This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TGCN.2018.2890041, IEEE Transactions on Green Communications and Networking

Multi-Operator Cooperation for Green Cellular Networks with Spatially Separated Base Stations Under Dynamic User Associations

Md. Farhad Hossain, *Member, IEEE*, Kumudu S. Munasinghe, *Senior Member, IEEE*, and Abbas Jamalipour, *Fellow, IEEE*

***Abstract*—This paper presents a cooperation framework for sharing base stations (BSs) among N number of collocated radio-access networks (RANs) for improving energy efficiency (EE). The proposed framework is equally applicable for collocated and non-collocated BSs belonging to multiple RANs. To the best of our knowledge, this paper is the first for developing such cooperation mechanisms among the spatially separated BSs of N RANs. Independent hard-core Poisson point process (HCPP) is used for modeling the locations of BSs with a minimal inter-BS distance, while locations of user equipment devices (UEs) are modeled using Poisson point process (PPP). The proposed cooperation mechanisms enable the networks to serve UEs of other RANs allowing some BSs to switch into sleep mode for better EE. Call continuity, signal quality and call blocking limits are guaranteed during this dynamic BS switching. For avoiding high complexity of the generalized EE optimization problem, heuristically guided algorithms with different dynamic UE association policies are proposed. Network performance including fairness of the proposed cooperation under a wide range of system settings is thoroughly investigated. Simulation results clearly demonstrate a substantial improvement in EE as well as an extremely fair cooperation. Comparisons with the other works further validate the proposed framework.**

***Index Terms*—Multi-operator cooperation; green cellular networks; user association; BS switching; fairness;**

I. Introduction

Exponential increase of energy utilization in cellular networks has become one of the primary concerns for operators from both economical and environmental aspects [1], [2]. The major energy hungry element of a cellular system is the base stations (BSs) in radio access network (RAN) consuming around 60-90% of the total demand [3], [4]. Therefore, reduction in energy consumption in BSs drawn great interest of the stake holders. On the other hand, with the deployment of more and more BSs, location of BSs is turning to be more random instead of regular hexagonal pattern. Many recent studies identify that instead of basic hexagonal grid or Poisson point process (PPP), hardcore Poisson point process (HCPP) based modeling could emulate a more realistic spatial distribution of BSs in modern networks [5], [6].

A high degree temporal-spatial diversity in traffic is very common in cellular networks [7]–[9]. Consequently, during the recent years, various proposals for improving energy efficiency (EE) by switching off BSs during low-traffic periods have emerged [1], [3], [10]–[15]. On the other hand, given the real scenarios of the coexistence of multiple network operators (MNOs), infrastructure sharing among MNOs is envisaged as a viable scheme for reducing both capital (CAPEX) and operational (OPEX) expenditures [13], [16], [17]. Infrastructure sharing can be generally of three types - active, passive and roaming-based [18]–[21]. In passive sharing, mainly masts and cell sites are shared, whereas active elements including RANs and core networks are shared in active sharing. Multi operator core network (MOCN) and Multi operator RAN (MORAN) are the most discussed architectures for active sharing. On the other hand, in roaming-based sharing, UEs of one operator is served by another operator for a certain defined footprint on a permanent basis, where there is no coverage of the former operator.

A recent study concludes that despite the technical challenges, the potential benefits of infrastructure sharing can be as much as €2 billion [22]. A major benefit of such inter-operator cooperation is the obvious improvement in network EE [16], [17]. According to a European study [23], energy consumption of mobile networks can be reduced by up to 60% through infrastructure sharing. Such cooperation can also lead to better service quality for mobile users and enhanced network performance by providing ubiquitous access, better signal quality, improved reliability, optimized network planning, efficient utilization of network capacity, reduced radio frequency transmission, fast load balancing, and both vertical and soft handoffs supports [13], [17], [21], [24]–[26]. Consequently, major cellular network operators and vendors around the world have also shown great interest on multi-operator cooperation based infrastructure sharing [19]. However, although the principle is simple in theory, MNO cooperation possesses several technical and logistical challenges. Feasible profit division mechanism among the MNOs, alterated signal quality distribution due to frequent inter-RAN handoff of UEs, compatibility issues among MNOs of heterogeneous technologies, requirement of strong coordination among the RANs as well as the core networks of the cooperating operators, handset capabilities for multi-RAN connectivity and handoff supports are some of the major challenges [27]. Therefore, 3rd generation partnership project (3GPP) is actively working in developing standards for identifying the requirements, architectures and management issues for implementing infrastructure sharing in practice [28], [29].

A switching threshold based energy saving scheme through cooperation among multiple RANs was investigated in our previous work of [30]. However, the system model is based on the assumption of collocated BSs allowing traffic offloading by a BS only to the other collocated BSs. Besides, UE locations and required quality of service (QoS) are completely overlooked during traffic offloading. Whereas, our another work in [31] proposed an energy saving cooperation scheme for sharing BSs between two RANs. Six different algorithms by using various BS selection and user association policies are outlined. However, the proposed framework in this work is applicable for cooperation between only two operators. In light of this, this paper develops cooperation schemes among N number of operators for improving EE through BS sharing and thus helps to understand the dynamics of EE with the number of networks. This paper proposes new algorithms as well as comprehensively updates and extends previous algorithms for accommodating the cooperation scenarios among N networks. Moreover, instead of using PPP as in [31], locations of BSs in the networks are modeled in a more realistic fashion by using HCPP for keeping a minimum distance between any two BSs belonging to the same operator. Furthermore, an additional QoS constraint, namely, call blocking is included in the proposed user associations. Fairness is also introduced as a new performance metric for further validation of the proposed framework. The main contributions of this paper thus can be summarized as below:

- We propose a generalized dynamic multi-operator cooperation framework for sharing BSs among N number of geographically collocated RANs for improving EE. The framework is applicable not only to N operators scenario, but also for cooperation among irregularly placed non-collocated BSs belonging to these N operators. To the best of our knowledge, this is the first approach for improving EE in such networks. For modeling this spatial separation of cooperating BSs, locations of BSs in each network are modeled using independent HCPPs. Distribution of UEs in the RANs are modeled using independent PPPs.
- Under the proposed framework, N RANs cooperate for sharing each other's traffic which is regulated by the instantaneous traffic and other system settings. Eventually a set of BSs from the N RANs are selected to switch into low power sleep mode, while the other BSs are left in high power active mode for serving UEs. Thus, the N RANs are dynamically reconfigured with time using a reduced number of active BSs for improving EE.
- We also formulate a generalized EE optimization problem for selecting the optimal set of active BSs, which is a challenging combinatorial problem with high computational complexity. Therefore, for the ease of practical implementation, heuristically guided nine different algorithms with dynamic user associations are proposed. Under these algorithms, service continuity of UEs are guaranteed by maintaining a minimum signal strength and call blocking is kept within the target limit. Besides, fairness among the operators as well as the energy cost for UE sharing is also taken into account.
- We thoroughly investigate the performance of the proposed multi-operator cooperation framework using extensive simulations. Impact of network parameters including the number of cooperating networks, HCPP thinning radius, BS and UE densities, UE associations, call blocking limits, signal quality requirement and BS power profile on the degree of EE improvement and other system parameters are critically analyzed. Fairness of the proposed cooperation is also investigated using Jain's fairness index. Presented results demonstrate that the framework is capable to significantly improve the overall EE of the cooperating networks with very high fairness. Performance of the proposed framework is also compared with that of the other state-of-the-art works.

