eICIC Optimization Improvements in Downlink Resource Allocation in LTE-A HetNets

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Abstract—Resource allocation mechanisms and management of inter-cell interference coordination (ICIC) are fundamental characteristics of the LTE-A network for achieving maximum capacity. Cell densification serves as a promising candidate solution for meeting the demand posed by mobile users, as well as optimizing coverage. However, the transmit power difference between the introduced picocells and the legacy macrocells essentially leads to challenges that limits system performance, especially for those users located at the edge of the cell. As a means of providing a clear understanding, the authors thus formulate the optimization problem as game theory, in order to maximize a modified utility function, which aims at making improvements on the eICIC. Based on exact potential game formulation, we optimize almost blank subframe (ABS) and cell selection bias (CSB) settings for both macrocells and picocells in a distributed manner. Simulation results illustrate important performance gains on the service fairness of the users, and especially for cell edge users, where the averaged throughput increases by up to 51%, when compared to eICIC optimization without our modified utility function.

Index Terms—Resource Allocation, Inter-Cell Interference, LTE-A Networks, HetNets, Game Theory.

I. INTRODUCTION

WITH the rise of increasingly agile and efficient media [1], the high quality of service (QoS) has attracted the attention of mobile operators and the research areas in recent years. In this context, the Third Generation Partnership Project (3GPP) introduced the Long Term Evolution-Advanced (LTE-A) standard [2]. In the LTE-A network, the main objective is to achieve higher network capacity compared to that of LTE network.

Next generation cellular systems promise a significant increase in cell throughput and improved spectral efficiency compared to current systems. To achieve these goals, network densification is a key element in increasing system coverage and meeting the growing demands for mobile data in a cost-effective manner due to its capability of frequency spectrum reuse and signal-to-interference-plus-noise ratio (SINR) [3].

As a result, inter-cell interference (ICI) issues arise that have a negative impact on user equipament (UE) throughput and system performance. ICI coordination (ICIC) techniques are proposed for mitigating ICI and improving UEs throughput without reducing spectral efficiency.

In a heterogeneous networks (HetNets) architecture, the coverage area of a macrocell is overlaid with several low-power access nodes, such as picocells, femtocells, and relays [4]. The transmission power of macrocells is much higher than that of picocells, so mobile users who are physically located near picocells may be attracted to macrocells, which can create underutilized picocells and overcrowded macrocells. On the other hand, the surrounding macrocells of a picocell can generate higher rates of interference for a user associated with the picocell. Therefore, in these networks, smart user association, resource allocation, and interference management schemes are required for achieving performance gains. However, to tackle these issues, enhanced inter-cell interference coordination (eICIC) has been introduced in 3GPP Release-10 [5]. Two representative techniques are briefly summarized below.

(i) Almost blank subframe (ABS) is configured on macrocells so that the macrocell ceases data transmissions in certain time slots, which reduces interference on picocells, and

(ii) Cell selection bias (CSB) is used to balance the received signal power from macrocells to a user so that a user is not necessarily associated with the macrocell that provides the strongest received power.

The use of ABS patterns can help reduce the interference from macrocells to picocells. To achieve the maximum possible performance gain using eICIC, joint optimization in ABS patterns and CSB values is required [6]. However, by ceasing transmission at certain timeslots using ABS, the eICIC can reduce the proper utilization of macrocell resources.

In light of the aforementioned, in this paper, the authors provide a distributed algorithm that jointly optimizes the ABS patterns and CSB values in HetNets. We formulate the problem as an exact potential game, through the adaptation of the game theoretic frameworks found in [7] as well as propose some improvements to these algorithms in order to achieve better performance, called eICIC+. Through simulation studies, we show that the proposed optimization can deliver improvements of around 51% over average user throughput. In turn, service fairness among users can also be greatly improved.

In summary, the main contributions of this paper are the following.

- We propose an extension of the eICIC optimization that uses an exact potential game, through use of a modified utility function (including statistics based on past throughput history and weight input (β and γ)).
- The authors also investigate and compare the performance of different schedulers for downlink channel in LTE-

A HetNets. We evaluate the performance with Matlab simulations in order to demonstrate the relevance of the approach, mainly for cell edge users.

- Finally, the robustness of the eICIC+ optimization is tested against the eICIC scheme. We provide an analytical investigation of the algorithm eICIC+ and comprehensive performance study regarding eICIC.

This paper is organized as follows. Section II reviews literature on eICIC optimization as well as studies that apply game theory to this problem. We then introduce an overview on eICIC on LTE-A networks in Section III, while system modeling is presented in Section IV. The proposed algorithm, as well as the downlink schedulers used in this paper are described in Section V and the evaluation results are presented and discussed in Section VI, followed by the evaluation scenario. Finally, in Section VII we draw our conclusions and highlight some potential future studies.

II. RELATED WORK

This section reviews literature related to eICIC optimization in LTE-A HetNets, highlighting the contributions reached from our proposed solution.

