Energy-efficient resource allocation for ultra-dense licensed and unlicensed dual-access small cell networks

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Abstract—In this study, an energy-efficient self-organized framework for sub-channel allocation and power allocation is presented for ultra-dense small cell networks, which can operate in both licensed and unlicensed bands. In order to protect legacy WiFi devices (operating in unlicensed bands), we consider the LTE operation in unlicensed bands based on CSAT, in which 'ON' and 'OFF' duty cycle approach is utilized. On the other hand, there are severe interference management problems among small cells (operating in licensed and unlicensed bands) and between macro cells and small cells (operating in licensed bands) due to co-channel and ultra-dense deployment of small cells. This article proposes a self-organized optimization framework for the allocation of sub-channels and power levels by exploiting a non-cooperative game with the objective to maximize the energy efficiency of dual-access small cells without creating harmful impact on coexisting network entities including macro cell users, small cell users, and legacy WiFi devices. Simulation results show that the proposed scheme outperforms (6% and 11%) and (8% and 18%) the round-robin and the spectrum-efficient schemes, respectively for two different small cell scenarios. In addition, it is shown that for less CSI estimation errors $\varsigma = 0.02$, the maximum performance degradation of the proposed scheme is reasonably small (5.5%) as compared to the perfect CSI.

Index Terms—Self-organization, sub-channel allocation, power allocation, non-cooperative game, small cells, licensed band, unlicensed band.

1 INTRODUCTION

2 **D**UE to the proliferation of real-time bandwidth hun-
3 gry applications such as video streaming, online
4 gaming and mobile computing, there is a sharp increase
5 in the bandwidth demand. According to a recent report by
6 Cisco Global Mobile Data Traffic Forecast [1], there will be
7 around 11 billion mobile devices by 2019 which is above
8 the world's expected population at that time (7.6 billion).
9 Also, it is reported by the industry that cellular traffic is
10 doubling every year; therefore, cellular network should
11 be able to deal with the 1000x increase in cellular traffic
12 by 2020 [2]. This increase in the traffic demand imposes
13 critical challenges in terms of meeting the quality of service
14 (QoS) requirements from the existing cellular network
15 architecture. The limiting factor here is the licensed spec-
16 trum, which is a real bottleneck in meeting the increasing
17 traffic demand. On the other hand, the continuous increase
18 in the cellular traffic is also a serious threat to the energy
19 consumption of future cellular networks and it has a direct
20 impact on the operating cost (OPEX) of cellular operators.

21 Thereby, an energy-efficient design for the future cellular
22 networks is needed.

23 To cope with the ever increasing traffic demands, vari-
24 ous innovative technologies/methodologies have been de-
25 veloped such as non-orthogonal multiple access (NOMA),
26 multiple-input multiple-output (MIMO), carrier aggre-
27 gation (CA), small cells, context awareness, etc [3]–[6].
28 Among various options, small cells, which are deployed
29 as underlay within macro cells, boost the coverage and ca-
30 pacity by reusing the licensed spectrum. *Qualcomm* states
31 that the dense deployment of small cells is the foundation
32 of the 1000x vision of the fifth generation (5G) cellular
33 network [7]. This ultra-dense deployment of small cells
34 increases the coverage per square kilometer and the capac-
35 ity by reusing the spectrum. More specifically, this ultra-
36 dense deployment contributes a 56-fold in the 1000-fold
37 traffic demand [8]. Although this ultra-dense deployment
38 holds great promise for enhancing the spectrum efficiency
39 by exploiting both spatial and universal frequency reuse,
40 the co-location of small cells underlaid in macro cells
41 creates severe interference management problems. In this
42 context, recent scientific literature focuses on the interfer-
43 ence management for enhancing the spectrum efficiency
44 [9]–[11], while energy efficiency is almost neglected. The
45 increase in the spectrum efficiency corresponds to high
46 throughput but at the cost of large energy consumption
47 which is mostly not suitable for energy-aware networks or
48 constrained devices [12]. Recently, energy efficiency, which
49 is defined as information bits per unit of transmit energy

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(bits/J), has received significant attention from industry, academia, and standardization bodies. Some studies have revealed that energy efficiency will be an integral part of the 5G cellular networks, especially for the ultra-dense small cell environment for meeting the QoS requirements [8]. Thus, we can say that both spectrum efficiency and energy efficiency will be critical for interference management in the ultra-dense small cell environment, which is confirmed when looking at the 5G vision and requirements [13]. *Hu et al.* [13] propose a cooperative mechanism for finding a balance between energy efficiency and spectrum efficiency, but it is not suitable for the ultra-dense environment because it incurs huge information exchange overhead. On the contrary, this work aims to propose an efficient and a less complex scheme which does not require cooperation and thus, minimizes the information exchange overhead.

Also, WiFi hotspot has been successfully utilized for offloading the cellular traffic from licensed band to unlicensed band [14]. Considering the benefits of small cells and WiFi hotspots, one natural enhancement of small cells is to operate in both licensed (e.g. LTE or third generation (3G)) and unlicensed (e.g. WiFi) bands simultaneously. We refer to these enhanced small cells as the dual-access small cells since they can operate in both licensed and unlicensed bands. The coexistence of LTE and WiFi in unlicensed bands has recently gained significant attention and in this regard, two prominent standardization efforts have been made: LTE in unlicensed spectrum (LTE-U) [15] and Licensed Assisted Access (LAA) [16]. LTE-U was standardized by the LTE-U forum which is based on Carrier Sense Adaptive Transmission (CSAT) for selecting 'ON' and 'OFF' duty cycles according to WiFi transmission occupancy. Whereas, LAA was standardized by the 3rd Generation Partnership Project (3GPP) in Release 13 and uses the listen-before-talk (LBT) technique (similar to WiFi). In this work, we consider LTE-U based CSAT and leave LAA for future investigations. The term dual access small cell that we use in this work can be termed as LTE-U based on CSAT. Later in this article, we will use the terms dual access small cells and LTE-U interchangeably.

The rapid evolution of LTE-U raises critical concerns on the coexistence of LTE and WiFi. Primarily, the coexistence of LTE and WiFi is a challenging problem. The main challenge is to find a balance between the operation of LTE and the proprietary technologies including WiFi that operate in unlicensed bands. Traditionally, LTE was designed to operate centrally as a non-contention technology and has no concern with cross-tier interference i.e., interference from other technologies. In addition, LTE is a streaming technology which means that even in the absence of data traffic, control and reference signals are transmitted over-the-air. On the contrary, WiFi is a contention-based technology and it only transmits when the channel is not occupied. This makes WiFi an ideal candidate to operate in unlicensed bands. Due to these fundamental differences, the operation of traditional LTE in unlicensed bands could have a significant impact on the performance of WiFi [17]. Even though due to the adoption of CSAT in LTE, its operation can degrade the WiFi performance [18]. We also observed the similar performance degradation trend by

experimentally validating the LTE impact on WiFi by using open source LTE implementation [19]. This degradation mainly because of two factors: (i) the incompatible LTE-U duty cycle mechanism with WiFi devices and (ii) the lack of an efficient coexistence mechanism when LTE and WiFi devices are far apart from each other and the received power is low [20]. To address such coexistence problems, this paper considers dual-access small cells based on the CSAT approach which provides a coexistence mechanism by using 'ON' and 'OFF' duty cycles for LTE and other unlicensed technologies including WiFi [21]. In the LTE-U 'ON' period, each dual-access small cell base station (SBS) utilizes sub-channels from both licensed and unlicensed bands while the legacy WiFi devices backoff due to the adoption of the carrier-sense multiple access with collision avoidance (CSMA/CA) protocol. While in the 'OFF' period, the SBSs do not transmit and provide transmission opportunities to the legacy WiFi devices. In this work, we assume that 'ON' and 'OFF' periods are determined by each dual-access SBS in a self-organizing way and are based on the transmission occupancy of the legacy WiFi devices. However, this creates another challenge of interference management specially in the 'ON' period due to the co-channel operation of (i) small cells and macro cells in licensed bands and (ii) small cells and the legacy WiFi devices in unlicensed bands. In such a coexisting environment, meeting the QoS requirements is a critical challenge and for this, we aim to solve this by investigating sub-channel allocation and power allocation for dual-access small cell networks. Generally, a centralized architecture can be an option here for managing the interference optimally. However, such a centralized control is not applicable in the considered dense environment due to its lack of scalability and increased information exchange overhead.

Motivated from the above-mentioned concerns, in this work, a self-organized sub-channel allocation and power allocation scheme for the downlink of dual-access small cell networks is modeled as a non-cooperative game. Since for an ultra-dense environment centralized management approaches are not appropriate, we aim to propose a self-organizing solution and for this game-theoretic approaches are most suited. Such a game-theoretic approach provides a mathematical tool for modeling an optimization problem [22], [23]. The main goal of the proposed scheme is to enhance the energy efficiency of small cell networks while meeting the throughput requirements of small cell users, macro cell users, and the legacy WiFi devices. Thus, energy efficiency is considered as the QoS criterion of the proposed scheme. In the proposed non-cooperative game, the dual-access SBSs are the players of the game while the sub-channels and the power levels are the strategies of the game. Since the goal is to design an energy-efficient self-organized resource management scheme, the problem is formulated as follows: each player of the game (SBS) during the 'ON' period selects the sub-channels (from licensed and unlicensed bands) and the power levels for enhancing its energy-efficiency without creating harmful impact on the coexisting networking entities including small cell users, macro cell users, and the legacy WiFi devices. In addition, we propose that 'ON'

and 'OFF' periods are selected by each dual-access SBS in a self-organizing way based on the legacy WiFi devices occupancy. Concerning the complexity of the joint sub-channel allocation and power allocation problem, the joint problem is decomposed into two sub-problems: the sub-channel allocation and the power allocation. In the sub-channel allocation step, the allocation of sub-channels from both licensed and unlicensed bands is carried out with the concern of minimizing the impact of cross-tier and co-tier interference components. Where the cross-tier interference is the interference among different tiers i.e., small cells, macro cell, and legacy WiFi devices while the co-tier is between the same tier. In the power allocation step, the selection of power levels on the sub-channels (selected in the previous step) is carried out by exploiting dual-decomposition Lagrangian multipliers.

1.1 Contributions

The main contributions of our work are summarized as under:

- 1) A framework is proposed for solving the sub-channel allocation and power allocation problem in the downlink of dual-access small cells which operate in both licensed and unlicensed bands. The framework aims to maximize the energy efficiency of small cells using a non-cooperative game without compromising the QoS requirements of small cell users, macro cell users, and the legacy WiFi devices.
- 2) Since the energy-efficient sub-channel allocation and power allocation is in a fractional form and a non-convex optimization problem, traditional convex optimization techniques cannot be applied for finding the optimal solution. We first transform the problem into its equivalent subtractive form using the properties of non-linear fractional integer programming and then, propose an efficient and a less complex iterative algorithm for solving the sub-channel allocation and the power allocation individually. In addition, the proposed iterative algorithm is shown to converge to the optimal energy efficiency and to the Nash Equilibrium point.
- 3) Simulations results are carried out in terms of energy efficiency and spectrum efficiency to compare the proposed scheme utilizing both licensed and unlicensed bands with the comparative counterparts: a) the proposed scheme utilizing only licensed bands, b) the round robin non-cooperative power optimization game (RR-NPOG) [24], and c) the spectrum efficient scheme. The performance improvement of the proposed scheme as compared to the counterparts (a,b, and c) increases from 5%, 7.6%, and 10.9% to 7.73%, 11.04%, and 17.06%, respectively, with the increase of the small cell density from 20 to 40. In addition, the proposed scheme is evaluated for different levels of imperfection in estimating CSI: perfect CSI and imperfect CSI. Which concludes that for less CSI estimation errors $\varsigma = 0.02$, the maximum performance degradation of the proposed scheme

is reasonable small (5.5%) as compared to the perfect CSI.

