Novel Intercell Interference Mitigation Algorithms for Multicell OFDMA Systems With Limited Base Station Cooperation

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***Abstract*—Resource allocation in multicell downlink orthogonal frequency division multiple-access (OFDMA) systems is investigated, where base stations (BSs) first independently carry out subcarrier allocation and then mitigate intercell interference (InterCI) with the aid of very limited BS cooperation. Two novel InterCI mitigation algorithms are proposed. The first one is the distributed decision making assisted cooperation (DDMC) algorithm, and the second one is the centralized decision making assisted cooperation (CDMC) algorithm. When employing the DDMC algorithm, each BS independently makes the InterCI mitigation decisions (IMDs). By contrast, when employing the CDMC algorithm, the centralized IMDs are made with the aid of the cell-edge users' discrete InterCI information sharing among BSs. While both algorithms motivate maximization of the spectral efficiency (sum rate), the CDMC algorithm also aims to maximize the frequency reuse factor. In this paper, we study and compare the performance, including spectral efficiency of cell-edge users, frequency reuse factor, and overhead, of the multicell downlink OFDMA systems employing the proposed and other InterCI mitigation algorithms. Our studies show that both the DDMC and CDMC algorithms can achieve better spectral efficiency performance than the existing on–off power (OOP) algorithm. Moreover, the CDMC algorithm is capable of achieving performance close to the upper bound attained by the so-called full InterCI information assisted decision making (FIIDM) algorithm, which uses exhaustive search to determine the IMDs. Additionally, the CDMC algorithm is demonstrated to have the highest frequency reuse factor, in addition to its spectral efficiency advantage.**

***Index Terms*—Base station (BS) cooperation, intercell interference (InterCI), multicell, orthogonal frequency division multiple access (OFDMA), optimization, resource allocation, subcarrier allocation.**

I. Introduction

Orthogonal frequency division multiple access (OFDMA) has emerged as one of the key techniques for high-speed broadband wireless communications. In the literature, resource allocation in single-cell OFDMA systems has been widely investigated, particularly in association with subcarrier allocation [1]–[6]. However, mobile communication systems are typically multicell systems with frequency spectrum reused in geographic areas. Moreover, toward the future generations of wireless systems, unity of frequency reuse is desired. In this case, users may experience severe intercell interference (InterCI), resulting in significant performance degradation, if it is not efficiently managed.

In multicell communications, resource-allocation approaches proposed in the literature may be categorized into two classes, namely, centralized and distributed resource allocation, based on where and how the resource allocation is carried out. Specifically, in centralized resource allocation, central control units are used to collect the required information, which are also responsible for managing and allocating resources jointly to all users in all cells. Centralized resource allocation may consume the enormous resources, which could be exploited for data transmission, for information exchange, and for system controlling [7]. In the literature, there are a range of references, including [7]–[12], having proposed and studied the centralized resource allocation in multicell OFDMA systems. In [8], a load matrix approach for jointly managing both the InterCI and the intracell interference (IntraCI) experienced by users has been proposed. In [9], an NP-hard joint resource allocation problem for a two-cell OFDMA system has been approximated by a weighted sum throughput maximization problem. Using the geometric programming approach to transform the original mixed-integer nonconvex problems, in [7] and [11], the suboptimal subcarrier- and power-allocation solutions in the downlink OFDMA networks with BS coordination have been proposed. By contrast, in [12], the IntraCI of a subcarrier reused OFDMA networks has been dealt with.

In distributed resource allocation, every BS independently allocates its resources, usually based only on the intracell channel information and the interference measured locally. In comparison with the centralized approaches, distributed resource allocation has the main advantages of fast response to dynamic resource environments, fast time-varying channels, and low complexity for implementation. Distributed resource allocation in multicell OFDMA systems has been widely studied, as evidenced, e.g., by [13]–[18]. The distributed resource-allocation scheme proposed in [13] has considered jointly subcarrier, bit, and power allocation in multicell OFDMA systems. In [14], the distributed subcarrier allocation and power allocation in the multicell OFDMA networks with cognitive radio functionality have been studied. In [15], a distributed power-allocation scheme has been proposed for the multicell multiple-input–single-output OFDMA networks, where the channel state

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information (CSI) of all users is shared among the BSs. Very recently, interference-aware resource allocation has drawn attention [17], [18].

It can be understood that, to combat the InterCI existing in multicell OFDMA systems, one may employ sophisticated InterCI mitigation technique at the receiver side, by using, for example, maximum-likelihood detection, successive interference cancellation, and multiple-antenna-based interference nulling. On the other hand, BS cooperation can be another efficient InterCI mitigation approach, which shifts the processing burden to the BSs, rather than causing too much computational complexity at mobile terminals [16], [19], and [20]. For example, in [19] and [20], the scheduling and power allocation in the context of the multicell downlink OFDMA systems and other networks have been studied, by handling the InterCI via BS coordination supported by the CSI exchange among BSs. By contrast, the research studies in [10] and [21]–[23] have been devoted to the resource allocation in multicell OFDMA systems with full BS cooperation, which requires BSs to share both CSI and data. Under the constraint of certain backhaul capacity, a heuristic BS assignment algorithm has been proposed in [22], and a user-scheduling algorithm has been developed in [23], respectively. Furthermore, in [24] and [25], the energy efficiency issue of the BS-cooperation-based resource allocation in multicell OFDMA systems has been addressed.

Against the background, in this paper, we investigate both the subcarrier allocation and the InterCI mitigation in multicell downlink OFDMA systems. In our considered systems, each cell independently allocates subcarriers based on our proposed bidirectional worst subchannel avoiding (BWSA) algorithm [26]. Our focus is on the InterCI mitigation after the distributed subcarrier allocation. We propose two novel InterCI mitigation algorithms. The first one is the distributed decision making assisted cooperation (DDMC) algorithm, which motivates to maximize the payoff of BS cooperation, while simultaneously minimizing the cost caused by cooperation. The second InterCI mitigation algorithm proposed is named as the centralized decision making assisted cooperation (CDMC), which motivates to make the best InterCI mitigation decisions (IMDs) based on the limited discrete InterCI information of the cell-edge users shared among the BSs, to maximize both the spectral efficiency and the frequency reuse factor of the frequency spectrum. In this paper, we study and compare the spectral efficiency of cell-edge users, frequency reuse factor, overhead, etc., of the multicell downlink OFDMA systems employing the BWSA and various InterCI mitigation algorithms. Our studies and performance results show that both the proposed DDMC and CDMC algorithms are high-efficiency InterCI mitigation algorithms, which outperform the existing on–off power (OOP) algorithm in terms of the spectral efficiency. The CDMC algorithm outperforms the DDMC algorithm and is capable of achieving the sum rate close to the upper bound achieved by the full InterCI information assisted decision making (FIIDM) algorithm. In this FIIDM algorithm, cooperation decisions are made via the exhaustive search with ideal information about the InterCI. Additionally, the CDMC algorithm is demonstrated to have the highest frequency reuse factor in addition to its spectral efficiency advantage.

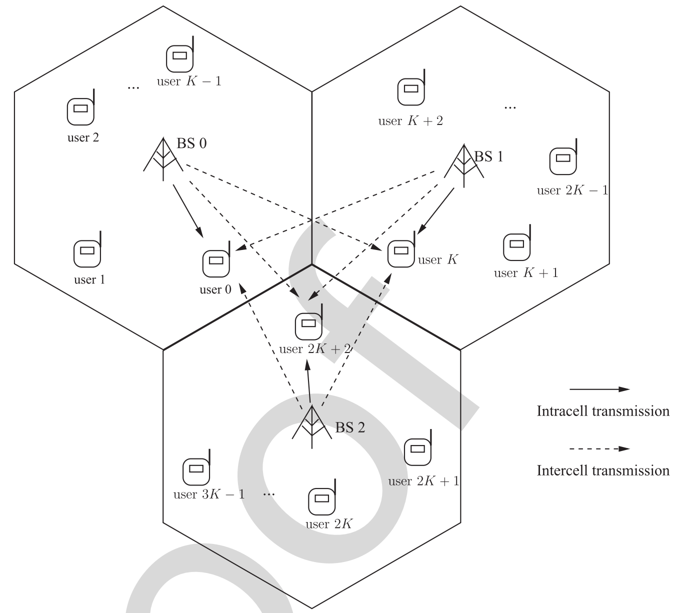

Fig. 1. Conceptual structure of the multicell downlink OFDMA systems.

The rest of this paper is organized as follows. Section II introduces the system model. Section III provides the general theory about the distributed subcarrier allocation and the InterCI mitigation. In Section IV, we discuss the FIIDM, which is the upper bound of our InterCI mitigation. Section V extends the OOP algorithm to the multicell downlink OFDMA systems. Sections VI and VII detail the proposed DDMC and CDMC algorithms, respectively. Performance results are shown in Section VIII. Finally, we summarize the main conclusions in Section IX.

II. System Model

To reflect the main features of multicell systems while making the problems relatively easy to manage, in this paper, we consider the same system model studied in [10] and [27]–[29], which is a three-cell downlink OFDMA system, as depicted in Fig. 1. In this system, each cell has one base station (BS) communicating with K mobile users. Each of the communication terminals, including both BSs and mobile users, is assumed to employ one antenna for signal receiving and transmission. The BSs communicate with their users based on OFDMA having in total M subcarriers.

We consider the extreme case that each cell supports $K = M$ users and, hence, each user is assigned one subcarrier. Note that we assume this extreme case for the sake of avoiding considering the trivial cases but focusing our attention on the InterCI mitigation. For the case where one user is assigned multiple subcarriers, the system can be modified to use our model by dividing one user into several ones of each assigned one subcarrier. However, in this case, the InterCI mitigation may become easier, owing to the reduced number of users involved. There is no IntraCI, since all users in one cell communicate on orthogonal subcarriers. However, without using InterCI mitigation, each user experiences InterCI from two users located

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in the other two cells, respectively, which are assigned the same subcarrier as the considered user. Based on the preceding assumptions, therefore, the subcarrier allocation should satisfy the constraints of

$$\bigcup_{m\in\mathcal{M}} \mathcal{F}_m^{(u)} = \mathcal{K}^{(u)} \quad \forall u \in \{0,1,2\} \tag{1}$$

$$\mathcal{F}_m^{(u)} \bigcap \mathcal{F}_{m'}^{(u)} = \emptyset, \quad m \neq m' \,\forall m, m' \in \mathcal{M}\, \forall u \in \{0,1,2\} \tag{2}$$

$$\left|\mathcal{F}_m^{(u)}\right| = 1 \quad \forall m \in \mathcal{M}\, \forall u \in \{0,1,2\} \tag{3}$$

where $\mathcal{M} = \{0, 1, \ldots, M-1\}$ is the set of subcarrier indexes, $\mathcal{F}_m^{(u)}$ contains the indexes of the users assigned to subcarrier m in cell u, and $\mathcal{K}^{(u)} = \{uK+0, uK+1, \ldots, uK+K-1\}$ holds the indexes of the K users in cell u. Note that, in the preceding equations, (1) explains that each BS assigns M subcarriers to its K users, whereas (2) and (3) impose the constraints that, in one cell, different users are allocated different subcarriers and one user is assigned just one subcarrier.

