Downlink Femtocell Interference Mitigation and Achievable Data Rate Maximization: Using FBS Association and Transmit Power Control Schemes

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Abstract—How to associate a femto user (FU) to an appropriate femto base station (FBS) to avoid interference and maximize the achievable data rate (ADR) of FUs have attracted much more attention in femtocell networks. The evidence provided in this paper proves it as an NP-complete problem. To maximize the ADR of the FUs, the methods for assigning FUs to neighboring FBSs are examined to determine the required transmit power level adjustments for the FBSs to mitigate the downlink (DL) interference among the FBSs and the macro base station (MBS). Traditionally, the linear programming (LP) approach is adopted to obtain the optimal solution for this problem. However, the LP approach requires substantially more time to obtain the solution. To improve the drawback, we propose an easy but smarter scheme, named smart FBS selection algorithm (SFSA), to distribute FUs to the non-interfered FBSs as well as to obtain the maximal ADR for each FU. If the SFSA fails to solve this problem, a DL power-control algorithm (DPCA) is employed to find a solution that causes the least amount of interference. The simulation results show that the SFSA and DPCA require only a minimal amount of computation time to obtain a feasible solution. The results show that the maximal data rates of the FUs obtained using the SFSA and DPCA are comparable to that of the LP approach.

Index Terms—Algorithm, data rate, femtocell selection, interference, power control, topology

I. INTRODUCTION

A VOIDING transmission interference in femtocell networks is an emerging problem for the fourth-generation communication networks. A femto base station (FBS) is a low power and cost-efficient base station (BS) that provides adequate coverage for small areas, making it highly suitable for indoor radio services [1], [2]. Because network subscribers can arbitrarily install FBSs [3], the topology of femtocell networks remains unfixed [4]. It is highly possible that FBSs could apply the maximal transmit power level (TPL) to serve femto users (FUs), thereby improving the signal-to-interference plus noise ratio (SINR) that supports high-speed data transmission [5]. However, in environments that contain numerous coexisting FBSs, an FU could select an inappropriate target FBS (TFBS) as its serving FBS (SFBS), thereby causing interference with nearby FBSs [6]. The flexible installation of FBSs could also cause problems that any FUs suffer unpredictable interference from nearby FBSs or the outdoor macro base station (MBS) in the downlink (DL) direction if they operate on a same frequency band [7].

Fig. 1 classifies the interference problem into two categories and six subcategories. The first interference category occurs in the DL direction, where the interference could affect a macro user (MU) or FU as a result of various signal sources, such as an MBS (Case I) or FBSs (Cases II and III). The second interference category occurs in the uplink (UL) direction, and includes signals transmitted from an MU (Case V) or FU (Cases IV and VI), which might interfere with any neighboring FBSs or overlaid MBSs in the UL direction. Accordingly, Cases I, II, and III are DL interference problems, whereas Cases IV, V, and VI are UL interference problems [8], [9]. This paper focuses on the DL interference problem. Selecting the appropriate FBSs to serve all FUs based on the SINR metric could relieve the interference problem.

Numerous previous studies have shown that the discussed radio interference problems can be solved by adopting either distributed manners [10]–[14] or centralized manners [5], [15]–[17]. The distributed manners solve the interference problem by allowing each FBS to follow predefined rules in an uncooperative way. However, the FBSs must frequently exchange...
relevant information, such as channel measurements, with neighboring FBSs via secure tunnels (i.e., backhaul networks), which consumes a substantial amount of bandwidth for the backhaul networks. Regarding the centralized manner, it has a higher probability of finding an optimal solution because the network topology information is more complete than that of the distributed manners. From our observation, it has numerous characteristics and benefits to develop centralized manners. The following six reasons support this argument:

1) Because the majority of FUs access FBSs in an indoor environment, their SINR values are relatively stable because the FUs are typically stationary or they move slowly, which implies that changes in their circumstances are rare [18].

2) The centralized manner have a higher probability of finding an optimal solution because the network topology information is more complete than that of a distributed manner.

3) Because the circumstances are typically unchanged, the need for information updates is less frequent; that is, the information update overhead required by a centralized manner is lower than that required by a distributed manner.

4) Conversely, the update overhead required to collect the complete network topology information is quite substantial if a distributed manner is adopted to obtain the optimal solution [19].

5) From operational and management perspectives, the centralized manners (e.g., the CPE WAN management protocol TR-069 [20] and the femto access point service data model TR-196 [21]) are always better than the distributed manners.

6) Although FBSs are installed by subscribers, the management system continues to enforce the FU to perform radio environment measurements via the FBS, and transmits data to construct the neighboring list and self-organizing network (SON) parameters [22].

Moreover, the E-UTRAN architecture [23] deploys an FBS gateway (GW) that allows the S1 interface among the FBSs and the evolved packet core (EPC) to support a large number of FBSs in scalable manner. In this architecture, FBSs automatically discover and connect to the FBS GWs. Thus, the FBS GW can acquire relevant information from the FBSs and execute the interference mitigation algorithm. Therefore, the goal of this study is to adopt a centralized manner to solve the problem of interference in femtocell networks as well as maximize the average achievable data rate (ADR) of all FUs.

Although the linear programming (LP) approach [24], [25] has been employed to obtain the optimal solution, this approach requires a substantial amount of time and computing resources. To overcome this drawback, a smart FBS selection algorithm (SFSA) is proposed to quickly find a feasible non-interfered femtocell network topology with the maximal TPL as a solution, if a solution exists. If the SFSA fails to find a feasible solution, a downlink power control algorithm (DPCA) is further employed to quickly derive the sub-optimal solution. Regardless of which algorithm is adopted, the obtained solution always fulfills the requirement that each FU in the system is served by only one FBS.

Previous studies have mitigated the interference problem by selecting appropriate cells [26]-[28]. In this paper, it is shown that the interference problem caused by FBS and FU matching can be solved by adopting graph theory. This problem is similar to the job assignments of the bipartite matching problem [29] in graph theory, although it is more complex because it must consider interference. Specifically, the contributions of this paper are highlighted as follows:

1) For a given number of FUs and FBSs with a set of tunable TPLs, proof shows that the problem of finding a non-interfered topology by using TPL control, as well as maximizing the average ADR per FU is an NP-complete problem.

2) The proposed SFSA and DPCA improve the average ADR of all FUs, while causing considerably less overhead than the distributed manners.

II. SYSTEM MODEL

The studied system is modeled as 2-tier heterogeneous femtocell networks [4] which consist of an MBS, $M$ FBSs, and $N$ FUs. The type of FBSs considered in this paper can be either an open subscriber group (OSG) FBS, or a closed subscriber group (CSG) FBS [8], [9]. The MUs are not considered in the studied model because only the DL interference problem with respect to the FUs [27] is considered. Let $B_f = \{ f_1, f_2, \ldots, f_M \}$ denote a set of FBSs. The number of elements in $B_f$ is represented as $|B_f| = M$. Similarly, let $U_f = \{ u_1, u_2, \ldots, u_N \}$ denote a set of FUs, and $|U_f| = N$.

