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Semi-distributed dynamic inter-cell interference coordination scheme for interference avoidance in heterogeneous networks

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Inter-cell interference (ICI) is a major problem in heterogeneous networks, such as two-tier femtocell (FC) networks, because it leads to poor cell-edge throughput and system capacity. Dynamic ICI coordination (ICIC) schemes, which do not require prior frequency planning, must be employed for interference avoidance in such networks. In contrast to existing dynamic ICIC schemes that focus on homogeneous network scenarios, we propose a novel semi-distributed dynamic ICIC scheme to mitigate interference in heterogeneous network scenarios. With the goal of maximizing the utility of individual users, two separate algorithms, namely the FC base station (FBS)-level algorithm and FC management system (FMS)-level algorithm, are employed to restrict resource usage by dominant interference-creating cells. The distributed functionality of the FBS-level algorithm and low computational complexity of the FMS-level algorithm are the main advantages of the proposed scheme. Simulation results demonstrate improvement in cell-edge performance with no impact on system capacity or user fairness, which confirms the effectiveness of the proposed scheme compared to static and semi-static ICIC schemes.

KEYWORDS
femtocells, heterogeneous networks, inter-cell interference coordination, LTE, resource allocation

1 | INTRODUCTION

Mobile operators believe that network intensification via heterogeneous networks (HetNets), which are formed using small cells, such as femtocells (FCs), can facilitate exabyte capacity increases in 5G networks [1]. FCs cost-effectively enhance indoor coverage and capacity by offloading data traffic from macrocell (MC) networks to low-cost fixed broadband networks transparently to provide ubiquitous coverage to indoor users. Femtocell base stations (FBSs) are small, short-range, low-power, user-installed cellular base stations that provide high-quality voice and data services, particularly indoors [2]. Over air interfaces, FBSs can offer radio coverage for any existing cellular standard, such as long-term evolution (LTE), worldwide interoperability for microwave access, and the universal mobile telecommunications system [3]. There is an expectation of the mass deployment of FCs in upcoming years based on their benefits for both end users and mobile operators. However, closed subscriber group (CSG) operation [4], where only authorized users allowed to connect to an FBS, and the independent sharing of radio resources has introduced interference management as a major technical challenge in FC networks.

In an LTE FC network, inter-cell interference (ICI) occurs in the scenario where the same resource block (RB) is assigned to the users of more than one base station (BS). Severe interference during downlinking causes degradation in quality of service (QoS) for cell-edge users and negatively affects overall system capacity. Most previous studies on interference in FC networks have focused on distributed power control methods [5,6], various radio resource allocation schemes [7–9], cognitive radio resource management strategies using game theory [10,11], and beamforming techniques [12,13]. However, these methods incur substantial signaling overhead and various levels of computational complexity.

Conventionally, ICI is handled by static ICI coordination (ICIC) schemes, such as the reuse-3 scheme, which requires prior frequency planning [14]. However, such schemes cannot be applied to FC networks because FBSs are deployed by users in an ad hoc manner. Therefore, ICIC schemes that function dynamically based on interference information from neighboring transmitters must be employed because they can exploit channel variations to attain maximum interference avoidance gain. Our literature review revealed the widespread availability of important studies on interference avoidance through dynamic ICIC in homogeneous network scenarios. Additionally, a few enhanced-ICIC (e-ICIC) techniques have been proposed to mitigate cross-tier interference in HetNets by giving priority to MC user QoS provisioning.

A dynamic ICIC scheme using the iterative Hungarian scheduling algorithm to mitigate interference in LTE networks was proposed in [15]. The challenges related to e-ICIC in HetNets were discussed in [16]. An interference management scheme with block diagonalization for macro/femto coexisting networks was proposed in [17]. A survey on ICIC techniques in LTE networks was presented in [18]. A quasi-distributed interference coordination scheme for enhancing system performance by controlling the interference level in a co-channel high-speed packet access HetNet was proposed in [19]. A decentralized dynamic Q-learning method for both frequency- and time-domain ICIC in two-tier HetNets was investigated in [20]. In [21], a dynamic fractional frequency reuse algorithm was proposed to mitigate downlink cross-tier interference in FC networks. Autonomous algorithms that jointly optimize frequency, power, and spatial resources for interference coordination in small cell network scenarios were proposed in [22]. The studies mentioned above focused on ICIC with the sole objective of mitigating cross-tier interference and prioritized MC user performance improvement. Additionally, these studies indicated a tradeoff between system throughput and cell-edge performance.

In contrast to existing works, we propose a novel semi-distributed dynamic ICIC scheme to mitigate both cross-tier and co-tier interference in HetNet scenarios. Here, we focus on interference avoidance by restricting radio resource usage by dominant interference-creating cells (interferers). The key contributions of this work are listed below.

- Initially, to determine the optimal resource restriction scheme for ICIC, a utility maximization problem is formulated with constraints on the usage of RBs by dominant interferers and maximum total transmission power. The improved performance of cell-edge users is guaranteed by including the user demand factor in the utility function, which is an indication of the service statuses of users.
- At the network level, to obtain a tractable solution to the problem described above, the proposed dynamic ICIC scheme includes two separate algorithms called the FBS-level algorithm and femtocell management system (FMS)-level algorithm. The FBS-level algorithm is used to prepare utility matrices and RB restriction requests for each of its nearby co-channel operating cells and forward this information to the FMS.
- The FMS-level algorithm is designed to resolve conflicting restriction requests optimally. It finalizes a refined RB restriction list for all FCs in the group with the goal of ensuring that restricted RBs are not used by dominant interferers. The FMS periodically sends refined RB lists to all FBSs at a time interval shorter than the channel coherence time. In this manner, the proposed scheme performs dynamic ICIC and achieves the expected performance gains.

The proposed ICIC scheme is compared to the reuse-1, reuse-3, and semi-static ICIC schemes based on cell-edge performance, system capacity, and user fairness. Simulation results obtained using a proportional fair (PF) scheduler and Hungarian scheduler illustrate the superiority of the proposed ICIC scheme, which improves cell-edge performance with no impact on system capacity and maintains fairness among all users.