As shown in Fig. 1, the BSs are located at the centers of the cells, and each cell has K users, which are assumed to obey uniform distribution. In each of the three cells, we assume for simplicity the ideal power control as in [2], [3], [21], and [22], to maintain the same average received power of one unit per user. Furthermore, we assume that InterCI only exists between adjacent cells as the result of propagation path loss. Let the InterCI be characterized by a factor α. Then, when taking into account of the combined effect of propagation path loss and shadowing, we can have [30]

$$\alpha = \sqrt{\left(\frac{d_0}{d_1}\right)^{\mu} 10^{\frac{\zeta_0-\zeta_1}{10}}} \tag{4}$$

where d_0 and d_1 represent the distances from a BS to the considered intracell and intercell users, respectively; μ is the path loss exponent, whereas ζ_0 and ζ_1 (in dB) are the zero-mean Gaussian random variables with a standard deviation Υ (in dB), which account for the shadowing effect [30]. In addition to the propagation path loss and shadowing effects, signals transmitted from BSs also experience fast fading, which is assumed to be the independent Rayleigh flat fading in terms of different users.

Let us assume that a data symbol to be transmitted by BS u to its intracell user k ($k \in \mathcal{K}^{(u)}$) is expressed as $x_k^{(u)}$, which satisfies $E[x_k^{(u)}] = 0$ and $E[|x_k^{(u)}|^2] = 1$. Since the M subcarriers in one cell are assumed to be orthogonal, the signal received by user k of cell u can be written as

$$\begin{aligned} y_k^{(u)} &= h_{k,m}^{(u)} w_{k,m}^{(u)} x_k^{(u)} \\ &+ \underbrace{h_{k,m}^{(u')}\alpha_{k',k}^{(u')} w_{k',m}^{(u')} x_{k'}^{(u')} + h_{k,m}^{(u'')}\alpha_{k'',k}^{(u'')} w_{k'',m}^{(u'')} x_{k''}^{(u'')}}_{\text{InterCI}} + n_k^{(u)} \end{aligned} \tag{5}$$

when assuming that $k \in \mathcal{F}_m^{(u)}$, $k' \in \mathcal{F}_m^{(u')}$, and $k'' \in \mathcal{F}_m^{(u'')}$, which means that users k, k', and k'' in cells u, u', and u'', respectively, are assigned to share subcarrier m. Hence, users k, k', and k'' are referred to as the *cosubcarrier* users. In (5), $n_k^{(u)}$ represents the Gaussian noise at user k, which is assumed to obey the complex Gaussian distribution with zero mean and a variance of $2\sigma^2 = 1/\gamma_s$, where γ_s denotes the average signal-to-noise ratio (SNR) per symbol. $h_{k,m}^{(u)}$ denotes the fast fading gain on the mth subcarrier from BS u to user k, and $h_{k,m}^{(u')}\alpha_{k',k}^{(u')}$ represents the InterCI that user k receives from BS u', when it uses subcarrier m to send signals to user k'. Here, $h_{k,m}^{(u')}$ is the fast fading gain on the mth subcarrier from BS u' to user k, and $\alpha_{k',k}^{(u')}$ is the corresponding InterCI factor. In this paper, we assume that the uplinks and the downlinks are operated in the time division duplex mode, and a BS is capable of acquiring the AQ1
CSI of the channels between the BS and its K intracell users. In this case, a BS is capable of preprocessing the signals to be transmitted to its intracell users by setting $w_{k,m}^{(u)}$ seen in (5) as $w_{k,m}^{(u)} = (h_{k,m}^{(u)})^* / \sqrt{|h_{k,m}^{(u)}|^2}$, where $(\cdot)^*$ denotes the conjugate operation. We assume that any BS does not have the CSI of the InterCI channels, including both the slow and fast fading, which is possibly due to the complexity constraint. From (5), the signal-to-interference-plus-noise ratio (SINR) for user k can be expressed as

$$\begin{aligned} \gamma_{k,m}^{(u)} &= \frac{\left|h_{k,m}^{(u)}\right|^2}{\left|h_{k,m}^{(u')}\alpha_{k',k}^{(u')}\right|^2 + \left|h_{k,m}^{(u'')}\alpha_{k'',k}^{(u'')}\right|^2 + 2\sigma^2} \\ &= \frac{\left|h_{k,m}^{(u)}\right|^2}{I_{u',k} + I_{u'',k} + 2\sigma^2}, \quad m \in \mathcal{M} \end{aligned} \tag{6}$$

where $I_{u',k} = |h_{k,m}^{(u')}\alpha_{k',k}^{(u')}|^2$ is the InterCI power received by user k from BS u'. Alternatively, (6) can be written as

$$\begin{aligned} \gamma_{k,m}^{(u)} &= \frac{1}{\left(\eta_{k,m}^{(u)}\right)^{-1} + \left(A_{k,m}^{(u)}\right)^{-1}} \\ \eta_{k,m}^{(u)} &= \frac{\left|h_{k,m}^{(u)}\right|^2}{I_{u',k} + I_{u'',k}} \qquad A_{k,m}^{(u)} = \frac{\left|h_{k,m}^{(u)}\right|^2}{2\sigma^2} \end{aligned} \tag{7}$$

where $\eta_{k,m}^{(u)}$ and $A_{k,m}^{(u)}$ are the signal-to-interference ratio (SIR) and the SNR of user k in cell u, respectively.

From (6) and (7), we imply that, to achieve high SINR at low implementation complexity, we may design the subcarrier allocation motivating to maximize the channel gains from a BS to its K intercell users, while we design the InterCI mitigation aiming to minimize the InterCI with the backhaul cost as low as possible. For these purposes, we consider two InterCI mitigation methods, which are the *power off* and *BS cooperation*. With the power off method, the transmissions to some users experiencing strong InterCI are turned off. The method is easy to operate, does not require BS cooperation, and is sometimes very efficient, as shown in [31].

By contrast, when the BS cooperation method is employed, we assume that a mobile user can estimate the strength of the signal from its own BS and the power of the InterCI signals from the two interfering BSs. As the BS cooperation motivates

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reliance on the lowest possible backhaul cost, we assume that there is no CSI sharing among the BSs. In this case, a promising BS cooperation scheme is the classic space–time block coding (STBC) [32], which only needs to exchange the data symbols of the users requiring BS cooperation. Consequently, when two BSs use, for example, Alamouti's STBC [32], to send information to one user, two orders of transmit diversity can be achieved. This way, we may enhance the detection reliability and/or the throughput of the system, in comparison with the power off scheme. Let us illustrate this following (5). Let us assume that BS u' cooperates with BS u to transmit $x_k^{(u)}(t)$ and $x_k^{(u)}(t+T)$ to user k based on Alamouti's scheme [32], where T represents the symbol duration. Then, the observations received by user k at times t and $t+T$ can be written as

$$y_k^{(u)}(t) = h_{k,m}^{(u)} x_k^{(u)}(t) + h_{k,m}^{(u')} \alpha_{k',k}^{(u')} x_k^{(u)}(t+T) + h_{k,m}^{(u'')} \alpha_{k'',k}^{(u'')} x_{k''}^{(u'')}(t) + n_k^{(u)}(t) \quad (8)$$

$$y_k^{(u)}(t+T) = -h_{k,m}^{(u)} \left(x_k^{(u)}(t+T)\right)^* + h_{k,m}^{(u')} \alpha_{k',k}^{(u')} \left(x_k^{(u)}(t)\right)^* + h_{k,m}^{(u'')} \alpha_{k'',k}^{(u'')} x_{k''}^{(u'')}(t+T) + n_k^{(u)}(t+T). \quad (9)$$

Assume that user k is capable of estimating the channels from BSs u and u'. Then, it can form the decision variables for detecting $x_k^{(u)}(t)$ and $x_k^{(u)}(t+T)$ as

$$r_k^{(u)}(t) = \left(h_{k,m}^{(u)}\right)^* y_k^{(u)}(t) + h_{k,m}^{(u')} \alpha_{k',k}^{(u')} \left(y_k^{(u)}(t+T)\right)^* \quad (10)$$

$$r_k^{(u)}(t+T) = \left(h_{k,m}^{(u')} \alpha_{k',k}^{(u')}\right)^* y_k^{(u)}(t) - h_{k,m}^{(u)} \left(y_k^{(u)}(t+T)\right)^*. \quad (11)$$

From (10) and (11), we can derive the SINR of user k for detecting $x_k(t)$ and $x_k(t+T)$, which is

$$\gamma_k^{(u)} = \frac{\left|h_{k,m}^{(u)}\right|^2 + \left|h_{k,m}^{(u')} \alpha_{k',k}^{(u')}\right|^2}{\left|h_{k,m}^{(u'')} \alpha_{k'',k}^{(u'')}\right|^2 + 2\sigma^2}. \quad (12)$$

Note that the preceding cooperation is usually set up, when BS u' generates strong InterCI on user k, which means that the term of $|h_{k,m}^{(u')} \alpha_{k',k}^{(u')}|^2$ in the preceding equation has a relatively large value. In this case, the SINR of (12) resulted from the cooperation can be significantly enhanced in comparison with the SINR of (6) of the case without BS cooperation, which consequently improves the multicell system's overall throughput.

III. General Theory

Here, we address the general theory of the distributed subcarrier allocation and the design motivation for the InterCI mitigation in the multicell downlink OFDMA systems. For achieving relatively low-complexity implementation, in this paper, we propose to first carry out the distributed subcarrier allocation and then operate the InterCI mitigation, when different levels of BS cooperation are considered. The distributed subcarrier allocation is motivated to maximize the sum rate of each cell, with the optimization problem described as

$$\left\{\mathcal{F}_m^{(u)}, \forall m\right\}^* = \arg \max_{\left\{\mathcal{F}_m^{(u)}, \forall m\right\}} \left\{ \sum_{k \in \mathcal{K}^{(u)}} \log_2\left(1 + \gamma_k^{(u)}\right) \right\} \quad \forall u \in \{0,1,2\} \quad \text{subject to (1)–(3)} \quad (13)$$

where $\gamma_k^{(u)}$ is the SINR of user k in cell u, such as that in (6). In (13), $\{\mathcal{F}_m^{(u)} \forall m\}$ means testing all the possible subcarrier allocations for cell u, whereas $\{\mathcal{F}_m^{(u)} \forall m\}^*$ returns the final results of the subcarrier allocation.