2 RELATED WORK

The concept of aggregating radio resources is nowadays an active research topic and in this context, the literature includes several works that address the coexistence of LTE and WiFi. On the other hand, an energy-efficient design specially for a dense environment has recently gained significant attention from the scientific community. Based on this, we present the related work in three parts: i) energy-efficient resource allocation in wireless networks, ii) general approaches for LTE and WiFi coexistence, and iii) game-theoretic approaches for LTE and WiFi coexistence.

2.1 Energy-efficient resource allocation in wireless networks

Li et al. [12] present a comprehensive survey on an energy-efficient design of wireless networks and highlight key areas such as information-theoretic analysis, MIMO techniques, relaying, and resource allocation for meeting the QoS requirements. Due to the explosion of high data rate applications in future wireless networks, more energy will be consumed for meeting such requirements. Therefore, it is imperative to design energy-efficient mechanisms while satisfying the requirements. On the other hand, future wireless networks will be extremely dense and in this regard, centralized management architectures are not suitable due to their lack of scalability and increased information exchange overhead. *Meshkati et al.* [25] present a detailed overview of energy-efficient resource allocation mechanisms in wireless networks using game theoretic approaches. In a dense environment, game-theoretic approaches are most suited due to their ease of scalability and reduced information exchange overhead. *Xie et al.* [26] investigate and formulate an energy-efficient resource allocation problem for heterogeneous femto cell cognitive radio networks cells using a Stackelberg game. It only considers co-tier interference and for cross-tier, it is assumed that a spectrum resource borrowed from a primary network can only be allocated to a single femto base station. This assumption is not valid for a dense environment. *Arani et al.* [27] present a self-organized mechanism for joint channel and power allocation with the concern of maximizing the energy efficiency of heterogeneous networks using a non-cooperative game. It only considers co-channel interference but in a dense environment where LTE and WiFi operate in similar unlicensed bands, cross-channel interference also becomes important. Considering the importance of cross-channel interference, we include it in the problem formulation and by doing so better spectrum decisions can be made. *Samarakoon et al.* [28] propose a joint power control and user scheduling scheme for enhancing the energy efficiency of ultra-dense small cell networks using a dynamic stochastic game. It does not address the coexistence problem of LTE and WiFi, which is the prime focus of our work. Also, the scheme in [28], cannot be directly applied to solve the formulated problem in this work.

2.2 General approaches for LTE and WiFi coexistence

Zakrzewska et al. [29] propose an idea of splitting the control plane (C-plane) and the user data plane (U-plane) where the C-plane of small cells is provided by a macro base station (MBS) while the U-plane is provided by SBSs. This splitting concept can be employed in dual-access small cells which can operate in both licensed and unlicensed bands. However, the authors do not consider interference management, which is indeed of vital importance when considering coexisting and dense environments. *Khawer et al.* [30] propose an interference coordination scheme for a CSAT gating mechanism in LTE-U and illustrate multi-operator network performance. *Lui et al.* [31] propose a resource allocation scheme for balancing the traffic between licensed and unlicensed bands while the WiFi throughput is maintained by an optimization framework. *He et al.* [32] present a novel proportional fair scheme for a fair coexistence of LTE and WiFi is proposed. Despite of the interesting results [29]–[32], all the focus is on spectrum efficiency by managing or avoiding the interference while energy efficiency is ignored and the solutions in these propositions cannot be directly converted to energy efficiency problems. In addition, all the works focus on a centralized control environment which is not suitable in a ultra-dense environment as it poses formidable computational complexity.

2.3 Game-theoretic approaches for LTE and WiFi coexistence

Etkin et al. [33] propose a sharing between LTE and WiFi using a repeated non-cooperative game. A similar scheme with an extended model is proposed in [34] using a repeated non-cooperative game. The authors in [35], [36] propose a spectrum allocation problem in unlicensed bands using a non-cooperative game in which the base stations are the players and the spectrum resources are the strategies of the game. The goal in their proposition is to optimize the spectrum efficiency for both downlink and uplink. *Thakur et al.* in [37] present a resource allocation and a cell selection mechanism for femto cell networks operating in licensed and unlicensed bands. For the resource allocation scheme, they propose a non-cooperative game and a Q-learning framework for LTE operating in licensed and unlicensed bands. Finally, they combine the resource allocation scheme with the cell selection and show the performance improvements in terms of throughput and energy efficiency. However, they do not consider co-tier and cross-tier interference which is a challenging problem in a dense environment. In addition, they model the resource allocation problem while maximizing the throughput instead of energy efficiency. Despite some efforts on the exploitation of game-theoretic approaches for the LTE and WiFi coexistence, all the propositions consider only the spectrum efficiency as the performance objective and the ultra-dense environment is not considered. In addition, the propositions cannot be directly converted to energy efficiency problems in order to achieve the required performance.

According to the best of our knowledge, a self-organized framework for an energy-efficient sub-channel

allocation and power allocation for ultra-dense small cell networks which can satisfy the minimum QoS requirements of small cell users, macro cell users, and legacy WiFi devices, has not been investigated so far. In addition, the extension of the results [26], [33]–[37] cannot lead to a reduced complexity iterative sub-channel and power allocation solution. We proposed a similar energy-efficient self-organizing framework for a multi-tier device-to-device communication environment [38]. In [38], the original fractional form of energy efficiency was considered as the objective function. And because of its non-convex nature, a sub-optimal solution for channel allocation and power allocation is proposed using an iterative non-cooperative game approach. On the contrary, in this work, we transform the fractional form of energy efficiency into its subtractive which leverages to find a tractable solution using dual-multiplier Lagrangian optimization.

The following points make our investigation novel and worth investigating. First, most of the existing literature on the coexistence of LTE and WiFi focus on spectrum efficiency, while energy efficiency is largely ignored. In this study, we aim to propose an energy-efficient sub-channel allocation and power allocation scheme while satisfying a) the minimum capacity requirement of dual-access SBSs and b) the maximum tolerable interference by macro cell users and the legacy WiFi devices. Second, the interference management is also a critical issue in LTE-U based on CSAT, especially during the ‘ON’ period and this is far more important in the considered dense small cell environment. Third, a self-organized framework for dual-access small cells is proposed without any involvement of a centralized entity which is an attractive option for the dense environment. Fourth, a novel less-complex iterative algorithm for the sub-channel allocation and power allocation is proposed, which is shown to converge to the Nash Equilibrium.

The rest of the paper is structured as follows: the system model and the problem formulation are presented in Section 3. The objective function transformation is presented in Section 4. The proposed self-organizing framework for the sub-channel and the power allocation is given in Section 5 and the simulation results are presented in Section 6. Finally, Section 7 concludes the paper.

3 SYSTEM MODEL AND PROBLEM FORMULATION

3.1 Network model

A network model of the dual-access small cell network is shown in Fig. 1. Considering the co-channel environment, the two main interference components that are present in the ‘ON’ period of LTE-U based CSAT are: *cross-tier* and *co-tier*. The former one is comprised of interference between small cells and macro cells (operating in licensed bands), and between small cells and the legacy WiFi devices (operating in unlicensed bands). The later one is comprised of interference among small cells (operating in licensed and unlicensed bands). The ‘ON’ period of LTE-U is based on a number of WiFi characteristics including traffic load, node density, etc., and is proposed to be determined by each dual-access SBS in a self-organizing way. This overcomes the scalability problem in the centralized management of

small cell networks. Due to the determination of 'ON' and 'OFF' periods at the SBS level, it becomes extremely important and challenging to manage the co-tier and cross-tier interference components. Since the calculation of 'ON' and 'OFF' periods is based on the detection of WiFi signals, it is possible that the received signal power of some legacy WiFi devices is too low to be identified by the carrier sense mechanism in CSAT [39]. Consequently, the transmission of LTE-U in the 'ON' period can interfere with the legacy WiFi devices. In order to protect and respect the QoS requirement of the legacy WiFi devices, we assume according to [40] that a control channel is set up over the wired backhaul between the neighbouring SBSs and WiFi stations. If the QoS requirement of the legacy WiFi devices is violated, the concerned SBS will get an alert via the control channel which switches its period from 'ON' to 'OFF' accordingly. In addition, we assume that the legacy WiFi devices operating in unlicensed bands follow the LBT technique which is important for maintaining a fair coexistence between LTE-U and other unlicensed technologies. However, if a technology operates in unlicensed bands and does not use LBT such as Bluetooth, the following solutions can be utilized (in any order) for addressing the problem and adjusting the duty cycle of LTE-U SBSs: (i) coordination of dual-access SBSs and the technology which does not employ LBT via a control channel (ii) assessment of the activity of the technology, and (iii) prediction of transmission of the technology using machine learning techniques [41] [42] [43].

In the proposed self-organizing framework, each dual-access SBS has to perform three tasks iteratively: *sensing*, *learning*, and *tuning*. In the *sensing* task, each SBS interacts with the environment and acquire channel gains from both licensed and unlicensed bands. For determining the LTE-U 'ON' or 'OFF' period, each SBS detects the WiFi transmission and adjust the duty cycle periods accordingly. In the *learning* task, an iterative mechanism is taken into account for the allocation of sub-channels and power levels with the concern of enhancing the energy efficiency while guaranteeing the QoS requirements of small cell users, macro cell users, and the legacy WiFi stations. In the *tuning* task, the best learned strategies in task 2 are updated by each dual-access SBS. The objective of the proposed self-organizing framework is to enhance the energy efficiency by exploiting sub-channels and power levels in ultra-dense small cell networks without creating harmful impact on the other network entities. In this study, we make the following assumptions:

- 1) *Channel state information (CSI) availability*: It is assumed that each dual-access SBS has the capability to acquire CSI from macro cell users (operating in licensed bands), small cell users (operating in both licensed and unlicensed bands), and the legacy WiFi devices (operating in unlicensed band). Uplink CSI can be obtained at SBSs from the uplink pilots transmitted by macro cell users, small cell users, and the legacy WiFi devices. In case of time division duplexing (TDD), downlink CSI can be estimated due to the channel reciprocity between the uplink and the downlink [44]. While in frequency division duplexing (FDD), due to

the lack of the reciprocity, estimation of downlink CSI is a difficult task and is achieved through separate downlink sounding and feedback from all the tier users. Although the CSI of the users far apart from the SBSs are hardly obtained in practice, the impact of such interferers is so small that the proposed algorithm provides an upper bound on the performance of the practical system. In order to evaluate the impact of errors in estimating the actual CSI, an analysis is also carried out with imperfect CSI.

- 2) *Control channels for QoS satisfaction*: In order to satisfy the QoS requirements of macro cell users, small cell users, and the legacy WiFi devices, we assume that reliable control channels are available that connect MBSs, SBSs and WiFi access points. In case the QoS requirements of small cell users, macro cell users, and/or the legacy WiFi devices are not satisfied, the particular SBS will be alerted from the SBS, the MBS, and/or the WiFi access point in order to change the strategies.
- 3) *Synchronization on sub-channels*: A tight synchronization is assumed among the transmitters so that the interference only occurs whenever there is a transmission on similar sub-channels.

3.2 System model

In this study, we consider the downlink of dual-access small cell networks with a frequency reuse-1 in an orthogonal frequency-division multiple access (OFDMA)-based two-tier cellular environment, which comprises of K macro cells each operated by a MBS at its center overlaid with N dual-access small cells each operated by a SBS. In addition, the frequency reuse-1 corresponds that each dual-access SBS has complete access to licensed and unlicensed bands. The total number of Y macro cell users and X small cell users are randomly deployed within coverage of K macro cells and N small cells, respectively. Furthermore, we consider that there are E legacy WiFi devices within coverage of K macro cells and these are randomly deployed around the vicinity of N small cells. Although we consider the duty cycle approach of CSAT for the fair LTE and WiFi coexistence, still there is an impact of interference of dual-access SBSs on the legacy WiFi devices and vice versa (both operating in unlicensed band). This interference is possible in two cases: (i) the transmission of SBSs is not detected by the legacy WiFi devices due to the hidden terminal problem and this happens because of the incompatibility of CSAT and carrier-sense multiple access (CSMA) and (ii) the transmission of the legacy WiFi devices can interfere with SBSs due to lack of LBT in LTE-U. In order to model this interference, we consider that the number of legacy WiFi access points that interfere with the dual-access SBSs is represented as V , where $V \subset E$.