Several algorithms for elCIC optimization, ABS patterns and CSB values are proposed in the literature. Disjoint optimization of ABS and CSB is performed in [8], where the ABS patterns are simplified as fractional numbers, and the convergence of the algorithms is proven using stochastics theorems. The authors of the paper presented in [9] propose a learning algorithm that optimizes CSB values in the frequency domain, and further extend the idea to optimizing CSB values in both the time and frequecy domains in [10].

When joint optimization is performed, it is often in a centralized entity. In [11], where ABS patterns and CSB values are jointly optimized and the surrounding macrocells of a picocell must offer ABSs on the same subframes. The algorithm has provable guarantees, and furthermore, it accounts for network topology, traffic load and the interference map for picocells and macrocells. The authors of [12] propose optimized ABS patterns and CSB values jointly and efficiently for large networks. System level simulation results illustrate significant gains from the optimization in both network capacity and data rate fairness. The collaborators Bedekar and Agrawal, in [13], simplify the joint ABS and CSB optimization problem in order to optimize ABS ratios and propose an iterative algorithm that successively improves the assignment of users to cells and the muting proportion, and prove its convergence to the optimal solution.

A distributed eICIC algorithm is proposed in various studies [14]–[18]. In [14], a distributed algorithm is proposed by Pang *et al.*, where the number of ABS is determined without considering CSB values. The optimization is only done for static configurations using long-term statistics. The authors in [15] present a dynamic eICIC by adapting the ABS patterns in response to variations in network load. In [16], the operation of eICIC in a realistic deployment is proposed based on site-specific data from a dense urbanized European capital. In [17], the authors use moving average crossover (MAC)

based on trading know-how to propose a new dynamic ABS eICIC algorithm, and through use of system-level simulations, attest that the proposed algorithm outperforms the best placed eICIC. Finally, the study in [18], which shows that dynamic ICIC can provide useful and stable performance gains in both homogeneous and heterogeneous networks. One also notes that the gains of dynamic ICIC are greater in heterogeneous networks of macrocells and picocells than in homogeneous networks of only macrocells.

Currently, several papers have been published with proposals for game theory based interference mitigation for LTE/LTE-A networks. Potential game based solutions for distributed eICIC optimization are considered in [7], [19]–[21].

Although ICIC is a subject that has been very well explored by academics and the telecommunications industry, the literature is lacking studies that explore improvements to eICIC schemes. Thus, this paper presents a performance comparison between the eICIC optimization, and a scenario with the optimized coordination technique, eICIC+.

III. OVERVIEW ON EICIC IN LTE-A NETWORKS

To deal with the interference problem in HetNets, such as cell overlap between macrocells and picocells, enhanced ICIC (eICIC) has made several improvements to overcome the limitations of previous ICIC schemes. However, its actual implementation is not clearly specified by the standard and there is no indication as to how to set the CSB and ABS parameters for different network configurations. In this section, we describe the main eICIC parameters.

A. Almost blank subframe (ABS)

The main change from static ICIC is the addition of time domain partitioning schemes based on time resource partitioning to limit interference to users on the outer edge of picocells. According to the work in [19], the specification of ABS defines a pattern of sub-frames during which a macrocell should mute and as such does not send any traffic channels. The ABS mechanism is illustrated in Fig. 1.
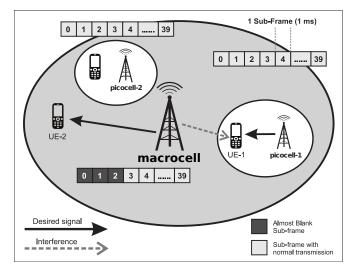

Fig. 1. ABS technique for interference in LTE-A HetNets. ©IEEE [19].

This pattern is signaled in the form of a 40-subframe bitmap lasting 40 ms. A neighboring picocell that possesses UEs interfered by the macrocell will preferentially schedule those UEs in the protected subframes. Other UEs located at the cell center can be scheduled over all subframes since the interference experienced from the macrocell aggressor is negligible compared to the signal of the picocell.

The UE-1, associated with picocell-1, suffers macrocell interference because it is located on the edge of a picocell. During each of the three subframes patterns of 40 ms, the macrocell is muted and sends no data traffic. Interference is reduced during such ABS; as picocell-1 will take advantage of the scheduled UE-1.

During ABS, macrocell does not transmit physical a downlink shared channel (PDSCH), creates "protected" subframes or "muting" for a picocell by reducing its transmit power, but for backward compatibility certain signals must be transmitted on all downlink subframes, even if muted [22].

The eICIC proposal in the LTE standards allows the time-sharing of subframes to link transmissions between macrocells and picocells, in order to mitigate the high interference experienced especially by picocell downlink users. The notion of eICIC via ABS is often coupled in the literature with another important technique for HetNets, namely that of appropriate resource allocation to ensure that picocells are not underused and not overloaded.

