm{SINR}_{\text{reuse-1}} &= \frac{R^{-\alpha}}{2 \times R^{-\alpha} + 3 \times (2R)^{-\alpha}} \\ &= \frac{1}{2 + 3 \times (2)^{-\alpha}}. \end{aligned} \tag{19}$$

We note that the SINR increases faster with increasing path loss exponent when a larger number of interferers are assumed. The frequency reuse factor is the rate (C) at which the same frequency can be used in the network. It is $1/L$ where L is the number of cells which cannot use the same frequencies for transmission [21]. The capacity limit for cell edge users for reuse of one can be approximated as

$$C_{\text{reuse-1}} = 1.\log_2\left(1 + \mathrm{SINR}_{\text{reuse-1}}\right)\ b/s/Hz. \tag{20}$$

4.2.2 Case II: reuse-3

Let us now assume a reuse of three for cell numbers 1, 5, and 6 only. In this case, the interference from two dominant interferers at distance R (cells 5 and 6) from the MS is eliminated. The distance of the 3 cells = $2R$ and 6 cells = $2.7R$. So, this results in a worst-case SINR as given below.

$$\begin{aligned} \mathrm{SINR}_{\text{reuse-3}} &= \frac{R^{-\alpha}}{\frac{3 \times (2R)^{-\alpha} + 6 \times [2.7R]^{-\alpha}}{3}} \\ &= \frac{3}{3 \times (2)^{-\alpha} + 6 \times (2.7)^{-\alpha}}. \end{aligned} \tag{21}$$

The capacity limit for cell edge users for reuse of three

$$C_{\text{reuse-3}} = \left(\frac{1}{3}\right)\log_2\left(1 + \mathrm{SINR}_{\text{reuse-3}}\right)\ b/s/Hz. \tag{22}$$

4.2.3 Case III: reuse-7

Now, let us assume a reuse of seven implemented in cell numbers 1–7. In addition to the interference from two dominant interferers at distance R (cells 5 and 6) for the case of reuse of three, the interference from two interferers at distance $2R$ (cells 4 and 7) and another two interferers at distance $2.7R$ (cells 2 and 3) is eliminated. This results in a worst-case SINR as given below.

$$\mathrm{SINR}_{\text{reuse-7}} = \frac{R^{-\alpha}}{\frac{(2R)^{-\alpha}+4\times[2.7R]^{-\alpha}}{7}} = \frac{7}{(2)^{-\alpha}+4\times(2.7)^{-\alpha}}. \tag{23}$$

In a similar way, we can get the capacity limit for reuse of seven

$$C_{\text{reuse-7}} = \left(\frac{1}{7}\right)\log_2\left(1+\mathrm{SINR}_{\text{reuse-7}}\right)\ b/s/Hz. \tag{24}$$

However, when a frequency reuse scheme, for example, with a reuse of three, is applied, the interference from these multiple users receiving on the downlink in BS1 is eliminated. This results in a larger improvement in SINR and correspondingly larger improvements in downlink capacity or throughput. Moreover, since the starting SINR with reuse of one is low, the capacity scales approximately linearly with SINR and therefore results in larger gains in downlink capacity for cell edge users. The comparison of three frequency reuse is shown in Table 1.

5 Performance analysis for multicell cellular network with ICI

This section addresses the cell edge performance considering the ICI. From (2), the ICI plus noise is given by

$$\tilde{\boldsymbol{n}} = \sum_{j=1, j\neq k}^{L} \boldsymbol{H}_k x_j + \boldsymbol{n}_k. \tag{25}$$

The covariance matrix of $\tilde{\boldsymbol{Q}}_k$, conditioned on the user's location and the log-normal shadowing, can be derived as

$$\tilde{\boldsymbol{Q}}_k = E\left(\tilde{\boldsymbol{n}}_k \tilde{\boldsymbol{n}}_k^H\right) = \begin{bmatrix} 1+\frac{Pc}{M}\sum_{j=2, j\neq k}^{L}\frac{g_{1,j}}{d_{1,j}^{\alpha}} & & 0 \\ & \ddots & \\ 0 & & 1+\frac{Pc}{M}\sum_{j=2, j\neq k}^{L}\frac{g_{L,j}}{d_{L,j}^{\alpha}} \end{bmatrix} \otimes I_M, \tag{26}$$