The remainder of this paper is organized as follows. Section 2 explains the system model of the two-tier LTE FC network. Section 3 details the proposed semi-distributed dynamic ICIC scheme. Section 4 presents system-level simulation details and discusses the results obtained, as well as the computational complexity issues of the proposed ICIC scheme. Finally, Section 5 contains our concluding remarks.

2 | SYSTEM MODEL

In this study, we considered the downlink transmission of a two-tier LTE FC network, where FCs are overlaid on a single hexagonal MC. We assume that FBSs are deployed in a dual-strip-model FC block [23] located at a distance D_1 from the central MC base station (MBS). Additionally, we assume that FBSs are located at the centers of their corresponding FCs. All the FBSs deployed in one FC block form a group that is associated with the FMS. In FC networks, the FMS serves as a central controller and gateway to the cellular system. It remotely configures the FBS through the *Fm* interface, which is an operation, administration, and management interface based on technical report TR-069 [24]. Let $F = \{F_1, F_2, \ldots, F_K\}$ be the set of K CSG FBSs deployed in one FC block and $f_i = \{1, 2, \ldots, J_i\}$ be the set of J_i FC user equipment (FUE) served by FBS i. We assume that all pieces of FUE, which are available randomly inside apartments, know the reference signals of nearby cells and that they can identify interference individually. A typical example of the two-tier FC network model under investigation is presented in Figure 1. In Figure 1, the non-overlapping coverage of FBSs is presented for illustrative purposes. However, the practical coverage of FCs may overlap because their coverage radii vary from 10 m to 50 m [5] based on downlink total transmission power.

In an LTE downlink, orthogonal frequency division multiplexed access (OFDMA) is used as an air interface. The total system bandwidth B is divided into orthogonal subcarriers, which are combined into L RBs, each having a bandwidth of $B_{\mathrm{RB}} = B/L$. We denote the set of RBs as $\mathcal{L} = \{1, 2, \ldots, L\}$. The assignment of the same RB by more than one BS (MBS or FBSs) to their users gives rise to ICI. For example, cell-edge FUE experiences high path loss and receives significant interference from nearby co-channel-operating BSs. As a result, this FUE is more susceptible to poor-quality RBs with low signal-to-interference-plus-noise-ratios (SINRs).

An optimal resource allocation scheme that aims to maximize utility may ignore such deprived cell-edge FUE because it does not make a significant contribution to total throughput compared to FUE close to the FBS. However, it is important to avoid interference on such FUE to guarantee minimum data throughput requirements and fairness among users. In this study, we focused on interference avoidance by restricting resource usage by dominant interferers. To determine the optimal RB restriction, the following utility maximization problem is considered:

$$\text{maximize} \quad \sum_{i=1}^{K} \sum_{f=1}^{J_i} \sum_{l=1}^{L} u_{fi}^{l} \mu_{fi}^{l}, \tag{1}$$

$$\text{s.t. } \mu_{fi}^{l} \in \{0, 1\} \quad \forall \{f, l\}, \tag{2}$$

$$I_i^l = \sum_{f=1}^{J_i} \mu_{fi}^{l}, \tag{3}$$

$$\sum_{f} \sum_{l} P_{fi}^{l} \le P_{\mathrm{t}} \quad \forall \{f, l\}, \tag{4}$$

where u_{fi}^{l} is the achievable utility of FUE f (a registered user of FBS i) on RB l, μ_{fi}^{l} is an indicator representing the assignment of RB l to UE f, I_i^l is an indicator representing whether or not RB l is restricted on FBS i, P_{fi}^{l} is the transmission power for FBS i on RB l, and P_{t} is the total transmission power of the FBS. The achievable utility is given by

$$u_{fi}^{l} = R_{fi}^{l} d_{fi}, \tag{5}$$

where R_{fi}^{l} is the achievable throughput of FUE f on RB l and d_{fi} is the user demand factor. The user demand factor is an indication of UE service status and is defined as

$$d_{fi} = \frac{R_i}{R_{fi} + \rho}, \tag{6}$$

where R_i is the average throughput across all UE served by FBS i, R_{fi} is the average throughput of FUE f over a certain time window, and the parameter ρ is a constant small value that prevents the demand factor from growing to infinity. Throughput-deprived cell-edge users will have a higher demand factor, meaning the utility factor will favor them to improve their performance. The constraint in (2), which has a binary integer type, is helpful for indicating whether or not