The rest of the paper is organized as follows. Section II presents a comprehensive study on the related works. Considered network model and the performance metrics are presented in Sections III and IV respectively. The proposed energy saving framework along with the optimization problem is presented in Section V. Whereas, Section VI presents the algorithms with the proposed user association policies. Simulation results with a thorough analysis are provided in Section VII. The paper finally concludes in Section VIII by summarizing our key findings.

II. Related Works

In recent time, the concept of BS sharing among multiple coolocated RANs for saving energy has drawn considerable attention [30], [32]–[41]. This research trend has also been recognized by 3GPP [28], [29].

In [30], authors proposed a traffic threshold based energy saving BS switching scheme in an environment of multiple RANs. The proposed scheme sequentially offloads traffic from one BS to the others during low-traffic periods. The scheme is applicable only for regular hexagonal cell layouts. In [32], authors outlined several energy saving cooperation strategies between collocated BSs of two RANs. Using these strategies, traffic of the switched off BS is transferred to the other collocated active BS for saving energy. On the other hand, authors in [33] introduced a game theory based centralized energy saving BS switching off strategy for a system with two RANs. Various cost-based functions are integrated into this game for assiting the operators to decide the profitability of infrastructure sharing. The same authors then extended their work in [34] for generalizing the game theoretic based BS sharing scheme among multiple RANs. This approach is of distributed type and attains a dominant strategy equilibrium resulting in cost minimization for each operator. On the other hand, a microeconomic analysis for sharing BSs between two RANs by formulating the problem as a non-cooperative game was presented in [35]. Several factors including traffic distributions, energy costs, capacity, and revenue and penalty of happy and unhappy UEs are taken into account. It is found that the existence and the number of Nash Equilibria depend on the network settings. Whereas, a Bayesian game based BS sharing mechanism among multiple RANs by using an energy consumption based new BS utility model was presented in [36]. This mechanism is demonstrated to be capable to simultaneously accomplish incentive compatibility, budget balance and participation constraints. A Nash bargaining solution (NBS) based decentralized technique for fair sharing of backup power supply by re-associating users among the multiple operators was presented in [38].

BS sharing problem among multiple RANs for saving energy was further extended to heterogeneous networks (Het-

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Nets) in [37], [39], [40]. In particular, [39] proposed a multiobjective combinatorial auction scheme such that MNOs can compete for acquiring access to third party owned small cell (SC) BSs for offloading their respective macrocell traffic. Winning SCs allows BSs of RANs to switch into sleep mode for reducing energy utilization as well as network cost. The work in [40] considered MNOs with HetNets having own SCs, where both macrocell BSs and SCs are shared among the RANs. All the works in [30], [32]–[40] are based on the basic assumption that macrocell BSs of all the operators are collocated. Thus, these schemes are not appropriate for the real network environments. Furthermore, none of the above papers except [37], [38], [40] considered the location of UEs, signal quality and UE association problem for formulating the proposed mechanisms. However, all these factors are crucial for developing practical schemes.

On the other hand, a multi-operator collaboration framework for saving energy by sharing BSs was presented in [41]. This paper introduces a roaming price for helping an operator to make decision whether to cooperate or not. The proposed collaboration techniques of this paper are designed by assuming that cells belonging to a network are of equal area with regularly spaced BSs, which is deemed unrealistic for modern networks. Moreover, only threshold data rate based user association scheme is proposed and call blocking probability is overlooked. The work in [40] is also a roaming-cost-based traffic sharing scheme among the rival MNOs with HetNets over a specific area for a pre-specified duration. A Shapley value based bankruptcy game (BSV) is designed for distributing the obtained cost among the cooperative MNOs, while maintaining fairness as well as keeping the scheme profitable compared to the non-cooperative option. However, this paper considers only one macrocell per MNO which are of equal area, while the macrocell BSs are collocated making the system impractical as discussed earlier. Furthermore, as discussed above, our work in [31] proposed a cooperation framework for sharing BSs between only two RANs for saving energy. This paper also did not consider call blocking for associating UEs, while locations of BSs in the networks are modeled using PPP which is far from real scenario.

Our proposed framework presented in this paper is free from all the aforementioned limitations and more realistic. Our techniques are applicable for cooperation among any number of RANs, and thus more practical and in a generalized form. In addition, consideration of spatial separations among BSs belonging to different cooperating RANs and maintenance of a minimum distance among the BSs of individual RAN by modeling the locations of BSs using HCPP have not been reported yet. Furthermore, various dynamic user association techniques with the consideration of signal quality and call blocking are proposed and thoroughly investigated.

III. Network Model

This section presents the considered network layout and other system components in the context of orthogonal frequency division multiple access (OFDMA)-based long-term evolution system (LTE) systems with the feasibility to be adopted to other cellular systems. For the convenience of readers, important notations used in this paper are listed in Table I.

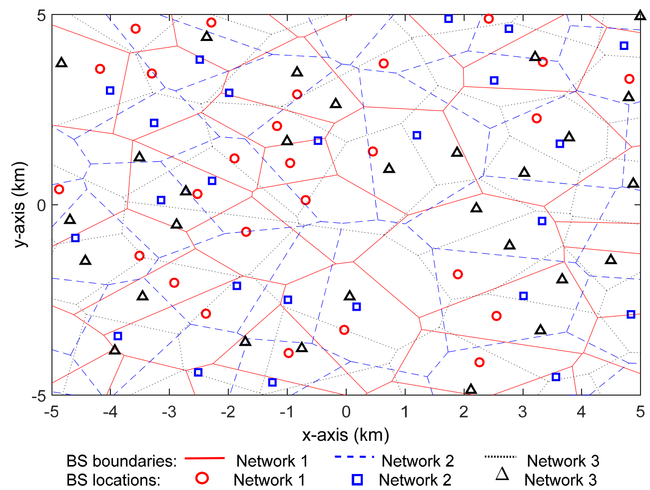


Fig. 1: A snapshot of the network layout with $N = 3$ geographically collocated RANs.