Because FBSs are employed to improve the coverage ratio, all of the FBSs are operated within the MBS’s radio coverage range at an identical frequency band, and each FBS has $K$ TPLs for DL transmit power adjustment. The received signal power from $f_i$ to $u_j$ is expressed as:

$$P_{ij} = P[|l_i|^\mu - L_{ij}],$$

(1)

where $P[|l_i|^\mu]$ represents the transmit power of $f_i$ with TPL $l_i = 0, 1, \ldots, K$, and $L_{ij} = 10^\log_{10}(d(f_i, u_j)) + \mu + \omega_{ij}$ denotes the path loss (in dB). Here, $d(f_i, u_j)$ is the distance measured in meters between $f_i$ and $u_j$, $\omega_{ij}$ is the wall loss (in dB), and $\mu$ is a constant which accounts for path losses. If $l_i = K$, then $f_i$ operates at the maximal TPL to serve the FUs. If $l_i = 0$, then $f_i$ is inactive and it cannot provide access service to the FUs. The notations $P_{ij}$ and $P[|l_i|^\mu]$ are measured in dBm. Under ideal settings, it is assumed that the omni-directional transmit power decays as the $c$-th power of distance.

Definition 1. The FU $u_j$ is said to be in the radio coverage of the FBS $f_i$ with TPL $l_i$ in the DL direction if the received signal power $P_{ij}$ of $u_j$ exceeds the given power level threshold $\Gamma$, i.e., $P_{ij} > \Gamma$.

Definition 2. Let $l_{\min}[i,j] = 1, 2, \ldots, K$ denote the minimum required TPL that allows $u_j$ to be within the radio coverage of $f_i$. If $l_{\min}[i,j] > K$, the value of $l_{\min}[i,j]$ shall be set as $\infty$ to indicate that $f_i$ cannot reach $u_j$. 

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Let the femtocell networks be represented as the bipartite graph \( G(L) = (B_f \cup U_f, E(L)) \) with the bipartition \( (B_f, U_f) \), where \( L = \{l_1, l_2, \ldots, l_M\} \) is the set of each FBS’s operating TPL, and \( E(L) = \{(f_i, u_j) \mid l_{\text{min}}[i,j] \leq l_i\} \) is the set of edges between \( f_i \) and \( u_j \). The edge \((f_i, u_j) \in E(L)\) implies that \( u_j \) is located within the radio coverage area of \( f_i \) with TPL \( l_i \). The relationship between \( f_i \) and \( u_j \) is represented by the minimal required TPL matrix \( M_{M \times N} = [m_{ij}] \) where

\[
m_{ij} = \begin{cases} 
  l_{\text{min}}[i,j], & \text{if } (f_i, u_j) \in E(L), \\
  0, & \text{if } (f_i, u_j) \notin E(L).
\end{cases}
\]

We show one possible matrix \( M_{5 \times 6} \) for Fig. 2(a) as

\[
M_{5 \times 6} = \begin{pmatrix}
3 & 4 & 0 & 0 & 0 & 0 \\
4 & 5 & K & 0 & 0 & 0 \\
0 & K & 4 & K & 0 & 0 \\
0 & 0 & 3 & 3 & 0 & 0 \\
0 & 0 & 0 & 5 & 4 & K
\end{pmatrix}.
\]

Let \( G(L_K) = (B_f \cup U_f, E(L_K)) \), where \( L_K = \{l_i \mid l_i = K \mid 1 \leq i \leq M\} \), be the bipartite graph that all FBSs are operating at the maximal TPL. The potential CFBSs of any vertex \( u_j \) can be determined by using the maximal TPL, and is denoted as \( N_f(u_j) = \{f_i \mid (f_i, u_j) \in E(L_K)\} \). Fig. 2(a) can be assumed as all FBSs operate at the maximal TPL and we have \( N_f(u_1) = \{f_1, f_2\}, N_f(u_2) = \{f_1, f_2, f_3\}, N_f(u_3) = \{f_2, f_3, f_4\}, N_f(u_4) = \{f_3, f_4, f_5\}, N_f(u_5) = \{f_4, f_5\}, \) and \( N_f(u_6) = \emptyset \). Let \( N_{u_i}(f_i) = \{u_j \mid (f_i, u_j) \in E(L)\} \) denote the set of FUs located in the coverage area of \( f_i \) with TPL \( l_i \). Thus, the FUs of each \( f_i \) with the maximal TPL in Fig. 2(a) are \( N_{u_1}(f_1) = \{u_1, u_2\}, N_{u_2}(f_2) = \{u_1, u_2, u_3\}, N_{u_3}(f_3) = \{u_2, u_3, u_4\}, N_{u_4}(f_4) = \{u_3, u_4, u_5\}, \) and \( N_{u_5}(f_5) = \{u_4, u_5, u_6\} \).

After receiving the list of CFBSs, the coordinator assigns each FU to an appropriate FBS from the \( N_f(u_j) \) as its SFBS based on the received signal power or the network topology. Then, the selection matrix \( A = [a_{ij}] \) is obtained, where

\[
a_{ij} = \begin{cases} 
  1, & \text{if } f_i \text{ is selected as the SFBS by } u_j \text{ with } P[l_i], \\
  0, & \text{otherwise}.
\end{cases}
\]

The operating \( l_i \) of \( f_i \) shall be the maximal TPL among \( l_{\text{min}}[i,j] \), which satisfies \( a_{ij} \neq 0 \) and \( j = \{1, 2, \ldots, N\} \), i.e., \( l_i = \max_{1 \leq j \leq N} m_{ij} \times a_{ij} \). The selection relationship of \( f_i \) to all FUs is the \( i \)-th row of \( A_{M \times N} \) and is shown as \( A_i = [a_{i1}, a_{i2}, \ldots, a_{iN}] \). The number of FUs served by an FBS can be represented as \( \sum_{j=1}^{N} a_{ij} \).

**Definition 3.** An FBS is active if at least one FU selects it as the SFBS, i.e., \( \sum_{j=1}^{N} a_{ij} > 0 \). An FBS is inactive and enters sleep mode if no FUs are served by it, i.e., \( \sum_{j=1}^{N} a_{ij} = 0 \).