where $\otimes$ denotes the Kronecker product. According to the central limit theorem, ICI is asymptotically Gaussian when the number of interferers is large. So, $\tilde{\boldsymbol{n}}_k$ can be approximated as an equivalent Gaussian noise with covariance (25). With the Gaussian approximation for the ICI, the mutual information of the downlink channel, given the channel matrix $\boldsymbol{H}_k$ and the noise covariance $\tilde{\boldsymbol{Q}}_k$, can be written as

$$\begin{aligned} I &= \log_2\det\left(\boldsymbol{I}_{LN} + \frac{P}{M}\boldsymbol{H}_{k,j}\boldsymbol{H}_{k,j}^H\tilde{\boldsymbol{Q}}_k^{-1}\right) = \log_2\det\left(\boldsymbol{I}_{LN} + \frac{P}{M}\boldsymbol{H}_{k,j}^H\tilde{\boldsymbol{Q}}_k^{-1}\boldsymbol{H}_{k,j}\right) \\ &= \log_2\det\left[\boldsymbol{I}_M + \frac{Pc}{M}\sum_{j=1}^{K}\left(1+\frac{Pc}{M}\sum_{j=2, j\neq k}^{L}\frac{g_{k,j}}{d_{k,j}^{\alpha}}\right)^{-1}\boldsymbol{H}_{k,j}^H\boldsymbol{H}_{k,j}\right], \\ &= \log_2\det\left[\boldsymbol{I}_M + \frac{Pc}{M}\sum_{j=1}^{K}\left(1+\frac{Pc}{M}\sum_{j=2, j\neq k}^{L}\frac{g_{k,j}}{d_{k,j}^{\alpha}}\right)^{-1}\times\frac{g_{k,j}}{d_{k,j}^{\alpha}}\boldsymbol{B}_{k,j}^H\boldsymbol{B}_{k,j}\right] \end{aligned} \tag{27}$$

where $\tilde{\boldsymbol{Q}}_k^{-1}$ denotes the inverse matrix of $\tilde{\boldsymbol{Q}}_k$. The location-specific spectral efficiency of the distributed antenna selection with ICI is defined as

$$C(\mu_k, \omega_k) = E\log_2\det\left[\boldsymbol{I}_M + \frac{Pc}{M}\sum_{j=1}^{K}\left(1+\frac{Pc}{M}\sum_{j=2, j\neq k}^{L}\frac{g_{k,j}}{d_{k,j}^{\alpha}}\right)^{-1}\times\frac{g_{k,j}}{d_{k,j}^{\alpha}}\boldsymbol{B}_{k,j}^H\boldsymbol{B}_{k,j}\right]. \tag{28}$$

6 Power constraints for per base stations

In this section, we present the sum rate maximization problem for the downlink in cooperative multicell system. A variety of inter-cell cooperation schemes have been proposed to mitigate ICI, ranging from a fully cooperative network to partially coordinated beamforming [24–27]. We focus on the network MIMO approach with limited cooperation, where cooperating BSs act as a single distributed MIMO transmitter and interference from other cell is treated as noise. The power constraint corresponding to BS applies to the transmit covariance matrix of BS k which can be defined as

$$\boldsymbol{Q}_k = \sum_k \boldsymbol{V}_k \Omega_k \boldsymbol{V}_k^H, \tag{29}$$

where Ω_k denotes the diagonal element of $\boldsymbol{Q}_k$, corresponding to the power allocated to the kth user. Therefore, sum rate maximization problem with per-cell power constraints can be expressed as

Table 1 Comparison of frequency reuse

Frequency reuse	SINR	Cell edge channel capacity
Reuse-1	$\mathrm{SINR}_{\text{reuse 1}} = \frac{1}{2+3\times(2)^{-\alpha}}$	$C_{\text{reuse 1}} = 1.\log_2(1+\mathrm{SINR}_{\text{reuse 1}})$
Reuse-3	$\mathrm{SINR}_{\text{reuse 3}} = \frac{3}{3\times(2)^{-\alpha}+6\times(2.7)^{-\alpha}}$	$C_{\text{reuse 3}} = \left(\frac{1}{3}\right)\log_2(1+\mathrm{SINR}_{\text{reuse 3}})$
Reuse-7	$\mathrm{SINR}_{\text{reuse 7}} = \frac{7}{(2)^{-\alpha}+4\times(2.7)^{-\alpha}}$	$C_{\text{reuse 7}} = \left(\frac{1}{7}\right)\log_2(1+\mathrm{SINR}_{\text{reuse 7}})$

$$\arg\max_{\{\boldsymbol{\Omega}_k\}} \sum_{j=1, j\neq k}^{L} \log\left|\boldsymbol{I} + \boldsymbol{H}_{j,k}\boldsymbol{V}_{j,k}\boldsymbol{\Omega}_k\boldsymbol{V}_{j,k}^H\boldsymbol{H}_{j,k}^H\right|$$
$$s.t.\ tr\left\{\sum_k \boldsymbol{V}_k\boldsymbol{\Omega}_k\boldsymbol{V}_k^H\right\}\leq P_k,\ k=1,\ldots,K$$
$$\boldsymbol{\Omega}_k\geq 0,\ k=1,\ldots,K. \tag{30}$$