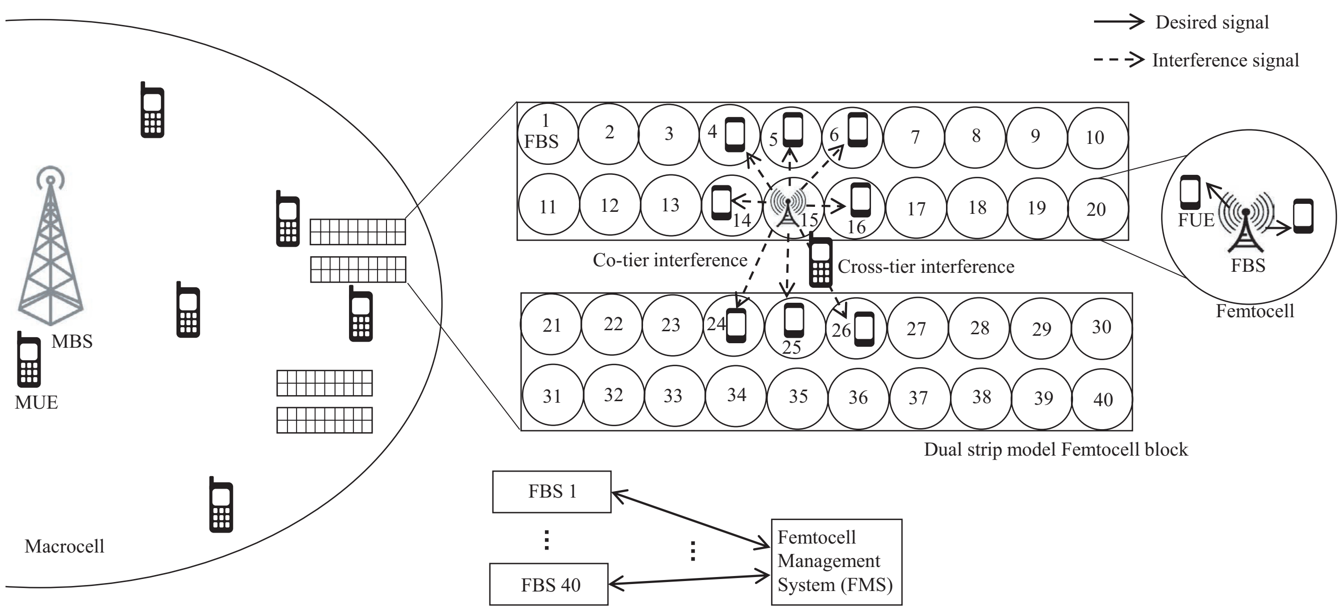

FIGURE 1 Two-tier femtocell network model

RB l is used for UE f. Similarly, the constraint in (3) indicates whether or not the usage of RB l is restricted. If the usage of RB l is restricted for dominant interferers, then it will be allocated to the users of FBS i. The constraint in (4) is meant to limit the maximum total transmission power of FBS i.

FC user SINR and achievable throughput depend on interference from nearby co-channel-operating BSs. We denote M and j as the indices of cross-tier (MC) and K_1 ($< K$) inter-FC interferers, respectively. For RB l, the SINR Γ^l_{fi} at FUE f in FBS i is calculated as

$$\Gamma^l_{fi} = \frac{P^l_{fi} H^l_{fi}}{P^l_M H^l_M I^l_M + \sum_{j=1, j\neq i}^{K_1} P^l_j H^l_j I^l_j + B_{\mathrm{RB}} N_{\mathrm{o}}}, \tag{7}$$

where P^l_M and P^l_j represent the transmission power on RB l allocated by MC layer and FC layer interferers, respectively. Here, the parameter N_{o} is the additive white Gaussian noise (AWGN) power spectral density. The link gain parameters H^l_{fi}, H^l_M, and H^l_j represent the link-gain between FBS i and FUE f on RB l and the link gain of interference from the MBS and nearby co-channel FBSs j imposed on RB l, respectively. We assume that path loss is identical on all RBs assigned to any particular FUE. The link gain parameters include large-scale path loss, fading, shadowing, and antenna gains. The RB restriction indicators I^l_M and I^l_j are given by

$$I^l_M = \sum_{f=1}^{J_i} \mu^l_{fM}; \quad I^l_j = \sum_{f=1}^{J_i} \mu^l_{fj}, \tag{8}$$

where μ^l_{fM} and μ^l_{fj} show the assignment of RB l on the MBS and FBS j, respectively. The RB restriction indicators take on values of zero or one depending on whether or not the l-th RB is restricted in MC M and FBS j, respectively. Based on their proximity, co-tier interferers have a significant effect on the quality of RBs and most interference avoidance gain can be attained by enforcing restrictions on these interfering FBSs.

The dominant interferer set φ is arranged in descending order of interference power, which varies from $\varphi = \{\}$ to $\varphi = \{\varphi_M, \varphi_F\}$, denoting no interferer restriction, the MC layer interferer restriction φ_M, and total K_1 FC interferer restriction $\varphi_F = \{\varphi_{F1}, \ldots, \varphi_{FK1}\}$. Therefore, it is evident that $\Gamma^l_{fi|\varphi=\{\}} < \Gamma^l_{fi|\varphi=\{\varphi M\}} < \Gamma^l_{fi|\varphi=\{\varphi F1\}} < \cdots \Gamma^l_{fi|\varphi=\{\varphi F1,\ldots,\varphi FK1\}} < \Gamma^l_{fi|\varphi=\{\varphi M,\varphi F1,\ldots,\varphi FK1\}}$, which represents the SINRs when no layers, the MC layer, FC layer, and both th MC and FC layer interferers are restricted in their use of RB l in FC i, respectively. To satisfy the minimum throughput requirements of users, the above SINRs are mapped to achievable user throughputs as $R^l_{fi|\varphi=\{\}} < R^l_{fi|\varphi=\{\varphi M\}} < R^l_{fi|\varphi=\{\varphi F1\}} < \cdots R^l_{fi|\varphi=\{\varphi F1,\ldots,\varphi FK1\}} < R^l_{fi|\varphi=\{\varphi M,\varphi F1,\ldots,\varphi FK1\}}$, respectively. Here, $R^l_{fi|\varphi=\{\}}$ represents the achievable minimum throughput and $R^l_{fi|\varphi=\{\varphi M,\varphi F1,\ldots,\varphi FK1\}}$ represents the achievable maximum throughput. Interference avoidance gain does not increase significantly with a greater number of interferer restrictions because the dominant interferer set φ is arranged in descending order of interference power. Therefore, only justifiable RB restrictions should be made to avoid spectrum utilization loss. Any particular FBS must make a decision regarding RB restriction based on the user demand factor d_f, and any significant gain achievable by imposing restrictions. For this purpose, a throughput threshold function is defined as follows:

$$\lambda^{\mathrm{th}}_f = \begin{cases} e^{(1-d_f)} & d_f \geq 1 \\ \infty & d_f < 1 \end{cases}. \tag{9}$$

Here, RB restrictions are made only when the FBS can achieve a considerable interference avoidance gain. Execution of restrictions based on this throughput threshold will favor users who have received low average service in the FC. Explicitly, if $R^l_{fi|\varphi=\{\varphi F1\}} \geq R^l_{fi|\varphi=\{\}} + \lambda^{\mathrm{th}}_f$, then one dominant interferer FBS F_1 will be restricted to favor UE f and if $R^l_{fi|\varphi=\{\varphi F1,\varphi F2\}} \geq R^l_{fi|\varphi=\{\varphi F1\}} + \lambda^{\mathrm{th}}_f$, then the top-two dominant interferers can be restricted and the process repeats. However, solving the utility maximization problem at a network-wide scale is computationally impractical. Therefore, we propose a semi-distributed dynamic ICIC scheme that employs two separate algorithms to perform justifiable resource restriction for dominant interferers. This approach makes the problem tractable because it operates on RB restriction requests prepared locally by each FBS. The FMS can then process restriction requests from FBSs deployed in FC blocks as disjoint groups.