The selection relationship of all FBSs to \( u_j \) is the \( j \)-th column of \( A_{M \times N} \), and is expressed as \( A_j = [a_{1j}, a_{2j}, \ldots, a_{Mj}] \). An FU can only be assigned to an SFBS so that \( \sum_{i=1}^{M} a_{ij} = 1 \). As shown in Fig. 2(a), let each FU be served by the nearest FBS. Accordingly, \( u_1 \) and \( u_2 \) select \( f_1 \) as their SFBSs, \( u_3 \), \( u_4 \), and \( u_5 \) select \( f_4 \) as their SFBSs, and \( u_6 \) selects \( f_5 \) as its SFBS. The selection relationship among the five FBSs and six FUs is

\[
A_{5 \times 6} = \begin{pmatrix}
1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}.
\]

Following the SFBS selection process for all FUs, each FU may be served by an FBS with or without interference, depending on the topology of \( G(L_K) \). Subsequent to the SFBS selection process, the new connection relationship of \( G(L) \) can be expressed as the matrix \( C_{M \times N}(L) = [c_{ij}] \), which is represented as

\[
c_{ij} = \begin{cases} 
  0, & \text{if } l_i < m_{ij} \text{ or } m_{ij} = 0, \\
  1, & \text{if } l_i \geq m_{ij} \text{ and } a_{ij} = 1, \\
 -1, & \text{if } l_i \geq m_{ij} \text{ and } a_{ij} = 0.
\end{cases}
\]

If any \( u_j \) is not within the radio coverage of \( f_i \) with \( P[l_i] \) (i.e., \( l_i < l_{\text{min}}[i,j] \)), the connection relationship \( c_{ij} \) is set to 0. Conversely, if \( u_j \) is within the radio coverage of \( f_i \) with \( P[l_i] \) (i.e., \( l_i \geq l_{\text{min}}[i,j] \)), \( f_i \) is either selected as the SFBS by \( u_j \), or it becomes the interfering FBS (IFBS) of \( u_j \). In other words,
if $f_i$ is the IFBS of $u_{ij}$, then $c_{ij} = -1$. If $f_i$ is the SFBS of $u_{ij}$, then $c_{ij} = 1$. If $f_i$ cannot connect with $u_{ij}$, then $c_{ij} = 0$. As shown in Fig. 2, base on (5), the connection matrix becomes

$$C_{5 \times 6}(L) = \begin{pmatrix}
1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & -1 & -1 & 1
\end{pmatrix},$$

(7)

where $L = \{4, 0, 0, 3, K\}$.

The calculation of matrix $C_{M \times N}(L)$ can be used for determining the interference status of $G(L)$. In the graph $G(L_K)$, all FUs can be reached by at least one FBS with the maximal TPL, i.e., $|N_f(u_{ij})| \geq 1$, $\forall u_{ij} \in U_f$. If $\sum_{i=1}^M \sum_{j=1}^N c_{ij} = N$, this implies that each FU is served by only one FBS without interference. Otherwise, $\sum_{i=1}^M \sum_{j=1}^N c_{ij} < N$ because the interference between the FU and FBS decreases the value. In this example, $f_5$ interferes with $u_4$ and $u_5$ so that $\sum_{i=1}^5 \sum_{j=1}^6 c_{ij} = 4 < 6$.

**Definition 4.** A set $G(L)$ is non-interference femtocell networks if $\forall u_{ij} \in U_f$ are served by an $f_i$ without interference, i.e., $\sum_{i=1}^M \sum_{j=1}^N c_{ij} = N$.

The received SINR of $u_{ij}$ from SFBS $f_i$ can be obtained by

$$\psi_{ij} = \frac{P[l_i](10^{-L_{ij}}/10)}{\sum_{f_{ij} \in B(f_i)} P[l_k](10^{-L_{kj}}/10) + \sigma^2},$$

(8)

where $\sigma$ is the variance of additive white Gaussian noise (AWGN) and $f_0$ denotes the MBS. The ADR from $f_i$ to $u_j$ follows Shannon’s formula [31] and is given by

$$R_j = \frac{W}{|N_u^i(f_i)|} \log_2(1 + \psi_{ij}),$$

(9)

where $W$ denotes the total bandwidth of $f_i$, and $|N_u^i(f_i)|$ denotes the number of FUs served by $f_i$. According to (9), the average ADR of all FUs, denoted as $\varpi$, is obtained by

$$\varpi = \sum_{u_{ij}} R_j/N.$$  

(10)

After the FUs report the acquired CFBS list information to the coordinator, the coordinator can obtain the maximal TPL graph $G(L_K)$ which includes all possible relationships among the FUs and FBSs. Subsequently, the FBS GW sends commands to order the FBSs to adjust their TPLs accordingly to avoid causing interference to the FUs associated with neighboring FBSs. Consequently, the goal of this study is to find a set $L$, such that $G(L)$ is non-interference femtocell networks. The FBS selection and power control problem to be solved can find $L$ where

$$\sum_{i=1}^M \sum_{j=1}^N c_{ij} = N \text{ and } \varpi \text{ is maximized.}$$

(11)

**Theorem 1.** A given femtocell network topology of $G(L) = (B_f \cup U_f, E(L))$ with $M$ FBSs and $N$ FUs; the problem of finding a non-interference topology relation by selecting the TPL $l_i$ of each $f_i$ such that $\sum_{i=1}^M \sum_{j=1}^N c_{ij} = N$ and sets $N_u^i(f_i)$ are disjoint as well as maximizing $\varpi$ is NP-complete.

**Proof.** Denote the problem as $\mathcal{P}$ and the subproblem $\mathcal{P}'$ of $\mathcal{P}$ that finds a non-interference femtocell network topology relation by selecting the TPL $l_i$ of each $f_i$ such that $\sum_{i=1}^M \sum_{j=1}^N c_{ij} = N$ and sets $N_u^i(f_i)$ are disjoint. Let a finite set $A = \{g_1, g_2, \ldots, g_K, g_1, \ldots, g_M\}$ and the sizes $|g_1|, |g_2|, \ldots, |g_M| \in \mathbb{N}$, where $g_{ij} = |N_u^i(f_i)|$ with a selected TPL $l_i = 0, 1, \ldots, K$, constitute an arbitrary instance of a partition problem. Define $\sum_{g \in G} |g_{ij}|$ to be equal to $N$, where each $f_i$ can be selected only once. The problem $\mathcal{P}'$ is to find a subset $A' \subseteq A$, where the sum of the sizes of the elements in $A'$ is exactly $N$, which is the subset sum problem, and has been proved to be NP-complete [30]. Because $\mathcal{P}' \subset \mathcal{P}$ and $\mathcal{P}$ is NP-complete, $\mathcal{P}$ is NP-complete. Thus, the proof is complete.

\[\Box\]