B. Cell selection bias (CSB)

An important approach for user association that has attracted a lot of interest lately is the concept of biased user association. This has been proposed by 3GPP in Release 10 [23], to extend the coverage of macrocells and increase their load. This mechanism is also called cell range extension (CRE). The strength of the power received by a user from a picocell would be artificially added by an offset, in order to offload macrocells and to ensure that more users attach to picocells. This offset is often named cell selection bias (CSB) [19]. The CSB mechanism is described in Fig. 2.
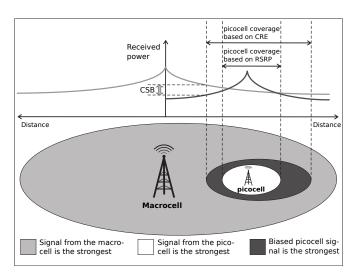

Fig. 2. CSB technique for interference in LTE-A HetNets. ©IEEE [19].

Each two neighboring cells range from $(-24dB)$ to $(24dB)$ but reasonable values are in the 10dB range. In general, some reciprocity is required in the CSB where CSB from macrocell-1 to macrocell-2 is equal to minus CSB from macrocell-2 to macrocell-1. Playing with the offset, artificially biases the attraction of a neighboring cell, this can "force" the user to perform the handover from or towards this neighboring cell in an indirect manner. For instance, when CSB from a macrocell to a picocell increases, it implies that more users would be offloaded from the macrocell to the picocell and this enlarges the coverage of the macrocell [24].

The purpose of CRE is to offload more traffic from macrocells to picocells and hence achieve larger cell splitting gains. By adding a CSB, the service area of picocells increases and more users are offloaded to picocells. The need for hetnets interference management schemes stems from the fact that users in the picocell expansion area are more vulnerable to stronger interference signals than useful signals from the associated serving picocell [25].

IV. SYSTEM MODEL

We consider a randomly generated HetNet that consists of macrocells and as such denote $\mathcal{M}$ and $\mathcal{P}$ as the set of all macrocells and picocells, respectively. Denote $\mathcal{M}_c$ and $\mathcal{P}_c$ as the macrocell and picocells in the center cluster of the HetNet, where the center cluster is surrounded by six clusters which are identical to the center cluster. We define that there is only one macrocell located at the center of each hexagon, and each hexagon has the same number of picocells. In addition, we adopt the system model adapted in [7]. Table I summarizes the notation used in this paper.

Let $\mathcal{U}$ be the set of all users in the system. Denote $\mathcal{M}_u$ as the macrocell that is located in the same hexagon as user u. We assume that only the macrocells in the same hexagon or in the adjacent hexagons can serve a user. Moreover, let $\mathcal{U}_i$ be the set of users associated with station i, where $i \in \mathcal{M} \cup \mathcal{P}$. The vector λ specifies the CSB values of all macrocells and picocells, where λ_i, the CSB value of station i, belongs to a predefined set C. Let $P_{i,u}^{Rx}$, be the RSRP of user u from station i, and the received power depends on the transmission power of the station, the distance between the station and the UE, and the loss due to shadow fading. Equation 1 gives the station that serves user u

$$\epsilon(u, \lambda) \triangleq \underset{i \in \mathcal{M} \cup \mathcal{P}}{argmax} (P_{i,u}^{Rx} + \lambda_i). \tag{1}$$

Let us assume there are N_S subframes in the time domain and N_R resource blocks (RBs) in the frequency domain. All subframes have the same duration, and all RBs are identical in terms of bandwidth. A PRB is formed by a pair of subframe and RB, and we denote $N_B := N_S \cdot N_R$ as the total number of PRBs available at each macrocell. All macrocells transmit at a fixed power level on PRBs that correspond to non-ABSs, and all picocells transmit at a fixed power level on all PRBs.

In this paper, we assume that only the macrocells would offer ABS while the picocells always transmit on all subframes. Let α_m be the binary vector specifying the ABS pattern of

macrocell m, where $\alpha_{m,j} = 0$ means the j-th subframe of macrocell m is an ABS and $\alpha_{m,k} = 1$ means the k-th subframe of macrocell m is a non-ABS, respectively. The signal to noise plus interference ratio (SINR) of a user u on PRB b when associated with macrocell m can be calculated as

$$SINR_{u,b}^m = \frac{h_{u,b}^m P_{m,u}^{Rx} \cdot \alpha_m(\tau(b))}{P_{\iota_m,u,b}^{IF} + N_0\, \mathcal{B}}, \qquad (2)$$

where $h_{u,b}^m$ gives the fast fading gain on PRB b from macrocell m to user u, $\tau(b)$ returns the subframe index of PRB b, ι_m denotes the set of stations whose transmission will interfere with the users located in the same hexagon as macrocell m, $P_{\iota_m,u,b}^{IF}$ is the sum of interference user u received from stations in ι_m at PRB b, N_0 denotes the additive white gaussian noise (AWGN) spectral density, and $\mathcal{B}$ is the bandwidth of a PRB. Similarly, the SINR of user u on PRB b when associated with picocell p is given by

$$SINR_{u,b}^p = \frac{h_{u,b}^p P_{p,u}^{Rx}}{P_{\iota_p,u,b}^{IF} + N_0\, \mathcal{B}}. \qquad (3)$$