3 | SEMI-DISTRIBUTED DYNAMIC ICIC SCHEME

In this section, we describe the proposed semi-distributed dynamic ICIC scheme, which includes FBS-level and FMS-level algorithms to perform dynamic ICIC in FC networks. Because the proposed ICIC scheme includes a type of clustering (grouping) and a semi-central processing approach, it is considered to be a semi-distributed approach. In semi-distributed ICIC schemes, there is a tradeoff between centralized and decentralized ICIC approaches. Here, the resource allocation among FBSs that are deployed in an FC block is finalized by the FMS, while user scheduling is decentralized for every individual FBS. It is noteworthy that the proposed ICIC scheme can effectively reduce both cross-tier and co-tier interference.

The FBS-level algorithm implemented at each FBS functions in a distributed manner. It prepares a utility matrix ($\mathbf{U}_{Ji\times L}$) and RB restriction requests for each of its nearby co-channel-operating MC and FC interferers. The RB

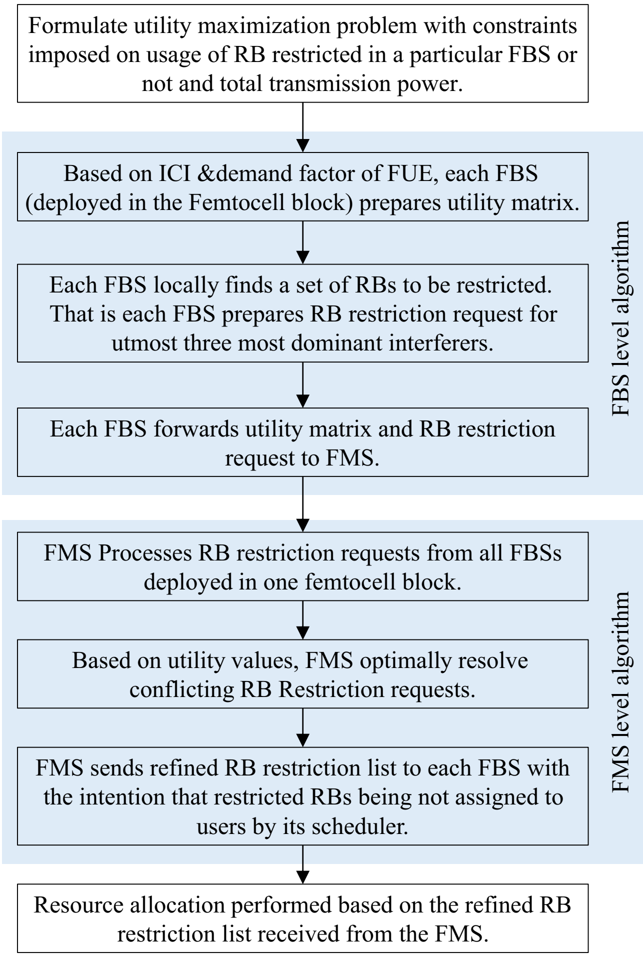

FIGURE 2 An overview of the proposed ICIC scheme

restriction requests for MC interferers are sent to the radio network controller (RNC) and handled by its logical entity. RB restriction requests for FC interferers are forwarded to the FMS, which processes requests from all FBSs in an FC block. It considers utility values to resolve conflicting requests optimally. The FMS then forwards a refined RB restriction list to each FBS to ensure that restricted RBs are not scheduled to users of dominant interferers. Note that the entire RB restriction process is repeated periodically with a periodicity shorter than the channel coherence time.

Because most existing works have investigated the cross-tier interference problem, we focus on co-tier interference mitigation by using the FMS-level algorithm in this paper. The operations involved in the FMS-level algorithm would be performed by the logical entity of the RNC to mitigate cross-tier interference. An overview of the proposed ICIC scheme is presented in Figure 2.

3.1 | FBS-level algorithm

Based on FUE demand factors and downlink channel quality, each FBS prepares a utility matrix and applies the