III. SMART FBS SELECTION AND POWER CONTROL ALGORITHMS

A. The Smart FBS Selection Algorithm

As discussed, if an FU is within the overlapping area of two FBSs, only one of the FBSs can operate at the maximal TPL. To determine whether a feasible solution exists for this problem, the graph $G$ can be transformed into the interference graph $G_I$, which only contains FBSs (Fig. 2(b)). Let $G_I = (B_f, E_I)$ be the interference graph among the FBSs, where $E_I = \{(f_i, f_j) \mid |N_u^i(f_i) \cap N_u^j(f_j) \neq \emptyset, \forall f_i, f_j \in B_f\}$ is the set of edges between the FBSs; $N_u^i(f_i)$ denote the set of FBSs that are potentially interfering with the FUs associated to $f_i, \forall u_{ij} \in N_u^i(f_i)$ and $N_u^j(f_j) \subseteq B_f$. It is said that $f_i$ interferes with $f_j$ if $(f_i, f_j) \in E_I$. In Fig. 2, the best solution to mitigate interference is to select $f_2$ and $f_5$ (($f_2, f_5) \notin E_I$) to provide access services to all the FUs (see Fig. 2(d)), and $\sum_{i=1}^M \sum_{j=1}^N c_{ij} = N$. To do so, the SFSA is employed to find a subset $F_S(i) \subseteq B_f$ with the maximal TPL such that $\forall u_{ij} \in U_f$ are non-interfered.

**Algorithm I.** Smart FBS Selection Algorithm.

**Step 1:** Let $B_f = \{f_1, f_2, \ldots, f_M\}$ in ascending order, an FBS set $B := B_f, k := 1$. Let $B'_{f_i}$ be a set of subsets $F_S(k) \subseteq B_f$ and $B'_{f_i} := \emptyset$.

**Step 2:** Select the first element, say $f_1$, and move it from $B$ to $F_S(k)$.

**Step 3:** Test all remaining elements $f_j \in B$. If $f_j$ interferes with $f_i, i \neq j$, then remove $f_j$ from $B$. Otherwise, $f_j$ remains in $B$.

**Step 4:** If $B \neq \emptyset$, then go to Step 2.

**Step 5:** If all FBSs in $F_S(k)$ could serve all $u_{ij} \in U_f$, then add $F_S(k)$ into $B'_{f_i}$.

**Step 6:** Rotate $B_f$ to the left such that $B_f = \{f_n, f_{n-1}, \ldots, f_1\}, B := B_f$, and $k := k + 1$. If $k \leq M$, then go to Step 2.

**Step 7:** If $B'_{f_i} \neq \emptyset$, then select a maximal value of $|F_S(h)|$, where $F_S(h) \in B'_{f_i}, h = 1, 2, \ldots, M$. Otherwise, no non-interference solution without power control scheme exists ($B'_{f_i} = \emptyset$), then select an $F_S(h), h = 1, 2, \ldots, M$, which has a maximal value of $\sum_{f_i \in F_S(h)} |N_u^K(f_i)|$ as the final result.
The SFSA is the first phase to test the $G(L_K)$, regardless of whether any solution for a topology of non-interfered femtocell networks exists. In Fig. 2(a), let $B_f = \{f_1, f_2, f_3, f_4, f_5\}$, and $U_f = \{u_1, u_2, u_3, u_4, u_5, u_6\}$. The SFSA first selects $f_1$ as an active FBS (Fig. 2(c)). Next, $f_1$ is moved from $B_f$ to $F_S(1) = \{f_1\}$. To avoid interference, the neighboring FBSs of $u_1$ and $u_2$ (i.e., $f_2$ and $f_3$) are also removed from $B_f (B_f = \{f_4, f_5\})$. Subsequently, $f_4$ is selected as the active FBS, and is then moved from $B_f$ to $F_S(1) = \{f_1, f_4\}$. Next, remove $f_5$ from $B_f$ to avoid interference. Because $B_f$ becomes empty, the SFSA verifies whether $F_S(1)$ covers all $u_j \in U_f$. However, in this example, $u_6$ is left in $U_f$ such that $F_S(1)$ does not cover all $u_j \in U_f$ (i.e., $|\bigcup_{f \in F_S(1)} N_{f_u}(f)| < |U_f|$); thus, the SFSA does not add $F_S(1)$ into $B_f$.

Then, the SFSA does left rotation of $B_f$ such that $B_f = \{f_2, f_3, f_4, f_5, f_1\}$, and repeats Steps 2–5. Next, $f_2$ is selected and moved from $B_f$ to $F_S(2) = \{f_2\}$. To avoid interference, the neighboring FBSs of $u_1$, $u_2$, and $u_3$ (i.e., $f_1$, $f_3$, and $f_1$) are removed from $B_f (B_f = \{f_5\})$. The SFSA then removes $f_5$ from $B_f$ and adds it to $F_S(2) = \{f_2, f_5\}$. Finally, $F_S(2)$ is added to $B_f$ because all $u_j \in U_f$ can be covered by $f_i \in F_S(2)$ as shown in Fig. 2(d). The SFSA then repeats Steps 2–5 to find the non-interfered topology until $f_1$ becomes the first element of $B_f$ again. Eventually, $F_S(2)$ is selected as the result and the connection relationship matrix is

$$C_{5 \times 6}(L) = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 1
\end{pmatrix}, \quad (12)$$

where $L = \{0, K, 0, 0, K\}$. The time complexity of SFSA is $O(M^2)$ because the worst case is that each FU only has one CFBS, i.e., $|N_j(u_j)| = 1$.

To understand the limitation of SFSA, we perform a simulation to show the probability of identifying a non-interference femtocell network topology, where all FUs are non-interfered, by adopting the SFSA. The simulation environment and parameters are detailed in Section IV. Fig. 3 shows that SFSA is not suitable for finding the solution of the non-interference femtocell networks when $|B_f|$ is large or $|U|$ is large. Based on this result, the power control approach is proposed in the following subsection to overcome the drawback of the SFSA.

B. The Downlink Power Control Algorithm

In the previous subsection, the SFSA was proposed to find $F_S(i)$ at the maximal TPL. However, such a solution might not exist. For example, Fig. 2(c) represents a scenario in which the selected FBSs cannot serve all of the FUs without interference. After selecting $\{f_1, f_4\}$ as the active FBSs, $u_6$ becomes an MU that is assigned to the overlaid MBS because none of the FBSs can provide access services. Moreover, the receiver remains capable of decoding the received packets if the SINR of the received signal is larger than a specific threshold. In Fig. 2(c), $u_6$ is not served by any FBS. If $f_5$ is activated to serve $u_6$, it becomes an interference source to $u_4$ and $u_5$. However, the received SINR of $u_4$ and $u_5$ might be greater than the threshold because the strength of the received signal power from $f_5$ might be insufficient to cause interference with $u_4$ and $u_5$. In this situation, $f_5$ can be activated to serve $u_6$; furthermore, $u_4$ and $u_5$ can also be non-interfered FUs if $f_5$ reduces the TPL.