However, the problem in (13) is a mixed-integer nonconvex problem that is very hard to solve. Therefore, as done in [6], [26], and [33], the distributed subcarrier allocation can be motivated to maximize the SNRs of all the users in one cell without considering the impact of InterCI. Correspondingly, this optimization problem can be expressed as

$$\left\{\mathcal{F}_m^{(u)}, \forall m\right\}^* = \arg \max_{\left\{\mathcal{F}_m^{(u)} \forall m\right\}} \left\{A_k^{(u)}, k \in \mathcal{K}^{(u)}\right\} \ \forall u \in \{0,1,2\} \quad \text{subject to (1), (2), (3)} \quad (14)$$

where $A_k^{(u)}$ is the SNR of user k, such as that defined in (7). Based on (14), in [26], we have designed a BWSA algorithm for the single-cell OFDMA systems, which is demonstrated to have low complexity and to be capable of achieving near-optimum performance. In this paper, we investigate the performance of the multicell downlink OFDMA systems employing the BWSA algorithm in association with our proposed and other InterCI mitigation algorithms.

As the subcarrier allocation considered earlier does not deal with the InterCI, after the subcarrier allocation, the InterCI mitigation is then operated for the cell-edge users. Let us define the user set of cell u as $\hat{\mathcal{K}}^{(u)} = \{k | \eta_k < \eta_t, k \in \mathcal{K}^{(u)}\}$, where η_t represents an SIR threshold. The threshold η_t can be set according to various communication objectives. Then, the users in set $\tilde{\mathcal{K}}^{(u)}$ are called the cell-edge users of cell u. Here, the set $\tilde{\mathcal{K}}^{(u)}$ includes both the users in $\hat{\mathcal{K}}^{(u)}$ and the users in $\mathcal{K}^{(u)} - \hat{\mathcal{K}}^{(u)}$ that share the same subcarriers as the users in $\hat{\mathcal{K}}^{(u')}$ of cell u' and the users in $\hat{\mathcal{K}}^{(u'')}$ of cell u''. In general, our InterCI mitigation motivates to maximize the sum rate of the cell-edge users by solving the optimization problem of

$$\boldsymbol{D}^* = \arg \max_{\boldsymbol{D}} \left\{ \sum_{u=0}^{2} \sum_{k \in \tilde{\mathcal{K}}^{(u)}} \log_2\left(1 + \gamma_k^{(u)}\right) \Big| \left\{\mathcal{F}_m^{(u)}, \forall m, u\right\}^* \right\} \quad (15)$$

where $3M$-length IMD vector can be written in the form of $\boldsymbol{D} = [\boldsymbol{D}_0^T, \ldots, \boldsymbol{D}_{M-1}^T]^T$, where $(\cdot)^T$ is the transpose operation. Here, $\boldsymbol{D}_m = [D_{0,m}, D_{1,m}, D_{2,m}]^T$ is referred to as the IMD vector of subcarrier m, which defines the transmission states of the users in the three cells assigned to subcarrier m.

To minimize the cost of backhaul resources for BS cooperation, in this paper, we classify $D_{u,m}$ only into three states. Let us again assume that subcarrier m is assigned to users k, k', and

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k'' in cells u, u', and u'', respectively. Then, the three states of $D_{u,m}$ are defined as

$$D_{u,m} = \begin{cases} k, & \text{BS } u \text{ transmits } x_k^{(u)} \text{ to its intracell user } k \text{ on subcarrier } m \\ -1, & \text{BS } u \text{ switches off its transmission on subcarrier } m \\ k' \text{ (or } k''), & \text{BS } u \text{ cooperates to transmit } x_{k'}^{(u')} \left(\text{or } x_{k''}^{(u'')}\right) \text{ to user } k' \text{ (or } k'') \text{ in cell } u' \text{ (or } u'') \text{ on subcarrier } m. \end{cases} \quad (16)$$

Correspondingly, the InterCI mitigation is carried out under the constraints of

$$D_{u,m} \in \{k, k', k'', -1\} \quad (17)$$

$$\sum_{u=0}^{2} D_{u,m} \geq -2 \quad (18)$$

for $u \in \{0, 1, 2\}$ and $m \in \mathcal{M}$. Note that the constraint of (18) prevents from switching off all the three transmissions on one subcarrier. Furthermore, as shown in Section II, InterCI only exists among the three users sharing a subcarrier. Therefore, the InterCI mitigation can be considered subcarrier by subcarrier independently without performance loss. Hence, by considering the constraints of (17) and (18), we can rewrite the optimization problem of (15) as

$$\boldsymbol{D}_m^* = \arg\max_{\boldsymbol{D}_m} \left\{ \sum_{u=0}^{2} \log_2\left(1 + \gamma_k^{(u)}\right) \quad k \in \tilde{\mathcal{K}}^{(u)} \cap \mathcal{F}_m^{(u)} \middle| \left\{\mathcal{F}_m^{(u)} \forall u\right\}^* \right\}$$
$$\forall m \in \mathcal{M}$$
$$\text{subject to (17) and (18).} \quad (19)$$

It can be shown that both (15) and (19) are the mixed-integer nonlinear nonconvex problems, whose optimal solutions are extremely hard to derive. In the following, we will propose two novel InterCI mitigation algorithms, namely, the DDMC and the CDMC, which aim to find the promising suboptimal solutions for the problem of (19). Furthermore, we extend the OOP algorithm [31], [34], and [35] to the multicell downlink OFDMA systems and investigate its performance in association with the BWSA subcarrier allocation. Additionally, as a benchmark, we also consider the FIIDM scheme, which uses exhaustive search to find the optimal solutions for (19).

IV. Full Intercell Interference Information Relied Decision Making Algorithm

As aforementioned, the OOP, DDMC, and CDMC algorithms will be compared with the FIIDM algorithm, which relies on the continuous InterCI information, in contrast to the discrete InterCI information used by the DDMC and CDMC algorithms. Furthermore, the FIIDM algorithm uses exhaustive search to find the optimum solutions to the problem of (19). Hence, its performance represents an upper bound of the InterCI mitigation algorithms considered. The FIIDM algorithm can be described by Algorithm 1 with the aid of some further explanation.

***Algorithm 1*: (FIIDM Algorithm)**

Initialization:
(1) Set $\tilde{\mathcal{K}}_m = \{k | k \in \tilde{K}^{(u)} \cap \mathcal{F}_m^{(u)}, \forall u \in \{0,1,2\}\}, \forall m \in \mathcal{M}$.
(2) Set $D_{u,m} = k$ if $\mathcal{F}_m^{(u)} = \{k\}, \forall u \in \{0,1,2\}, \forall m \in \mathcal{M}$.
For Subcarrier $m \in \mathcal{M}$:
If $\tilde{\mathcal{K}}_m \neq \emptyset$, the *central unit* (CU) first collects the InterCI information of all the users in $\tilde{\mathcal{K}}_m$ and then **executes** the following.

Step 1 Compute the sum rates of all the optional decisions with power off only. The optional decisions include the following.
(1) Power off to one user: $\hat{D}_{u,m} = -1$, $\hat{D}_{u',m} = D_{u',m}$, $\hat{D}_{u'',m} = D_{u'',m}$, $\forall u, u', u'' \in \{0,1,2\}$ and $u \neq u' \neq u''$.
(2) Power off to two users: $\hat{D}_{u,m} = \hat{D}_{u',m} = -1$, $\hat{D}_{u'',m} = D_{u'',m}$, $\forall u, u', u'' \in \{0,1,2\}$ and $u \neq u' \neq u''$.

Step 2 Compute the sum rates of all the optional decisions with cooperation only. The optional decisions include the following.
(1) Cooperation between two BSs: $\hat{D}_{u,m} = \hat{D}_{u',m} = D_{u,m}$, $\hat{D}_{u'',m} = D_{u'',m}$, $\forall u, u', u'' \in \{0,1,2\}$ and $u \neq u' \neq u''$.
(2) Cooperation among three BSs: $\hat{D}_{u,m} = \hat{D}_{u',m} = \hat{D}_{u'',m} = D_{u,m}$, $\forall u, u', u'' \in \{0,1,2\}$ and $u \neq u' \neq u''$.

Step 3 Compute the sum rates of all the optional decisions with power off and/or cooperation. The optional decisions include the following.
(1) One BS sets power off to one user while the other two BSs cooperate for one user: $\hat{D}_{u,m} = \hat{D}_{u',m} = D_{u,m}$, $\hat{D}_{u'',m} = -1$, $\forall u, u', u'' \in \{0,1,2\}$ and $u \neq u' \neq u''$.

Step 4 The CU first identifies the best one among the preceding optional decisions, which can be expressed as AQ2

$$\boldsymbol{D}_m = \arg\max_{\hat{\boldsymbol{D}}_m} \left\{ \sum_{k \in \tilde{\mathcal{K}}_m} \log_2(1 + \gamma_k) \right\} \quad (20)$$

where $\hat{\boldsymbol{D}}_m = [\hat{D}_{u,m}, \hat{D}_{u',m}, \hat{D}_{u'',m}]^T$. Then, the CU informs the final IMD vector $\boldsymbol{D}_m = [D_{u,m}, D_{u',m}, D_{u'',m}]^T$ to the three BSs.

As shown in Algorithm 1, the FIIDM algorithm assumes that there is a CU, which is capable of collecting the ideal continuous InterCI information of all the cell-edge users. Based on the InterCI information collected, the CU then makes the

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optimum IMDs by exhaustive search and finally informs them to the BSs. From Algorithm 1, we can find that there are in total 21 optional decisions for one cell-edge user group, such as that in $\tilde{\mathcal{K}}_m$, containing three cosubcarrier users. Specifically, at Step 2, the FIIDM algorithm may turn off one or two transmissions to the three users, which gives six optional decisions. At Step 3, any one or two BSs may help another BS to set up a cooperative transmission, which gives nine different decisions. Finally, at Step 4, two BSs may cooperate while the other one is turned off, resulting in total six optional decisions. Therefore, there are in total 21 optional decisions. In Algorithm 1, (20) finds the best one among these 21 optional decisions.

From Algorithm 1 and the preceding analysis, we know that, for the three-cell OFDMA systems, the decision-making process of the FIIDM algorithm does not impose much complexity. As for each $\tilde{\mathcal{K}}_m$, there are only three cosubcarrier users, resulting in 21 optional decisions to be considered. However, the algorithm requires the continuous InterCI information of the cell-edge users for decision making, which may be sent to a CU or shared by the three BSs. This process may impose a heavy complexity burden on the backhaul network, particularly when there are a big number of the cell-edge users. Furthermore, it may be very hard to implement the FIIDM algorithm in the practical scenarios having a large number of cells. Therefore, we propose the more practical DDMC and CDMC algorithms, which only require the limited discrete InterCI information.

V. On–Off Power Intercell Interference Mitigation

The OOP algorithm employs an efficient method to combat InterCI, which does not require BS cooperation. It has been widely studied and used in multicell communication systems, for example, in [31], [34], and [35]. The basic principle of the OOP algorithm is to allow a BS to turn off the transmission on the subchannels conflicting strong InterCI. By doing this, there are two benefits. First, transmission on the poor subchannels can be avoided, which saves power for the future transmission, when the subchannels become better. Second, the InterCI imposed by these subchannels on the other cells can also be removed. The OOP algorithm is usually scheduled to be carried out by a BS one at a time, to avoid that two or three cells simultaneously turn off the transmission on the same subcarrier.