TABLE 1 FBS-level algorithm

%Preparation of utility matrix

1. for $f=1$ *to* J_i do
2. for $l=1$ *to* L do
3. $\varphi \leftarrow \{\}$; Calculate $\Gamma^l_{fi|\varphi=\{\}}$ and $R^l_{fi|\varphi=\{\}}$ with $I^l_M=1$;
4. $\varphi \leftarrow \{\varphi_M\}$; Calculate $\Gamma^l_{fi|\varphi=\{\varphi M\}}$ and $R^l_{fi|\varphi=\{\varphi M\}}$ with $I^l_M=0$;
   $I^l_j=1|j \neq i; j=1, \ldots, K_1$, for $\varphi_M \in \varphi$.
5. $\varphi \leftarrow \{\varphi_{F1}\}$; Calculate $\Gamma^l_{fi|\varphi=\{\varphi F1\}}$ and $R^l_{fi|\varphi=\{\varphi F1\}}$ with $I^l_j=0|j \neq i$;
   $j=1, \ldots, K_1$, for $\varphi_{F1} \in \varphi$.
6. $\varphi \leftarrow \{\varphi_{F1}, \varphi_{F2}\}$; Calculate $\Gamma^l_{fi|\varphi=\{\varphi F1, \varphi F2\}}$ and $R^l_{fi|\varphi=\{\varphi F1, \varphi F2\}}$ with
   $I^l_j=0|j \neq i; j=1, \ldots, K_1$, for $\varphi_{F1}, \varphi_{F2} \in \varphi$
7. $\varphi \leftarrow \{\varphi_{F1}, \varphi_{F2}, \varphi_{F3}\}$; Calculate $\Gamma^l_{fi|\varphi=\{\varphi F1, \varphi F2, \varphi F3\}}$ and $R^l_{fi|\varphi=\{\varphi F1, \varphi F2, \varphi F3\}}$;
   with $I^l_j=0|j \neq i; j=1, \ldots, K_1$, for $\varphi_{F1}, \varphi_{F2}, \varphi_{F3} \in \varphi$
8. if $R^l_{fi|\varphi=\{\varphi M\}} \geq R^l_{fi|\varphi=\{\}} + \lambda^{th}_f$ then
9. RB l marked for restricting its usage in MBS
10. end if
11. if $R^l_{fi|\varphi=\{\varphi F1\}} \geq R^l_{fi|\varphi=\{\}} + \lambda^{th}_f$ then
12. RB l marked for restricting its usage in one dominant interferer φ_{F1}.
13. end if
14. if $R^l_{fi|\varphi=\{\varphi F1, \varphi F2\}} \geq R^l_{fi|\varphi=\{\varphi F1\}} + \lambda^{th}_f$ then
15. RB l marked for restricting its usage in two dominant interferers
    φ_{F1} and φ_{F2}.
16. end if
17. if $R^l_{fi|\varphi=\{\varphi F1, \varphi F2, \varphi F3\}} \geq R^l_{fi|\varphi=\{\varphi F1, \varphi F2\}} + \lambda^{th}_f$ then
18. RB l marked for restricting its usage in three dominant interferers
    φ_{F1}, φ_{F2}, and φ_{F3}.
19. end if
20. end for
21. end for
22. Fill the corresponding entry of $\mathbf{U}_{J_i \times L}$ with $u^l_{fi} = R^l_{fi}\, d_{fi}$ considering the above RB restrictions.

Hungarian algorithm to it repetitively to find the RB restriction requests for each of its dominant nearby interferers. The RB restriction requests are then forwarded to the FMS. Table 1 contains pseudo-code for the FBS-level algorithm.

3.1.1 | Utility matrix preparation

Conditional SINRs and user throughputs must be calculated repeatedly to prepare the utility matrix. Therefore, the following steps are iterated for each UE and RB:

- Initially, a dominant interferer set φ is generated by arranging the co-channel interferers in descending order of received interference power.

- The SINRs for a user f on RB l, namely $\Gamma^l_{fi|\varphi=\{\}}$, $\Gamma^l_{fi|\varphi=\{\varphi M\}}$, $\Gamma^l_{fi|\varphi=\{\varphi F1\}}$, …, $\Gamma^l_{fi|\varphi=\{\varphi F1,\ldots,\varphi FK1\}}$, and $\Gamma^l_{fi|\varphi=\{\varphi M,\varphi F1,\ldots,\varphi FK1\}}$, which correlate to restrictions of no layers, the MC layer, FC layer, and both MC and FC layers, respectively, are used to identify dominant interferers based on (7).
- The achievable throughputs corresponding to the above SINRs, namely $R^l_{fi|\varphi=\{\}}$, $R^l_{fi|\varphi=\{\varphi M\}}$, $R^l_{fi|\varphi=\{\varphi F1\}}$, …, $R^l_{fi|\varphi=\{\varphi F1,\ldots,\varphi FK1\}}$, and $R^l_{fi|\varphi=\{\varphi M,\varphi F1,\ldots,\varphi FK1\}}$, respectively, are determined.
- If $R^l_{fi|\varphi=\{\varphi M\}} \geq R^l_{fi|\varphi=\{\}} + \lambda^{\text{th}}_f$, then the MBS is marked for restricting the usage of RB l.
- If $R^l_{fi|\varphi=\{\varphi F1\}} \geq R^l_{fi|\varphi=\{\}} + \lambda^{\text{th}}_f$, then the most dominant interfering FBS F_1 is marked for restricting the usage of RB l.
- If $R^l_{fi|\varphi=\{\varphi F1,\varphi F2\}} \geq R^l_{fi|\varphi=\{\varphi F1\}} + \lambda^{\text{th}}_f$, then the two most dominant interfering FBSs F_1 and F_2 are marked for restricting the usage of RB l.
- If $R^l_{fi|\varphi=\{\varphi F1,\varphi F2,\varphi F3\}} \geq R^l_{fi|\varphi=\{\varphi F1,\varphi F2\}} + \lambda^{\text{th}}_f$, then the three most dominant interfering FBSs F_1, F_2, and F_3 are marked for restricting the usage of RB l.

After finding the inter-cell dominant interfering FBSs to be restricted on each RB and each FUE f, the achievable throughput R^l_{fi} is calculated. Next, the utility matrix is formed based on the achievable utility using (5), where each entry is coupled to the respective dominant interferers to be restricted, as well as the achieved utility when the RB is used by the corresponding FUE.

3.1.2 | Obtaining an RB restriction request list

The dynamic Hungarian algorithm is applied to the utility matrix to prepare RB restriction requests. The Hungarian algorithm is a type of combinatorial optimization algorithm that can solve any one-to-one assignment problem with guaranteed optimality in polynomial time. The dynamic Hungarian algorithm is appropriate in any domain that requires the repeated optimal solving of assignment problems for which costs may change dynamically [25]. RBs are tentatively allocated to reserve them for each UE based on the following steps:

1. Apply the dynamic Hungarian algorithm to the utility matrix $\mathbf{U}_{Ji\times L}$. As $J_i \ll L$, a maximum of J_i RBs yielding the maximum sum utility will be allocated to the corresponding FUE J_i.
2. If any of the J_i chosen entries has a restriction marked, the corresponding RB will be added to the restriction list for the corresponding interferer.
3. The remaining columns are suitable for the chosen entries that were deleted from the utility matrix. The dynamic Hungarian algorithm is then applied to the updated matrix.
4. Steps two and three are repeated until all RBs are tentatively allocated to FUE.

After the process above is completed, all FBSs will have a list of RBs requiring restricted usage at each of their nearby dominant interferers. RB restriction requests for the MC layer are forwarded to the RNC. Similarly, restriction requests for the FC layer are forwarded to the FMS.