The total number of G and H sub-channels are assumed to be available from licensed and unlicensed bands, respectively, and the number of sub-channels acquired by each SBS is denoted as: Q and J , respectively, such that $Q \leq G$ and $J \leq H$, while the number of sub-channels acquired by each MBS is denoted as G . The

Fig. 1. Proposed self-organizing framework for ultra-dense dual-access small cell network.

total number of R power levels are available on the sub-channels acquired by each SBS, while the power levels on the sub-channels acquired by MBSs are assumed to be fixed. Moreover, let G_v , H_v and R_v denote the sets of sub-channels from licensed band, unlicensed band, and power levels such that $G_v = \{1, 2, \dots, G\}$, $H_v = \{1, 2, \dots, H\}$, and $R_v = \{1, 2, \dots, R\}$, respectively.

The transmission power of the k th MBS in the licensed band sub-channels and of the n th dual-access SBS in the licensed and unlicensed band sub-channels are represented as $P_{k,g}^M \in [P_{k,1}^M, P_{k,2}^M, \dots, P_{k,G}^M]$, $P_{n,g}^{S,L} \in [P_{n,1}^{S,L}, P_{n,2}^{S,L}, \dots, P_{n,G}^{S,L}]$ and $P_{n,h}^{S,UL} \in [P_{n,1}^{S,UL}, P_{n,2}^{S,UL}, \dots, P_{n,H}^{S,UL}]$, respectively, where $P_{n,g}^{S,L} = 0$ if the g th sub-channel from the licensed band is not acquired by the n th SBS; otherwise, $P_{n,g}^{S,L} \neq 0$. The similar argument holds for $P_{k,g}^M$ and $P_{n,h}^{S,UL}$. The maximum power constraint on the acquired Q and J sub-channels by MBSs and SBSs is given by P_{MAX}^M and P_{MAX}^S such that $\sum_{g=1}^G P_{k,g}^M \leq P_{MAX}^M$ and $\sum_{g=1}^G P_{n,g}^{S,L} + \sum_{h=1}^H P_{n,h}^{S,UL} \leq P_{MAX}^S$, respectively.

The performance of the proposed scheme is evaluated in terms of energy efficiency (expressed in bits/J) of the dual-access small cell networks. The signal-to-interference-plus-noise ratio (SINR) on a macro cell user associated with the k th MBS operating on the g th sub-channel is given in (1) on the next page.

where $G_{kk,g}^{M \rightarrow M}$, $G_{ak,g}^{M \rightarrow M}$, and $G_{nk,g}^{S \rightarrow M,L}$ are the channel gains on the similar sub-channels between the k th MBS and the associated macro cell user, between the k th MBS and the a th MBS, and between the n th SBS and the k th MBS, respectively; δ_{kg}^M , $\delta_{ng}^{S,L}$, $\delta_{nh}^{S,UL}$, and $\delta_{vh}^{Leg-W,UL}$ are

the binary indicators which correspond to whether the g th sub-channel from the licensed band and the h th sub-channel from the unlicensed band is used by the k th MBS, the n th SBS and the v th legacy WiFi access point respectively; and finally, σ^2 is the noise power. Similarly, the SINR on the g th sub-channel from the licensed band and the h th sub-channel from the unlicensed band of the n th SBS is given in (2) and (3) on the next page.

According to the additive modeling of error in estimating CSI as proposed in [45], here the imperfect CSI $G_{nn,g}^{S \rightarrow S,L}$ is modeled as the deviation from the actual CSI $G_{nn,g}^{S \rightarrow S,L}$ and is written as:

$$G_{nn,g}^{S \rightarrow S,L} = G_{nn,g}^{S \rightarrow S,L} + \Omega_{nn,g}^{S \rightarrow S,L}, \forall n. \quad (4)$$

where $\Omega_{nn,g}^{S \rightarrow S,L}$ is the channel estimation error and is modeled by a zero mean Gaussian random variable with variance $\varsigma_{nn,g}^{S \rightarrow S,L}$. Additionally, the random variable $\Omega_{nn,g}^{S \rightarrow S,L}$ is independent and identically distributed (i.i.d) on G and H sub-channels from the licensed and unlicensed bands, respectively, and on all the tiers including small cells, macro cells, and the legacy WiFi devices. For the sake of simplicity, we consider a minimum mean square error (MMSE) channel estimator and because of that the CSI estimation error and the actual CSI become mutually uncorrelated [46]. Similarly, the imperfect CSI of the remaining channel gains in (1), (2), and (3) are modeled by (4). For the sake of simplicity, we use the actual CSI notations in the remainder of the paper. However, the corresponding imperfect CSI is introduced according to (4).

The average throughput of the k th MBS operating in

$$SINR_{k,g}^M = \frac{P_{k,g}^M G_{kk,g}^{M \rightarrow M}}{\sigma^2 + \underbrace{\sum_{a=1, a \neq k}^K \delta_{ag}^M P_{a,g}^M G_{ak,g}^{M \rightarrow M}}_{\text{macro cell-licensed-components}} + \underbrace{\sum_{n=1}^N \delta_{ng}^{S,L} P_{n,g}^{S,L} G_{nk,g}^{S \rightarrow M,L}}_{\text{small cell-licensed-components}}}, \forall k, g, \quad (1)$$

$$SINR_{n,g}^{S,L} = \frac{P_{n,g}^{S,L} G_{nn,g}^{S \rightarrow S,L}}{\sigma^2 + \underbrace{\sum_{k=1}^K \delta_{kg}^M P_{k,g}^M G_{kn,g}^{M \rightarrow S}}_{\text{macro cell-licensed-components}} + \underbrace{\sum_{a=1, a \neq n}^N \delta_{ag}^{S,L} P_{n,g}^{S,L} G_{an,g}^{S \rightarrow S,L}}_{\text{small cell-licensed-components}}}, \forall n, g, \quad (2)$$

$$SINR_{n,h}^{S,UL} = \frac{P_{n,h}^{S,UL} G_{nn,h}^{S \rightarrow S,UL}}{\sigma^2 + \underbrace{\sum_{a=1, a \neq 1}^N \delta_{ah}^{S,UL} P_{a,h}^{S,UL} G_{an,g}^{S \rightarrow S,UL}}_{\text{small cell-unlicensed-components}} + \underbrace{\sum_{v=1}^V \delta_{vh}^{Leg-W,UL} P_{v,h}^{Leg-W,UL} G_{vn,h}^{Leg-W \rightarrow S,UL}}_{\text{Legacy WiFi-unlicensed-components}}}, \forall n, h. \quad (3)$$

the licensed band and the n th SBS operating in the licensed and unlicensed bands is given by,

$$\Psi_k^M = \frac{W}{G} \sum_{g=1}^G \delta_{kg}^M \log_2 (1 + SINR_{k,g}^M), \forall k, \quad (5)$$

$$\Psi_n^{S,L} = \frac{W}{G} \sum_{g=1}^G \delta_{ng}^{S,L} \log_2 (1 + SINR_{n,g}^{S,L}), \forall n, Q \leq G, \quad (6)$$

$$\Psi_n^{S,UL} = \frac{W}{H} \sum_{h=1}^H \rho_n \delta_{nh}^{S,UL} \log_2 (1 + SINR_{n,h}^{S,UL}), \forall n, J \leq H. \quad (7)$$

where W represents the system bandwidth, ρ_n is the 'ON' period and $1 - \rho_n$ is the 'OFF' period of the LTE-U. In the proposed dual-access framework, ρ_n is determined by each SBS which is based on the determined WiFi transmission occupancy of dual-access SBSs and the legacy WiFi devices in unlicensed bands. In order to determine this, the dual-access SBSs are required to turn their radio frequency (RF) transmission 'OFF' which can guarantee the precise estimation of WiFi traffic. In addition, the sensing time needs to be sufficiently large to allow the SBSs to precisely estimate the WiFi traffic. In order to fine tune the decisions regarding the 'ON' and 'OFF' periods, the received WiFi signal is averaged by each SBS [47].

The total average throughput of the n th SBS, operating in both licensed and unlicensed sub-channels is given by,

$$\Psi_n^S = \Psi_n^{S,L} + \Psi_n^{S,UL}, \forall n. \quad (8)$$

Also, the energy efficiency (expressed in bits/J) of the n th SBS is given in (9) on the next page. Where p_c is the circuit power of the transmitter and is assumed to be constant in this work.

Although we consider the downlink, the similar scheme can be employed for the uplink as in [48] in which CSI is estimated at SBSs from the orthogonal uplink pilots from macro cell users, small cell users and the legacy WiFi devices.

3.3 Notations

The notations and abbreviations used in Table 1 will be used throughout the rest of the paper.

3.4 Problem formulation

Since the goal of the study is to enhance the energy efficiency of the dual-access small cell network by exploiting sub-channel allocation and power allocation from licensed and unlicensed bands, the problem **P1** is formulated along with the system constraints and is given in (10) and (11) on the next page. Where $G_{kn,g,z}^{S \rightarrow M,L}$ is the channel gain between the n th SBS and the z th macro user of the k th MBS operating on the g th sub-channel. The similar description holds for $G_{vn,h,e}^{S \rightarrow Leg-W,UL}$, but between the n th SBS and n th legacy WiFi device. The binary indicators $\delta_{ng}^{S,L}$ and $\delta_{nh}^{S,UL}$ are the output optimization variables and are included in **P1** in the form of A_n^S , while δ_{kg}^M and $\delta_{vh}^{Leg-W,UL}$ are the binary input indicators and are updated randomly.

The constraint C1 refers to the minimum capacity requirement of dual-access SBSs and is represented as R_{MIN}^S . The value is proposed to be selected by the operator of SBSs. If the constraint is violated, then the SBS gets an alert from the MBS to change the strategies so that the minimum capacity requirement can be achieved. The constraint C2 is used to protect macro cell users from dual-access SBSs operating in licensed bands. For this, the maximum tolerable limit is selected and is represented as $\zeta^{M,L}$ which can be adjusted by the MBS operator based on the location of users in the coverage area. In case the constraint C2 is violated, the concerned SBS gets an alert

$$EE_n^S = \frac{\frac{W}{G} \sum_{g=1}^G \delta_{ng}^{S,L} \log_2 (1 + SINR_{n,g}^{S,L}) + \frac{W}{H} \sum_{h=1}^H \rho_n \delta_{nh}^{S,UL} \log_2 (1 + SINR_{n,h}^{S,UL})}{\sum_{g=1}^G \delta_{ng}^{S,L} (P_{n,g}^{S,L} + p_c) + \sum_{h=1}^H \rho_n \delta_{nh}^{S,UL} (P_{n,h}^{S,UL} + p_c)}, \forall n. \quad (9)$$

TABLE 1
Notation and assumptions.