Thus, the problem is categorized as a convex optimization problem. The sum power constraint is given by

$$tr(\boldsymbol{Q}_k) = \sum_{k=1}^{K}\sum_{i=1}^{L}\boldsymbol{\Omega}_k^j \leq P_k, \tag{31}$$

where $P_{\text{sum}} = \sum_{k=1}^{L} P_k$. The sum rate maximization reduces to

$$\arg\max_{\{\Omega_k\}} \sum_{k=1}^{K}\sum_{j=1}^{L}\log\left(1+\Lambda_k^j\boldsymbol{\Omega}_k^j\right). \tag{32}$$

Letting $\Lambda_k^j = \boldsymbol{H}_k^H\boldsymbol{H}_k$ denotes the diagonal element for $j = 1, \ldots, L$. For per-BS power constraints, we can use Lagrange duality and the sub-gradient iteration method as given in the following. The Lagrangian function for (32) is given by

$$\mathscr{L}(\boldsymbol{\Omega},\boldsymbol{\lambda}) = \sum_{k=1}^{K}\sum_{j=1}^{L}\log\left(1+\Lambda_k^j\boldsymbol{\Omega}_k^j\right) - \boldsymbol{\lambda}P, \tag{33}$$

where $\lambda \geq 0$ is a vector of dual variables corresponding to the BS power constraints. The KKT conditions are given by

$$\frac{\partial\mathscr{L}}{\partial\boldsymbol{\Omega}_k^j} = \frac{1}{1+\Lambda_k^j\boldsymbol{\Omega}_k^j}\Lambda_k^j - \lambda \leq 0. \tag{34}$$

Solving for q_k^j, we find

$$\frac{\Lambda_k^j}{1+\Lambda_k^j\Omega_k^j} - \boldsymbol{\lambda} = 0 \Rightarrow \boldsymbol{\Omega}_k^j = \left[\frac{1}{\boldsymbol{\lambda}} - \frac{1}{\Lambda_k^j}\right]. \tag{35}$$

The solution of (35) subject to the sum power constraint is given by the water filling. It follows that the dual problem can be solved by the vector of dual variables λ.

7 Simulation results

In this section, the cell edge performance is evaluated via MATLAB simulations. We plot SINR with and without assuming ICI as a function of distance from the cell center d for a MS receiving transmission in Fig. 5 from Eqs. (15)–(16). The total background noise in a 10-MHz bandwidth is $N_0 = -104$ dBm. Also, we assume the BS transmit power of $P = 46$ dBm. We note that the SINR gain by ICI elimination is larger for lower SINR MSs. The lower SINR happens when d approaches R, which is the case for cell edge MSs. The relative gains in throughput by ICI eliminations are expected to be even larger for low SINR MSs as the capacity scales almost linearly at lower SINR. For high SINR users, small gains in SINR by ICI elimination do not translate into any meaningful gains in throughput. From this discussion, we can