Let us illustrate in the following the OOP algorithm with the aid of an example. Assume that subcarrier m is allocated to users k, k', and k'' in cells u, u', and u'', respectively. Then, we can express the subchannel qualities on subcarrier m in a matrix form as

$$\boldsymbol{A}_m = \begin{bmatrix} A^{(u)}_{k,m} & A^{(u)}_{k',m} & A^{(u)}_{k'',m} \\ A^{(u')}_{k,m} & A^{(u')}_{k',m} & A^{(u')}_{k'',m} \\ A^{(u'')}_{k,m} & A^{(u'')}_{k',m} & A^{(u'')}_{k'',m} \end{bmatrix} = \begin{bmatrix} \frac{\left|h^{(u)}_{k,m}\right|^2}{2\sigma^2} & \frac{\left|h^{(u)}_{k',m}\alpha^{(u)}_{k,k'}\right|^2}{2\sigma^2} & \frac{\left|h^{(u)}_{k'',m}\alpha^{(u)}_{k,k''}\right|^2}{2\sigma^2} \\ \frac{\left|h^{(u')}_{k,m}\alpha^{(u')}_{k',k}\right|^2}{2\sigma^2} & \frac{\left|h^{(u')}_{k',m}\right|^2}{2\sigma^2} & \frac{\left|h^{(u')}_{k'',m}\alpha^{(u')}_{k',k''}\right|^2}{2\sigma^2} \\ \frac{\left|h^{(u'')}_{k,m}\alpha^{(u'')}_{k'',k}\right|^2}{2\sigma^2} & \frac{\left|h^{(u'')}_{k',m}\alpha^{(u'')}_{k'',k'}\right|^2}{2\sigma^2} & \frac{\left|h^{(u'')}_{k'',m}\right|^2}{2\sigma^2} \end{bmatrix} \quad (21)$$

where $A^{(i)}_{j,m}$ represents the subchannel quality of the transmission from BS i to user j on subcarrier m. Based on a column of $\boldsymbol{A}_m$, we can calculate a user's SIR. For example, the SIR of user k is given by $\eta^{(u)}_{k,m} = A^{(u)}_{k,m}/(A^{(u')}_{k,m} + A^{(u'')}_{k,m})$.

Let us consider one realization of the preceding example, and the matrix is given by

$$\boldsymbol{A}_m = \begin{bmatrix} 2.1909 & 0.0018 & 0.5078 \\ 1.4294 & 1.8621 & 0.1583 \\ 0.1168 & 3.3187 & 1.6459 \end{bmatrix}. \quad (22)$$

Then, by setting different SIR thresholds, the OOP algorithm generates different results for the IMD vectors $\boldsymbol{D}_m$ and derives different sum rates $C_\Sigma = \sum_{i\in\{k,k',k''\}} \log_2(1+\gamma_i)$. Note that, for the example, we assume the unit noise power. Specifically, for (22), when the SIR thresholds are $\eta_t = -5$, 0, and 5 dB, respectively, the OOP algorithm gives the IMDs as

$$\begin{cases} \text{(a)}: D_{u,m}=k, D_{u',m}=k', D_{u'',m}=k'', & \text{if } \eta_t = -5 \text{ dB} \\ \text{(b)}: D_{u,m}=k, D_{u',m}=-1, D_{u'',m}=k'', & \text{if } \eta_t = 0 \text{ dB} \\ \text{(c)}: D_{u,m}=D_{u',m}=-1, D_{u'',m}=k'', & \text{if } \eta_t = 5 \text{ dB} \end{cases} \quad (23)$$

which are explained as follows. First, if $\eta_t = -5$ dB $= 0.316$, there is no user turned off, since the SIRs of the three users are all higher than this SIR threshold. In this case, the sum rate on subcarrier m is $C_\Sigma = 2.4039$. Second, when $\eta_t = 0$ dB $= 1$, during the first stage, user k stays on, since its SIR is $\eta^{(u)}_{k,m} = 1.4171 > \eta_t$. During the second stage, the transmission to user k' is switched off, as its SIR of $\eta^{(u')}_{k',m} = 0.5608$ is lower than the threshold. During the third stage, user k'' finds that its SIR is higher than the threshold, after user k'' is turned off. Hence, it stays on. In this case, the sum rate becomes $C_\Sigma = 2.6311$, which is higher than $C_\Sigma = 2.4039$ of the first case. Finally, when $\eta_t = 5$ dB $= 3.1623$, the OOP algorithm turns off the transmissions to users k and k''. In this case, the sum rate attained on subcarrier m is $C_\Sigma = 1.4038$, which is also lower than that obtained in the case of $\eta_t = 0$ dB.

From the preceding example, we know that the performance of the system employing the OOP algorithm is highly dependent on the SIR threshold. If an improper SIR threshold is set, it may turn off too many or too few subchannels, which may lead to the degradation of throughput performance.

VI. Distributed Decision Making Assisted Cooperation Intercell Interference Mitigation

Here, we propose a novel InterCI mitigation scheme referred to as the DDMC. As its name suggests, the DDMC algorithm introduces BS cooperation to improve the system performance. In Section III, we have shown the benefits from the cooperative transmission to a user, if the cooperative BS imposes strong InterCI on the user. However, the cost for this cooperation is the increase of the complexity for information exchange between the BSs, and the cooperative BS has to stop transmitting information to its own user. Therefore, our DDMC algorithm is motivated to maximize the payoff from cooperation, while simultaneously minimizing the cost caused by cooperation.

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In the DDMC algorithm, the BSs are scheduled to make their IMDs successively and independently. When the SIR measured by a user is lower than the SIR threshold, it informs its BS to take one of the two actions: setting up a cooperative transmission for the user and switching off the transmission to the user. Let us use in the following the example shown in (21) to explain the principles. Assume that the SIR of user k is lower than the threshold η_t, the rules for user k to choose the desired action are

$$\text{Cooperation from BS } u', \text{ if } I_{u',k} > I_c \ \& \ I_{u'',k} \le I_c \quad (24)$$

$$\text{Cooperation from BS } u'', \text{ if } I_{u',k} \le I_c \ \& \ I_{u'',k} > I_c \quad (25)$$

$$\text{Power off, if } I_{u',k} > I_c \ \& \ I_{u'',k} > I_c \\ \text{or } I_{u',k} \le I_c \ \& \ I_{u'',k} \le I_c. \quad (26)$$

In the preceding equation, I_c is the cooperation threshold, which can be set according to the various communication objectives, for example, maximization of sum rate. Note that a user can only ask for cooperation when there is only one strong InterCI.

Let us now explain in detail why the rules in (24)–(26) are introduced with the aid of the example considered. First, suppose user k obtains the cooperation from BS u', then the SINRs of users k, k', and k'' become

$$\gamma_{k,m}^{(u)} = \frac{\left|h_{k,m}^{(u)}\right|^2 + I_{u',k}}{I_{u'',k} + 2\sigma^2} \qquad \gamma_{k',m}^{(u')} = 0$$

$$\gamma_{k'',m}^{(u'')} = \frac{\left|h_{k'',m}^{(u'')}\right|^2}{I_{u,k''} + I_{u',k''} + 2\sigma^2}. \quad (27)$$

From (27), we can know that the SINR of user k can be significantly improved, as the conditions in (24) are met. In this case, the sum rate of the three users is most probably increased, owing to making use of the strong InterCI of $I_{u',k}$. By contrast, when the conditions in (26) are met, we can know from (27) that the sum rate contributed by BS cooperation is insignificant. In these cases, it is better to simply turn off the transmission to user k, while keeping the other two users active.

In more detail, let us consider the values given in (22), from which we can find that the SIRs of the three uses are $\eta_{k,m}^{(u)} = 1.417$, $\eta_{k',m}^{(u')} = 0.5608$, and $\eta_{k'',m}^{(u'')} = 2.471$, respectively. By setting the various SIR thresholds and InterCI thresholds for cooperation, the DDMC algorithm yields the IMD variables as

$$\begin{cases} \text{(a)} : D_{u,m} = k, D_{u',m} = D_{u'',m} = k' & \text{, if } \eta_t = 0 \text{ dB}, \ I_c = 1 \\ \text{(b)} : D_{u,m} = D_{u',m} = k, D_{u'',m} = -1 & \text{, if } \eta_t = 5 \text{ dB}, \ I_c = 1. \end{cases} \quad (28)$$

Let us first consider the case of (a) in (28). In this case, user k stays on during the first stage, as its SIR is higher than η_t. During the second stage, user k' finds that its SIR is lower than η_t. Then, it informs BS u' to request the cooperation from BS u'', since $I_{u,k'} \le I_c$ and $I_{u'',k'} > I_c$, and the conditions in (26) are met. As a result, BS u'' switches off its transmission to user k'' and helps to transmit information to user k'. Consequently, the sum rate of subcarrier m is $C_\Sigma = 3.5213$, which is higher than that achieved by the OOP algorithm. Similarly, in the case of (b) in (28), the DDMC algorithm obtains the decision: BS u obtains the cooperation from BS u' for user k, while BS u'' turns off the transmission to user k''. Consequently, the sum rate achieved is $C_\Sigma = 2.2080$. Clearly, the sum rate is higher than 1.4038 obtained by the OOP algorithm for the corresponding case.

Based on the previous analysis and the examples, we can now summarize the DDMC algorithm as follows.

***Algorithm 2*: (DDMC Algorithm)**

For Stage $u = 0, 1, 2$:
For User $k \in \mathcal{K}^{(u)}$:
Initialization: Set $D_{u,m} = k$ if $\mathcal{F}_m^{(u)} = \{k\}, m \in \mathcal{M}$.
User k estimates its SIR $\eta_{k,m}^{(u)}$. If $\eta_k < \eta_t$, **execute** the following.

Step 1 User k informs BS u the requirement of InterCI mitigation. Go to Step 2 if (26) is met; otherwise, go to Step 3.

Step 2 BS u switches off the transmission to user k, yielding $D_{u,m} = -1$.

Step 3 BS u requests BS u' (or u'') for cooperation if (24) [or (25)] is met.
(1) BS u' (or u'') accepts the request if it has not accepted the cooperation requirement from another BS, giving $D_{u',m} = k$ (or $D_{u'',m} = k$). Then, go to Step 4.
(2) Otherwise, BS u' (or u'') refuses the request of BS u and proceeds to Step 2.

Step 4 BS u sends the data of user k to BS u' (or u''), and the two BSs carry out the STBC-based transmission to user k.

VII. Centralized Decision Making Assisted Cooperation Intercell Interference Mitigation

Here, we propose another InterCI mitigation scheme called CDMC, which motivates to make the best IMDs, to maximize the sum rate of the users on a subcarrier, and to improve the frequency reuse of the subcarriers. In addition to the assumptions made for the DDMC algorithm, the BSs operated under the CDMC are also assumed to share the "three-valued InterCI information" of the cell-edge users.