Fig. 4(a) shows an example that the FUs except $u_1$ receive interference from the neighboring FBSs if the TPL control technique is not applied. The solid circles represent the maximal coverage area for $f_1$, $f_2$, and $f_3$, and the dashed circle is the required TPL for $f_1$ to provide access services to $u_1$. In this example no solutions are found if the SFSA is applied. For example, Fig. 4(b) shows that $u_3$ becomes an interfered FU, and $u_1$ becomes an MU only if $f_2$ and $f_3$ are active. In this case, only $u_2$ can be a non-interfered FU (in the figure, served by $f_2$). Figs. 4(c) and 4(d) depict the FBS selection with no interfered FUs. Because $u_1$ has only one CFBS ($f_1$ in the figure), $f_1$ is activated to ensure that no FUs become MUs. The power control algorithm is applied if the interference cannot be solved only by turning off some FBSs. Fig. 4(e) shows an example of the FBS's TPL control and selection scheme, where $u_1$ is served by $f_1$ with a minimal TPL, denoted as $l_{\min}^u = l_{\min}^1[1, 1]$; thus, $u_2$ and $u_3$ are respectively served by $f_2$ and $f_3$ with appropriate TPLs.

As discussed, the FBSs can be classified into the following two types: 1) type-A; and 2) type-B. Let $F_A$ and $F_B$ denote the sets of type-A and type-B FBSs, respectively, and $B_f = F_A \cup F_B$. The definition of the type-A and type-B FBSs are detailed as follows.

- **Type-A FBS**: An $f_i$ is a type-A FBS if one of its subscribers $u_j$ has only one CFBS. Accordingly, $f_i \in F_A$ shall always be active and the minimal TPL $l_{\min}^u = l_{\min}^i[i, j]$ to provide access services for this kind of FU within its coverage area. For example, $f_3$ and $f_4$ in Fig. 5 are the case of $F_A$. Notice that the active CSG FBS is classified as $F_A$ because it has one authorized FU at least. The set $F_A$ is expressed as

$$F_A = \{f_i \mid |N_j(u_j)| = 1, \exists u_j \in N_{f_i}^K(u_j)\}. \quad (13)$$

- **Type-B FBS**: An $f_i$ is a type-B FBS if all of its FUs $u_j$ have more than one CFBS. Accordingly, $f_i \in F_B$ may
either degrade its TPL, or turn off its power to minimize the interference. In Fig. 5, \( f_1 \) and \( f_2 \) are the case of the set \( F_B \), which is expressed as

\[
F_B = \{ f_i \mid |N_f(u_j)| > 1, \forall u_j \in N_u^K(f_i) \}. \tag{14}
\]

According to the type of CFBSs allocated to the FUs, the FUs can be classified into the following three types: 1) type-A1; 2) type-A2; and 3) type-B. Let \( U_A^{(1)}, U_A^{(2)} \), and \( U_B \) denote the set of type-A1, type-A2, and type-B FUs, and \( U_f = U_A^{(1)} \cup U_A^{(2)} \cup U_B \). The type-A and type-B FUs are defined as follows:

- **Type-A1 FU**: A \( u_j \) is a type-A1 FU if it has only one CFBS, i.e., \( |N_f(u_j)| = 1 \). The CFBSs of \( U_A^{(1)} \) shall be active to provide access service. In Fig. 5, \( u_j \) belongs to \( U_A^{(1)} \). If an FU is subscribed to a CSG FBS, the FU is classified as a \( U_A^{(2)} \) FU. The set \( U_A^{(1)} \) is expressed as

\[
U_A^{(1)} = \{ u_j \mid |N_f(u_j)| = 1, \forall u_j \in U_f \}. \tag{15}
\]

- **Type-A2 FU**: A \( u_j \) is a type-A2 FU if it has more than one CFBS where at least one of its CFBSs belongs to \( F_A \) and \( l_{\min}[i,j] < l_{\min}^{(2)} \). Fig. 5 shows the case where \( u_2 \) could be \( U_A^{(2)} \). The type-A2 FU shall select \( f_i \in F_A \) as its SFBS to avoid immediately receiving interference from \( f_i \). The set \( U_A^{(2)} \) is expressed as

\[
U_A^{(2)} = \{ u_j - U_A^{(1)} - U_B \}. \tag{16}
\]

- **Type-B FU**: A \( u_j \) is a type-B FU if it has more than one FBS belonging to \( F_B \). The \( u_j \in U_B \) plays a critical role in finding a non-interfered topology of femtocell networks if \( u_j \) can select an appropriate FBS as its SFBS. Fig. 5 shows an example of \( U_B \) where \( u_1 \in U_B \). The set \( U_B \) is expressed as

\[
U_B = \{ u_j \mid |N_f(u_j)| > 1 \land \& \land N_f(u_j) \in F_B, \forall u_j \in U_f \}. \tag{17}
\]

To evaluate the benefit of selecting the SFBS for each \( u_j \), an objective function \( r_{ij} \) is designed to represent the ADR of each connected link between \( f_i \) and \( u_j \). The objective function is modelled as the sigmoid function and is expressed as

\[
r_{ij} = \begin{cases} 
\frac{2}{1 + e^{-\alpha \psi_{ij}}} - 1, & \text{if } f_i \text{ is the SFBS of } u_j, \\
0, & \text{otherwise,}
\end{cases} \tag{18}
\]

where \( \alpha > 0 \) is the coefficient of the received SINR of the user, \( -\infty < \psi_{ij} < \infty \), that determines the slope of \( r_{ij} \). When the value of \( \alpha \) increases, the curve of \( r_{ij} \) becomes steeper. The objective function \( r_{ij} \) has similar property with the Shannon’s capacity formula given in (9). Since Shannon’s capacity formula always obtains the positive value, we design the objective function \( -1 < r_{ij} < 1 \) to determine an inappropriate FBS selection, e.g., \( r_{ij} < 0 \). We note that the system operator can use \( \alpha \) to adjust the enthusiasm of the DPCA for practical use. The power control problem can be formulated as

\[
\max \sum_{i=1}^{M} \sum_{j=1}^{N} r_{ij}, \tag{19}
\]

which is subject to

\[
\sum_{i=1}^{M} a_{ij} = 1, \forall u_j \in U_f. \tag{20}
\]

The DPCA is detailed as follows.

**Algorithm II. Downlink Power Control Algorithm.**

**Step 1**: Initially, set the TPL of each \( f_i \) to be maximal and then set the minimal operating TPL of each \( f_i \in F_A \) as

\[
l_{\min}^{(i)} := \max_{u_j \in U_A^{(1)}[i,j]} l_{\min}^{(2)}, \varphi' := 0 \land \varphi'' := 0.
\]

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\]

The DPCA is detailed as follows.