A. Network Layout

We consider a geographical area $\mathcal{A} \subset \mathbb{R}^2$ served by N independent RANs, each operating in a different frequency. Each RAN is assumed to have its own BSs covering the entire area $\mathcal{A}$. Universal frequency reuse is considered within each RAN. Unlike the previous works, we consider the general scenario where BSs belonging to the N RANs are spatially seperated located in random locations[1]. For accounting the random locations of BSs and the spatial separation amomg the BSs belonging to different RANs, HCPP is used for modeling the locations of BSs. To do so, locations of BSs in each RAN are first modeled as PPP and then a thinning process is applied for obtaining the HCPP. In general, if the spatial distribution of nodes over a terrain is of PPP Φ with density λ, then the number of points in a bounded set $\mathcal{S}$ has a Poisson distribution with mean $\lambda|\mathcal{S}|$ and can be given by [43]

$$P(\Phi(\mathcal{S}) = k) = e^{-\lambda|\mathcal{S}|} \frac{(\lambda|\mathcal{S}|)^k}{k!} \tag{1}$$

If a thinning process is then applied on this PPP model such that no two nodes can stay closer than a certain distance h, also called as thinning radius, results in a HCPP distributed nodes. In this paper, we model the locations of BSs using a Matérn HCPP resulting a modified BS density $\hat{\lambda}$ given by [43]

$$\hat{\lambda} = \frac{1 - \exp(-\lambda \pi h^2)}{\pi h^2} \tag{2}$$

[1]Although most of the current works considered collocated BSs (i.e., tower sharing among the operators), it poses several critical technical challenges [42]. Major challenges include the non-optimal placement of RF and microwave antennas due to the space constraint, and the non-optimal design of microwave link leading to poor coverage. Thus, tower sharing is a real challenge as most of the cities have 4-6 collocated operators. Moreover, collocated BSs belonging to different operators is a special case of our scenario of non-collocated BSs. Thus, our cooperation framework can directly be applied to the scenario of collocated BSs.

TABLE I: Summary of the important notations

N	Number of cooperating RANs
N_s	Percentage of sleep mode BSs
E_s	Average energy savings
η_{EE}	Average EE
η_G	EE improvement
$\lambda_{n,b}(\lambda_{n,u})$	PPP intensity of BSs (UEs) in n^{th} RAN
h	Thinning radius
$\mathbb{B}$	Set of BSs of all the N RANs
$\mathbb{B}_n$	Set of BSs of n^{th} RAN
$\mathcal{B}_{i,n}$	i^{th} BS of n^{th} RAN
$\mathbb{B}_{ON}$	Set of active BSs from all N RANs
$\mathbf{B_{ON,n}}$	Set of active BSs of n^{th} RAN
$\mathbb{B}^*(\mathbb{B}_c)$	Set of dBSs (cBSs)
$\mathcal{A}_{i,n}$	Coverage area of $\mathcal{B}_{i,n}$
$U^k_{i,n}$	k^{th} UE in $\mathcal{B}_{i,n}$
$(x^b_{i,n}, y^b_{i,n})$	Cartesian coordinate of $\mathcal{B}_{i,n}$
$(x^{k,u}_{i,n}, y^{k,u}_{i,n})$	Coordinate of $U^k_{i,n}$
$M_{i,n}$	Number of UEs in $\mathcal{B}_{i,n}$
$N_{n,u}$	Number of UEs in n^{th} RAN
$\delta_{i,n}$	PLPC of $\mathcal{B}_{i,n}$
$p_{i,n}(P^{i,n}_m)$	Total (maximum) operating power of $\mathcal{B}_{i,n}$
$P^{Tx}_{i,n}$	Maximum TP of a TRX chain of $\mathcal{B}_{i,n}$
$p^{i,n}_s$	Sleep mode power of $\mathcal{B}_{i,n}$
$L_{i,n}$	LF of BS $\mathcal{B}_{i,n}$
$L^{(q)}_{i,n}$	LF of q^{th} TRX chain of $\mathcal{B}_{i,n}$
L_i	LF of BS $\mathcal{B}_i \in \mathbb{B}^*$
$P^k_{i,n}$	TP for $U^k_{i,n}$
$P^{k,R}_{i,n}$	Received power at $U^k_{i,n}$
$\mathcal{I}^{k,opt}_{i,n}$	Inter-RAN interference at $U^k_{i,n}$
$\mathcal{I}^{k,ext}_{i,n}$	Inter-cell interference at $U^k_{i,n}$
$\mathcal{I}^{k,int}_{i,n}$	Intra-cell interference at $U^k_{i,n}$
$\gamma^k_{i,n}$	SINR at $U^k_{i,n}$
$\psi^k_{i,n}$	Achievable SE at $U^k_{i,n}$
$P^{i,n}_b$	Call blocking probability in $\mathcal{B}_{i,n}$
$C_{i,n}$	Capacity of $\mathcal{B}_{i,n}$ in terms of RBs
$d^{k,u}_{i,n}$	Euclidean distance of $U^k_{i,n}$ from a cBS

A view of an environment having $N = 3$ RANs with HCPP distributed BSs is shown in Fig. 1. In practice, the locations of BSs in one RAN are not decided by the locations of BSs in other RANs. Thus, the locations of BSs in the N RANs can be modeled as N independent HCPPs. These N HCPPs for BSs are generated from N independent PPPs with intensity $\lambda_{n,b}, n = 1, 2, ..., N$, which can be denoted as $\Phi_{n,b} = \{(x^b_{i,n}, y^b_{i,n}) : \forall i\}$, where $(x^b_{i,n}, y^b_{i,n})$ is the two-dimensional Cartesian coordinate of i^{th} BS of n^{th} RAN denoted by $\mathcal{B}_{i,n}$. Now, let $\mathbb{B} = \{\mathbb{B}_1, \mathbb{B}_2, ..., \mathbb{B}_N\}$ be the set of BSs of N RANs under HCPP models (i.e., after thinning). Here, $\mathbb{B}_n = \{\mathcal{B}_{1,n}, \mathcal{B}_{2,n}, ..., \mathcal{B}_{|\mathbb{B}_n|}\}, n = 1, 2, ..., N$ is the set of BSs of n^{th} RAN. Let $\mathcal{A}_{i,n}$ be the coverage area of $\mathcal{B}_{i,n}$ and thus $\cup_{i=1}^{|\mathbb{B}_n|}\mathcal{A}_{i,n} = \mathcal{A}, \forall n$.