3.2 | FMS-level algorithm

The FMS receives RB restriction requests from a group of FBSs and optimally resolves conflicting requests. Note that the groups of FBSs deployed in each FC block are considered to be disjoint groups. Simultaneously, more than one FBS may forward an RB restriction request for any specific RB to the FMS. The FMS must decide to accept a restriction request from one FBS and reject the same request from other FBSs. Therefore, the main task associated with the FMS-level algorithm is to resolve conflicting restriction requests optimally. For example, in the transmission time interval (TTI) k, let $\vartheta = \{p, q, r\}$ be the set of FBSs that are requesting restricted use of RB l for any other FBSs. In other words, FBS p has a restriction request for FBSs q and r, or vice versa, or both p and q have restriction requests for each other. Assume that pieces of FUE f_p and f_q are the candidates for RB l in FBSs p and q, respectively. For any RB l, the problem at the FMS is formulated as follows:

$$\text{maximize} \quad Y = \sum_{j=p,q\in\vartheta} u^l_{fj}\zeta^l_j, \tag{10}$$

$$\text{s.t. } \zeta^l_p + \zeta^l_q \leq 1, \tag{11}$$

where the binary variables ζ^l_p and ζ^l_q represent RB restriction requests. The value of ζ^l_p (or ζ^l_q) is one if the request for restricting RB l by FC p (or q) is accepted. Otherwise, it is zero. Based on the utility values of p and q for RB l, the FMS determines the value of ζ^l_p (or ζ^l_q). For example, assume FBSs p, q, and r attain utility values for RB l of five, three, and eight, respectively. In this case, the objective function is $Y = 5\zeta^l_p + 3\zeta^l_q + 8\zeta^l_r$ and the constraints are $\zeta^l_p + \zeta^l_q \leq 1$, $\zeta^l_q + \zeta^l_r \leq 1$, and $\zeta^l_p + \zeta^l_r \leq 1$. Clearly, $\zeta^l_p = 0$, $\zeta^l_q = 0$, and $\zeta^l_r = 1$ provide the maximum value of Y. Therefore, FBS r must be reserved for RB l. Explicitly, the RB restriction requests of FBSs p and q are rejected and only the request of FBS r is accepted. The FMS resolves RB request contradictions and sends refined RB restriction lists to all FBSs in the corresponding group. The proposed RB restriction request processing algorithm is executed at regular intervals with a periodicity shorter than the channel coherence time and longer than the scheduling interval. Once an RB restriction list is available at the FBS, scheduling is performed based on this list and scheduler criteria. Scheduling has a significant effect on user throughput and fairness for a given number of resources. In this study, a PF scheduler and Hungarian scheduler were employed to test the effectiveness of the proposed method.

4 | PERFORMANCE EVALUATION OF PROPOSED ICIC SCHEME

In this section, we analyze the performance of the proposed ICIC scheme by comparing it to static and semi-static ICIC schemes. System-level simulation results for cell-edge user performance, average system capacity, fairness, and user satisfaction are presented to demonstrate the superiority of the proposed scheme.

4.1 | Simulation environment and parameters

The test network topology consisted of a single hexagonal MC site with its MBS located at the center. An FC block representing dual strips of buildings, where each strip contained 2 × 10 single-floored apartments with sizes 10 m × 10 m [23], was considered as an FC deployment scenario. One such FC block was positioned 400 m away from the MBS. One FBS was positioned at the center of each apartment. Within the FC block, users were uniformly distributed with a minimum distance of one meter from their corresponding FBS. All FBSs were considered as a group and associated with the FMS. The probability of an FBS in the FC block being active was set to 0.8 (ie, 32 FBSs were active out of the 40 total FBSs deployed in the FC block). The FBS-level algorithm was executed on all active FBSs. The system bandwidth is 20 MHz; therefore one hundred usable RBs available per TTI. We assume that the FCs occupy one half of the total number of RBs. Each FBS operates at a fixed power level of 10 dBm. Power allocated to RBs subject to the total power constraint in (4). Link adaptation performed based on the channel quality indicator (CQI) received at every TTI. Hence, adaptive modulation and coding (AMC) used with their corresponding coding rates [26], and 10% block error rate are used for determining threshold values of AMC. One hundred snapshots simulated with each of three hundred RBs duration, and the average user throughput values are collected. RB restriction processing is performed at six RB time interval and scheduling performed at every RB time duration. The simulation parameters used are listed in Table 2.

The path loss model for an urban FC deployment dual strip model from Table 20.4.2.2 in [23] was used to estimate the link gains of desired signals and interference signals. An AWGN power spectral density of −174 dBm/Hz and shadowing effect using a log-normal random variable with a standard deviation of 4 dB were included. An equal demand factor for all users was assumed. A full buffer traffic model was considered for our simulations. Average user throughput and system capacity statistics were collected based on the SINRs of scheduled RBs. If an SINR was less than the SINR threshold Γ^{thres} for the consistent modulation scheme, then failure of packet transmission was assumed and re-transmission was performed with higher priority in the subsequent TTI. YALMIP, which is a toolbox for modeling and optimization in MATLAB, and LPSOLVE, which is a mixed-integer linear programming solver, were used in combination with MATLAB to solve the binary-integer optimization problem at the FMS.

4.2 | Simulation results

Simulation results are discussed based on the cumulative distribution function (CDF) of user throughput, average system capacity, fairness, and user satisfaction.

4.2.1 | Effects of user throughput

Typically, cell-edge UE experiences significant interference and its achieved throughput analysis provides important information regarding fairness among the users in a cell and overall system performance. Because 5th percentile throughput reflects the throughput of cell-edge UE, we analyzed cell-edge user performance by comparing 5th percentile throughput values. The proposed method was compared to the reuse-1, reuse-3, and semi-static ICIC schemes, where reuse-1 represents no ICIC and reuse-3 represents static ICIC. The CDFs of average user throughput when using the PF and Hungarian schedulers were obtained.