**Algorithm II. Downlink Power Control Algorithm.**

**Step 1**: Initially, set the TPL of each \( f_i \) to be maximal and then set the minimal operating TPL of each \( f_i \in F_A \) as

\[
l_{\min}^{(i)} := \max_{u_j \in U_A^{(1)[i,j]} \overline{u_{j}}:u_{j}} l_{\min}^{(2)}, \varphi' := 0 \land \varphi'' := 0.
\]
FBS selection using the DPCA is when all $u_j \in U_A^1$; let $u_j \in U_A^2$ select $f_i \in \{F_A \cap N_f(u_j)\}$ with minimal $l_{\min}[i, j]$ as its SFBS and $a_{ij} := 1$.

Step 3: Let each $u_j \in U_B$ select $f_i \in N_f(u_j)$ with $l_{\min}[i, j]$ as its temporal SFBS and $a_{ij} := 1$.

Step 4: Let $F_i^j$ be a set of CFBSs of $u_j$ except its temporal SFBS $f_i$ and $F_i^j := N_f(u_j) - \{f_i\}, \forall u_j \in U_B$; let $U_{ij}'$ be a set of FUs and $U_{ij}' := U_{ij}$.

Step 5: Determine the operating TPL of each $f_i \in B_f$ according to the selection matrix $A$ by using the TPL selection function $l_{ij} = \max_{1 \leq j \leq N} a_{ij} \times m_{ij}$.

Step 6: Calculate $r_{ij} := \frac{2}{1 + e^{-\omega_{ij}}} - 1, \forall u_j \in U^f_j$; obtain the objective value $\varphi := \sum_{i=1}^{M} \sum_{j=1}^{N} r_{ij}$.

Step 7: If $\varphi > \varphi'$, then $\varphi' := \varphi$ and update $A$.

Step 8: Randomly pick up a $u_j$ from $U_{ij}'$. Select a new $f_i \in F_i^j$ as its new temporal SFBS and $F_i^j := F_i^j - \{f_i\}$. Repeat Steps 5–7 until $F_i^j = \emptyset$.

Step 9: If $U_{ij}' \neq \emptyset$, then go to Step 8.

Step 10: If $\varphi' > \varphi''$, then $\varphi'' := \varphi'$ go to Step 4. Otherwise, terminate the DPCA.

The $\varphi''$ obtained by the DPCA is the local optimal solution (i.e., $\varphi$ is locally maximized) because the worst case for the FBS selection using the DPCA is when all $u_j \in U_B$. The time complexity of the DPCA is $O(M|U_B|^3)$. Thus, the value of $|U_B|$ dominates the DPCA computation time. If a type-A1 FU is removed from $G(L)$, the consequence may lead some type-A2 FUs to become type-B FUs, and increases the value of $|U_B|$. Although a greater number of type-B FUs increase the computation complexity, the average ADR could also be improved. Because the proposition of this study is to serve all FUs, discarding any FUs to improve the system’s ADR is not considered.

Because the DPCA works in a centralized manner, it is particularly suitable for centrally managed femtocell networks. As discussed, only the FUs that belong to $U_B$ can improve the objective value by changing SFBSs. The DPCA can command a $u_j \in U_B$ to select a new SFBS if the reassociation with that SFBS can improve the objective value. The improvement comes from the fact that the new selected SFBS might allow the FU or other FUs which associate with any neighboring FBSs to obtain a better SINR. The DPCA repeatedly tests all $u_j \in U_B$ to improve the objective value until the objective value cannot be improved.

Fig. 5 shows four possible network topologies when there exists $L$ which allows each FU to be served by only one FBS. Table I shows all possible results. For example, $m_{ij}$ is the required TPL for $f_i$ to provide access service to $u_i$. In Scenario D, because $u_3$ has only one CFBS, it selects $f_3$ as the SFBS. Subsequently, $f_3$ is classified into $F_A$ and it is the only one CFBSs of $u_2$. When $m_{32} > m_{22}$ and $m_{31} > m_{11}, f_3$ does not interfere with $u_2$ because $m_{33} < m_{32}$. Accordingly, $u_2$ (classified into $U_B$) can select $f_2$ or $f_3$ as its SFBS depending on the relationship between $m_{22}$ and $m_{32}$. Because $m_{32} > m_{22}$, $u_2$ selects $f_2$ as its SFBS. Finally, $u_1$ selects $f_1$ as its SFBS because $m_{21} > m_{11}$. The final network topology is identical to that of Case IV (Fig. 5(d)).

#### C. FBS Operating Information

Assume the FBS has $K$ kinds of preambles, $p_k, k = 1, 2, \ldots, K$, which correspond to $K$ TPLs. The FBS sends preamble $p_k$ with TPL $k$ to let FUs identify the FBS’s transmitting power. After receiving preambles from neighboring FBSs periodically, the FU is able to construct a CFBS list. The FU constructs the $l_{\min}[i, j]$ by taking the minimal received preamble coming from $f_i$. The data element of the CFBS list consists of $(f_i, l_{\min}[i, j])$, where $f_i$ represents the CFBS-ID. As discussed in Section II, after receiving the CFBS list from its served FUs, the FBS constructs an FBS operating information (FOI) message and sends to the FBS GW via the SI interface (backhaul networks). The FOI message is sent to the FBS GW once the contents of FOI message are changed. The FOI message consists of $\langle\text{sequence #}, \text{FBS-ID, a list of tuples } [u_j, \text{CFBS list}]\rangle$. At the beginning, the FBS GW collects the FOI messages and then constructs the network topology based on graph theory. The sequence # is used for checking the freshness of the FOI message. The FBS GW executes the SFSA or DPCA based on the network topology and maintains a list of all FBS’s recommended TPLs. Each FBS adjusts its TPL upon receiving the TPL adjustment command requested by the FBS GW.

### IV. Simulation Results

This section presents a series of simulations to compare the performance of the proposed approaches, the SFSA and DPCA, with other approaches, such as the LP approach, fractional frequency reuse (FFR) approach [32], graph-based clustering strategy (GCS) approach [5], and maximal received-power-based FBS selection (MRFS) approach. The FFR is the most popular approach for traditional cell planning. It allows the FBSs to use a partial channel based on the interference.
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Fig. 6. A snapshot of the simulation scenario.