On the other hand, locations of UEs of the N RANs are modeled as N independent PPPs with intensity $\lambda_{n,u}, n = 1, 2, ..., N$ and denoted by $\Phi_{n,u} = \{(x^{k,u}_{i,n}, y^{k,u}_{i,n}) : i = 1, 2, ..., |\mathbb{B}_n|; k = 1, 2, ..., M_{i,n}\}$, where $(x^{k,u}_{i,n}, y^{k,u}_{i,n})$ is the Cartesian coordinate of k^{th} UE of $\mathcal{B}_{i,n}$ denoted as $U^k_{i,n}$ and $M_{i,n}$ is the total number of UEs in $\mathcal{B}_{i,n}$. Thus the total number of UEs in n^{th} RAN is $N_{n,u} = \sum_{i=1}^{|\mathbb{B}_n|} M_{i,n}$.

In the original network, we consider that each UE is associated with the closest BS resulting in coverage areas that comprise a Voronoi tessellation space. BSs are considered to be equipped with omnidirectional antennas and capable in switching between active and sleep modes. Besides, UEs are assumed capable to support connectivity with multiple RANs potentially of heterogeneous technologies operating in different frequencies. On the other hand, considering motion of UEs as isotropic and relatively slow, UEs are assumed stationary for the duration of network reorganizing by switching BSs. Though in LTE, a UE can be scheduled to one or multiple resource blocks (RBs) [44], without losing the generality, we consider one RB per UE. We also consider equal transmit power (TP) over all RBs.

B. Link Model

Received power $P_R(d)$ in dBm at a UE located at a distance d from its serving BS can be given by

$$P_R(d) = P_t - P_L(d) + X_\sigma \tag{3}$$

where P_t is the TP in dBm and $P_L(d)$ is the total path-loss in dB. Whereas X_σ is the amount of shadow fading modeled as a log-normally distributed random variable with zero mean and standard deviation σ dB. On the other hand, this paper adopts the WINNER+ non-line-of-sight (NLOS) urban macro-cell path-loss model [45], which gives a path-loss as below

$$\begin{aligned} P_L(d) = {} & (44.9 - 6.55\log_{10} h_{BS})\log(d) \\ & + 5.83\log_{10} h_{BS} + 14.78 + 34.97\log_{10} f_c \end{aligned} \tag{4}$$

where d and BS height h_{BS} are in metre, and carrier frequency f_c is in GHz.

C. Power Consumption Profile of BSs

Extensive literaure surveys identify that macrocell BS power profile can be of three types - fully load proportional (FLP), non-load proportional (NLP) and partially load proportional (PLP) [11], [12], [31], [46], [47]. FLP BSs draw power linearly related to load consuming zero power at zero traffic, NLP types consume constant power irrespective of traffic, while PLP BSs have both load-dependent linearly varying and load-independent constant power consumption parts. This paper considers a generalized BS power consumption profile. This model includes a single variable named as power-load proportionality constant (*PLPC*) denoted as $\delta_{i,n} \in [0, 1]$ for BS $\mathcal{B}_{i,n}$.

Let BS $\mathcal{B}_{i,n}$ has total N_T transceiver (TRX) chains. Now, assuming equal maximum operating power $P^{i,n}_m$, equal sleep mode power $p^{i,n}_s$ and equal PLPC $\delta_{i,n}$ for all of these N_T

chains, instantaneous total operating power of $\mathcal{B}_{i,n}$ can be given by [11], [12]

$$p_{i,n} = \begin{cases} \sum_{q=1}^{N_T} \left[(1-\delta_{i,n}) L_{i,n}^{(q)} P_m^{i,n} + \delta_{i,n} P_m^{i,n} \right] & \text{(active)} \\ \sum_{q=1}^{N_T} p_s^{i,n} & \text{(sleep)} \end{cases} \tag{5}$$

where $0 \leq L_{i,n}^{(q)} \leq 1$ is the load factor (LF) of the q^{th} TRX chain, while the LF of BS $\mathcal{B}_{i,n}$ can be written as $L_{i,n} = \frac{1}{N_T} \sum_{q=1}^{N_T} L_{i,n}^{(q)}$. LF in an LTE system is the ratio of the number of RBs in use to the total number of available RBs [48], [49]. On the other hand, $P_m^{i,n} = w_{i,n} P_{i,n}^{Tx} + v_{i,n}$. Here, $P_{i,n}^{Tx}$ is the maximum TP of a chain, and $w_{i,n}$ and $v_{i,n}$ are constants [12], [50]. Besides, for considering various sleep mode power of BSs, we model it as $p_s^{i,n} = \delta_{i,n} v_{i,n}$. It is clear that $\delta_{i,n}$ determines the level of dependency of $p_{i,n}$ on $L_{i,n}^{(q)}$. More specifically, $\delta_{i,n} = 0, 1$ and $0 < \delta_{i,n} < 1$ for FLP, NLP and PLP type BSs respectively.

IV. Performance Metrics

A. Sleep Mode BSs and Energy Savings

Let $s_{i,n} \in \{0, 1\}$ be the status parameter of BS $\mathcal{B}_{i,n}$, where $s_{i,n} = 0$ and 1 indicate its sleep and active modes respectively. Then percentage of sleep mode BSs averaged over N RANs can be given by

$$N_s = \frac{\sum_{n=1}^{N} \sum_{i=1}^{|\mathbb{B}_n|} (1 - s_{i,n})}{\sum_{n=1}^{N} |\mathbb{B}_n|} \times 100\% \tag{6}$$

After redistribution of UEs among the N RANs, total power consumption in BS $\mathcal{B}_{i,n}$ becomes

$$\hat{p}_{i,n} = \Bigg[s_{i,n} \sum_{q=1}^{N_T} \left[(1-\delta_{i,n}) \hat{L}_{i,n}^{(q)} P_m^{i,n} + \delta_{i,n} P_m^{i,n} \right] + (1 - s_{i,n}) \sum_{q=1}^{N_T} p_s^{i,n} \Bigg], \forall i, \forall n \tag{7}$$

where $\hat{L}_{i,n}^{(q)}$ is the new $L_{i,n}^{(q)}$. Average energy savings of the N RANs can then be written as

$$E_s = \left[1 - \frac{\sum_{n=1}^{N} \sum_{i=1}^{|\mathbb{B}_n|} \hat{p}_{i,n}}{\sum_{n=1}^{N} \sum_{i=1}^{|\mathbb{B}_n|} p_{i,n}} \right] \times 100\% \tag{8}$$