Parameters	Meaning
MBS	Macro cell base station;
SBS	Dual-access small cell base station;
K	Number of macro cells;
N	Number of small cells;
E	Number of Legacy WiFi APs;
V	Number of Legacy WiFi APs that are outside the sensing range of SBS;
X	Number of macro cell users;
Y	Number of small cell users;
k	Index for macro cell;
n	Index for dual-access small cell;
e	Index for Legacy WiFi access point;
G	Total pool of sub-channels from licensed band;
Q	Number of sub-channels from licensed band acquired by each SBS at a particular time;
H	Total pool of sub-channels from unlicensed band;
J	Number of sub-channels from unlicensed band acquired by each SBS at a particular time;
G_v	Set of sub-channels from licensed band;
H_v	Set of sub-channels from unlicensed band;
W	System bandwidth;
R	Transmission power levels;
R_v	Set of transmission power levels;
L	Indicator for licensed band;
UL	Indicator for unlicensed band;
$P_{n,g}^{S,L}$	Transmission power of the n th SBS on the g th sub-channel from licensed band;
$P_{n,h}^{S,UL}$	Transmission power of the n th SBS on the h th sub-channel from unlicensed band;
$P_{k,g}^M$	Transmission power of the k th MBS on the g th sub-channel from licensed band;
$G_{nk,g}^{S \rightarrow M,L}$	Perfect channel gain between the n th SBS and the k th MBS operating on the g th sub-channel from licensed band;
$G_{nn,g}^{S \rightarrow S,L}$	Imperfect channel gain between the n th SBS and the associated small cell user operating on the g th sub-channel from licensed band;
$\Omega_{S \rightarrow S,L}^{nn,g}$	Channel estimation error between the n th SBS and the associated small cell user operating on the g th sub-channel from licensed band;
$\varsigma_{nn,g}^{nn,g,L}$	Variance of the channel estimation error between the n th SBS and the associated small cell user operating on the g th sub-channel from licensed band;
δ_{kg}^M	Binary indicator which indicates whether the g th sub-channel from licensed band is used by the k th MBS;
ρ_n	'ON' period of SBSs;
$\Psi_n^{S,L}$	Average throughput of the n th SBS operating on licensed band sub-channels;
$\Psi_n^{S,UL}$	Average throughput of the n th SBS operating on unlicensed band sub-channels;
A_n^S	Sub-channel allocation vector of the n th SBS;
P_n^S	Power allocation vector of the n th SBS;
θ_n	Strategy profile associated with the n th SBS;
U_n	Utility function associated with the n th SBS;
A_n^{*S}	Optimal sub-channel allocation vector of the n th SBS;
P_n^{*S}	Optimal power allocation of the n th SBS;
$\zeta_{nn,g}^{M,L}$	Maximum interference incurred by SBSs in licensed sub-channels that a MBS can tolerate;
$\kappa^{Leg-W,UL}$	Maximum interference incurred by SBSs in unlicensed sub-channels that a legacy WiFi device can tolerate;
R_{MIN}^S	Minimum capacity requirement of dual-access SBSs;
η_n^{*S}	Maximum energy efficiency of the n th SBS;
U_n	Utility function of the n th SBS;

via the established control channels that connects SBSs and MBSs. Similarly, to protect the legacy WiFi devices, the maximum allowed interference limit represented as $\kappa^{Leg-W,UL}$ is used in the constraint C3. Again, if the interference exceeds the limit, the culprit WiFi device sends an alert to the SBS to change the strategies via the established control channels between WiFi access points and SBSs. The constraints C4 and C5 correspond to the selection of G and H sub-channels from the pool of Q and J sub-channels from licensed and unlicensed bands, respectively. The constraint C6 imposes the maximum power transmission limit of P_{MAX}^S on SBSs while selecting the power levels on the G and H sub-channels.

4 OBJECTIVE FUNCTION TRANSFORMATION

The assignment variables $\delta_{ng}^{S,L}$ and $\delta_{nh}^{S,UL}$ for selecting the sub-channels from licensed and unlicensed bands in

P1 make the problem a combinatorial programming one, which is NP-hard [49]. The fractional form objective function in (9) generally is not a concave function but by assuming certain conditions on the constraints, the function can fall into the class of it [50]. Thus, the objective function in (9) is non-convex and traditional convex optimization techniques cannot be applied for finding the optimal solution. The only option left is to employ a brute force method but the complexity of such a method increases exponentially with sub-channels and powers levels, which is not suitable even for a small network. Therefore, we aim to propose an efficient and a less-complex solution for such a challenging problem.

In order to do so, we transform the problem **P1** in (10) using a non-linear fractional integer programming approach [51]. Then, we develop an effective sub-channel allocation and power allocation scheme for solving the en-

$$P1 : (A_n^{*S}, P_n^{*S}) = \arg \max_{A_n^S \in [1,0]^{\{G_v \cup H_v\}}, P_n^S \in R_v^{\{G_v \cup H_v\}}} \frac{\frac{W}{G} \sum_{g=1}^G \delta_{ng}^{S,L} \log_2 (1 + SINR_{n,g}^{S,L}) + \frac{W}{H} \sum_{h=1}^H \rho \delta_{nh}^{S,UL} \log_2 (1 + SINR_{n,h}^{S,UL})}{\sum_{g=1}^G \delta_{ng}^{S,L} (P_{n,g}^{S,L} + p_c) + \sum_{h=1}^H \rho \delta_{nh}^{S,UL} (P_{n,h}^{S,UL} + p_c)}, \quad (10)$$

$$C1 : \Psi_n^{S,L} + \Psi_n^{S,UL} \geq R_{MIN}^S, \forall n, \quad (11a)$$

$$C2 : \sum_{g=1}^G P_{n,g}^{S,L} G_{kn,g,z}^{S \rightarrow M,L} \delta_{ng}^{S,L} \leq \zeta^{M,L}, \forall k, z, n, \quad (11b)$$

$$C3 : \sum_{h=1}^H P_{n,h}^{S,UL} G_{vn,h,e}^{S \rightarrow Leg-W,UL} \delta_{nh}^{S,UL} \leq \kappa^{Leg-W,UL}, \forall v, e, n, \quad (11c)$$

$$C4 : \sum_{g=1}^G \delta_{ng}^{S,L} \leq Q, \forall n, \quad (11d)$$

$$C5 : \sum_{h=1}^H \delta_{nh}^{S,UL} \leq J, \forall n, \quad (11e)$$

$$C6 : \sum_{g=1}^G \delta_{ng}^{S,L} P_{n,g}^{S,L} + \sum_{h=1}^H \delta_{nh}^{S,L} P_{n,h}^{S,UL} \leq P_{MAX}^S. \quad (11f)$$

ergy efficiency maximization problem. Since the objective function in **P1** has a non-linear fractional programming form [51], we can define the maximum energy efficiency η_n^{*S} as:

$$\eta_n^{*S} = \frac{\phi_{num}(A_n^{*S}, P_n^{*S})}{\phi_{den}(P_n^{*S})}, \quad (12)$$

where $A_n^{*S} = (A_n^{*S,L}, A_n^{*S,UL}) = ((\delta_{n,1}^{*S,L}, \delta_{n,2}^{*S,L}, \dots, \delta_{n,G}^{*S,L}), (\delta_{n,1}^{*S,UL}, \delta_{n,2}^{*S,UL}, \dots, \delta_{n,H}^{*S,UL}))$, $P_n^{*S} = (P_n^{*S,L}, P_n^{*S,UL})$, $\phi_{num} = \frac{W}{G} \sum_{g=1}^G \delta_{ng}^{S,L} \log_2 (1 + SINR_{n,g}^{S,L}) + \frac{W}{H} \sum_{h=1}^H \rho \delta_{nh}^{S,UL} \log_2 (1 + SINR_{n,h}^{S,UL})$, and $\phi_{den} = \sum_{g=1}^G \delta_{ng}^{S,L} (P_{n,g}^{S,L} + p_c) + \sum_{h=1}^H \rho \delta_{nh}^{S,UL} (P_{n,h}^{S,UL} + p_c)$.

Theorem 1. The maximum energy efficiency η_n^{*S} is achieved if the condition in (13) on the next page is satisfied.

Proof: The proof of Theorem 1 is given in Appendix A. $\square$

Thus, Theorem 1 reveals that for any objective function, which is in a fractional form, there exists an equivalent objective function in a subtractive form e.g., $\phi_{num}(A_n^S, P_n^S) - \eta_n^{*S} \phi_{den}(P_n^S)$ in our case. However, the optimal energy efficiency η_n^{*S} in (12) cannot be achieved directly and in order to obtain that, we propose an iterative Algorithm 1 in Section 5. Therefore, the problem **P1** can be transformed into its equivalent problem **P2** and is represented as:

$$P2 : (A_n^{*S}, P_n^{*S}) = \max_{A_n^S \in [1,0]^{\{G_v \cup H_v\}}, P_n^S \in R_v^{\{G_v \cup H_v\}}} \phi_{num}(A_n^S, P_n^S) - \eta_n^{*S} \phi_{den}(P_n^S), \quad (14)$$

subject to: C1 - C6.

The transformed problem **P2** in (14) is in a subtractive form and constitutes a tractable and a feasible solution. In order to develop an effective algorithm for solving the problem **P2**, we can define the following function $F(\eta_n^S) = \max_{A_n^S \in [1,0]^{\{G_v \cup H_v\}}, P_n^S \in R_v^{\{G_v \cup H_v\}}} \phi_{num}(A_n^S, P_n^S) - \eta_n^{*S} \phi_{den}(P_n^S)$ with Lemma 1 given below.

Lemma 1. For all feasible A_n^S , P_n^S , and η_n^S , $F(\eta_n^S)$ is a strictly monotonic decreasing function in η_n^S , and $F(\eta_n^S) \geq 0$.

Proof: The proof of Lemma 1 is given in Appendix B. $\square$

In the remainder of the paper, we use the transformed problem **P2**.

5 NON-COOPERATIVE GAME FORMULATION FOR SUB-CHANNEL ALLOCATION AND POWER ALLOCATION

5.1 Non-cooperative game

A non-cooperative game is a powerful mathematical tool and is used for a variety of resource allocation problems in wireless networks [52]. In the problem formulation in Section 3 and its transformation in Section 4, we consider

$$\max_{A_n^S \in [1,0]^{\{G_v \cup H_v\}}, P_n^S \in R_v^{\{G_v \cup H_v\}}} \phi_{num}(A_n^S, P_n^S) - \eta_n^{*S} \phi_{den}(P_n^S) = \phi_{num}(A_n^{*S}, P_n^{*S}) - \eta_n^{*S} \phi_{den}(P_n^{*S}) = 0. \quad (13)$$

that each dual-access SBS is a selfish and an irrational player, which tends to increase its utility function. Therefore, the problem **P1** presented in (10) and its equivalent subtractive transformed form **P2** in (14) can be modeled as a non-cooperative game. In this study, we model the joint sub-channel allocation and power allocation for dual-access small cells via a non-cooperative game. Specifically, this joint allocation is represented by a normal form game such that $\Gamma = \{N, \theta_n, U_n\}$, where N is the finite number of players, θ_n is the strategy associated with each player, and U_n is the utility function which associates the reward to each player. Mathematically, the utility function can be thought of as a mapping function that maps the strategy θ_n into a real number $\mathbb{R}$ such that $U_n : \theta_n \rightarrow \mathbb{R}$. In addition, the strategies of the other players involved in the game is represented by $\theta_{-n} = \{\theta_1, \theta_2, \dots, \theta_{n-1}, \theta_{n+1}, \dots, \theta_N\}$.

In the proposed non-cooperative game, a set of N dual-access SBSs are the players of the game, which interact with the environment in a self-organizing manner and select the strategies θ_n : the sub-channels and the power levels. Mathematically, the strategy of the game is represented as $\theta_n = \{A_n^S, P_n^S\}$, where $A_n^S = \{A_{n,g}^{S,L}, A_{n,g}^{S,UL}\}$ is an indication vector that corresponds to the allocation of the Q and J sub-channels from the total pool of G and H sub-channels, respectively, while $P_n^S = \{P_{n,g}^{S,L}, P_{n,g}^{S,UL}\}$ refers to the power levels on the selected sub-channels from both licensed and unlicensed bands. For a given A_n^S and P_n^S , the strategies of the other players can be represented as $A_{-n}^S = \{A_1^S, A_2^S, \dots, A_{n-1}^S, A_{n+1}^S, \dots, A_N^S\}$ and $P_{-n}^S = \{P_1^S, P_2^S, \dots, P_{n-1}^S, P_{n+1}^S, \dots, P_N^S\}$, respectively. Since the goal of the proposed non-cooperative game is to enhance the energy efficiency, the utility function is considered as the transformed form problem **P2** and is written as:

$$U_n(A_n^S, P_n^S) = \phi_{num}(A_n^S, P_n^S) - \eta_n^{*S} \phi_{den}(P_n^S). \quad (15)$$

Definition 1. For a given A_n^S and P_n^S , the best response dynamics of the joint sub-channel allocation and power allocation of the n th dual access SBS is written in (16) on the next page.

The joint sub-channel allocation and power allocation in the transformed form in **P2** is a mixed integer non-linear problem which is generally intractable in its original form [53]. In order to provide an efficient and a less-complex solution, we follow the traditional approach [54], [55], and solve the problem **P2** in two steps: sub-channel allocation and power allocation.