The rate achieved by user u at PRB b is denoted as $r_{u,b}$, where $b \in [1, N_B]$. Due to the small-scale fading and potentially different ABS patterns of the interfering macrocells, a user can obtain different throughput on different PRBs and the rate achieved is calculated by Shannon's capacity formula, i.e.,

$$r_{u,b} = \begin{cases} \mathcal{B} \cdot \log_2(1 + SINR_{u,b}^m), & m \in \mathcal{M}, \qquad (4a) \\ \mathcal{B} \cdot \log_2(1 + SINR_{u,b}^p), & p \in \mathcal{P}. \qquad (4b) \end{cases}$$

Let $x_{u,b}$ be a binary variable indicating whether PRB b is allocated to user u by its serving station, where $x_{u,b} = 1$ means that PRB b is allocated to user u and $x_{u,b} = 0$ means otherwise. Denote w_u as the positive weighting factor of user u such that the each user has a throughput utility function, but no minimum rate is guaranteed, which can be interpreted as best effort user. We formulate the eICIC optimization problem as follows

$$maximize \sum_{i \in \mathcal{M} \cup \mathcal{P}} \sum_{u \in \mathcal{U}_i} w_u \cdot ln \sum_{b=1}^{N_B} x_{u,b} \cdot r_{u,b}, \quad (5a)$$

$$subject\ to \sum_{u \in \mathcal{U}_m} x_{u,b} = \alpha_m(\tau(b)),$$

$$\forall m \in \mathcal{M}_c,\ b \in [1, N_B],\ \alpha_m \in A, \qquad (5b)$$

$$\sum_{u \in \mathcal{U}_p} x_{u,b} = 1,\ \forall p \in \mathcal{P}_c,\ b \in [1, N_B], \qquad (5c)$$

$$x_{u,b} \in \{0, 1\},\ \forall u \in \mathcal{U},\ b \in [1, N_B], \qquad (5d)$$

$$\lambda(s) \in C,\ \forall s \in \mathcal{P}_c, \qquad (5e)$$

where 5b specifies that a macrocell can adopt one of the ABS patterns in A and only non-ABS PRBs can be assigned to the users such that at most one user can occupy a PRB, 5c states that all PRBs from picocells can be allocated to the users and at most one user can occupy a PRB, and 5e means that a picocell can adopt one of the CSB values specified in C.

TABLE I
SUMMARY OF NOTATION

Notation	Description
A	Set of vectors from which macrocells can choose ABS pattern
$\mathcal{B}$	Bandwidth per RB
C	Set of CSB values from which a picocell can choose from
$\epsilon(u, \lambda)$	The macrocell that user u is associated with
$h_{u,b}^i$	Fading gain from station i to user u at PRB b
$\mathcal{M}$	Set of all macrocells
$\mathcal{M}_c$	Set of macrocells in the center cluster
$\mathcal{M}_u$	Set of macrocells that is located in the same hexagon as user u
N_0	Noise power spectral density
N_B	Number of PRB
N_R	Number of RB (in frequency domain)
N_S	Number of subframes (in time domain)
N_i^{Att}	Set of stations whose i user attachment can be affected by the change of CSB value of station i
N_i^{IF}	is the set of stations whose attached users can be interfered by the transmissions of station i
$\mathcal{P}$	Set of all picocells
$\mathcal{P}_c$	Set of picocells in the center cluster
$P_{i,u}^{Rx}$	The RSRP of user u from station i
$P_{\iota_m,u,b}^{IF}$	The sum of interference at user u received from stations in ι_m at PRB b
$r_{u,b}$	Achieved rate of user u at PRB b
$\tau(b)$	The index of subframe of PRB (b)
S_i	Set of the strategy of player i
$\mathcal{U}$	Set of all users in the system
$\mathcal{U}_i$	Set of users associated with macrocells in set i or with macrocell i in the system
$x_{u,b}$	Indicator of whether user u occupies PRB b of the serving station
w_u	Weighting factor of UE u
α_m	ABS pattern of macrocell m
λ	Vector specifying CSB values of all macrocells
λ_i	Vector specifying CSB values of station i
ι_m	The set of stations whose transmission will interfere with the users located in the same hexagon as macrocell m
β	Weight of metric J
γ	Weight of metric J

V. DISTRIBUTED SOLUTION FOR EICIC OPTIMIZATION

In this section, the authors herein aim at developing a distributed solution to the problem described in Section IV by formulating an exact potential game based on the algorithm described in paper[7]. In addition, we present the downlink schedulers Φ used in this paper.

A. Exact Potential Game Formulation

Potential games were defined and their properties discussed in [26]. A game is called an exact potential game if there exists an exact potential function such that the change in the value of the exact potential function due to the change of a player's strategy is the same as the change of the player's payoff. The key to the exact potential game formulation is found in the appropriate definition of the payoff function.

A finite game consists of a finite set of players, a finite set of strategies of each player, and the payoff functions of the players, where the payoff of a player is a function of the strategies played by all the players. A strategy profile gives the strategies adopted by all the players, and a Nash equilibrium can be achieved if players take turns randomly and play their

best responses or better responses [27], where it is understood that all other players fix their strategies.