B. Energy Efficiency

Signal-to-interference-plus-noise-ratio (SINR) at k^{th} UE $U_{i,n}^k$ from its serving BS $\mathcal{B}_{i,n}$ is given by

$$\gamma_{i,n}^k = \frac{P_{i,n}^{k,R}}{\mathcal{I}_{i,n}^{k,opt} + \mathcal{I}_{i,n}^{k,ext} + \mathcal{I}_{i,n}^{k,int} + \mathcal{P}_N} \tag{9}$$

where $P_{i,n}^{k,R}$, $\mathcal{I}_{i,n}^{k,opt}$, $\mathcal{I}_{i,n}^{k,ext}$, $\mathcal{I}_{i,n}^{k,int}$ and $\mathcal{P}_N$ are the received power, inter-RAN interference, inter-cell interference, intra-cell interference and the thermal noise power respectively. As operators are assumed to operate in different frequencies, no inter-RAN interference exists. Similarly, use of orthogonal frequency bands in OFDMA-based BSs results in zero intra-cell interference. On the other hand, due to the switching of operating modes of BSs and re-association of UEs, distribution of inter-cell interference can alter throughout the network, which is highly complex to track. Therefore, we assume that by adopting appropriate frequency allocation techniques, inter-cell interference is mitigated and managed to remain unchanged [11], [12], [40], [51].

Now, spectral efficiency (SE) in bps/Hz with the consideration of adaptive modulation and coding (AMC) can be given by [48]

$$\psi_{i,n}^k = \begin{cases} 0 & \textit{if } \gamma_{i,n}^k < \gamma_{min} \\ \xi \log_2(1 + \gamma_{i,n}^k) & \textit{if } \gamma_{min} \leq \gamma_{i,n}^k < \gamma_{max} \\ \psi_{max} & \textit{if } \gamma_{i,n}^k \geq \gamma_{max} \end{cases} \tag{10}$$

where $0 \leq \xi \leq 1$, γ_{min}, ψ_{max} and γ_{max} are the attenuation factor, minimum required SINR, maximum SE and the SINR at which ψ_{max} is achieved. Then, the EE denoted as η_{EE} of the system averaged over all UEs, BSs and N RANs can be defined as

$$\eta_{EE} = \frac{\sum_{n=1}^{N} \sum_{i=1}^{|\mathbb{B}_n|} \sum_{k=1}^{M_{i,n}} W_{RB} \psi_{i,n}^k}{\sum_{n=1}^{N} \sum_{i=1}^{|\mathbb{B}_n|} \hat{p}_{i,n}}, \text{bits/joule} \tag{11}$$

where W_{RB} is the bandwidth per RB in Hz. Then the EE improvement provided under the proposed framework over the original networks with no cooperation denoted by η_G can be given as

$$\eta_G = \left(\frac{\eta_c}{\eta_o} - 1 \right) \times 100\% \tag{12}$$

where η_o and η_c are the EE of the original networks and the networks under the proposed framework respectively.

C. Fairness in Cooperation

While the question is the cooperation among N independent cellular operators, fairness in profit achievement is the crucial motivating factor for bringing them together in the proposed cooperative coalition. Therefore, we investigate the fairness of our proposed algorithms using the widely used Jain's fairness index. This paper considers the amount of energy savings by i^{th} operator $(i = 1, 2, ..., N)$ as its corresponding achieved profit from the cooperation. Thus, the fairness of the proposed cooperation algorithms in saving energy of the operators is quantified using the Jain's fairness index as given below [52]

$$f(x) = \frac{\left[\sum_{i=1}^{N} x_i \right]^2}{N \sum_{i=1}^{N} x_i^2} \tag{13}$$

where x_i is the amount of energy savings of i^{th} operator.

V. Proposed Multi-Operator Cooperation for Energy Efficiency

A. Multi-Operator Cooperation

This paper proposes a cooperation framework for improving EE through BS sharing among N cellular networks. We assume that all these N operators are motivated to cooperate with each other for improving overall EE.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TGCN.2018.2890041, IEEE Transactions on Green Communications and Networking

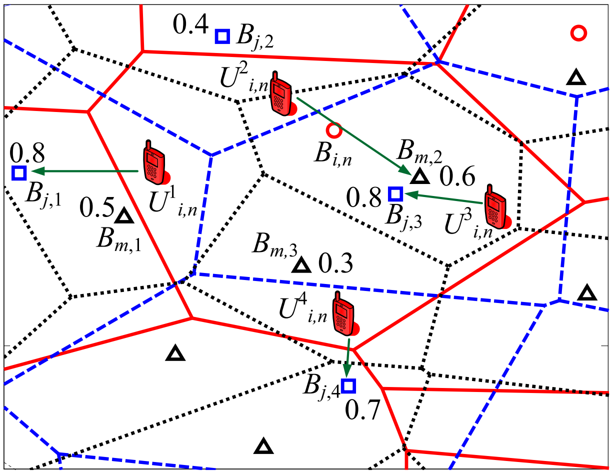


Fig. 2: UE re-association of BS $\mathcal{B}_{i,n}$ under *DAL* algorithm with *dynamic ascending* traffic based *d*BS sequencing and *L*-based *c*BS selection and sequencing.

In the proposed framework, a BS serves its own UEs as well as shares UEs from other BSs belonging to the other RANs and its own RAN as well. Thus, by leveraging the inherent temporal-spatial traffic diversity, a central coordinator determines which BSs of which RANs to remain active and which to switch into sleep mode. Consequently, some BSs of the cooperating RANs distribute their traffic to the other BSs and thus the entire network is provisioned in a dynamic fashion. This provisioning is done periodically, while the period is adjustable and network specific. Furthermore, no operator assistance is required for this provisioning task and thus the scheme is self-organizing in nature. For associating UEs from one BS to another, location of UEs as well as the existing traffic of these concerned BSs is taken into consideration, while QoS, namely, call blocking and service continuity with the desired SINR is maintained. It is worthwhile to mention here that for the operation of the central coordinator, all the operators must be in an agreement for sharing their information, such as traffic in each BS, UE locations, received SINR at UEs and the required QoS[2].

The basic concept of the multi-operator cooperation between three RANs is illustrated in Fig. 2, which is later explained in details with specific cases in Section VI. The numbers shown beside the BSs in the figure represent the normalized traffic level in those BSs. As shown in the figure, BS $\mathcal{B}_{i,n}$ is supposed to distribute its traffic to other BSs such that it can switch into sleep mode for saving energy. To do so, the four UEs of $\mathcal{B}_{i,n}$ denoted as $U^1_{i,n} - U^4_{i,n}$ are associated to four other BSs (as shown by the arrows) of other RANs and then $\mathcal{B}_{i,n}$ switches into sleep mode. A BS whose UEs are distributed is named as *donor* BS (*d*BS), while the set of BSs to which a UE can be re-associated from a *d*BS are termed as *candidate* BSs (*c*BS). On the other hand, a *c*BS which accepts a UE from a *d*BS is called as *acceptor* BS (*a*BS). Thus, *a*BS is user-specific as a *d*BS can have multiple UEs, which can be re-associated with different *a*BSs. The proposed UE re-association from *d*BSs to *a*BSs is governed by the UE association policies, existing traffic of the corresponding BSs, required signal strength, acceptable call blocking rate and other design parameters.