5.2 Sub-channel allocation

In the sub-channel allocation step, the following Theorem provides the optimal sub-channel allocation for the given power levels computed in the previous iteration. Here, N SBSs select G and J sub-channels from licensed and unlicensed bands, respectively, from (17).

Theorem 2. A group of Q and J sub-channels from the pool of G and H sub-channels in licensed and unlicensed bands can only be allocated to the n th dual-access SBS, if the following condition is satisfied:

$$(A_n^{*S}) = \arg \min_{A_n^S \in [1,0]^{\{G_v \cup H_v\}}} \left(\sum_{g=1}^G \delta_{ng}^{S,L} \frac{I_{n,g}^{S,L}}{G_{nn,g}^{S \rightarrow S,L}} + \sum_{h=1}^H \rho \delta_{nh}^{S,UL} \frac{I_{n,h}^{S,UL}}{G_{nn,h}^{S \rightarrow S,UL}} \right), \quad (17)$$

where $I_{n,g}^{S,L} = \sigma^2 + \sum_{k=1}^K \delta_{kg}^M P_{k,g}^M G_{kn,g}^{M \rightarrow S} + \sum_{a=1, a \neq n}^N \delta_{ag}^{S,L} P_{a,g}^{S,L} G_{an,g}^{S \rightarrow S,L}$ and $I_{n,h}^{S,UL} = \sigma^2 + \sum_{a=1, a \neq n}^N \delta_{ah}^{S,UL} P_{a,h}^{S,L} G_{an,h}^{S \rightarrow S,UL}$

Proof: Given the power allocation of the n th player, the best response of the sub-channel allocation is represented as:

$$(A_n^{*S}) = \arg \max_{A_n^S \in [1,0]^{\{G_v \cup H_v\}}} U_n(A_n^S | P_{-n}^S), \quad (18)$$

s.t. C4 and C5

Since the utility function is transformed from (9) to (15), the sub-channel allocation represented in (17) can be written as:

$$(A_n^{*S}) = \arg \max_{A_n^S \in [1,0]^{\{G_v \cup H_v\}}} \phi_{num}(A_n^S, P_n^S) - \eta_n^{*S} \phi_{den}(P_n^S). \quad (19)$$

In order to prove the condition (17) in Theorem 2, we put (2), (3), $I_{n,g}^{S,L}$, $I_{n,h}^{S,UL}$, and the definitions from (12) ($\phi_{num}(A_n^S, P_n^S)$, η_n^{*S} , $\phi_{den}(P_n^S)$) in (19) and a new representation of the sub-channel allocation can be formed in (20) which is given on the next page.

Assuming ω_1 and ω_2 to be the target SINR on the selected sub-channels from licensed and unlicensed bands and substituting the power levels of the corresponding SBS $P_{n,g}^{S,L} = \frac{\omega_1 I_{n,g}^{S,L}}{G_{nn,g}^{S \rightarrow S,L}}$ and $P_{n,h}^{S,UL} = \frac{\omega_2 I_{n,h}^{S,UL}}{G_{nn,h}^{S \rightarrow S,UL}}$, we get a new sub-channel allocation representation (21) given on the next page. Furthermore, we found that the sub-channel allocation representation in (21) is equivalent to the expression below and hence, Theorem 2 is proved.

$$(A_n^{*S}) = \arg \min_{A_n^S \in [1,0]^{\{G_v \cup H_v\}}} \left(\sum_{g=1}^G \delta_{ng}^{S,L} \frac{I_{n,g}^{S,L}}{G_{nn,g}^{S \rightarrow S,L}} + \sum_{h=1}^H \rho \delta_{nh}^{S,UL} \frac{I_{n,h}^{S,UL}}{G_{nn,h}^{S \rightarrow S,UL}} \right). \quad (22)$$

□

5.3 Power allocation

Given the sub-channel allocation of each SBS, the power allocation problem can be modeled as a non-cooperative power optimization game such that $\Gamma' = \{N, P_n^S, U_n\}$.

$$\left(A_n^{*S}, P_n^{*S}\right) = \max_{A_n^S \in [1,0], \{G_v \cup H_v\}, P_n^S \in R_v^{\{G_v \cup H_v\}}} \phi_{num} \left(A_n^S, P_n^S\right) - \eta_n^{*S} \phi_{den} \left(P_n^S\right). \quad (16)$$

$$\begin{aligned} \left(A_n^{*S}\right) = \arg \max_{A_n^S \in [1,0], \{G_v \cup H_v\}} & \frac{W}{G} \sum_{g=1}^G \delta_{ng}^{S,L} \log_2 \left(1 + \frac{P_{n,g}^{S,L} G_{nn,g}^{S \rightarrow S,L}}{I_{n,g}^{F,L}}\right) + \frac{W}{H} \sum_{h=1}^H \rho \delta_{nh}^{S,UL} \log_2 \left(1 + \frac{P_{n,h}^{S,UL} G_{nn,h}^{S \rightarrow S,UL}}{I_{n,h}^{S,UL}}\right) \\ & - \eta_n^{*S} \left(\sum_{g=1}^G \delta_{ng}^{S,L} P_{n,g}^{S,L} + \sum_{h=1}^H \rho \delta_{nh}^{S,UL} P_{n,h}^{S,UL} + p_c (Q + \rho J) \right). \end{aligned} \quad (20)$$

$$\begin{aligned} \left(A_n^{*S}\right) = \arg \max_{A_n^S \in [1,0], \{G_v \cup H_v\}} & \frac{W}{G} \sum_{g=1}^G \delta_{ng}^{S,L} \log_2 (1 + \omega_1) + \frac{W}{H} \sum_{h=1}^H \rho \delta_{nh}^{S,UL} \log_2 (1 + \omega_2) \\ & - \eta_n^{*S} \left(\omega_1 \sum_{g=1}^G \delta_{ng}^{S,L} \frac{I_{n,g}^{S,L}}{G_{nn,g}^{S \rightarrow S,L}} + \omega_2 \sum_{h=1}^H \rho \delta_{nh}^{S,UL} \frac{I_{n,h}^{S,UL}}{G_{nn,h}^{S \rightarrow S,UL}} + p_c (Q + \rho J) \right). \end{aligned} \quad (21)$$

Since the utility function of the proposed scheme depends upon the behavior (power levels) of two or more players, we model the power optimization problem via a non-cooperative power optimization game [56]. For the given sub-channel allocation, the best response dynamics of the n th player is represented as

$$\left(P_n^{*S}\right) = \arg \max_{P_n^S \in R_v^{\{G_v \cup H_v\}}} U_n \left(P_n^S | P_{-n}^S\right), \quad (23)$$

s.t.C1 - C6

The players involved in the non-cooperative power optimization game optimize their power levels independently on Q and J sub-channels. Since the goal of the optimization problem is to enhance the energy efficiency of dual-access small cells without creating harmful impact on small cell users, macro cell users, and the legacy WiFi devices, the power optimization is carried out within the network constraints C1 - C6.

For a given sub-channel allocation, the utility function in subtractive form is a convex function of P_n^S and the power level strategy is also convex. Thus, the Karush-Kuhn-Tucker (KKT) condition can be applied to find out the optimal solution.

The Lagrangian associated with the transformed problem **P2** in (14) is written in (24) on the next page, where $\alpha_n, \beta_n, \gamma_n$, and χ_n are the Lagrangian multipliers associated with the constraints C1, C2, C3, and C6, respectively.

The equivalent dual problem can be decomposed into two sub problems: the maximization problem solves the power allocation on the selected sub-channels and the minimization problem solves for the Lagrangian multipliers which is given by,

$$\min_{\alpha_n \geq 0, \beta_n \geq 0, \gamma_n \geq 0, \chi_n \geq 0} \max_{P_n^S \in R_v^{\{G_v \cup H_v\}}} \lambda_{EE} \left(P_n^S, \alpha_n, \beta_n, \gamma_n, \chi_n\right). \quad (25)$$

For a given energy efficiency η_n^S , the solution is given

in (26) on the next page,

The Lagrangian multipliers $\alpha_n, \beta_n, \gamma_n$, and χ_n are updated according to the gradient method and are given below,

$$\alpha_n(\tau + 1) = \left[\alpha_n(\tau) - \mu_{m,\beta}(\tau) \left(\nabla_n^{S,L} + \nabla_n^{S,UL} - R_{MIN}^S \right) \right]. \quad (27)$$

$$\begin{aligned} \beta_n(\tau + 1) = & \left[\beta_n(\tau) - \mu_{n,\gamma}(\tau) \left(\zeta^{M,L} \right. \right. \\ & \left. \left. - \sum_{g=1}^G P_{n,g}^{S,L} G_{kn,g,z}^{S \rightarrow M,L} \delta_{ng}^{S,L} \right) \right]. \end{aligned} \quad (28)$$

$$\begin{aligned} \gamma_n(\tau + 1) = & \left[\gamma_n(\tau) - \mu_{\gamma}(\tau) \left(\kappa^{Leg-W,UL} \right. \right. \\ & \left. \left. - \sum_{h=1}^H P_{n,h}^{S,UL} G_{e,b,n}^{S \rightarrow Leg-W,UL} \delta_{nh}^{S,UL} \right) \right]. \end{aligned} \quad (29)$$

$$\begin{aligned} \chi_n(\tau + 1) = & \left[\chi_n(\tau) - \mu_{\chi}(\tau) \left(P_{MAX}^S \right. \right. \\ & \left. \left. - \sum_{g=1}^G \delta_{ng}^{S,L} P_{n,g}^{S,L} + \sum_{nh}^{S,L} P_{n,h}^{S,UL} \right) \right]. \end{aligned} \quad (30)$$

5.4 Proposed iterative algorithm

The proposed iterative algorithm employs two steps: the sub-channel allocation and the power allocation. Based on Lemma 1, an iterative algorithm is proposed to solve the transformed problem **P2** by updating $\eta_n^{(i),F}$ in each iteration. In addition, the proposed algorithm ensures that

$$\lambda_{EE} \left(P_n^S, \alpha_n, \beta_n, \gamma_n \right) = \Phi_{num} \left(A_n^S, P_n^S \right) - \eta_n^S \phi_{den} \left(P_n^S \right) + \alpha_n \left(\Psi_n^{S,L} + \Psi_n^{S,UL} - R_{MIN}^S \right) + \beta_n \left(\zeta^{M,L} - \sum_{g=1}^G P_{n,g}^{S,L} G_{kn,g,z}^{S \rightarrow M,L} \delta_{ng}^{S,L} \right) + \gamma_n \left(\kappa^{Leg-W,UL} - \sum_{h=1}^H P_{n,h}^{S,UL} G_{e,b,n}^{S \rightarrow Leg-W,UL} \delta_{nh}^{S,UL} \right) + \chi_n \left(P_{MAX}^S - \sum_{g=1}^G \delta_{ng}^{S,L} P_{n,g}^{S,L} + \sum_{h=1}^H \delta_{nh}^{S,L} P_{n,h}^{S,UL} \right), \quad (24)$$

$$P_n^{*S} = \left(P_{n,g}^{*S,L}, P_{n,h}^{*S,UL} \right)$$

$$P_n^S = \left(\left[\delta_{gn}^{S,L} \frac{\frac{W}{Q}(1 + \alpha_n) \log_2 e}{\eta_n^S + \beta_n G_{kn,g,z}^{S \rightarrow M,L}} - \delta_{gn}^{S,L} \frac{\sigma^2 + \sum_{k=1}^K P_{k,g}^M G_{kn,g}^{M \rightarrow S} \delta_{kg}^M + \sum_{a=1, a \leq n}^N G_{an,g}^{S \rightarrow S,L} \delta_{ag}^{S,L}}{G_{nn,g}^{S \rightarrow S,L}} \right]^+ \right. \\ \left. \left[\delta_{hn}^{S,UL} \frac{\frac{W}{J}(1 + \alpha_n) \log_2 e}{\eta_n^S + \gamma_n G_{e,b,n}^{S \rightarrow Leg-W,UL}} - \delta_{hn}^{S,UL} \frac{\sigma^2 + \sum_{a=1, a \leq n}^N P_{a,h}^{S,UL} G_{an,h}^{S \rightarrow S,UL} \delta_{ah}^{S,UL}}{G_{nn,h}^{S \rightarrow S,UL}} \right]^+ \right). \quad (26)$$

$\eta_n^{(i),F}$ increases in each iteration and gives the optimal energy efficiency performance. Further, it can be seen that the proposed iterative algorithm comprises of two steps: sub-channel allocation and power allocation. In the sub-channel allocation step, the allocation of Q and J sub-channels from the total pool of G and H sub-channels in licensed and unlicensed bands, respectively, is carried out by each dual-access small cells with the concern of minimizing the impact of interference. In the power allocation step, the power levels on the selected sub-channels are evaluated via a non-cooperative power optimization game under the constraints C1 - C6. In addition, in each iteration of the iterative algorithm the parameter $\eta_n^{(i),F}$ is updated until the optimality is achieved.