**TABLE II**

<table>
<thead>
<tr>
<th>Approach</th>
<th>Manner</th>
<th>TPL</th>
<th>Spectrum Splitting</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP</td>
<td>Distributed</td>
<td>Adaptive</td>
<td>N/A</td>
</tr>
<tr>
<td>MRFS</td>
<td>Centralized</td>
<td>Fixed</td>
<td>N/A</td>
</tr>
<tr>
<td>SFSA</td>
<td>Centralized</td>
<td>Fixed</td>
<td>N/A</td>
</tr>
<tr>
<td>DPCA</td>
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<td>Adaptive</td>
<td>N/A</td>
</tr>
<tr>
<td>FFR</td>
<td>Centralized</td>
<td>Fixed</td>
<td>A</td>
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<tr>
<td>GCS</td>
<td>Centralized</td>
<td>Adaptive</td>
<td>A</td>
</tr>
</tbody>
</table>

The indoor hot-spot path-loss model [33] between the FUs and MBSs is adopted for this simulation. The scenario in this simulation focuses on the conditions of radio propagation in relatively high-traffic hot-spot areas, e.g., conference halls, shopping malls, and teaching halls. It is assumed that a user within the coverage area of any femtocell should be served by only one FBS. The FBS will enter the sleep mode (being inactive) if no FUs select it as the SFBS. All FUs follow the procedures described in Section III-C to gather the necessary information for use in centralized manners. The remaining simulation parameters are shown in Table III.

**TABLE III**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>10 MHz, all resources allocated to FUs and MUs</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2 GHz</td>
</tr>
<tr>
<td>MBS Tx power</td>
<td>35 dBm</td>
</tr>
<tr>
<td>FBS Tx power</td>
<td>15 dBm</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>0 dBi</td>
</tr>
<tr>
<td>The coefficient α</td>
<td>0.9</td>
</tr>
<tr>
<td>Receiver noise density</td>
<td>−166 dB/Hz</td>
</tr>
<tr>
<td>Path loss</td>
<td>Indoor hot-spot [33]</td>
</tr>
<tr>
<td>Penetration loss</td>
<td>20 dB (also known as wall loss)</td>
</tr>
<tr>
<td>FU height</td>
<td>1.5 meters</td>
</tr>
</tbody>
</table>

**Fig. 7.** Ratio of non-interfered femtocell networks achieved by the SFSA, DPCA, LP, FFR, GCS, and MRFS.

- **Ratio of non-interfered femtocell networks:** the probability of identifying a non-interference femtocell network topology, where all FUs are non-interfered.
- **Ratio of non-interfered FUs:** the ratio of non-interfered FUs that the FBS selection scheme can achieve in $G$.
- **Number of active FBSs:** the number of FBSs activated by the FBS selection scheme. The higher the number of active FBSs, the greater the amount of available bandwidth for the FUs is.
  - **Average SINR per FU:** the average SINR of all FUs.
  - **Average ADR per FU:** the average ADR (Mbps) for each FU. The higher the average ADR for each FU, the higher the system ADR is.
  - **Average ADR per MU:** the average ADR (Mbps) for each MU. The lower the number of MUs served by MBS, the higher the ADR per MU is, i.e., if a greater number of MUs is served by the FBSs, the remaining MUs’ ADRs will be improved.

The indoor hot-spot path-loss model [33] between the FUs and FBSs is adopted for this simulation. The scenario in this simulation focuses on the conditions of radio propagation in relatively high-traffic hot-spot areas, e.g., conference halls, shopping malls, and teaching halls. It is assumed that a user within the coverage area of any femtocell should be served by only one FBS. The FBS will enter the sleep mode (being inactive) if no FUs select it as the SFBS. All FUs follow the procedures described in Section III-C to gather the necessary information for use in centralized manners. The remaining simulation parameters are shown in Table III.
by splitting the spectrum among FBSs if there are FUs in the femtocell overlapping area (e.g., the Type-A2 or Type-B FUs). Therefore, all FUs are non-interfered. The disadvantage of FFR and GCS is that the FBS gets less bandwidth to serve FUs if the number of the Type-A2 and Type-B FUs is greater than one. The only difference between FFR and GCS is whether it has the TPL control scheme. We show the effect and disadvantage in Fig. 10 and Fig. 11; we will discuss them later.

Fig. 7 shows another fact that the FBS selection with power control schemes (e.g., the LP and DPCA) outperform those algorithms without the power control scheme (e.g., the SFSA and MRFS) except the GCS. However, the disadvantage of the power control scheme is that it consumes a lot of computation time to get the solution. We will discuss and compare the computation time at the last of this section. The figure shows that the DPCA outperforms the SFSA, although it takes longer time. The results show that the SFSA is suitable for finding the non-interference femtocell networks when the values of $|U|$ and $|B_f|$ are low. However, as the value of $|B_f|$ increases, the capacity of the SFSA diminishes rapidly when $|B_f| = 60$ or $|B_f| = 100$. Conversely, as $|U|$ increases, it becomes increasingly difficult to find the non-interference femtocell networks because the number of FUs located in the overlapping area of two or more FBSs also increases. When $|U| > 80$ and $|B_f| = 100$, it approaches impossible to find the non-interference femtocell networks by employing the SFSA. Based on these results, the DPCA can adopt the TPL control to minimize the level of interference to achieve more non-interfered femtocell networks as compared to the SFSA. Therefore, by adopting the DPCA, the ratio of finding the non-interference femtocell networks can be improved substantially, even if the value of $|U|$ is high.

Fig. 8 shows the ratio of non-interfered FUs to all active FUs achieved by these six approaches. This result shows an interesting discovery that the SFSA still obtains 92% non-interfered FUs, even in the condition of $|U| = 100$ and $|B_f| = 100$. This result implies that the achievement of SFSA is not so worse (i.e., the ratio of non-interfered FUs is greater than 90%), even when the probability of finding 100% non-interfered FUs is zero (see Fig. 7(c)). Fig. 8 also shows that the DPCA approaches the optimal solution (the LP approach). If the DPCA is applied, the ratio of non-interfered FUs can be improved to more than 98%, even in high-density environment, i.e., $|U| = 100$ and $|B_f| = 100$. This result can be improved by activating more FBSs and applying a relatively lower TPL to serve the FUs.

Fig. 9 shows the needed number of FBSs activated by these six approaches under three femtocell deployment densities. Because the FBSs are purchased and deployed by customers, the density of the FBSs may be high in hot-spot areas. However, adding more FBSs could result in unexpected interference problems and decrease the average ADR per FU. Therefore, the FBS selection scheme (turning on or turning off the FBS) must be applied to solve the femtocell interference problem. Taking the DPCA for example, when $|U| = 100$, the ratio of active FBSs is 60.86% (12.17/20) when $|B_f| = 20$, 50.89% (30.53/60) when $|B_f| = 60$, and 42.84% (42.84/100) when $|B_f| = 100$. This result indicates that the DPCA turns off higher portion of FBSs (57.16%) in the high density scenario than that (39.14%) in the low density scenario when $|U| = 100$ for interference avoidance.