As stated above, it is essential for the central coordinator to access the required information from all the N operators. Therefore, it should be placed in such a way that collecting the required information invokes less signaling overhead and lower latency. One such option can be of placing it as a gateway in between the RANs and the core networks, where each RAN will access its corresponding core network through this gateway. This approach is quite similar to the 3GPP proposed gateway core network (GWCN) configuration being developed for MNO cooperation [29]. It is to be noted that the 3GPP architectures and its functional requirements for MNO cooperation are yet to be finalized.

B. Optimization Problem

The goal of the proposed multi-operator cooperation for BS sharing is to optimize EE averaged over all N RANs. Thus the objective is to determine an optimum set of active BSs $\mathbb{B}_{ON} = \{\mathbf{B_{ON,1}}, \mathbf{B_{ON,2}}, ..., \mathbf{B_{ON,N}}\}$, where $\mathbf{B_{ON,n}} \subseteq \mathbb{B}_n$ is the set of active BSs of n^{th} RAN. The other BSs in $\{\mathbb{B}_n \setminus \mathbf{B_{ON,n}}\}, \forall n$ are switched into sleep mode. Thus the optimization problem can be presented as below

$$\arg\max_{\mathbb{B}_{ON}} \frac{\sum_{n=1}^{N}\sum_{i=1}^{|\mathbb{B}_n|}\sum_{k=1}^{M_{i,n}} W_{RB}\psi^k_{i,n}}{\sum_{n=1}^{N}\sum_{i=1}^{|\mathbb{B}_n|}\hat{p}_{i,n}} \tag{14}$$

s.t.,

$$\bigcup_{i,n} \mathcal{A}_{i,n} = \mathcal{A}, \mathcal{B}_{i,n} \in \mathbb{B}_{ON} \tag{15}$$

$$\gamma^k_{i,n} \geq \gamma_{th}, \forall U^k_{i,n}, \forall k, \forall i, \forall n \tag{16}$$

$$P^{i,n}_b \geq P^{th}_b, \forall i, \forall n, \forall \mathcal{B}_{i,n} \in \mathbb{B}_{ON} \tag{17}$$

$$M_{i,n} \leq C_{i,n}, \forall i, \forall n, \forall \mathcal{B}_{i,n} \in \mathbb{B}_{ON} \tag{18}$$

$$\sum_{k=1}^{M_{i,n}} P^k_{i,n} \leq P^{Tx}_{i,n}, \forall i, \forall n, \forall \mathcal{B}_{i,n} \in \mathbb{B}_{ON} \tag{19}$$

where γ_{th}, $P^{i,n}_b$, P^{th}_b, $P^k_{i,n}$ and $C_{i,n}$ are the minimum SINR required for continuing effective communication, call blocking rate in $\mathcal{B}_{i,n}$, acceptable call blocking limit, TP for $U^k_{i,n}$ and the capacity of BS $\mathcal{B}_{i,n}$ in terms of RBs respectively. Here, $P^{i,n}_b$ refers to the percentage of call blocked in BS $\mathcal{B}_{i,n}$ due to the unavailability of LTE RBs. This blocked calls include both the newly arrived call requests and the handoff calls from other BSs. In the above optimization problem, coverage is guaranteed by (15), whereas QoS parameters, namely, service continuity with desired SINR and call blocking limit are

[2]Network operators are usually competitor to each other and hence are naturally reluctant to share information. Thanks to the collective understandings of policy makers, regulatory bodies and network operators on the potential benefits, a trend for inter-operator cooperation has emerged in recent time. Besides, it is essential to have a balanced profit among the operators. In case the profit is not balanced, there must be an agreement on the business strategies for distributing the net profit among the operators. Game theoretic models, economic theories, introduction of roaming-price, eco-inspired networking, etc. can be used for formulating such strategies. However, development of such strategies is beyond the scope of this paper and will be considered in future works.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TGCN.2018.2890041, IEEE Transactions on Green Communications and Networking

guaranteed by (16) and (17) respectively. It is intuitive that as the received SINR at a UE after re-association with an *a*BS can be different than that from the currently associated BS, throughput of the UE can be affected. On the other hand, (18) and (19) correspond to the limitations of available RBs and TP in each BS respectively.

VI. Proposed Algorithms

The optimization problem formulated in Section V-B is a highly challenging combinatorial problem with a large search space $\mathcal{O}(2^{\sum_{n=1}^{N}|\mathbb{B}_n|})$. Therefore, for the ease of implementation by avoiding the complexity of the optimization problem, we propose a heuristically guided framework for determining the set of active BSs $\mathbb{B}_{ON}$ with reduced computational complexity. To investigate a wide range of potential approaches for improving EE, we propose various *d*BS and *c*BS sequencing schemes for developing UE re-association policies. Various multi-operator cooperation algorithms are then proposed by integrating these UE re-association policies as outlined below.

A. dBS Sequencing

*d*BS sequencing scheme determines the priority order of BSs of all the N RANs in which they are sequentially allowed for distributing their respective UEs. This paper proposes *d*BS sequencing schemes of both *dynamic* and *static* nature. Under the *dynamic* scheme, at every instant of network provisioning approach, based on the instantaneous aggregated traffic $L_{i,n}, \forall i, \forall n$, all the $|\mathbb{B}| = \sum_{n=1}^{N}|\mathbb{B}_n|$ BSs of the cooperating RANs are sorted. That is, a modified set of $\mathbb{B}$, i.e., the set of *d*BSs denoted as $\mathbb{B}^* = \{\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_{|\mathbb{B}|}\}$ is created. We propose and investigate two types of *d*BS sequencing, namely, in *ascending* and *descending* order of $L_{i,n}$. In case of *ascending* sequencing, $\mathbb{B}^*$ is such that $L_i \leq L_j, i < j$, where L_i is the LF of BS $\mathcal{B}_i \in \mathbb{B}^*$. This implies that the *d*BS with the lowest traffic is allowed to distribute its traffic first, then $\mathcal{B}_2$ with the next lowest traffic and so on. On the other hand, in case of *descending* sequencing, $\mathbb{B}^*$ is such that $L_i \geq L_j, i < j$ implying that the *d*BS with the highest load distributes traffic first and so on.