The following Theorem 3 and Theorem 4 elaborate the existence of a Nash Equilibrium point and the convergence to the optimal energy efficiency, respectively.

Theorem 3. A Nash Equilibrium point exists in the proposed non-cooperative power optimization game $\Gamma' = \{N, P_n^S, U_n\}$. The optimal strategy set of power allocation $\{(P_{n,g}^{*S,L}, P_{n,h}^{*S,UL}) \mid n \in N, g \in G, h \in H\}$ which is achieved by applying Algorithm 1 is the Nash Equilibrium.

Proof: The proof of Theorem 3 is given in Appendix C. $\square$

Theorem 4. The proposed iterative Algorithm 1 converges to the optimal energy efficiency $\eta_n^{*S}, \forall n \in N$.

Proof: The proof of Theorem 4 Appendix D. $\square$

5.5 Implementation issues and complexity analysis

In this section, the implementation issues and complexity analysis of the proposed scheme are discussed. In the proposed self-organizing framework, each SBS only needs to estimate the received interference rather than the precise sub-channel allocation and power allocation strategies of other players. According to (17) and (22), the required

information can be obtained by the estimated interference. Since we consider the downlink, each SBS can acquire CSI from its associated small cell users which estimate the downlink channels gains of all the interferers including K MBSs, $N - 1$ SBSs, and V legacy WiFi access points. In TDD based systems, downlink CSI can be estimated due to the channel reciprocity between uplink and downlink. However, in FDD based systems, downlink CSI is possible by extra downlink sounding and feedback from users [44]. The channel gains $G_{nn,g}^{S \rightarrow S,L}$, $G_{kn,g}^{M \rightarrow S}$, $G_{an,g}^{S \rightarrow S,L}$, $G_{nn,h}^{S \rightarrow S,UL}$, and $G_{vn,h}^{Leg-W \rightarrow S,UL}$ are required in the sub-channel allocation and the power allocation steps. These channel gains can be estimated by measuring the downlink channel gains on G licensed and H unlicensed channels from MBSs (operating in licensed channels only), SBSs (operating in licensed and unlicensed channels), and the legacy WiFi devices (operating in unlicensed channels only) from small cell users and pass them to the concerned SBS. In real systems, it can be hard to precisely estimate CSI and for this, we carried out an analysis of the proposed scheme with imperfect CSI. Thus, Algorithm-1 can be implemented in each dual-access SBS by utilizing local information and have little interaction with the MBS.

We analyse and compare the computational complexity of the proposed scheme (Algorithm-1) with the RR-NPOG scheme in a multi small cellular environment. The details of RR-NPOG are given in Section 6. For the sub-channel allocation step, the computation complexity can be represented as $O(N(G+H))$. Given Δ_i is the maximum number of iterations for the power allocation step, the computational complexity can be represented as $O(\Delta_i N)$. Therefore, given Δ_0 is the maximum number of iterations for the iterative sub-channel allocation and power allocation scheme, the over computational complexity of Algorithm-1 is $O(\Delta_0(N(G+H) + \Delta_i N))$. It is noted that Δ_0 and Δ_i are the maximum number of iterations of the proposed iterative and power allocation steps, respectively. However, within the maximum iteration counts, the convergence

can be achieved if there is no further improvement in the energy efficiency and the computational complexity is lesser than $O(\Delta_0(N(G+H) + \Delta_i N))$. The computational complexity of the proposed scheme without using Lagrangian optimization in the power allocation step is written as $O(\Delta_0(N(G+H) + \Delta_i NR))$ which justifies the usage of optimization in the power allocation step. The computational complexity of RR-NPOG is represented as $O(\Delta_0 N(1 + \Delta_i))$. Although the computational complexity of the RR-NPOG is lower compared to the proposed scheme, the energy efficiency performance of our scheme is significantly higher. This is discussed in detail in Sections 6.2 - 6.4.

Algorithm 1: Energy efficient sub-channel and power allocation

Input:

- Set the energy efficiency parameter $\eta_n^S = 0$, maximum number of iteration for iterative algorithm: $\Delta_o = 20$, maximum number of iterations for non-cooperative power optimization game: $\Delta_i = 20$.
- All link gains that connect macro cells and small cells pairs on the pool of licensed Q and unlicensed H sub-channels.
- All link gains that connect V legacy WiFi devices (that are outside the sensing range of small cells) and the small cells operating on the pool of unlicensed H sub-channels.

Output:

- Sub-channel and power allocation, $\theta^* = \{A_n^{*S}, P_n^{*S}\}$
- Optimal energy efficiency, η_n^{*S}

while the maximum iteration Δ_o has passed **do**

Step-1: Sub-channel allocation

for each SBS (player) **do**

$\{A_n^{*S}\} \leftarrow$
 $\arg \min_{A_n^S \in [1,0] \{G_v \cup H_v\}} \left(\sum_{g=1}^G \delta_{ng}^{S,L} \frac{I_{n,g}^{S,L}}{G_{nn,g}^{S,L}} \right.$
 $\left. + \sum_{h=1}^H \rho \delta_{nh}^{S,UL} \frac{I_{n,h}^{S,UL}}{G_{nn,h}^{S,UL}} \right)$, s.t. C4 and C5.
 $\{A_n^S\} \leftarrow \{A_n^{*S}\}$

end

Step-2: Power allocation

Initialize $P_n^S \leftarrow 0, \forall n$

while the maximum iteration Δ_i has passed **do**

for each SBS (player) **do**

$\{P_n^{*S}\} \leftarrow$
 $\arg \max_{P_n^S \in R_v^{G_v \cup H_v}} \Phi_{num}(A_n^S, P_n^S) -$
 $\eta_n^{(i),S} \Phi_{den}(P_n^S)$, s.t. C1-C6.
 $\{P_n^S\} \leftarrow \{P_n^{*S}\}$
if $\Phi_{num}(A_n^S) - \eta_n^{(i),S} \Phi_{den}(P_n^S) \leq \epsilon_r$ **then**
 $\{A_n^{*S}\} \leftarrow \{A_n^S\};$
 $\{P_n^{*S}\} \leftarrow \{P_n^S\};$
 $\eta_n^{*S} \leftarrow \frac{\Phi_{num}(A_n^S, P_n^{*S})}{\Phi_{den}(P_n^{*S})};$
break;
else
 $\eta_n^{(i),S} \leftarrow \frac{\Phi_{num}(A_n^S, P_n^S)}{\Phi_{den}(P_n^S)};$
 $i \leftarrow i + 1;$
end

end

end

return $\theta^* \leftarrow \{A_n^{*S}, P_n^{*S}\}, \eta_n^{*S}$

6 SIMULATION RESULTS

In this section, the energy efficiency performance of the proposed self-organizing framework is evaluated in terms of: 1) the convergence; 2) the energy efficiency distribution; 3) the impact of varying sub-channels, G, H, Q ,

and J ; 4) the impact of dual-access small cell density, N ; and 5) the impact of legacy WiFi access points, V . In addition, the spectrum efficiency performance of the proposed scheme and RR-NPOG is also evaluated with respect to the small cell density. In addition, in each of the analysis, the proposed scheme is evaluated with perfect and imperfect CSI such that 'Proposed scheme (perfect CSI)' and 'Proposed scheme (imperfect CSI)'. The inclusion of this imperfectness in CSI is to analyze the degradation of the proposed scheme when CSI is not precisely known. For the sake of comparison, two self-organizing schemes using round-robin non-cooperative power optimization (labelled as RR-NPOG) and a spectrum efficiency game (labelled as spectrum efficient) are utilized which can be considered as the representatives schemes.

The goal of the RR-NPOG scheme is to enhance the energy efficiency which is similar to the proposed scheme. However, it utilizes a round robin (RR) mechanism as the sub-channel allocation step and uses the similar power optimization game approach. The concern of comparing the proposed scheme with RR-NPOG is to show the importance of jointly optimizing sub-channels and power levels. The goal of the spectrum efficient scheme is to enhance the spectrum efficiency instead of the energy efficiency. The reason for this comparison is to investigate how much energy efficiency performance is archived if the proposed game is aligned with spectrum efficiency and not with energy efficiency.

6.1 Simulation setup

We consider the downlink of OFDMA-based two-tier cellular networks operating in the carrier frequency of 2GHz which closely follows the 3GPP TR 25.814 specifications. Further, for the sake of simplicity, a single macro cellular environment ($K = 1$) is considered with a radius of 1000m. In addition, there are N small cells underlaid within the macro cell each with a radius of 40m. Each MBS and SBS is located at the center of the corresponding cell and X and Y are the macro cell users and the small cell users, respectively, and are randomly deployed within a coverage area of each cell. In order to illustrate the impact of the legacy WiFi devices on the small cells that are outside their sensing range, different values of V are considered such that $V \in \{5, 10, 15, 20\}$

The total pool of licensed and unlicensed bands is divided into G and H sub-channels, respectively, where each sub-channel has a bandwidth of 180KHz. In order to evaluate the efficiency of the proposition, different pool of licensed and unlicensed sub-channels are also considered such that $G \in \{10, 20\}$ and $H \in \{10, 20\}$. Further, the total number of sub-channels acquired by each SBS is considered to be $Q \in \{2, 4, 5, 6, 8\}$ and $J \in \{2, 4, 5, 6, 8\}$ from licensed band and unlicensed bands, respectively, while the number of sub-channels acquired by each MBS is assumed to be fixed at $G = 10$ and 20, respectively. The maximum transmission power constraint on MBS and SBS operating on either licensed or unlicensed sub-channels is set as $P_{MAX}^M = 43\text{dBm}$ and $P_{MAX}^S = 23\text{dBm}$, respectively. Also, in total $R = 100$ power levels are considered that are uniformly distributed in the range

from -100 to 23 dBm. Finally, a constant circuit power of $p_c = 100$ mW is considered (similarly as in [57]) and the noise spectral density is set to $N_0 = -141$ dBW/Hz. For modeling the imperfectness in estimating CSI, the variance of the estimation error $\varsigma_{n,g}^{S \rightarrow S, L}$ was considered as 0.02 and 0.2 , which illustrates the minimum and maximum CSI impairment impact, respectively, on the energy efficiency and the spectrum efficiency [58].

The pathloss models (PL) that we are utilizing in this study are in accordance with the 3GPP specification [59], [60] and can be expressed as:

- For macro cell and small cell (outdoor): $PL(\text{dB}) = 127 + 30 \log_{10}(d)$
- For macro cell and small cell (indoor): $PL(\text{dB}) = 128.1 + 37.6 \log_{10}(d)$

The log normal shadowing with the shadowing factors of 8 dB and 4 dB are utilized for indoor and outdoor environment, respectively. The performance of the proposed scheme against the counterparts are evaluated for 1000 different realization of the network and the average results in terms of the network realizations and the number of involved N SBSs are presented. The simulation of the proposed scheme along with the comparative counterparts including the RR-NPOG, spectrum-efficient games, and the channel modeling were carried out in MATLAB.