Figure 3 presents the CDFs of average user throughput when the PF scheduler is employed at the FBS. The universal

TABLE 2 Simulation parameters

Parameter	Value
Carrier frequency	2 GHz
System bandwidth	20 MHz
Number of subcarriers per RB	12
Number of RBs allotted to FCs	50
RB bandwidth B_{RB}	180 KHz
FBS transmission power	10 dBm
Penetration loss of inner wall	5 dB
Penetration loss of outer wall	20 dB
Spectral noise density N_{o}	−174 dBm/Hz
Target bit error rate	10^{-6}
Shadowing model	Log-normal fading with standard deviation of 4 dB
Traffic model	Full buffer

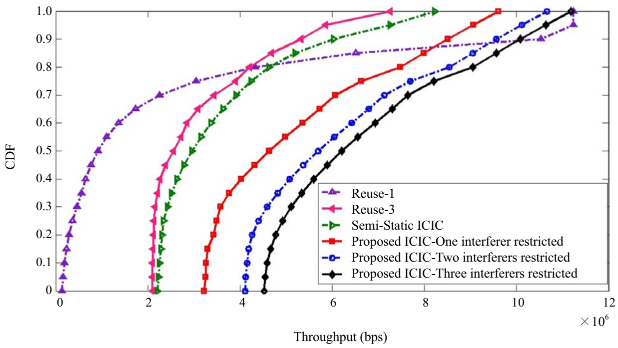

FIGURE 3 CDFs of user throughput (PF scheduler)

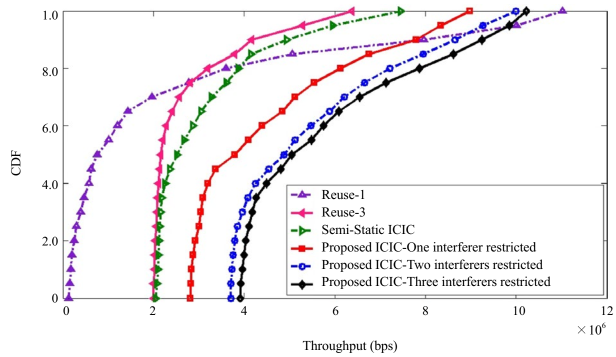

FIGURE 4 CDFs of user throughput (Hungarian Scheduler)

reuse of freely available RBs without imposing any restriction leads to the worst ICI scenario. Therefore, the reuse-1 scheme provides poor cell-edge throughput compared to the other methods. The reuse-3 scheme provides better cell-edge performance, but there is a considerable loss in peak UE throughput (95th percentile throughput) and system capacity. Notably, the semi-static ICIC scheme achieves approximately fourteen-fold gain in cell-edge throughput and 35.4% loss in peak UE throughput compared to the reuse-1 scheme. The proposed method (with atmost three dominant interferers restricted) achieves approximately 53% and 50% cell-edge throughput gains compared to the reuse-3 and semi-static ICIC schemes, respectively. Additionally, the proposed method achieves approximately 44% and 32% peak UE throughput gain compared to the reuse-3 and semi-static ICIC schemes, respectively.

Essentially, the proposed dynamic ICIC scheme provides superior peak UE throughput and cell-edge performance because the FMS resolves the RB restriction request conflicts of FBSs. To visualize the effects of dominant interferer restriction, the CDFs of UE throughput with one, two, and three dominant interferers restricted are presented in Figure 3. One can see that throughput decreases with three interferers restricted compared to two interferers restricted. Based on the short coverage range of FBSs, restricting three nearby dominant interferers yields a considerable interference avoidance gain. However, there is no significant improvement in either cell-edge performance or system throughput in the case when RBs are restricted for more than three dominant interferers. Furthermore, restricting additional RBs, which incurs additional penalties for nearby FBSs, results in greater throughput gain.

Figure 4 presents the CDFs of average user throughput when the Hungarian scheduler is employed. Similar to the PF scheduler, the proposed scheme also outperforms existing methods when using the Hungarian scheduler. However, both cell-edge UE throughput and peak UE throughput are lower than the corresponding values with the PF scheduler. The Hungarian algorithm can provide an optimal solution to any one-to-one assignment problem. However, it can provide only a sub-optimal solution when any user requires multiple RBs to satisfy the minimum throughput requirement. Therefore, the throughput is lower when the Hungarian scheduler is employed.

4.2.2 | Effects of system capacity, fairness, and user satisfaction

The average system capacity, fairness, and user satisfaction as functions of the number of active FBSs with the PF scheduler were calculated to investigate the effectiveness of the proposed method in terms of overall system performance. Figure 5 presents the average system capacity. The proposed ICIC scheme achieves enhanced system capacity compared to the static and semi-static ICIC schemes. The main disadvantage of the reuse-3 scheme, which achieves lower average system capacity, lies in its static characteristics related to resource allocation. In contrast, the proposed dynamic ICIC scheme (with one interferer restricted) achieves approximately 37% and 29% gains in system capacity compared to the reuse-1 scheme and semi-static ICIC scheme, respectively. Based on resource usage restriction for dominant interferers, interference signal power is reduced. Therefore, the proposed method ensures better SINRs and enhanced system capacity. It should be noted that the average system capacity achieved with three dominant

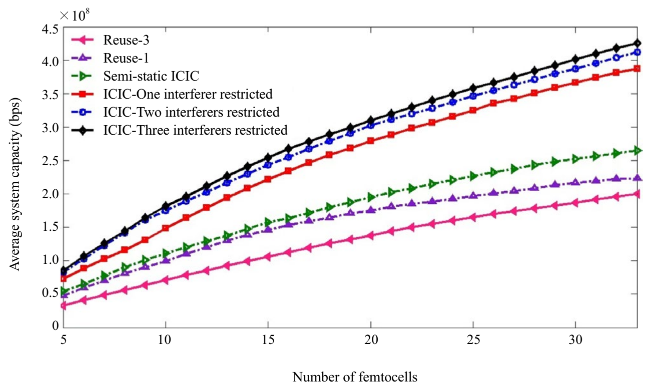

FIGURE 5 System capacity

interferers restricted is marginally greater than that with two interferers restricted. However, restricting more than three dominant interferers may lead to a loss in spectrum utilization.