On the other hand, in *static* *d*BS sequencing scheme, RANs as well as the *d*BSs in each network are prioritized in advance according to which they are allowed to distribute traffic. In addition, *d*BSs of a RAN can distribute traffic only to the BSs from the lower ranked RANs and to other BSs of its own RAN. This implies that the *d*BSs of n^{th} ranked RAN can re-associate UEs to the *c*BSs of $(n+1)^{th}$ to N^{th} ranked RANs and to other BSs of n^{th} RAN. Thus, *d*BSs of n^{th} ranked RAN are not allowed to distribute traffic to the *c*BSs of 1^{st} to $(n-1)^{th}$ ranked RANs.

B. cBS Selection and Sequencing

In the turn of a *d*BS to redistribute its traffic, all of its active UEs are re-associated with one of their respective *c*BSs. Otherwise, this *d*BS remains in active mode and continues to serve its UEs. Besides, we consider that only the active BSs are eligible to be a *c*BS such that no sleep mode BS is switched on. This paper proposes three different *c*BS selection schemes which are then sequenced for UE re-associations as explained below in the context of k^{th} UE $U_{i,n}^k$ of *d*BS $\mathcal{B}_{i,n}$ located at $(x_{i,n}^{k,u}, y_{i,n}^{k,u}) \in \mathcal{A}_{i,n}$.

1) Location (L)-based: Proposed *L*-based scheme utilizes the location information of a UE for first finding its *c*BSs to re-associate it with one of them. UE $U_{i,n}^k$ located at $(x_{i,n}^{k,u}, y_{i,n}^{k,u}) \in \mathcal{A}_{i,n}$ can only be associated with another *c*BS $\mathcal{B}_{r,s}$ if $U_{i,n}^k$ is within its Voronoi cell, i.e., $(x_{i,n}^{k,u}, y_{i,n}^{k,u}) \in \mathcal{A}_{r,s}$. Thus the set of *c*BSs for $U_{i,n}^k$ denoted as $\mathbb{B}_c$ consists of the $(N-1)$ other BSs belonging to $(N-1)$ RANs. Then, when *dynamic* *d*BS sequencing is used, *c*BSs are sequenced using the opposite scheme. More specifically, if an *ascending* traffic based scheme is used for *d*BS sequencing, *c*BSs are sorted in a *descending* order of their instantaneous traffic and vice versa. Thus the *c*BS with the highest traffic is given the first priority for accepting (i.e., to be an *a*BS) $U_{i,n}^k$, then the *c*BS with the next highest traffic and so on. On the other hand, if a *static* *d*BS sequencing is used, then the *c*BS with the highest priority is given the first preference for accepting $U_{i,n}^k$, then the *c*BS with the next highest priority and so on.

As shown in Fig. 2, BS $\mathcal{B}_{i,n}$ currently has four active UEs $U_{i,n}^1 - U_{i,n}^4$, which are to be distributed. As the location of $U_{i,n}^1$, i.e., $(x_{i,n}^{1,u}, y_{i,n}^{1,u}) \in \{\mathcal{A}_{j,1}, \mathcal{A}_{m,1}\}$, the set of *c*BSs for $U_{i,n}^1$ is $\{\mathcal{B}_{j,1}, \mathcal{B}_{m,1}\}$ and hence it can be re-associated with either $\mathcal{B}_{j,1}$ or $\mathcal{B}_{m,1}$ after satisfying other requirements. The same principle applies for UEs $U_{i,n}^2$, $U_{i,n}^3$ and $U_{i,n}^4$. An example of the sequence of *c*BSs at which they are approached for associating UEs $U_{i,n}^1$ and $U_{i,n}^2$ under *L*-based scheme with *ascending* *d*BS sequencing is demonstrated in Table II. The distances, traffic levels and the SINR values used in the example are chosen arbitrarily.

TABLE II: Demonstration of attempt order of *c*BSs for re-associating UEs $U_{i,n}^1$ and $U_{i,n}^2$ of *d*BS $\mathcal{B}_{i,n}$ under *L*-based *c*BS selection and sequencing with *ascending* *d*BS sequencing.

UE	$U_{i,n}^1$		$U_{i,n}^2$	
*c*BS	$\mathcal{B}_{j,1}$	$\mathcal{B}_{m,1}$	$\mathcal{B}_{j,2}$	$\mathcal{B}_{m,2}$
UE-*c*BS Distance (m)	600	200	300	800
Downlink SINR (dB)	4	-8	3	-5
*c*BS Traffic	0.8	0.5	0.4	0.6
*c*BS sequence	1^{st}	2^{nd}	2^{nd}	1^{st}

TABLE III: A summary of the proposed algorithms

Sl. no.	Algorithm	*d*BS nature	*d*BS sequencing	*c*BS sequencing
1	*DAL*	*Dynamic*	*Ascending*	*L*-based
2	*DAD*	*Dynamic*	*Ascending*	*D*-based
3	*DAS*	*Dynamic*	*Ascending*	*S*-based
4	*DDL*	*Dynamic*	*Descending*	*L*-based
5	*DDD*	*Dynamic*	*Descending*	*D*-based
6	*DDS*	*Dynamic*	*Descending*	*S*-based
7	*SFL*	*Static*	*Fixed*	*L*-based
8	*SFD*	*Static*	*Fixed*	*D*-based
9	*SFS*	*Static*	*Fixed*	*S*-based

2) Distance (D)-based: *D*-based scheme tries to associate the UE $U_{i,n}^k$ to the nearest available active BS. Thus the *c*BS set $\mathbb{B}_c$ for $U_{i,n}^k$ consists of all the active BSs in the N RANs except $\mathcal{B}_{i,n}$, one of which will be selected as the *a*BS. First, the Euclidean distances $d_{i,n}^{k,u}$ of $U_{i,n}^k$ from all the *c*BSs, i.e., $d_{i,n}^{k,u} = \sqrt{(x_{q,m}^b - x_{i,n}^{k,u})^2 + (y_{q,m}^b - y_{i,n}^{k,u})^2}, \forall q, \forall m, \mathcal{B}_{q,m} \in \mathbb{B}_c$ are calculated and then these *c*BSs are sorted in an ascending order of the distances. If the distance of $U_{i,n}^k$ is found to be equal from multiple *c*BSs, then those *c*BSs are sorted among themselves based on their instantaneous traffic using the same principle as proposed above in *L*-based approach.