The DDMC algorithm is unable to always yield the best decisions because of the lack of InterCI information, such as the example (b) in (28). Inspired by this observation, the CDMC algorithm motivates to make the better decisions based on the three-valued InterCI information shared among the BSs while keeping the complexity low. Let us refer again to the example of (21), where subcarrier m is assumed to be allocated to users k, k', and k'' in cells u, u', and u'', respectively. In the CDMC,

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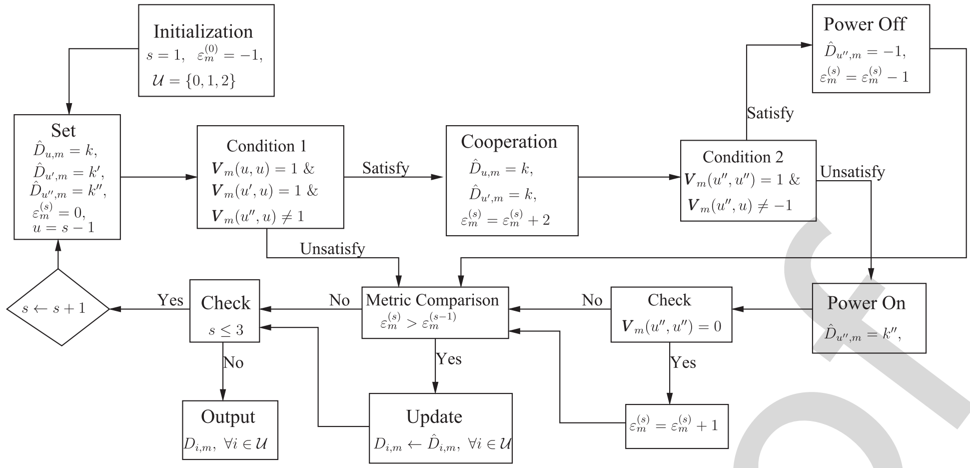

Fig. 2. Flowchart showing the operations of the CDMC algorithm in Case 1, when assuming $u \neq u' \neq u''$, and users k, k', k'' are in cells u, u', and u'', respectively.

the three values for the InterCI suffered by, e.g., user k from BS u', are defined as

$$v_{u',k} = \begin{cases} -1, & \text{if } I_{u',k} < I_o \\ 0, & \text{if } I_o \leq I_{u',k} < I_c \\ 1, & \text{if } I_{u',k} \geq I_c \end{cases} \quad (29)$$

where I_o and I_c are two new thresholds introduced for classifying the InterCI into three regions, which are as follows: 1) ignorable InterCI, when $v_{u',k} = -1$; 2) moderate InterCI, if $v_{u',k} = 0$; and 3) strong InterCI, when $v_{u',k} = 1$. Let the discrete InterCI among the three users be expressed as

$$\boldsymbol{V}_m = \begin{bmatrix} \nu_k & v_{u,k'} & v_{u,k''} \\ v_{u',k} & \nu_{k'} & v_{u',k''} \\ v_{u'',k} & v_{u'',k''} & \nu_{k''} \end{bmatrix} = \begin{bmatrix} \boldsymbol{v}_{k,m} & \boldsymbol{v}_{k',m} & \boldsymbol{v}_{k'',m} \end{bmatrix}. \quad (30)$$

Here, $\boldsymbol{V}_m$ is referred to as the discrete InterCI matrix, or simply the InterCI matrix, of subcarrier m, and $\boldsymbol{v}_{k,m} = [\nu_k \; v_{u',k} \; v_{u'',k}]^T$ is the InterCI vector of user j on subcarrier m. In (30), a nondiagonal element explains the strength of the InterCI between a BS and a user, which is given by (29). By contrast, a diagonal element indicates whether the corresponding user has its SIR below or above the SIR threshold η_t, which is defined as

$$\nu_i = \begin{cases} 1, & \text{if } \eta_i < \eta_t, \\ 0, & \text{if } \eta_i \geq \eta_t, \end{cases} \quad i = k, k', k''. \quad (31)$$

Based on the InterCI matrix $\boldsymbol{V}_m$ given by (30), the CDMC algorithm makes the decisions for a user according to the following four cases.

- Case 0 (*No Actions*): When $\nu_k = \nu_{k'} = \nu_{k''} = 0$, which means that the SIRs from BSs u, u', and u'' to users k, k', and k'' are all above the SIR threshold η_t. In this case, all BSs transmit data, respectively, to their users on subcarrier m.
- Case 1 (*Cooperation*): At least one of the three users on subcarrier m satisfies the following conditions:

$$\nu_k = 1 \;\&\; v_{u',k} = 1 \;\&\; v_{u'',k} \neq 1, k \in \mathcal{K}^{(u)} \quad u \neq u' \neq u'' \; \forall \, u \in \{0,1,2\}. \quad (32)$$

- Case 2 (*Possible Cooperation*): Any of the three users on subcarrier m does not satisfy the conditions in (32), but at least one of the users satisfies the following conditions:

$$\nu_k = 1 \;\&\; v_{u',k} = 1 \;\&\; v_{u'',k} = 1, \; k \in \mathcal{K}^{(u)} \quad u \neq u' \neq u'' \; \forall \, u \in \{0,1,2\}. \quad (33)$$

- Case 3 (*No Cooperation*): Any of the three users on subcarrier m does not satisfy the conditions of (32) and (33), but at least one of the users satisfies the following conditions:

$$\nu_k = 1 \;\&\; v_{u',k} \neq 1 \;\&\; v_{u'',k} \neq 1, \; k \in \mathcal{K}^{(u)} \quad u \neq u' \neq u'' \; \forall \, u \in \{0,1,2\}. \quad (34)$$

Let us discuss in the following the operations in the Cases of 1–3 in detail.

When the InterCI matrix $\boldsymbol{V}_m$ belongs to Case 1, the CDMC algorithm is operated as the flowchart shown in Fig. 2. In this case, cooperative transmission for a user with its SIR below the SIR threshold η_t can always be set up. To find the best cooperation option to maximize the sum rate of subcarrier m, as shown in Fig. 2, the decisions are made using three iterations indexed by s. Furthermore, for the sake of evaluating the quality of the decision made in an iteration, we introduce a metric $\varepsilon_m^{(s)}$ for the sth iteration of subcarrier m. It can be shown that, in Case 1, there are three possible strategies for InterCI mitigation.

Strategy 1: Two BSs cooperate to transmit to a user, while the other BS stops transmission. In this case, we have $\varepsilon_m^{(s)} = 1$, and the IMD variables are in the form of $D_{u,m} = k$, $D_{u',m} = k$, $D_{u'',m} = -1$.

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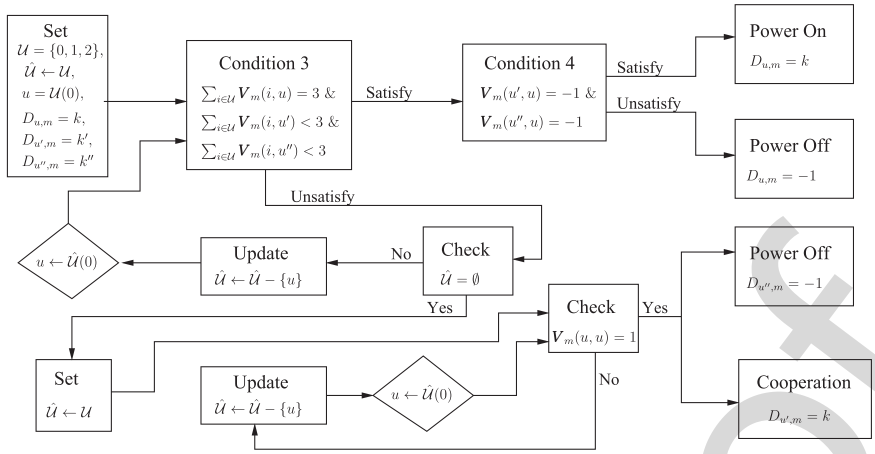

Fig. 3. Flowchart showing the operations of the CDMC algorithm in Case 2, when assuming that $u \neq u' \neq u''$; $u' < u''$, and users k, k', and k'' are in cells u, u', and u'', respectively.

Strategy 2: Two BSs cooperate to transmit to a user, while the other BS transmits to its own user with the SIR below the SIR threshold η_t. In this case, we have $\varepsilon_m^{(s)} = 2$ associated with the IMD variables taking the values as $D_{u,m} = k$, $D_{u',m} = k$, $D_{u'',m} = k''$.

Strategy 3: Two BSs cooperate to transmit to a user, while the other BS transmits to its own user with the SIR above the SIR threshold η_t. In this case, we have $\varepsilon_m^{(s)} = 3$, the IMD variables taking the values as $D_{u,m} = k$, $D_{u',m} = k$, $D_{u'',m} = k''$.

As stated previously, the CDMC algorithm motivates to maximize the sum rate of subcarrier m and the overall frequency reuse factor of the system. Hence, the algorithm makes the final decision in favor of these. Clearly, Strategy 1 has a very high probability to generate a smaller sum rate than Strategies 2 and 3, since Strategy 1 yields only one information transmission flow on subcarrier m. By contrast, Strategy 3 is the most desirable one, which has a much higher probability than the other two strategies to obtain a higher sum rate. This is because Strategy 3 allows cooperation between two BSs and another transmission from a BS to its user, yielding a high SIR. Hence, the cooperation in Strategy 3 has the least cost.

Let us further use the example of (22) to explain, when $\eta_t = 5$ dB and $I_c = 1$, $I_o = 0.1$. Then, when the CDMC algorithm is used, the InterCI matrix is given by

$$\boldsymbol{V}_m = \begin{bmatrix} 1 & -1 & 0 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix}. \qquad (35)$$

Explicitly, the operational situation is in Case 1, as the conditions in (32) are met for both users k and k'.

According to the operations in Fig. 2, during the first $(s = 1)$ iteration, the algorithm checks if a cooperation can be set up for user k. Since Condition 1 is met, a cooperation between BS u and BS u' can be set up for user k. However, BS u'' has to turn off the transmission to user k'', as Condition 2 of $\boldsymbol{V}_m(2,0) = 0$ is satisfied. Consequently, from the first iteration, the decisions derived are $\hat{D}_{u,m} = k$, $\hat{D}_{u',m} = k$, and $\hat{D}_{u'',m} = -1$, which belong to Strategy 1 and have a metric of $\varepsilon_m^{(1)} = 1$. During the second iteration, BS u' and BS u'' set up a cooperation for user k'. Furthermore, user k stays on because of $\boldsymbol{V}_m(0,1) = -1$. Therefore, from the second iteration, the decisions are $\hat{D}_{u,m} = k$, $\hat{D}_{u',m} = k'$, and $\hat{D}_{u'',m} = k'$; and the metric is $\varepsilon_m^{(1)} = 2$. During the third iteration, the algorithm finds that it is unable to set up a cooperation for user k''. Therefore, the final IMDs are given by the second iteration. It can be shown that, in this case, the sum rate achieved is $C_\Sigma = 3.5213$, which is much higher than $C_\Sigma = 2.208$ achieved by the DDMC.