Figure 6 presents Jain's fairness index [27] as a function of the number of active FBSs. Based on enhanced cell-edge and peak UE throughput, the proposed method always offers greater fairness across the entire network compared to the static and semi-static ICIC schemes.

User satisfaction in the network was also analyzed to confirm guaranteed QoS provisioning for all users. User satisfaction indicates how close user throughput is to the maximum achievable user throughput R_{max} [28]. All users in the FC have similar throughputs when user satisfaction approaches 100%. In contrast, when user satisfaction approaches 0%, there is a significant difference in the throughputs of different users. Figure 7 presents percentages of user satisfaction in the network. The proposed method achieves a gain of approximately 37% in terms of user satisfaction compared to the semi-static ICIC scheme.

Additionally, numerical results for the 5th and 95th percentiles of user throughput and system capacity for the reuse-1, reuse-3, semi-static ICIC, and proposed ICIC scheme with a PF scheduler and Hungarian scheduler are listed in Tables 3 and 4, respectively. Again, the superiority of the proposed ICIC scheme is confirmed. Additionally, the PF scheduler achieves enhanced throughput and system capacity compared to the Hungarian scheduler. In other words, the performance of

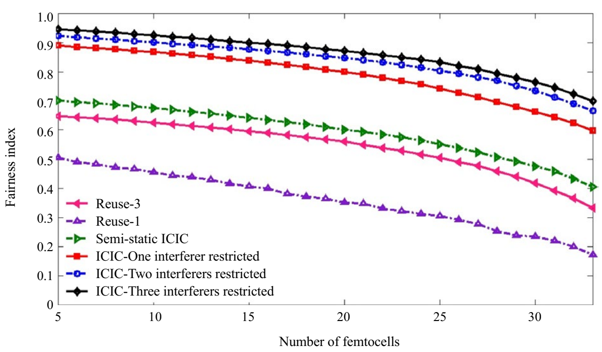

FIGURE 6 Fairness index

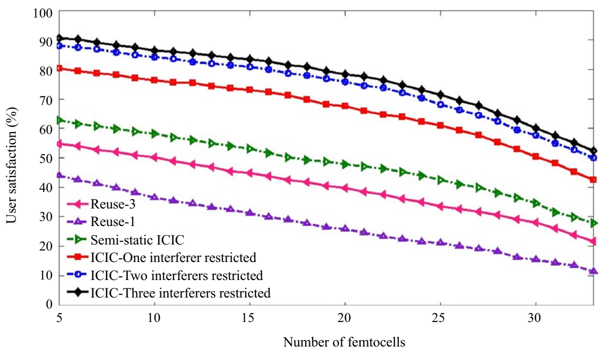

FIGURE 7 User satisfaction

TABLE 3 User throughput and system capacity (PF scheduler)

Scheme	User throughput (Mbps) 5th percentile	User throughput (Mbps) 95th percentile	System capacity (Mbps)
Reuse-1	0.153	11.244	157.57
Reuse-3	2.103	5.859	126.15
Semi-static ICIC	2.236	7.261	177.99
Proposed ICIC-one interferer restricted	3.254	9.066	253.23
Proposed ICIC-two interferers restricted	4.125	10.127	274.91
Proposed ICIC-three interferers restricted	4.547	10.643	284.42

TABLE 4 User throughput and system capacity (Hungarian scheduler)

Scheme	User throughput (Mbps) 5th percentile	User throughput (Mbps) 95th percentile	System capacity (Mbps)
Reuse-1	0.146	10.004	149.68
Reuse-3	2.008	5.297	118.78
Semi-static ICIC	2.072	5.961	170.75
Proposed ICIC-one interferer restricted	2.825	8.336	245.30
Proposed ICIC-two interferers restricted	3.711	9.270	266.96
Proposed ICIC-three interferers restricted	3.931	9.852	276.44

the Hungarian scheduler is marginally worse than that of the PF scheduler because it can provide only sub-optimal solutions when UE requires multiple RBs to satisfy the minimum throughput requirement.

4.3 | Complexity issues of the proposed ICIC scheme

The computational complexity associated with the FBS-level algorithm is $O(\min^2(J_i, L) \times \max(J_i, L))$. This complexity is introduced by the use of the dynamic Hungarian algorithm [29]. The complexity of the FMS-level algorithm depends on the number of FBSs that have conflicting RB restriction requests. If there are n pairwise conflicting requests for a specific RB, the number of binary variables to solve is $2n$ and the number of constraints is $3n$. Because the FBSs deployed in each FC block are considered to represent disjoint groups, the computational complexity of resolving conflicting resource restriction requests is reduced significantly. Signaling overhead is required for CQI feedback to perform link adaptation and additional signaling overhead may be incurred if a throughput-deprived FUE sends information regarding the three most dominant interferers to the serving FBS. Additionally, signaling between FBSs and the FMS is also required, which can be performed using high-speed internet protocol backhaul connections, meaning the overhead required for this signaling is negligible.

5 | CONCLUSION

In this paper, a novel hybrid dynamic ICIC scheme was proposed to mitigate both co-tier and cross-tier interference in two-tier FC networks. With the goal of maximizing individual user utility, radio resource usage was restricted for dominant interferers using two separate algorithms: the FBS-level and FMS-level algorithms. The FBS-level algorithm, which is implemented at each FBS, forwards RB restriction requests and utility matrices to the FMS. The FMS-level algorithm finalizes an RB restriction list based on the utility matrices and RB restriction requests gathered from all FBSs in the group. RB restriction request processing is performed at regular intervals with a maximum of three dominant interferers being restricted. The distributed functionality of the FBS-level algorithm and low computational complexity of the FMS-level algorithm are the main advantages of the proposed scheme. Performance metrics collected by employing the PF scheduler and Hungarian scheduler were presented to confirm the effectiveness of the proposed scheme. The proposed method with the PF scheduler outperforms both static and semi-static ICIC schemes by providing superior cell-edge user performance, system capacity, and fairness.

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