In the remainder of the sub-sections, the following naming conventions are used for the proposed scheme (with perfect and imperfect CSI) such that 'Proposed scheme (perfect CSI) L and UL: $G = 20, H = 20, Q = 5, J = 5$ ', 'Proposed scheme (imperfect CSI) L and UL: $G = 20, H = 20, Q = 5, J = 5$ ', and 'Proposed scheme L and UL: $G = 20$ and $H = 20$ '. For instance, 'Proposed scheme (perfect CSI) L and UL: $G = 20, H = 20, Q = 5, J = 5$ ' means that the proposed scheme (with perfect CSI) in which each SBS acquires $Q = 5$ sub-channels from the pool of $G = 20$ and $J = 5$ sub-channels from the pool of $H = 20$ licensed and unlicensed bands, respectively. Similarly, the other naming conventions such as 'RR-NPOG L and UL: $G = 10, H = 10, Q = 5, J = 5$ ', 'spectrum efficient L and UL: $G = 10, H = 10, Q = 5, J = 5$ ', etc. can be described in the same way. It is important to note that the perfect CSI is considered when it is not categorically mentioned in the result figures or in their description.

6.2 Convergence analysis

The energy efficiency convergence analysis of the proposed scheme along with the comparative counterparts for two difference scenarios $N = 20$ and 40 is shown in Fig. 2. The energy efficiency of the proposed scheme and the comparative counterpart schemes are determined from (9). The unavailability of precise CSI in the proposed scheme (with imperfect CSI) reduces the energy efficiency performance to 5% and 8% as compared to the proposed scheme (with perfect CSI) when the small cell density increases from $N = 20$ to 40 , respectively. Although all the considered schemes converge to the optimal points for both the scenarios ($N = 20$ and 40) in similar number of iterations, the spectrum efficient scheme performs worst even as compared to RR-NPOG, and this is because the objective function in the spectrum efficient scheme is not

Fig. 2. Convergence performance: $V = 5$.

aligned with energy efficiency. In addition, the comparison of the proposed scheme employing both licensed and unlicensed band with the one employing only licensed band reveals the importance of exploiting unlicensed band without creating harmful impact on other small cell users, the macro cell users and the legacy WiFi users. Moreover, it can also be concluded that for an energy efficient design, the power allocation using only the round robin sub-channel as in RR-NPOG is not sufficient. On the other hand, although the energy efficiency decreases with the increase of small cell density, the improvement of the proposed scheme in relation to the comparative ones (proposed scheme operating on the licensed band, RR-NPOG and spectrum efficient) in the listed order increases from 5% , 7.6% and 10.9% to 7.73% , 11.04% and 17.6% , respectively, for the same number of iterations.

6.3 Energy efficiency distribution

The cumulative distribution function (CDF) of the energy efficiency of the proposed scheme along with the counterparts for 1000 different network realizations, where each realization is averaged over the involved SBSs is shown in Fig. 3. The convergence point for each realization was considered fixed at the 20 th game iteration because after that there was no performance improvement of the proposed scheme and the counterparts. In addition, the results are plotted for two different small cell network densities $N = 20$ and $N = 40$. It can be seen that the performance trend of the proposed scheme and the comparative counterparts remain the same as in the convergence analysis plot. Similarly, The performance trend of the proposed scheme with perfect and imperfect CSI remains similar as in the convergence analysis result. The spectrum efficient scheme performs worst throughout the distribution which illustrates the importance of exploiting energy efficiency. In addition, the reason of incorporating unlicensed bands while comparing the proposed scheme operating on licensed

Fig. 3. Energy efficiency distribution: $V = 5$.

bands only reveals the benefit of aggregation without creating harmful impact on other network entities. Also, it can be evident that the optimized power allocation scheme with round-robin sub-channel allocation performs inefficiently and the joint approach of sub-channel allocation and power allocation provides a graceful improvement in the energy efficiency throughout the whole distribution. Specifically, the min-max energy bounds which is defined as 5% to 95% of the energy efficiency of the proposed scheme operating in licensed and unlicensed bands, proposed scheme operating on licensed bands, RR-NPOG and spectrum efficient are $[3.55.91 \times 10^8]$, $[3.124.988 \times 10^8]$, $[3.104.80 \times 10^8]$ and $[3.11 - 4.57 \times 10^8]$ for $N = 20$ and $[2.88 - 3.94 \times 10^8]$, $[2.453.63 \times 10^8]$, $[2.533.42 \times 10^8]$ and $[2.463.16 \times 10^8]$ for $N = 40$, respectively.

6.4 Energy efficiency and spectrum efficiency

Fig. 4 illustrates the results of the proposed scheme in terms of spectrum efficiency and energy efficiency (both for perfect CSI and imperfect CSI with $\varsigma = 0.02$ and 0.2) with respect to the transmit power of SBSs and for different small cell densities $N = 20$ and 40 . It can be seen that the energy efficiency increases for all the density and the CSI cases, and then goes down as the transmit power increases from -100 to 23 dBm, while the spectrum efficiency increases. The goal of the proposed scheme is to maximize the energy efficiency while meeting the minimum capacity requirement of SBSs indicated by R_{MIN}^S . We considered the maximum energy efficiency point as 10% less than the maximum point and the corresponding spectrum efficiency point R_{MIN}^S/W (bits/s/Hz) as shown by the vertical line in Fig. 4. The reason for this selection is that there is a significant rise in the spectrum efficiency as the energy efficiency reduces from the maximum point to 10%. However, the system operating point (energy efficiency and spectrum efficiency) can be selected anywhere in the region indicated by the double arrow in Fig. 4. Because after the crossing of the energy efficiency and spectrum efficiency curves there is a negligible increase in the spectrum efficiency but there is a huge drop in the energy efficiency. In order to quantify the imperfection in CSI estimation, the following two variance values are

Fig. 4. Energy efficiency and spectrum efficiency for perfect and imperfect CSI: $N = 20$ and $N = 40$.

taken into account such as $\varsigma = 0.02$ and 0.2 . It is noted that as the estimation error ς increases from 0.02 to 0.2 , there is a drop of 5.5% and 33.3% in the energy efficiency for the small cell density $N = 20$. It can be noted that as long as CSI error is small (e.g., $\varsigma = 0.02$), the maximum performance degradation of the proposed scheme (with imperfect CSI) is reasonable small (5.5%) as compared to the perfect CSI. Furthermore, the energy efficiency and the spectrum efficiency of the proposed scheme with perfect CSI each drops to 25% when the small cell density increases from $N = 20$ to $N = 40$. The reason is that the increase of the small cell density and the fixed pool of shared sub-channels (G and H), the spectrum efficiency decreases due to the increase in the number of interference components in SINR (according to (1) and (2)) and thus, the energy efficiency also decreases.

6.5 Impact of sub-channels G, Q, H, J

The impact of varying G, Q, H , and J on the energy efficiency of the proposed scheme and the comparative counterparts is shown in Fig. 5(a) and Fig. 5(b), for $N = 20$ and $N = 40$, respectively. It is clear that for the similar pool of sub-channels G and H and varying the sub-channels Q and J which are acquired by SBSs, the energy efficiency of the proposed scheme (perfect and imperfect CSI) increases at a faster rate as compared to the other comparative counterparts and this is due to the exploitation of the joint sub-channel allocation and power allocation. In addition, while comparing the results of $G = \{25, 50\}$ and $N = 20$ with $G = \{25, 50\}$ and $N = 40$ it is evident that the performance trend becomes more significant with the increase of small cell density which further illustrates the efficiency of the proposition.

Fig. 5. Impact of varying Q and J on the energy efficiency: $V = 5$ (a): $N = 20$ and (b) $N = 40$.

6.6 Impact of small cell density

The impact of varying the small cell density on the energy efficiency and the spectrum efficiency of the proposed schemes and the comparative counter parts is shown in Fig. 6 and 7, respectively. It is noted that due to the co-channel deployment, increasing the pool of sub-channels $\{G, H\}$ from $\{10, 10\}$ to $\{20, 20\}$ provides more opportunities for managing the interference and thus, enhances the energy efficiency and the spectrum efficiency. Moreover, as the sub-channel utilization increases (by increasing N or decreasing G and H), the proposed scheme in terms of spectrum efficiency and energy efficiency shows more graceful degradation compared to the counterpart schemes. Both the energy efficiency and the spectrum efficiency shows the similar decaying trend, the reason is that the goal of the optimization problem **P1** is to enhance or achieve 10% of the maximum energy efficiency while satisfying the minimum SBSs capacity requirement represented as R_{MIN}^S and the maximum tolerable interference by macro cell users and the legacy WiFi users represented as $\zeta^{M,L}$ and $\kappa^{Leg-W,UL}$, respectively, as represented in Fig. 4.

6.7 Impact of legacy WiFi access points

Since the determination of 'ON' and 'OFF' duty cycle is proposed to be done at the SBS level based on the detection of the WiFi signals, it is not always possible to correctly detect the presence of WiFi signals, especially if they are outside the sensing range of small cells. In order to see the impact of the such legacy WiFi access points on the energy efficiency, we are considering different densities of the legacy WiFi access points such that $V \in \{5, 10, 15, 20\}$ and is shown in Fig.8 . It can be seen as the density of the legacy WiFi access points increases, the energy efficiency reduces and this is due to the cross-tier interference (between the WiFi access points and the dual-access small cells) operating in similar unlicensed sub-channels. The decaying trend of the energy efficiency with respect to

Fig. 6. Impact of small cell density on energy efficiency: $V = 5$.

Fig. 7. Impact of small cell density on spectrum efficiency: $V = 5$.

the WiFi density is more prominent when the dual-access density N changes from 20 to 40. The reason being that on one hand the resource utilization increases (due to increase of small cells in the co-channel environment) but on the other hand, the impact of cross-tier interference also

Fig. 8. Impact of legacy WiFi access points: $G = 10$, $Q = 5$, $H = 10$ and $J = 5$.

increases (due to increase of WiFi access points).

7 CONCLUSION

In this study, a self-organizing framework for dual-access small (operating on both licensed and unlicensed bands) is presented aiming to enhance their energy efficiency performance by exploiting sub-channel allocation and power allocation without creating harmful impact on other network entities. More precisely, the proposed scheme mitigates the cross-tier and co-tier interference in the 'ON' period of dual-access small cells based CSAT. The proposed scheme is designed via a non-cooperative game, where each dual-access small cell is acting as the player and the sub-channels and the power levels are the strategies associated with each game. Since the goal of the proposition is to enhance the energy efficiency, the utility function of the proposed game is designed in a manner that is aligned not only with the energy efficiency but also the cross-tier and co-tier interference components, respectively. Furthermore, the fractional form objective function of the energy efficiency is transformed into a subtract form by a linear fractional programming approach which is proven to provide the convergence to the Nash Equilibrium. the other hand, in order to reduce the complexity of the proposed game using joint sub-channel allocation and power allocation, the joint approach is divided into two individual problems: the sub-channel allocation and the power allocation. Furthermore, the performance of the proposed scheme is compared not only with the conventional RR-NPOG and spectrum efficient schemes but also with the proposed scheme operating on only licensed band. The performance of the proposed scheme is also evaluated in terms of perfect and imperfect CSI. The performance gap of the proposed scheme makes it attractive for dense small cell environments.