The best response dynamics solves an exact potential game by iteratively finding the strategies that maximize the payoff functions of the players selected in each iteration [6]. We provide a distributed algorithm that jointly optimizes the ABS patterns and CSB values in HetNets. We formulate the problem as an exact potential game that allow us to solve them distributively using simple algorithms based on best/better response dynamics.

Using the approach in [7], let the stations be the players, so that $\mathcal{M} \cup \mathcal{P}$ defines the set of player. Each player i chooses a strategy s_i from a set of strategies $\mathcal{S}_i$. The underlying assumption is that ABS is allowed in macrocells but not in picocells, and all stations can set their CSB values according to C. Let vector s specify the strategies of all players, where $s(i)$ gives the strategy of station i. Define the strategies selected by all players except player i

$$\mathbf{s}_{-i} \triangleq (s_1, \ldots, s_{i-1}, s_{i+1}, \ldots, s_{|\mathcal{M}|+|\mathcal{P}|}), \quad (6)$$

as the strategies of all players other than player i. Denote

$$(s_i', \mathbf{s}_{-i}) \triangleq (s_1, \ldots, s_{i-1}, s_i', s_{i+1}, \ldots, s_{|\mathcal{M}|+|\mathcal{P}|}), \quad (7)$$

so that player i adopts strategy s_i' and the strategies of the remaining players are specified by s_{-i}.

Let $\mathcal{N}_i \triangleq \{i\} \cup \mathcal{N}_i^{IF} \cup \mathcal{N}_i^{Att}$, where $i \in \mathcal{M} \cup \mathcal{P}$, $\mathcal{N}_i^{IF}$ is the set of stations whose attached users can be inhibited by the transmissions of station i, $\mathcal{N}_i^{Att}$ is the set of stations whose i user attachment can be affected by the change of CSB value of station i. Let the utility of station $i \in \mathcal{M} \cup \mathcal{P}$ be

$$U_i(\mathbf{s}) \triangleq \sum_{u \in \mathcal{U}_i} w_u \cdot ln \sum_{b=1}^{N_B} (x_{u,b}) \cdot r_{u,b}, \quad (8)$$

where $x_{u,b}$ is obtained by some scheduling scheme given s so that the constraint in 5b, 5c and 5d are satisfied. The aggregate utility of all the players is given as

$$U(\mathbf{s}) = \sum_{i \in \mathcal{M} \cup \mathcal{P}} U_i(\mathbf{s}), \quad (9)$$

and the payoff function of player i is defined as

$$V_i(\mathbf{s}) \triangleq \sum_{j \in \mathcal{N}_i} U_j(\mathbf{s}). \quad (10)$$

In the following theorem, we show that when $\mathcal{N}_i^{IF} = i \cup N(i, 1)$, $U(s)$ is an exact potential function.

Theorem 1. If $\mathcal{N}_i^{IF} = i \cup N(i, 1)$, then $U(\cdot)$ is an exact potential function of the game Γ, so that Γ is an exact potential game.

Proof. See [7]. ∎

B. Proposal Improvements eICIC Optimization framework

In this paper, the objective is to prioritize the traffic of users located at the edge of the cell, which are those that face the highest levels of interference. We formulate the optimization problem as a game where, in order to maximize a modified utility function aiming at improvements on eICIC. This strategy exploits the diversity of users across the network in the frequency and time domain.

We adapt the game theoretic frameworks in [7], derived from Equation 11, as well as propose some improvements on these algorithms in order to achieve better performance, called eICIC+ and formulate the following problem

$$maximize \sum_{i \in \mathcal{M} \cup \mathcal{P}} \sum_{u \in \mathcal{U}_i} w_u \cdot ln \sum_{b=1}^{N_B} x_{u,b} \cdot r_{u,b}, \quad (11)$$

.

The proposed algorithm eICIC+ finds the right balance between fairness and throughput by adjusting certain variables in the metric [28]. The utility function considers the achieved throughput and instantaneous user data rates to increase the likelihood of allocation and to serve users according to priority requirements and thus achieve better network performance. In this sense, the option chosen to improve eICIC optimization performance was to change its metric to maintain its basic characteristics, for which the metric of eICIC+ optimization is presented below

$$maximize \sum_{i \in \mathcal{M} \cup \mathcal{P}} \sum_{u \in \mathcal{U}_i} w_u \cdot ln \sum_{b=1}^{N_B} x_{u,b} \cdot J, \quad (12a)$$

$$subject\ to\ J = \frac{[r_{u,b}]^\beta}{[\bar{r}_u(t)]^\gamma}. \quad (12b)$$

Different realizations of β and γ will affect the elements in average data rate and instantaneous data rate. Thus it is seen that the eICIC+ optimization seeks an adaptation both to deliver fairness to users as well as high transfer rates (e.g., see [28]).

The higher the β values, greater will be the achievable influence of the instantaneous data rate, thus improving the likelihood of serving a user with good channel conditions. This translates into a higher throughput on the network, but with a lower fairness index. As one increases the metric, one seeks to broaden the influence of the flow rate achieved at previous times, this increases the chance that a user who has reached lower throughput values will be scheduled, resulting in a low throughput of the network, but a high level of fairness can be predicted.