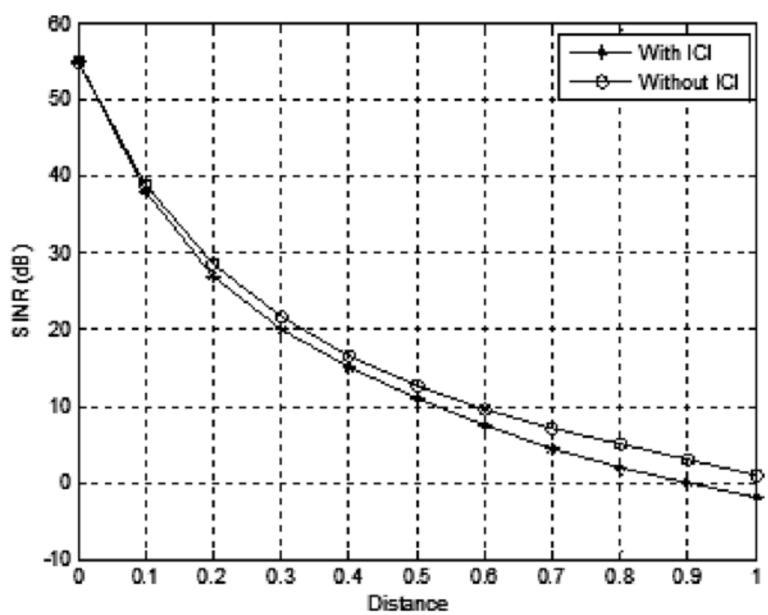

Fig. 5 SINR as a function of distance from the cell center

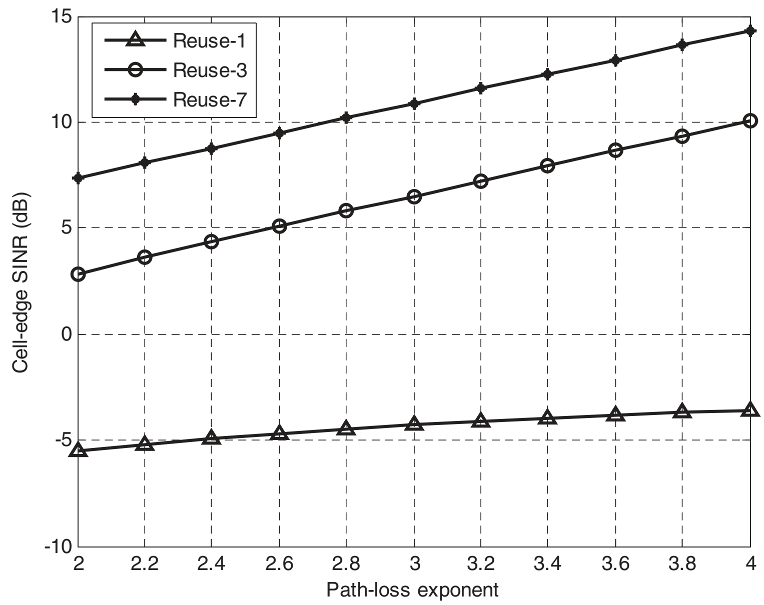

Fig. 6 Cell edge SINR for various reuse factors

conclude that ICI is more important for cell edge MSs than for the cell center MSs.

The cell edge SINR for various reuse factors is given in Fig. 6 from Eqs. (19), (21), and (23). We note that at a path loss exponent of 3.6, we observe an approximately 13-dB improvement in cell edge SINR by using reuse of three relative to reuse of one. A reuse of seven increases cell edge SINR by another 8 dB. Note that with a reuse of three and seven, the power spectral density on the transmitted bandwidth increases by a factor of 3 and 7, respectively. This is because, with a higher reuse, the frequency bandwidth used in each cell in the reuse scheme decreases. We have accounted for this increase in power spectral density in the above calculations.

The cell edge channel capacity limits for various reuse factors are plotted in Fig. 7 from Eqs. (18), (20), and (22). It can be noted that, at a path loss exponent of 3.6, a reuse of three provides approximately two times

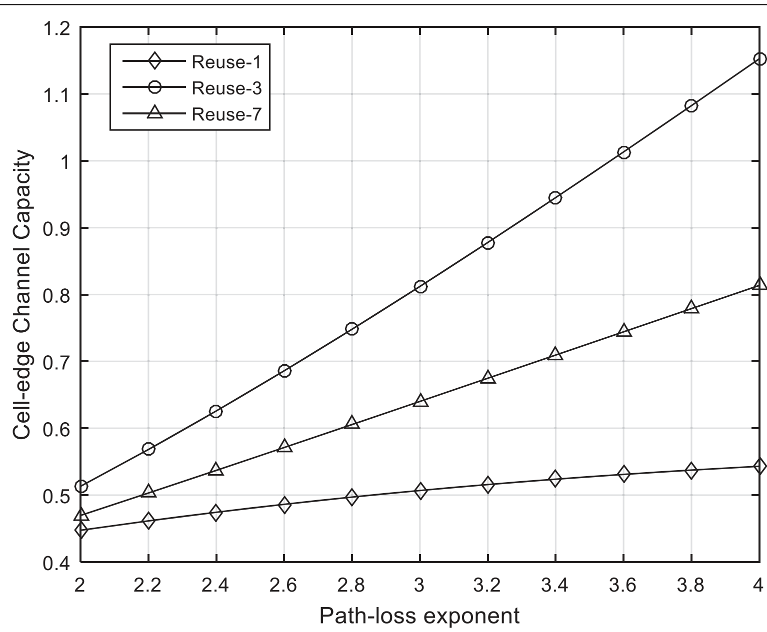

Fig. 7 Cell edge channel capacity for path-loss exponent with various reuse factors