Fig. 10 shows the average SINR per FU achieved by these six approaches under three femtocell deployment densities. The average SINR of FUs achieved by the FFR
is the highest among six approaches because this approach allows the FBSs to split spectrum into sub-spectrums, and lets each FU select the nearest FBS as its SFBS. Furthermore, the average SINR per FU achieved by the FFR is the highest even when \( |U| \) is high, i.e., in high-density environment. Besides, the FFR can achieve a better average SINR per FU than the GCS because the GCS also considers the TPL control to prevent the potential interference as possible. The primary reason is that the DPCA allows FBSs to apply the maximal TPLs to serve FUs and turns off those FBSs which become sources of interference. Compared with the SFSA and FFR, the average SINR per FU achieved by the DPCA decreases when \( |U| \) increases. This is because the DPCA allows FBSs to operate with lower TPLs, thereby facilitating service to a greater number of FUs. When \( |U| \) is low, the DPCA allows the FBSs to operate at higher TPLs to achieve higher ADR.

Fig. 11 compares the average ADR per FU and MU under different conditions of low, medium, and high density of FBSs. The portion of FUs and MUs is determined by different conditions of low, medium, and high density of FBSs. The portion of FUs and MUs is determined by different conditions of low, medium, and high density of FBSs. Fig. 11(a), (b), and (c) show that the DPCA achieves higher average ADR per FU than the SFSA, FFR, GCS, and MRFS in all densities. The achieved average ADR per MU by the DPCA approaches that obtained by the LP approach (the optimal solution). The primary reason is that the DPCA can take advantage of transmitting power, which facilitates the channel reuse effect; thus, the average ADR per MU is enhanced, especially when the value

![Graphs showing comparisons of average ADRs achieved by different approaches under varying |U|](image-url)
TABLE V
COMPARISONS OF COMPUTATION TIME AMONG THE SFSA, DPCA, AND LP

| $|U|$ | $|B_f|$ | Low | Medium | High |
|-----|--------|-----|--------|------|
|     |        | LF/SFSA | LP/DPCA | LF/SFSA | LP/DPCA | LF/SFSA | LP/DPCA |
| Low  |         | 230.71 | 15.77   | 1109125 | 417.36  | 16414949 | 5297.21 |
| Medium | 139.48 | 10.76  | 3629.92 | 17.12  | 49123.29 | 210.69  |
| High  | 117.65  | 3.555  | 3069.22 | 4.216  | 41424.12 | 50.73   |

Fig. 12. Overhead comparison of centralized manner versus distributed manner.

of $|U|$ is high. The gap between the DPCA and GCS becomes increasingly greater as $|U|$ increases. These results show the fact that the DPCA can address the goal of lowering the number of interfered FUs by using TPL control (as shown in Fig. 8), as well as maximizing the average ADR per FU. Notice that the average ADR per FU the DPCA achieves is 15 times higher than that obtained by the GCS when $|U| = 100$. This figure shows the disadvantage of spectrum splitting approaches like the FFR and GCS from these results.

We can conclude that taking the frequency reuse approach (e.g., the DPCA or LP) to tackle the femtocell interference problem is substantially superior to that of adopting spectrum splitting approaches (e.g., the FFR and GCS). Fig. 11(a), (b), and (c) also show another observation that the SFSA can get the average ADR per FU near that obtained by the LP and DPCA. This is because that the SFSA uses a smart FBS selection scheme to avoid interference and barter sacrificing a few FUs (see Fig. 8) to being interfered for getting more number of non-interfered FUs. The SFSA provides a feasible and simple solution to mitigate the femtocell interference for system operator.

Fig. 11(d), (e), and (f) show the impact of these six approaches on the average ADR per MU. The reason that the performance of the FFR and GCS is superior to that of the LP, SFSA, and DPCA is that the FFR and GCS allow the FBSs to serve all nearby users (becoming FUs). Consequently, most users become FUs and only a few users become MUs, and, thus, MUs get more bandwidth. It is more obvious when the $|B_f|$ is high and the $|U|$ is low.

Table IV shows a comparison of the SFSA, DPCA, FFR, and LP approaches in aspect of non-interfered FUs, the average ADR per FU, and the average ADR per MU under nine different density combinations by the FU to FBS density pairs. Table V shows the comparisons of computation time for executing the LP, SFSA, and DPCA. We use the fraction of LP/SFSA, for instance, to indicate the ratio of needed computation time of the LP to that of the SFSA. Table V shows the average values of nine combinations of low, medium, and high $|U|$ and $|B_f|$ scenarios. These results show that the LP requires substantially more computation time to achieve the optimal result, whereas the DPCA requires less time to achieve similar results. This finding becomes increasingly obvious when $|B_f|$ or $|U|$ is high.

Finally, Fig. 12 shows the overhead (i.e., the number of FOI messages exchanged in the femtocell networks within the macrocell) caused by adopting the centralized and distributed manners. In a centralized manner the FOI message only needs to be sent to the coordinator (the FBS GW) for computing. While in a distributed manner the FOI message has to be distributed to other FBSs. Without loss of generality, we only show how many FBSs required exchange messages (the overhead) caused by the distributed manner will be exchanged with the nearby FBSs when the required ratio of the number of nearby FBSs to the number of FBSs within the macrocell for the message updating (exchanging) is $x$, e.g., $x = 1$ (100%), $x = 2/3$ (67%), or $x = 1/3$ (33%) in the simulation. The needed exchanged messages can be easily calculated by $|B_f|(|B_f| − 1)$. As compared with the distributed manner, Fig. 12 shows that the overhead of SFSA and DPCA is relatively light (bounded as $|B_f|$). Conversely, the overhead of distributed manner grows with $|B_f|^2$. Moreover, as mentioned in the Section I, the centralized manner can easily let the network management system monitor and guarantee the network topology especially for the emergence service.

V. Conclusion

In this paper, the interference avoidance problem among FBSs is examined by presenting two algorithms that maximize the average ADR per FU as possible. We have proven the problem of finding a non-interfered femtocell network topology by adjusting operating TPL as well as maximizing the ADR per FU is NP-complete. The computation time of the LP is compared with those of the SFSA and DPCA by considering the time complexity of the proposed algorithms. The results show that the DPCA can achieve as good ADR per FU as LP obtains while the DPCA uses a relatively less computation time even in high $|B_f|$ or $|U|$ cases. Furthermore, when the value of $|B_f|$ or $|U|$ are relatively low, the SFSA is suitable.
for achieving non-interfered femtocell networks. Moreover, since the SFSA and DPCA are centralized manners, it may be unsuitable for application in highly dynamic network topology changed scenario. To address this drawback, future research should consider improving the capabilities of the DPCA to be a distributed manner that can adapt to the highly dynamic topology changing scenario.

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