Now, on the other hand, when the γ value is increased, the user-equal rate escalation scenario is achieved, thus delivering the same rate to all requesters. Thus, the algorithm metric is responsible for modifying the impact of the resource allocation policy on the expected instantaneous data rate for UEs on the network, so that with an equal rate for all users, the algorithm allocates resources for UEs such that they achieve an equal transfer rate.

Algorithm 1 provides more details of the eICIC+ optimization. Therefore the proposed eICIC+ optimization algorithm based on exact potential game formulation [7] is given as follows:

JOURNAL OF COMMUNICATION AND INFORMATION SYSTEMS, VOL. 35, NO.1, 2020.

20

Algorithm 1 eICIC+ optimization

1: Initialize the ABS and CSB patterns of all macrocells.
2: Initialize the CSB values of all picocells.
3: $\beta \leftarrow 0.7$
4: $\gamma \leftarrow 0.6$
5: Calculate V_i from Equation 10 based on Equation 12a
6: **repeat**
7:    Pick randomly a player $i \in \mathcal{M} \cup \mathcal{P}$
8:    **if** (strategies in s_i) **maximizes** (V_i) **then**
9:       Perform scheduling for all stations i in $\mathcal{N}_i^{Att}$ using scheduler Φ
10:       Evaluate V_i
11:    **else**
12:       Select the element in $A \times C$ that maximizes V_i.
13:    **end if**
14: **until** some stopping criterion is met.

C. Proportional Fair (PF) Scheduler

The PF tries to strike a balance between spectral efficiency and fairness by adjusting the scaling rate according to the instantaneous channel quality in relation to its performance over time [29]. For station s, the b-th PRB at subframe $\tau(b)$, given that the subframe is not an ABS, will be allocated to the following user

$$\widehat{u}_b \triangleq \underset{u \in \mathcal{U}_i}{argmax} \ \frac{r_{u,b}}{\bar{r}_u(\tau(b))}, \tag{13}$$

where $\tau(b)$ gives the subframe index of the b-th PRB, $b \in [1, B]$, and $\bar{r}_u(\tau(b))$ is the long-term average throughput of user u in subframe $\tau(b)$ which is calculated as

$$\bar{r}_u(t) = \left(1 - \frac{1}{s_w}\right)\bar{r}_u(t-1) + \frac{1}{s_w}\sum_{\{b|\tau(b)=t\}} r_{u,b} \cdot \mathcal{I}\{\widehat{u}_b = u\}. \tag{14}$$

In the equation above, s_w is the size window which is a design parameter and $\mathcal{I}\{\cdot\}$ is the indicator function.

The goal is to use the long-term average throughput $\bar{r}_u(t)$ to act as a data rate weighting factor $r_{u,b}$, so that users of channels with a low service quality can be attended to within the given period of time.

D. Round-Robin (RR) Scheduler

It is probably the simplest scheduler found in the literature [30]. It assigns resource block group (RBGs) sequentially to UEs without any concern for channel conditions, thereby, dividing available resources among active streams. If the number of RBGs is greater than the number of active streams, all streams can be allocated to the same subframe. In the next subframe, allocation will start from the last unallocated stream.

In scheduling, time resources are evenly divided among users one after the other and without any priority, scheduling is based on the availability of RBs during the scheduling process. The metric is similar to that of FIFO scheduling, the difference is in T_u, which is the last access to user u broadcast channel.

$$\widehat{u}_b \triangleq \underset{u \in \mathcal{U}_i}{argmax} \ t - T_u \tag{15}$$

VI. PERFORMANCE EVALUATION

In order to evaluate the performance of the eICIC optimization, a simulation environment in the MATLAB software was modeled with reference to [6]. Table II presents the main simulation parameters which are based on the paper described in [31].

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Antenna gain	14 dBi
Antenna per site	Omnidirectional x 1
Bandwidth	5 MHz
Cell geometry	Hexagonal
CSB values	$C := \{0,3,6,9,12,15\}$ dB
Dist. min. of macrocell per user	35 m
Dist. min. of macrocell to picocell	75 m
Dist. min. of picocell per user	10 m
eICIC +($\boldsymbol{\beta}$)	0.7
eICIC +($\boldsymbol{\gamma}$)	0.6
Inter macrocells distance	1000 m
Macrocell maximum power (P_t)	40 W
Number of RBs	25
Number of sites	7
Path loss from macrocell to user	$128.1 + 37.6 \log_{10} d$, d in km
Path loss from picocell to user	$140.7 + 36.7 \log_{10} d$, d in km
Penetration loss (PenL)	10 dB
Picocell maximum power (P_t)	1 W
RB bandwidth	180 kHz
Schedulers	Proportional Fair Round-Robin
Shadow fading (ζ)	Log-normal distribution
Subcarrier frequency	15 kHz
Thermal noise density	−174 dBm/Hz
Traffic model	Full buffer
TTI	1 ms

The geometry of the cell for our simulated LTE system is hexagonal. The scenario consists of 7 clusters consisting of macrocells and picocells, six adjacent to the central cluster. The six neighboring clusters of the central cluster are exact copies of the central cluster responsible for creating the interference scenario. The inter-macrocells distance is 1000 m, which corresponds to an LTE network deployed in an urban area. In each cell, 25 RBs are available as the operational bandwidth is 5 MHz. However, the traffic model is full buffer, meaning all available RBs are permanently allocated to the active UEs in the network.