Table 2 Simulation parameters

Parameters	Value
Number of cells	19
Number of cooperation BSs	7
Cell shape	Hexagon diagram
BS position	On circle with radius
User position	Cell edge
(BS, user) antenna number	(7, 3)
Carrier frequency	2 GHz
Bandwidth	10 MHz
Log-normal shadowing	Gaussian distribution with zero mean, 10-dB standard deviation
Transmission power (BS)	46 dBm
SNR	−15 to 20 dB
Path loss exponent	$\alpha = 3.5$
Path loss	$128.1 + 37.6\log_{10}(d)$
Fading	i.i.d. Rayleigh

improvement in cell edge throughput relative to the case of universal frequency reuse. Therefore, the potential improvement in performance is merely an indication of the gains achievable by ICIC for the cell edge users. We further note that reuse of seven while providing some capacity gains relative to universal frequency reuse performs worse than reuse of three.

A 19-cell full reuse multicell environment is simulated to analyze the performance of user capacity and SINR for two transmission scenarios, namely (i) without cooperation (ii) with cooperation. A cellular network of radius 500 m, operating at 1800 MHz with one cell edge user per cell, is considered for simulations. The channel gains for both signal and interference are based on path loss model including fading and log-normal shadowing. The shadowing component is a Gaussian random variable with zero mean and 10-dB standard deviation. Fading component is an i.i.d. random variable with zero mean and unit variance. The transmission power of each base station (at the antenna) is 46 dBm. The simulation parameters are shown in detail in Table 2.

From Fig. 8, when BSs do not cooperate, the channels from user k to BS k, $k \in \{1, 2, 3\}$, are not shared among the adjacent cells. Thus, the capacity is achieved when cells do not cooperate and therefore interference is limited. On the contrary, all cells cooperate in the sense that they proceed to joint decoding of the users operating at the same frequency. However, in the cooperative case, power allocation can be clearly performed under either sum power constraint or individual power constraint for each user. So BSs are connected by backhaul, the capacity maximizing number of cooperative cells.

8 Conclusions

In this paper, we focus on increasing the cell edge capacity in the multicell networks. We also propose the deployment scheme consisting of 19 cells with two tiers for the rectangular coordinate and show the cell edge performance of cellular systems with and without ICI

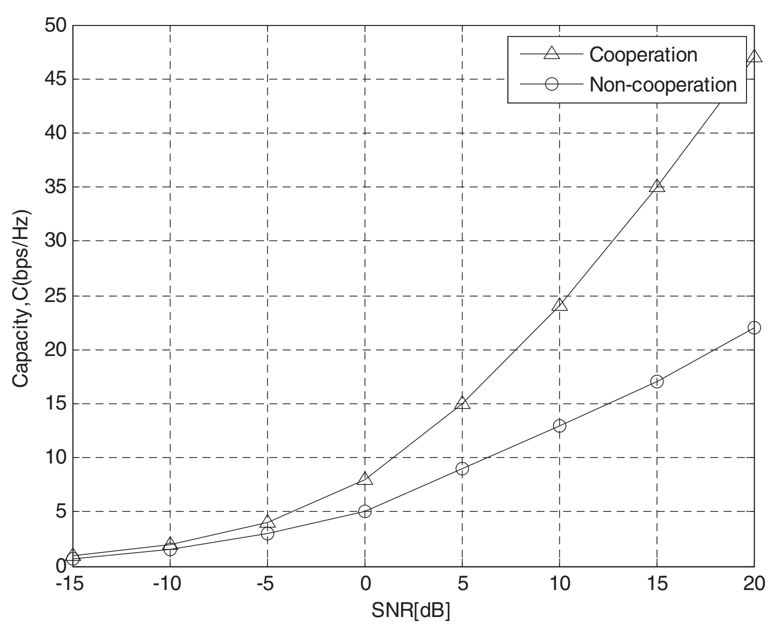

Fig. 8 Sum rate capacity of multiple cooperation

according to the distance from their BSs. We show that 13-dB improvement in the cell edge SINR with frequency reuse factor of three can be achieved compared to frequency reuse factor of one. BS cooperation has been proposed to mitigate the cell edge effect. The multicell coordinated MU-MIMO scheme is proposed to improve the cell edge user throughput, which can satisfy higher spectral efficiency requirements of the LTE Advanced systems as well as the capacity by maximizing the number of cooperative cells/BSs.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
All authors read and approved the final manuscript.

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