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REFERENCES

- [1] A. R. Elsherif, W.-P. Chen, A. Ito, and Z. Ding, "Resource allocation and inter-cell interference management for dual-access small cells," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 6, pp. 1082–1096, 2015.
- [2] R. Taori and A. Sridharan, "Point-to-multipoint in-band mmwave backhaul for 5g networks," *IEEE Communications Magazine*, vol. 53, no. 1, pp. 195–201, 2015.
- [3] B. Bangert, S. Talwar, R. Arefi, and K. Stewart, "Networks and devices for the 5g era," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 90–96, 2014.
- [4] C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, H. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, "Cellular architecture and key technologies for 5g wireless communication networks," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 122–130, 2014.
- [5] Z. Zhou, M. Dong, K. Ota, and Z. Chang, "Energy-efficient context-aware matching for resource allocation in ultra-dense small cells," *IEEE Access*, vol. 3, pp. 1849–1860, 2015.
- [6] R. Zhang, Z. Zheng, M. Wang, X. Shen, and L.-L. Xie, "Equivalent capacity in carrier aggregation-based lte-a systems: A probabilistic analysis," *IEEE Transactions on Wireless Communications*, vol. 13, no. 11, pp. 6444–6460, 2014.
- [7] Qualcomm, "1000x: more small cells, hyper-dense small cell deployments," Available at <http://www.qualcomm.com>.
- [8] C. Yang, J. Li, and M. Guizani, "Cooperation for spectral and energy efficiency in ultra-dense small cell networks," *IEEE Wireless Communications*, vol. 23, no. 1, pp. 64–71, 2016.
- [9] H. Zhang, S. Chen, X. Li, H. Ji, and X. Du, "Interference management for heterogeneous networks with spectral efficiency improvement," *IEEE Wireless Communications*, vol. 22, no. 2, pp. 101–107, 2015.
- [10] Y. Wang, H. Ji, and H. Zhang, "Spectrum-efficiency enhancement in small cell networks with biasing cell association and eicic: An analytical framework," *International Journal of Communication Systems*, vol. 29, no. 2, pp. 362–377, 2016.
- [11] A. Shahid, S. Aslam, H. S. Kim, and K.-G. Lee, "A doctive q-learning approach towards joint resource allocation and power control in self-organised femtocell networks," *Transactions on Emerging Telecommunications Technologies*, vol. 26, no. 2, pp. 216–230, 2015.
- [12] G. Y. Li, Z. Xu, C. Xiong, C. Yang, S. Zhang, Y. Chen, and S. Xu, "Energy-efficient wireless communications: tutorial, survey, and open issues," *IEEE Wireless Communications*, vol. 18, no. 6, 2011.
- [13] R. Q. Hu and Y. Qian, "An energy efficient and spectrum efficient wireless heterogeneous network framework for 5g systems," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 94–101, 2014.
- [14] S. Dimatteo, P. Hui, B. Han, and V. O. Li, "Cellular traffic offloading through wifi networks," in *Mobile Adhoc and Sensor Systems (MASS)*, 2011 IEEE 8th International Conference on. IEEE, 2011, pp. 192–201.
- [15] Lte-u forum. Available at <http://www.lteforum.org/>.
- [16] 3gpp release 13 specification, 2015. <http://www.3gpp.org/rele-13/>.
- [17] "lte-u technical report: coexistence study for lte-u sdl version 1.0," Available at <http://lteuforum.org/documents.html>.
- [18] A. M. Cavalcante, E. Almeida, R. D. Vieira, S. Choudhury, E. Tuomaala, K. Doppler, F. Chaves, R. C. Paiva, and F. Abinader, "Performance evaluation of lte and wi-fi coexistence in unlicensed bands," in *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*. IEEE, 2013, pp. 1–6.
- [19] V. Maglogiannis, D. Naudts, P. Willems, and I. Moerman, "Impact of lte operating in unlicensed spectrum on wi-fi using real equipment," in *Global Communications Conference (GLOBECOM)*, 2016 IEEE. IEEE, 2016, pp. 1–6.
- [20] N. Jindal and D. Breslin, "Lte and wi-fi in unlicensed spectrum: A coexistence study," *Google white paper*, 2015.
- [21] Qualcomm, "Qualcomm research lte in unlicensed spectrum: Harmonious coexistence with wifi," Qualcomm, Tech. Rep., 06 2014.

- [22] A. Shahid, S. Aslam, H. S. Kim, and K.-G. Lee, "Distributed joint resource and power allocation in self-organized femtocell networks: a potential game approach," *Journal of Network and Computer Applications*, vol. 46, pp. 280–292, 2014.
- [23] W. Li, W. Zheng, T. Su, and X. Wen, "Dual-utility based green power game in two-tier ofdma femtocell networks with firefly algorithm," in *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*. IEEE, 2013, pp. 452–457.
- [24] G. Miao, N. Himayat, G. Y. Li, and S. Talwar, "Distributed interference-aware energy-efficient power optimization," *IEEE Transactions on Wireless Communications*, vol. 10, no. 4, pp. 1323–1333, 2011.
- [25] F. Meshkati, H. V. Poor, and S. C. Schwartz, "Energy-efficient resource allocation in wireless networks," *IEEE Signal Processing Magazine*, vol. 24, no. 3, pp. 58–68, 2007.
- [26] R. Xie, F. R. Yu, H. Ji, and Y. Li, "Energy-efficient resource allocation for heterogeneous cognitive radio networks with femtocells," *IEEE Transactions on Wireless Communications*, vol. 11, no. 11, pp. 3910–3920, 2012.
- [27] A. H. Arani, A. Mehbodniya, M. J. Omid, F. Adachi, W. Saad, and I. Güvenç, "Distributed learning for energy-efficient resource management in self-organizing heterogeneous networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 10, pp. 9287–9303, 2017.
- [28] S. Samarakoon, M. Bennis, W. Saad, M. Debbah, and M. Latva-Aho, "Ultra dense small cell networks: Turning density into energy efficiency," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 5, pp. 1267–1280, 2016.
- [29] A. Zakrzewska, D. López-Pérez, S. Kucera, and H. Claussen, "Dual connectivity in lte hetnets with split control-and user-plane," in *Globecom Workshops (GC Wkshps), 2013 IEEE*. IEEE, 2013, pp. 391–396.
- [30] M. R. Khawer, J. Tang, and F. Han, "usica proactive small cell interference mitigation strategy for improving spectral efficiency of lte networks in the unlicensed spectrum," *IEEE Transactions on Wireless Communications*, vol. 15, no. 3, pp. 2303–2311, 2016.
- [31] F. Liu, E. Bala, E. Erkip, M. C. Beluri, and R. , "Small-cell traffic balancing over licensed and unlicensed bands," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 12, pp. 5850–5865, 2015.
- [32] H. He, H. Shan, A. Huang, L. X. Cai, and T. Quek, "Proportional fairness-based resource allocation for lte-u coexisting with wi-fi," *IEEE Access*, 2016.
- [33] R. Etkin, A. Parekh, and D. Tse, "Spectrum sharing for unlicensed bands," *IEEE Journal on selected areas in communications*, vol. 25, no. 3, 2007.
- [34] F. Teng, D. Guo, and M. L. Honig, "Sharing of unlicensed spectrum by strategic operators," in *Signal and Information Processing (GlobalSIP), 2014 IEEE Global Conference on*. IEEE, 2014, pp. 288–292.
- [35] M. Chen, W. Saad, and C. Yin, "Echo state networks for self-organizing resource allocation in lte-u with uplink-downlink decoupling," *IEEE Transactions on Wireless Communications*, 2016.
- [36] M. Chen, W. Saad, and C. Yin, "Optimized uplink-downlink decoupling in lte-u networks: An echo state approach," in *2016 IEEE International Conference on Communications (ICC)*. IEEE, 2016, pp. 1–6.
- [37] R. Thakur, V. J. Kotagi, and C. S. R. Murthy, "Resource allocation and cell selection framework for lte-unlicensed femtocell networks," *Computer Networks*, vol. 129, pp. 273–283, 2017.
- [38] A. Shahid, K. S. Kim, E. De Poorter, and I. Moerman, "Self-organized energy-efficient cross-layer optimization for device to device communication in heterogeneous cellular networks," *IEEE Access*, vol. 5, pp. 1117–1128, 2017.
- [39] M. Olbrich, A. Zubow, S. Zehl, and A. Wolisz, "Towards lte-u interference detection, assessment and mitigation in 802.11 networks using commodity hardware," *arXiv preprint arXiv:1702.04020*, 2017.
- [40] P. Gawłowicz, A. Zubow, and A. Wolisz, "Enabling cross-technology communication between lte unlicensed and wifi," in *IEEE INFOCOM*, 2018.
- [41] V. Maglogiannis, A. Shahid, D. Naudts, E. De Poorter, and I. Moerman, "Enhancing the coexistence of lte and wi-fi in unlicensed spectrum through convolutional neural networks," *IEEE Access*, vol. 7, pp. 28 464–28 477, 2019.
- [42] A. Shahid, J. Fontaine, M. Camelo, J. Haxhibeqiri, M. Saelens, Z. Khan, I. Moerman, and E. De Poorter, "A convolutional neural network approach for classification of lpwan technologies: Sigfox, lora and ieee 802.15. 4g," in *2019 16th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*. IEEE, 2019, pp. 1–8.
- [43] J. Fontaine, E. Fonseca, A. Shahid, M. Kist, L. A. DaSilva, I. Moerman, and E. De Poorter, "Towards low-complexity wireless technology classification across multiple environments," *Ad Hoc Networks*, vol. 91, p. 101881, 2019.
- [44] T. L. Marzetta, "How much training is required for multiuser mimo?" in *2006 Fortieth Asilomar Conference on Signals, Systems and Computers*. IEEE, 2006, pp. 359–363.
- [45] J. Wang, G. Scutari, and D. P. Palomar, "Robust mimo cognitive radio via game theory," *IEEE Transactions on Signal Processing*, vol. 59, no. 3, pp. 1183–1201, 2011.
- [46] H. Zhang, C. Jiang, X. Mao, and H.-H. Chen, "Interference-limited resource optimization in cognitive femtocells with fairness and imperfect spectrum sensing," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 3, pp. 1761–1771, 2016.
- [47] "Lte-u technology and coexistence," Available at <http://www.lteforum.org/workshop.html>.
- [48] H. Zhang, C. Jiang, N. C. Beaulieu, X. Chu, X. Wang, and T. Q. Quek, "Resource allocation for cognitive small cell networks: A cooperative bargaining game theoretic approach," *IEEE Transactions on Wireless Communications*, vol. 14, no. 6, pp. 3481–3493, 2015.
- [49] X. Xiao, X. Tao, and J. Lu, "Qos-aware energy-efficient radio resource scheduling in multi-user ofdma systems," *IEEE Communications Letters*, vol. 17, no. 1, pp. 75–78, 2013.
- [50] A. Zappone, E. Jorswieck et al., "Energy efficiency in wireless networks via fractional programming theory," *Foundations and Trends® in Communications and Information Theory*, vol. 11, no. 3–4, pp. 185–396, 2015.
- [51] W. Dinkelbach, "On nonlinear fractional programming," *Management science*, vol. 13, no. 7, pp. 492–498, 1967.
- [52] K. Akkarajitsakul, E. Hossain, D. Niyato, and D. I. Kim, "Game theoretic approaches for multiple access in wireless networks: A survey," *IEEE Communications Surveys & Tutorials*, vol. 13, no. 3, pp. 372–395, 2011.
- [53] J. Lee and S. Leyffer, "Mixed integer nonlinear programming, the ima volumes in mathematics and its applications, vol. 154," 2012.
- [54] K. Son, S. Lee, Y. Yi, and S. Chong, "Refim: A practical interference management in heterogeneous wireless access networks," *arXiv preprint arXiv:1105.0738*, 2011.
- [55] Z. Shen, J. G. Andrews, and B. L. Evans, "Adaptive resource allocation in multiuser ofdm systems with proportional rate constraints," *IEEE transactions on wireless communications*, vol. 4, no. 6, pp. 2726–2737, 2005.
- [56] D. Fudenberg and J. Tirole, "Game theory," 1991.
- [57] C. Patel, M. Yavuz, and S. Nanda, "Femtocells [industry perspectives]," *IEEE Wireless Communications*, vol. 17, no. 5, pp. 6–7, 2010.
- [58] Z. Chang, Z. Han, and T. Ristaniemi, "Energy efficient optimization for wireless virtualized small cell networks with large-scale multiple antenna," *IEEE Transactions on Communications*, vol. 65, no. 4, pp. 1696–1707, 2017.
- [59] E. U. T. R. Access, "Further advancements for e-utra physical layer aspects," *3GPP TR 36.814, Tech. Rep.*, 2010.
- [60] I. ETS, "Selection procedures for the choice of radio transmission technologies of the umts (umts 30.03 version 3.2. 0)," *Universal Mobile Telecommunications System (UMTS)*, 1998.

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