Simulation studies are performed on eICIC optimization by randomly generating 10 HetNets topologies and then the central cluster average of the performance measures of each topology. It is assumed that there is only one macrocell located in the center of each hexagon, and each hexagon has the same number of picocells. In the central cluster of each topology, a number of picocells (ranging from one to five), where the picocells are placed randomly. In addition, for each hexagon in the center cluster, six users are placed within 100 meters from each picocell and another four users are placed within the hexagon. The distribution of the distances from the six users who are intentionally placed within 100 meters of a picocell, and the directions from the picocell to the six users are random. The other four users are similarly generated except the reference point, which the respective macrocell.

It is assumed that users are static. In addition, each PRB experiences Rayleigh fading with variance 1. The shadow fading of a macrocell for a user is calculated by first adding a common shading value and a random shading value and dividing the sum by $\sqrt{2}$, where both shading values are generated according to the log normal distribution. The weighting factors of all users are set be 1, i.e., $w_u = 1$ for all u. N_S is set be 10 and N_R is set to 3. In all simulation results, we compared a technique that uses an exact potential game (named eICIC in the graphics), the proposed eICIC+ optimization and a scenario without interference control, NULL.

Spectral efficiency (SE) is defined as the average of bits transmitted per second per Hz (bps/Hz) of all allocated PRBs. The obtained SE results are shown in Fig. 3 and Fig. 4, considering the scheduling algorithms PF and RR, respectively. Noteworthy here is that with the increase of picocells, there is an improvement of SE when using the eICIC and eICIC+ techniques compared to the scenarios without interference control. Thus, such techniques proved to be important in terms of SE for the simulated scenario, that is, in HetNets with a higher densification level. In addition, it is noteworthy that the SE improvement was more significant in the scenario with the use of the PF scheduling algorithm.
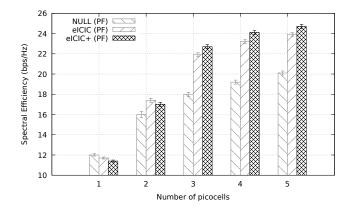

Fig. 3. Comparative index of SE as a function of the number of picocells using the PF algorithm.
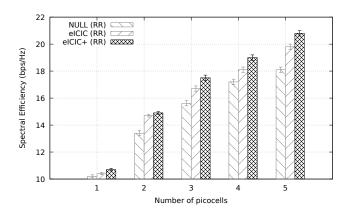

Fig. 4. Comparative index of SE as a function of the number of picocells using the RR algorithm.

The energy efficiency (EE) calculated as the number of

transmitted bits divided by the transmission power is presented in Fig. 5 and Fig. 6, considering the PF and RR scheduling algorithms, respectively. The use of eICIC and eICIC+ techniques resulted in an increase of EE in all scenarios with the exception of the one picocell scenario in conjunction with the use of the PF algorithm. In general, it is noted that the eICIC+ strategy had better results than the eICIC technique, proving to be a more appropriate technique for the coordination of interferences in the analyzed scenarios, especially with the increase in the number of picocells.

Since network densification is a key element in increasing system coverage and meeting in growing demand, the use of interference coordination techniques, particularly eICIC+, has enabled improvements in spectral and energy efficiency and are, therefore, important in expanding the capacity of the network.
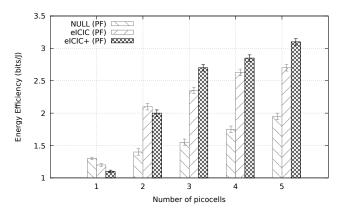

Fig. 5. Comparative index of EE as a function of the number of picocells using the PF algorithm.
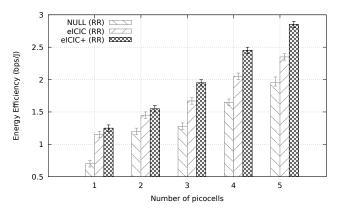

Fig. 6. Comparative index of EE as a function of the number of picocells using the RR algorithm.

The throughput of the worst 5% of rates achieved by users that tend to have the highest levels of interference is analyzed, that is, they are at the edge of the cell in the central cluster. Fig. 7 and Fig. 8 show the cumulative distribution function (CDF) of the said rate, considering the PF and RR scheduling algorithms, respectively, and each hexagon has five picocells. Through this configuration, eICIC optimization can improve the median value of the worst 5% users' achieved rates of

about 10.89% (7.65%) and eICIC+ optimization can further improve the median value by about 16.54% (12%) considering the PF (RR) algorithm.