Let us now address the operations of the CDMC algorithm operated under Case 2, the flowchart for which is shown in Fig. 3. There are two possible scenarios in Case 2. First, there is only one user, e.g., user k, having the SIR below η_t. In this case, as shown in Fig. 3, Condition 3 is satisfied, and user k suffers from two strong InterCI signals. Hence, due to the same reason for (26), the algorithm does not set up a cooperation for user k. Instead, it makes a decision about whether the transmission to user k should be switched off or kept on. Specifically, the transmission to user k is kept on, only when the transmission to it does not cause strong InterCI to the other two users, i.e., when Condition 4 is satisfied. Otherwise, the transmission to user k is switched off. Second, there are more than one user having the SIR below η_t. In this scenario, a cooperation can be set up for a user, e.g., user k, with low SIR, while the transmission to the other user is switched off in order not to interfere the cooperation. Consequently, in Case 2, there are two possible InterCI mitigation strategies; one is Strategy 1, which has been described under Case 1. The other one is Strategy 4, corresponding to the first scenario described earlier, which is stated as follows.

Strategy 4: Switching off the transmission to one user, while keeping the transmission to the other two users, corresponding to the IMD variables in the form of $D_{u,m} = -1$, $D_{u',m} = k'$, and $D_{u'',m} = k''$.

Finally, let us consider the CDMC algorithm operated under Case 3 with the aid of Fig. 4. In this case, no cooperation for the users with poor SIR can be established, and the algorithm only needs to decide whether some transmissions should be switched

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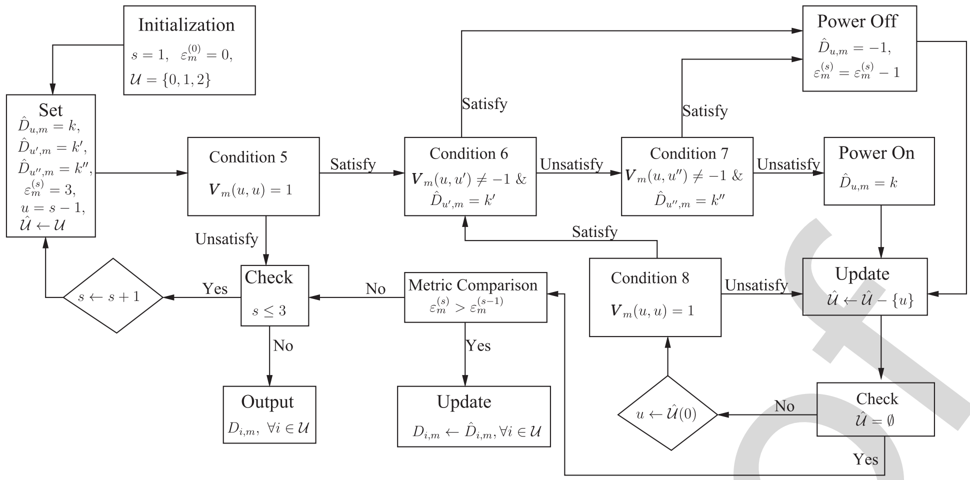

Fig. 4. Flowchart of Case 3 showing the operations of the CDMC algorithm, when assuming that $u\neq u'\neq u''$; $u'<u''$, and users k, k', and k'' are in cells u, u', and u'', respectively.

off to remove the strong InterCI imposing on the other users. As shown in Fig. 4, the final IMDs can be made after three iterations to consider all the possible options. Similar to Case 1, here, a metric $\varepsilon_m^{(s)}$ is introduced to evaluate the qualities of the decisions made during an iteration. As shown in Fig. 4, there are three optional decisions. The most desirable one is to keep all the three transmissions on subcarrier m, which gives a metric of $\varepsilon_m^{(s)}=3$. The next desirable decision is Strategy 4, which gives a metric of $\varepsilon_m^{(s)}=2$. The least desirable decision is given by Strategy 5, which is described as follows.

Strategy 5: Switching off two transmissions to two users while the other one remains on. Correspondingly, we have $\varepsilon_m^{(s)}=1$, and the IMD variables with the values of $D_{u,m}=-1$, $D_{u',m}=-1$, and $D_{u'',m}=k''$.

In summary, the principles of the CDMC algorithm considering Cases 0–3 can now be described as follows.

***Algorithm 3*: (CDMC Algorithm)**

Initialization:

(1) All users in the three cells estimate their SIRs: $\eta_{k,m}^{(u)}=|h_{k,m}^{(u)}|^2/(I_{u',k}+I_{u'',k})$, if $k\in\mathcal{F}_m^{(u)}$, $k'\in\mathcal{F}_m^{(u')}$, and $k''\in\mathcal{F}_m^{(u'')}$ and $m\in\mathcal{M}$; $\forall\,k\in\mathcal{K}^{(u)}$ and $\forall\,u\in\{0,1,2\}$.

(2) Set $\mathcal{K}_m=\{k|k\in\mathcal{F}_m^{(u)},\forall\,u\in\{0,1,2\}\}$, $\hat{\mathcal{K}}_m=\{k|\eta_k<\eta_t,k\in\mathcal{K}_m\},\forall\,m\in\mathcal{M}$.

For subcarrier $m\in\mathcal{M}$:
If $\hat{\mathcal{K}}_m\neq\emptyset$, **execute**:

Step 1 All discrete InterCI of the users in $\hat{\mathcal{K}}_m$ are sent to the head BS.

Step 2 Head BS asks for the discrete InterCI of all the users in $\mathcal{K}_m-\hat{\mathcal{K}}_m$. (*Note that, after Steps 1 and 2, the head BS has the knowledge of* $\boldsymbol{V}_m$.)

Step 3 Based on $\boldsymbol{V}_m$, the head BS makes the IMDs based on the strategies in Cases 1, 2, and 3, as described in Figs. 2–4.

Step 4 The head BS informs the other BSs the InterCI decisions by sending them the decisions of $\mathcal{D}_m$.

Note that, instead of letting a head BS make the decisions, we may let all the BSs make the decisions. This way, there is no need for a BS to inform the other BSs its decisions, but all the BSs have to share the InterCI information for making decisions. Specifically, in this approach, when a BS knows that one of its users has the SIR below the threshold η_t, it then broadcasts the discrete InterCI vector of the user, such as the vector $\boldsymbol{v}_{k,m}$ in (30), to the other two BSs. Once receiving the InterCI vector, the other two BSs also broadcast the InterCI information of their users sharing the same subcarrier, regardless of the SIR values of their users. This way, all the three BSs have the full knowledge of the discrete InterCI matrix of a subcarrier. Hence, they can make the same decisions in the principles of the CDMC under Case 1, 2, or 3.

So far, we have considered the principles of four types of InterCI mitigation algorithms, namely, the FIIDM, OOP, DDMC, and CDMC algorithms. In the context of a three-cell downlink OFDMA system, the InterCI mitigation is operated independently for the cell-edge user groups, each having three cosubcarrier users. We should note that these InterCI mitigation algorithms can all be modified for deployment in practical multicell systems, which may have a big number of cells, and each cell may host an arbitrary number of users. First, owing to the structure of practical cellular systems, one user can usually simultaneously receive strong InterCI from at most two neighboring cells, which happens when a user is located at the borders of three cells. Therefore, even in practical multicell systems, one cell-edge user group contains only three cosubcarrier users. Furthermore, if the three cosubcarrier users in one group are not related to the other cell-edge user groups, then all the algorithms considered in our paper can be directly applied for InterCI mitigation. However, there is a possibility that one

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user is simultaneously a member of two or more cell-edge user groups. In this case, the InterCI algorithms can be modified to simply switch off the transmission to a user belonging to two or more cell-edge user groups. In fact, our proposed DDMC and CDMC algorithms can be readily modified to implement this operation. This can be achieved by switching off the transmission to one user on a subcarrier, whenever the user's serving BS receives two or more requests from other BSs for cooperation. Second, concerning the case that different cells may have different numbers of users, this only affects the subcarrier allocation but not the InterCI mitigation, as the InterCI mitigation only considers cell-edge users. However, when the number of subcarriers is higher than the number of users in a cell, one benefit is that a cell-edge user has an extra option to choose another subcarrier experiencing less InterCI. Nevertheless, this paper focuses on the InterCI mitigation; we hence avoid considering these trivial cases.

VIII. Performance Results

Here, we provide a range of simulation results, to demonstrate and compare the achievable spectral efficiency performance of the multicell downlink OFDMA systems employing the BWSA subcarrier-allocation algorithm and the various InterCI mitigation algorithms. We assume that all subcarriers experience independent flat Rayleigh fading. The path loss exponent in (4) is assumed to be $\mu = 4.0$, and the standard deviation of the shadowing effect is $\Upsilon = 8$ dB. Furthermore, for the sake of explicit comparison, we address the performance by focusing on the cell-edge users in the system. In the following figures, the average spectral efficiency of cell-edge users per cell is given by

$$C = \frac{1}{3}\sum_{u\in\{0,1,2\}}\sum_{k\in\tilde{\mathcal{K}}^{(u)}}\log_2(1+\gamma_k), \text{ (bits/s/Hz/cell)}. \quad (36)$$

Correspondingly, the average spectral efficiency per cell-edge user is

$$C = \frac{1}{|\tilde{\mathcal{K}}|}\sum_{u\in\{0,1,2\}}\sum_{k\in\tilde{\mathcal{K}}^{(u)}}\log_2(1+\gamma_k), \text{ (bits/s/Hz/user)} \quad (37)$$

where $\tilde{\mathcal{K}} = \tilde{\mathcal{K}}^{(0)}\cup\tilde{\mathcal{K}}^{(1)}\cup\tilde{\mathcal{K}}^{(2)}$, and $\tilde{\mathcal{K}}^{(u)}$, $u\in\{0,1,2\}$ is defined in (15). In (36) and (37), γ_k is the SINR of user k, which is given by (6) or (7).

Fig. 5 compares the spectral efficiency performance of the different InterCI mitigation algorithms employed by the three-cell downlink OFDMA systems. From the results, we can obtain the following observations. First, for all the considered SIR thresholds, both the proposed DDMC and CDMC algorithms yield higher spectral efficiency than the OOP algorithm, and higher than the case without InterCI mitigation, labeled as "Non InterCI mitigation" in the figure. As shown in the figure, the DDMC and CDMC algorithms become more advantageous over the OOP algorithm as the threshold η_t reduces. This is because the DDMC and CDMC algorithms motivate to establish cooperative transmissions for the cell-edge users, instead

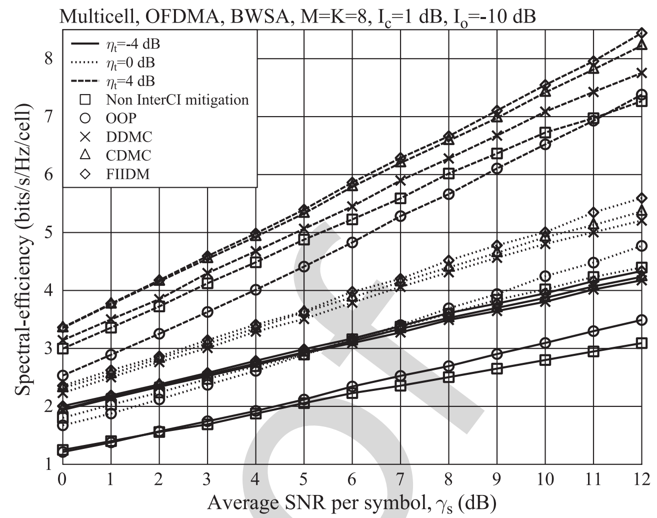

Fig. 5. Spectral efficiency of cell-edge users in the multicell downlink OFDMA systems employing the BWSA subcarrier-allocation algorithm and various InterCI mitigation algorithms.

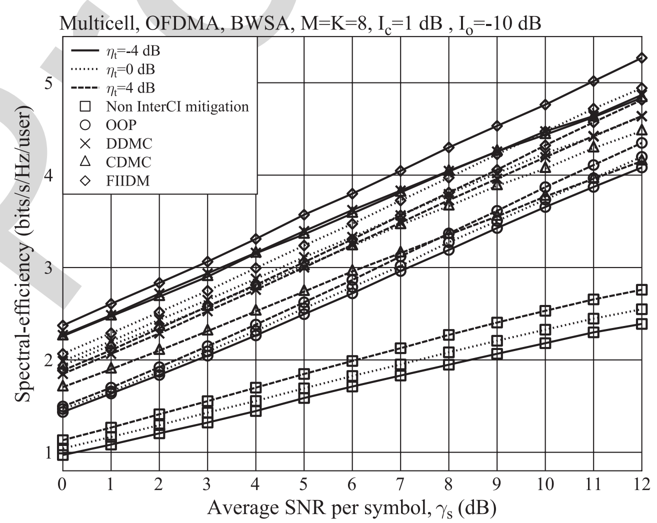

Fig. 6. Spectral efficiency per active cell-edge user in the multicell downlink OFDMA systems employing the BWSA subcarrier-allocation algorithm and various InterCI mitigation algorithms.

of simply switching off. As η_t reduces, the number of users requiring cooperation or switching off becomes less, which means that the "edge users" are closer to the cell's physical edge. In this case, setting up cooperation for the cell-edge users will be more beneficial than simply switching them off. Second, we can observe that the CDMC algorithm always outperforms the DDMC algorithm, and the gain becomes bigger as the SIR threshold η_t increases. This is because, in the CDMC algorithm, the BSs find the joint IMDs, whereas in the DDMC algorithm, each BS makes distributed IMDs only for its own users. Furthermore, the CDMC algorithm attains more SNR gain than the DDMC algorithm, when the number of cell-edge users increases, as a result of the increase of the SIR threshold η_t. Third, Fig. 5 shows that the OOP algorithm may become useless in InterCI mitigation, when the SIR threshold is high, such as $\eta_t = 4$ dB. In this case, there will be many

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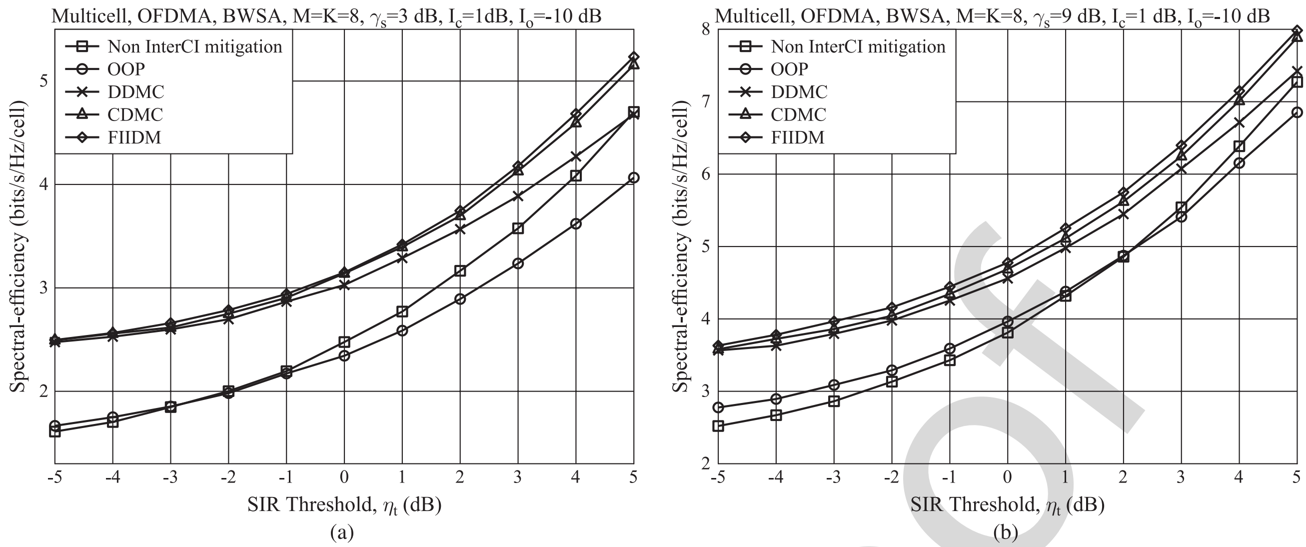

Fig. 7. Comparison of spectral efficiency performance of cell-edge users in the multicell downlink OFDMA systems employing various InterCI mitigation algorithms when different SIR thresholds are applied. (a) $\gamma_s = 3$ dB. (b) $\gamma_s = 9$ dB.

users turned off. Fourth, as shown in Fig. 5, the OOP algorithm becomes more effective, when the average SNR gets larger. Therefore, when the system is too noisy or when the switching off threshold is too high, too many users may be switched off, and the use of the OOP algorithm is not beneficial for the systems. Explicitly, the proposed DDMC and CDMC algorithms are capable of avoiding these drawbacks of the OOP algorithm, by setting up cooperation for cell-edge users, instead of simply turning them off. Finally, we can observe that the spectral efficiency performance attained by the CDMC algorithm is very close to that obtained by the FIIDM scheme, which uses the continuous InterCI information for decision making, whereas the CDMC algorithm only relies on the three-valued discrete InterCI information for decision making. As shown in the figure, the CDMC algorithm attains nearly the same spectral efficiency as the FIIDM scheme when the average SNR is relatively low.

In Fig. 6, we investigate the average spectral efficiency per active cell-edge user. First, we can observe that any of the three InterCI mitigation schemes significantly outperforms the case of Non InterCI mitigation. Second, the CDMC algorithm achieves lower spectral efficiency than the DDMC algorithm for all the SIR thresholds considered. The CDMC algorithm aims to maximize both the system's sum rate and the frequency reuse factor, whereas the DDMC algorithm is only sum rate motivated. Specifically, the DDMC algorithm simply switches off the transmission to the user when a cooperation is unavailable. By contrast, the CDMC algorithm still allows the transmission to the user, provided that this transmission does not cause strong InterCI to the other users. Consequently, given the same SIR threshold, the number of active cell-edge users resulted from the CDMC algorithm is higher than that resulted from the DDMC algorithm. This makes the average spectral efficiency per active edge user attained by the CDMC algorithm smaller than that obtained by the DDMC algorithm. Finally, the FIIDM scheme yields the highest spectral efficiency, as shown in Fig. 6.

Fig. 7 compares the spectral efficiency performance of the cell-edge users, when the SIR threshold varies in the range of -5 dB $\leq \eta_t \leq 5$ dB. From the figures, we observe that the proposed DDMC and CDMC algorithms outperform the other two algorithms considered. As shown in the figures, the spectral efficiency performance of the proposed DDMC and CDMC algorithms and the OOP algorithm are all dependent on the SIR threshold applied. By comparing Fig. 7(a) with Fig. 7(b), we can see that the intersection between the curves of the OOP algorithm and the Non InterCI mitigation case shifts from $\eta_t = -2$ dB to $\eta_t = 2$ dB, when the average SNR per symbol is increased from $\gamma_s = 3$ dB to $\gamma_s = 9$ dB. Note that, as shown in Fig. 7, the spectral efficiency in the case of Non InterCI mitigation also increases, as η_t increases. This is because more users are considered as the cell-edge users, as η_t increases, which makes the spectral efficiency evaluated by (36) increase. Note furthermore that, at a given SNR, when η_t increases, more users will be included as the cell-edge users, among which, more users could be turned off, when the OOP algorithm is applied. This makes the spectral efficiency of a cell achieved by the OOP algorithm become lower than that obtained by doing nothing. Furthermore, Fig. 7 once again shows that the proposed CDMC is capable of achieving the spectral efficiency close to that of the FIIDM scheme.

In Fig. 8, we show the effect of the InterCI cooperation threshold I_c and the off-power threshold I_o on the spectral efficiency per cell, when the multicell downlink OFDMA systems employ the DDMC or CDMC algorithms. Explicitly, in Fig. 8(a), for both the proposed algorithms, there are desirable I_c values, which result in the highest spectral efficiency. In general, when the threshold I_c becomes smaller, the proposed algorithms try to establish cooperation for more users. By contrast, when I_c becomes larger, they allow cooperation for fewer users. Note that, when $\eta_t = -4$ dB, Fig. 8(a) shows that the highest spectral efficiency per cell achieved by the DDMC and CDMC algorithms requires that -6 dB $\leq I_c \leq 6$ dB. However, the best I_c range for the two algorithms is reduced

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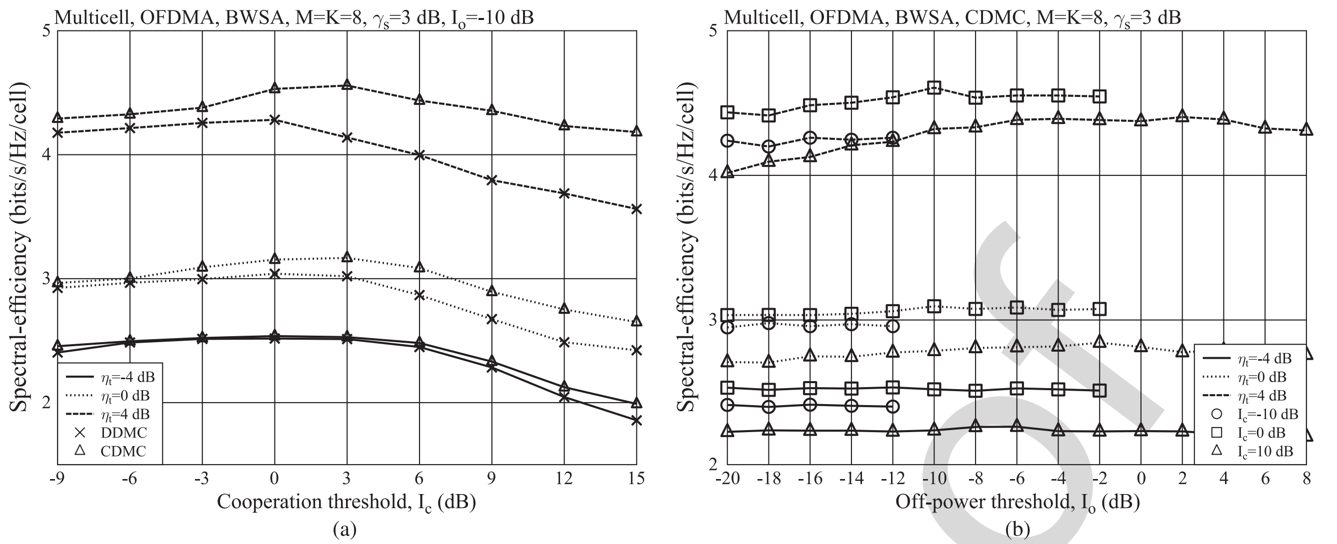