As a result, when mobile operators seek to improve throughput of the user edge cell, eICIC+ optimization in conjunction with the PF algorithm proves itself to be the most appropriate technique for these scenarios.
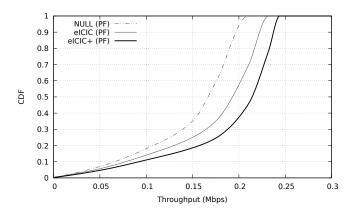

Fig. 7.   The cumulative distribution function (CDF) of the worst 5% users' achieved rates in the center cluster, where the PF scheduler is used and each hexagon has five picocells.
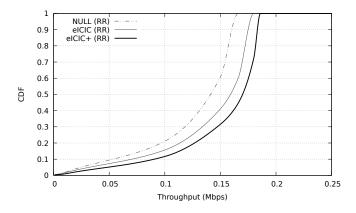

Fig. 8.   The cumulative distribution function (CDF) of the worst 5% users' achieved rates in the center cluster, where the RR scheduler is used and each hexagon has five picocells.

For other quantities of picocells, the improvements percentages range of the worst 5% users' achieved rates compared to the non-optimization case are shown on Table III.

It is important to note that in the one picocell scenario, although the eICIC+ scheme did not always achieve better SE and EE results than eICIC, the worst 5% users' achieved rates increased considerably for both scheduling algorithms. In addition, for the other quantities of picocells one also noted for the eICIC+ scheme an increase in the throughput of the worst 5% users' achieved rates, keeping the SE and EE higher than the eICIC scheme, especially when using the PF scheduling algorithm.

Another noteworthy point is that the use of the PF scheduling algorithm has always presented superior results for the statistics presented so far, in relation to the RR algorithm in the analyzed scenarios. Given this fact, it is noteworthy

TABLE III
PERCENTAGE OF THE WORST 5% USERS' ACHIEVED RATES

Picocells	Schedulers	Improvement (%) eICIC	Improvement (%) eICIC+
1	PF	30%	44%
	RR	13.05%	19.04%
2	PF	22.22%	25.92%
	RR	11.90%	17.87%
3	PF	17.63%	21.31%
	RR	11.88%	16%
4	PF	13.44%	19.03%
	RR	8.65%	14.77%
5	PF	10.89%	16.54%
	RR	7.65%	12%

that from two picocells the percentage of improvement of the worst 5% users' achieved rates, promoted by the eICIC+ scheme, when compared to eICIC, grew as the number of picocells increased. Thus, as the throughput of users with the highest levels of interference in the cell is a major concern of interference coordination schemes, the use of the eICIC+ scheme in conjunction with the PF algorithm, based on the results obtained, is a promising setting.

Table IV summarizes some key performance indicators of various optimization scenarios. We note here that the ABS and CSB optimization presented a growth on the mean achieved user rate, when compared to the case where no optimization is performed, where a user's achieved rate is calculated by adding the capacity of each PRB that is allocated to that user. This increase is intensified by the use of eICIC and especially eICIC+.

TABLE IV
FAIRNESS INDICES AND AVARAGE ACHIEVED USER RATE

Optimization	Schedulers	Mean UE Rate (bits/s/Hz)	Jain's Index
eICIC+	PF	196.02	0.6543
	RR	159.77	0.6891
eICIC	PF	189.86	0.6174
	RR	151.54	0.6263
ABS	PF	181.89	0.5646
	RR	149.68	0.5863
CSB	PF	172.89	0.5376
	RR	129.02	0.5431
No optimization	PF	168.07	0.5123
	RR	121.22	0.5203

With respect to the scheduling algorithms, one notes that the increase in the average rate obtained by employing the PF algorithm resulted in a reduction of the fairness index when compared to the RR algorithm.

In addition, we analyzed variations of the β and γ parameters used in eICIC+ optimization, according Table V. As a result, it was found that with the increase of β (0.7 to 0.75) there is a downward trend in the justice index and an increase in the UE average rate. On the other hand, with the increase of γ (0.6 to 0.7), a behavior contrary to the previous scenario was observed. These parameters can therefore be adjusted when one of the performance measures is to be optimized.

TABLE V
FAIRNESS INDICES AND AVARAGE ACHIEVED USER RATE

Parameters	Schedulers	Optimization		
		eICIC+	eICIC+ $\beta = 0.75$	eICIC+ $\gamma = 0.7$
Jain's	PF	0.6543	0.6233	0.6577
	RR	0.6891	0.6369	0.6899
Mean UE	PF	196.02	196.74	195.04
	RR	159.77	160.02	158.22

VII. CONCLUSION

This paper proposes a study and improvement of the eICIC optimization in downlink in LTE-A Hetnets. A performance comparison is presented between the eICIC coordination method presented in 3GPP Release-10, and a scenario with the optimized interference coordination proposal, eICIC+. Simulation results showed that eICIC+ optimization does in fact improve spectral efficiency and energy efficiency, especially in scenarios of higher grid densification. In addition, eICIC+ can generate significant gains in the throughput of users located at the edge of the cell, who face the highest levels of interference. The integration of the modified eICIC+ optimization with the PF scheduling algorithm proved to be a good option in the scenarios analyzed.

As future work, we highlight the need to study the integration of other scheduling algorithms with the eICIC+ technique and interaction with the β and γ parameters in order to optimize performance on a HetNet.

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24

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