Fig. 8. Comparison of spectral efficiency performance of cell-edge users in the multicell downlink OFDMA systems employing various InterCI mitigation algorithms with different InterCI cooperation thresholds I_c and off-power thresholds I_o. (a) Effect of I_c. (b) Effect of I_o.

to -3 dB $\leq I_c \leq 3$ dB when $\eta_t = 0$ dB and to -1 dB $\leq I_c \leq 1$ dB when $\eta_t = 4$ dB. This observation implies that the spectral efficiency achieved by the two proposed algorithms becomes more sensitive to the cooperation threshold I_c, as the SIR threshold increases. In Fig. 8(b), the results show that, at a low SIR threshold, such as $\eta_t = -4$ dB, the spectral efficiency per cell slightly varies, when different values of I_o are employed. However, the CDMC algorithm yields a more explicit fluctuating spectral efficiency per cell with respect to I_o, as the SIR threshold η_t gets higher. Overall, we see that the spectral efficiency achieved by the CDMC algorithm is not very sensitive to the InterCI off-power threshold I_o.

From Figs. 5 to 7, we may conclude that the SIR thresholds η_t for both the DDMC and CDMC algorithms should be chosen according to the design objectives, to yield a good tradeoff between performance and complexity. From Fig. 8, we are given to understand that the threshold I_c can be set to an appropriate value, so that a "good" fraction of users experiencing strong InterCI are identified for BS cooperation, to improve the spectral efficiency. Once the SIR threshold η_t and the cooperation threshold I_c are set, an off-power threshold I_o can then be chosen within a relative large range of $I_o < I_c$ by the CDMC algorithm, as shown in Fig. 8(b).

In Figs. 9 and 10, we investigate the frequency reuse factor of the downlink OFDMA systems. Explicitly, the frequency reuse factor obtained by the CDMC algorithm is significantly higher than those given by the other algorithms. We also observe that the frequency reuse factor obtained by the CDMC algorithm increases sharply, as η_t increases. By contrast, the frequency reuse factor achieved by the other two algorithms decreases, as η_t increases. The preceding observations imply that, with the CDMC algorithm, the multicell downlink OFDMA system can simultaneously provide services for more users, although some of them might have relatively low rates. By contrast, when the DDMC or the OOP algorithm is employed, the number of users switched off increases as η_t increases, which results in the drop of the frequency reuse factor. Fig. 9 shows that the frequency

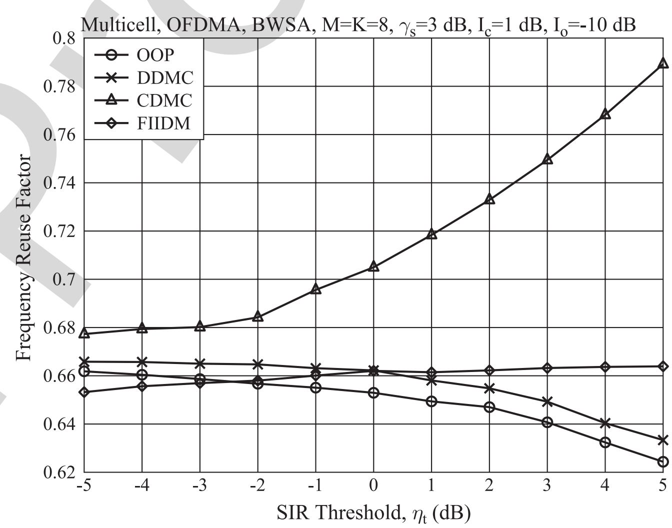

Fig. 9. Frequency reuse factor of cell-edge users in the multicell downlink OFDMA systems employing various InterCI mitigation algorithms with respect to different SIR thresholds η_t.

reuse factor achieved by the DDMC algorithm is slightly higher than that obtained by the OOP algorithm, owing to the cooperation introduced in the DDMC algorithm. Additionally, as shown in Fig. 9, the FIIDM algorithm yields a lower frequency factor than the DDMC and OOP algorithms in the low-η_t regimes. This means that, to maximize the spectral efficiency, the FIIDM algorithm has to turn off the transmissions with poor SIR.

Fig. 10 shows that the frequency reuse factor obtained by the CDMC algorithm increases toward one, as the InterCI cooperation threshold I_c increases. This is because, when the cooperation threshold I_c is set higher, it will be more difficult for the CDMC algorithm to establish cooperation for cell-edge users. Therefore, more cell-edge users will be kept on. Furthermore, as the figure shows, when $I_c \leq 0$ dB, the frequency reuse factor achieved by the CDMC algorithm slightly decreases, as the SIR threshold increases. For the DDMC algorithm, as

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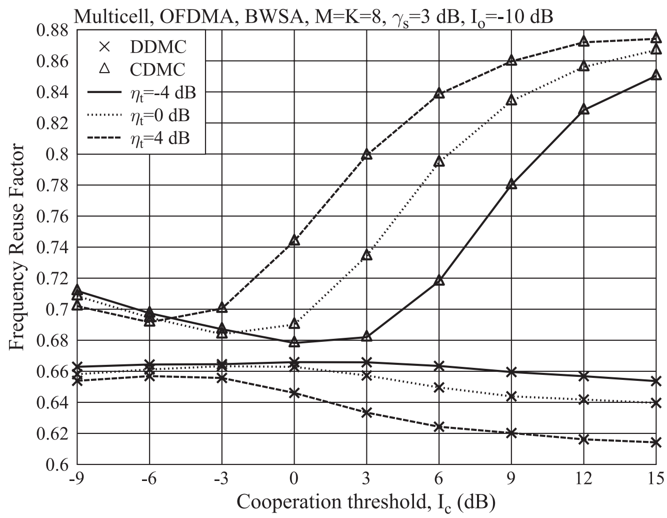

Fig. 10. Frequency reuse factor of cell-edge users in the multicell downlink OFDMA systems employing various InterCI mitigation algorithms with respect to different InterCI cooperation thresholds I_c.

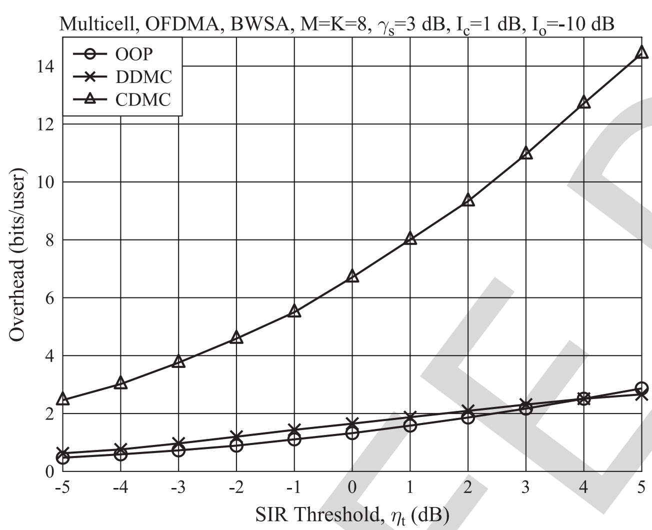

Fig. 11. Overhead required by the various InterCI mitigation algorithms.

shown in Fig. 10, the frequency reuse factor slightly decreases, as the threshold I_c increases. This is the result that the DDMC algorithm turns off more users, when the threshold I_c becomes higher.

Explicitly, the operations of the OOP, DDMC, and CDMC algorithms require different overheads. Hence, in Fig. 11, we compare the overhead required by the various InterCI mitigation algorithms. Here, the overhead is measured by the number of bits per user, which is obtained from the total overhead (bits) of a cell divided by the number of users in the cell. The overhead considered includes the control information transmitted between users and their BSs and those among BSs, plus the data symbols shared among the BSs for cooperation. For all the three InterCI mitigation algorithms, we assume that 1 bit is required to transmit a request for cooperation or off-power. Furthermore, in Fig. 11, we assume that, under the CDMC algorithm, the decisions are made by the head BS, as described in Algorithm 3. The discrete InterCI vector of a subcarrier, such as $\boldsymbol{v}_{k,m}$ in (30), has 18 different states. Hence, a BS needs 4 bits to convey the discrete InterCI vector of a subcarrier. Therefore, in total, 8 bits of overhead are required for the two BSs to inform the head BS their InterCI information of a subcarrier. In addition, another 3 bits are required for the head BS to broadcast the IMDs of a subcarrier to the other two BSs, since the decisions have nine states in total. As the number of cell-edge users increases, when the SIR threshold gets higher, Fig. 11 correspondingly shows that the required overhead for all the three algorithms increases, as the SIR threshold becomes higher. Furthermore, the CDMC algorithm requires higher overhead than the other two algorithms. However, the DDMC algorithm requires very low overhead, which is similar to that required by the OOP algorithm.

IX. Conclusion

In this paper, we have proposed the DDMC and CDMC algorithms for mitigating the InterCI among the cell-edge users sharing the same subcarrier. While both the DDMC and CDMC InterCI mitigation algorithms motivate to maximize the spectral efficiency, the CDMC algorithm also aims to maximize the frequency reuse factor. In this paper, we have compared from different perspectives the achievable performance of the downlink OFDMA systems employing the various InterCI mitigation schemes. Our studies and performance results show that both the DDMC and CDMC algorithms are capable of achieving higher spectral efficiency than the OOP algorithm, and, certainly, than the case without employing any InterCI mitigation. Although only the three-valued discrete InterCI information is shared among the BSs, the CDMC algorithm is capable of attaining nearly the same performance as the optimal FIIDM scheme that uses the continuous InterCI information for decision making.

Additionally, the CDMC algorithm is demonstrated to have the highest frequency reuse factor in addition to its spectral efficiency advantage, whereas the DDMC algorithm requires a small amount of overhead, which is similar to that of the OOP algorithm.

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Dr. Ni was a Voting Member of the IEEE 802.11 Wireless Standard Working Group and a Contributor to the IEEE Wireless Standards.

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AQ1 = TDD was expanded as "time division duplex." Please check if appropriate. Otherwise, please provide the corresponding expanded form.
AQ2 = STEP 5 in algorithm was changed to STEP 4. Please check if appropriate.
AQ3 = Please provide publication update in Ref. [26].
AQ4 = SDN was expanded as "software-defined networking." Please check if appropriate. Otherwise, please provide the corresponding expanded form.

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