Thereafter, UE $U_{i,n}^k$ is first tried to be associated with the nearest *c*BS. If the nearest *c*BS can't be selected as the *a*BS for $U_{i,n}^k$, then the attempt is moved to associate with the next nearest *c*BS and continued to the other *c*BSs until all of them are tried. If an *a*BS can't be found from the available *c*BSs for UE $U_{i,n}^k$, it remains associated with $\mathcal{B}_{i,n}$.

3) SINR (S)-based: Under *S*-based scheme, UE $U_{i,n}^k$ is tried to be associated with one of the active BSs supporting the best downlink SINR. Therefore, once again, the *c*BS set for $U_{i,n}^k$ consists of all the active BSs in the N RANs except $\mathcal{B}_{i,n}$. Then the *c*BSs are ordered according to the descending order of received SINR at $U_{i,n}^k$. Again, if SINR at $U_{i,n}^k$ from multiple *c*BSs is found to be equal, then similar to *D*-based approach, those *c*BSs are sorted among themselves based on their instantaneous traffic.

Then $U_{i,n}^k$ is first attempted to be associated with the *c*BS providing the highest SINR. If $U_{i,n}^k$ can not be associated with this *c*BS, then the *c*BS providing the next highest SINR is tried to be selected as the *a*BS for the UE and continued to the other BSs until all the cBSs are tried. Similar to other approaches, if association of $U_{i,n}^k$ with any of the *c*BSs fails, it remains associated with the current BS $\mathcal{B}_{i,n}$.

C. Algorithms

By combining the proposed *d*Bs and *c*BS sequencing schemes for UE re-associations as presented in Section VI-A and Section VI-B, we propose nine different algorithms of multi-operator cooperation for improving EE. The proposed algorithm acronyms are as follows: *DAL*, *DAD*, *DAS*, *DDL*, *DDD*, *DDS*, *SFL*, *SFD* and *SFS*. The first letters in the acronyms, namely, '*D*' and '*S*' indicate whether the *d*BS sequencing is *dynamic* or *static*. The second letters '*A*', '*D*' and '*F*' indicate the scheme of *d*BS sequencing for distributing traffic. Here, '*A*', '*D*' and '*F*' imply that *d*BSs are sorted according to the *ascending* order of traffic, *Descending* order of traffic and a predefined *fixed* sequence respectively. On the other hand, the third letters '*L*', '*D*' and '*S*' indicate whether the *c*BS selection and sequencing is *L*-, *D*- or *S*-based respectively. A summary of these nine algorithms is presented in Table III. Besides, Fig. 2 demonstrates the basic principle of UE re-association under *DAL* algorithm.

Now for deciding on a *d*BS whether to switch into sleep mode, the proposed algorithms start with a *d*BS sequencing scheme. According to the considered scheme, all the BSs are sequenced to find the set of *d*BSs $\mathbb{B}^* = \{\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_{|\mathbb{B}|}\} = \mathbb{B}$. Then the set of active BSs is initialized by setting $\mathbb{B}_{ON} = \mathbb{B}^*$. An algorithm then takes the first active *d*BS (i.e., $\mathcal{B}_1$) and using one of the *c*BS selection and sequencing schemes as proposed in Section VI-B, all UEs of $\mathcal{B}_1$ one by one are attempted to be distributed by re-associating them with their respective *c*BSs. For a re-association attempt to be successful, several conditions are to be met. Firstly, network coverage has to be maintained. Secondly, blocking of calls in the intended *a*BS must be within the acceptable limit P_b^{th}. Thirdly, received SINR at the UE from the *a*BS must be equal to or greater than γ_{th}. Finally, total TP and the total number of required RBs of

TABLE IV: Pseudo code of *DAS* algorithm for the proposed multi-operator cooperation for EE

1: Initialize: $\mathbb{B} = \{\mathbb{B}_1, \mathbb{B}_2, ..., \mathbb{B}_N\}$, $L_{i,n}, (x_{i,n}^b, y_{i,n}^b)$, $(x_{i,n}^{k,u}, y_{i,n}^{k,u}), \gamma_{i,n}^k, \forall i, \forall n, \forall k$
2: Sort $\mathbb{B}$ to find the set of *d*BSs $\mathbb{B}^* = \{\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_{|\mathbb{B}|}\}$ s.t., $L_i <= L_j, j > i$
3: Initialize $\mathbb{B}_{ON} = \mathbb{B}^*$
4: **for** $i = 1 : |\mathbb{B}^*|$
5: **If** $L_i = 0$
6: Set $\mathbb{B}_{ON} = \{\mathbb{B}_{ON} \setminus \mathcal{B}_i\}$
7: **Else**
8: Initialize the set of *c*BSs $\mathbb{B}_c = \{\mathbb{B}_{ON} \setminus \mathcal{B}_i\}$
9:: **for** $k = 1$: Number of UEs in BS $\mathcal{B}_i$
10: Calculate received SINR $\gamma_{k,i}$ at k^{th} UE in $\mathcal{B}_i$ from all other BSs in $\mathbb{B}_c$
11: Sort BSs in $\mathbb{B}_c$ in a descending order of $\gamma_{k,i}$ and denote as $\mathbb{B}_c^s = \{\mathcal{B}_{c,1}^s, \mathcal{B}_{c,2}^s, ..., |\mathbb{B}_c|\}$
12: **If** $\gamma_{k,i}$ is equal for multiple BSs in $\mathbb{B}_c^s$
13: Sort these BSs in a descending order of traffic to evaluate new $\mathbb{B}_c^{s,*} = \{\mathcal{B}_{c,1}^{s,*}, \mathcal{B}_{c,2}^{s,*}, ..., |\mathbb{B}_c|\}$
14: **Else** $\mathbb{B}_c^{s,*} = \mathbb{B}_c^s$
15: **End If**
16: **for** $d = 1 : |\mathbb{B}_c^{s,*}|$
17: Obtain received SINR at k^{th} UE from $\mathcal{B}_{c,d}^{s,*}$
18: Calculate call blocking rate, total transmit power requirement and total RB requirement in $\mathcal{B}_{c,d}^{s,*}$
19: **If** constraints (15)-(19) are met
20: Associate k^{th} UE with BS $\mathcal{B}_{c,d}^{s,*}$
21: Set $k = k + 1$ and Go to Step 10
22: **Else**
23: Set $d = d + 1$ and Go to Step 17
24: **End If**
25: **End for**
26: Set $k = k + 1$ and Go to Step 10
27: **End for**
28: **If** association of all UEs of BS $\mathcal{B}_i$ is successful
29: Set $\mathbb{B}_{ON} = \{\mathbb{B}_{ON} \setminus \mathcal{B}_i\}$
30: Set $i = i + 1$ and Go to Step 8
31: **Else**
32: Set $\mathbb{B}_{ON} = \mathbb{B}_{ON}$
33: Set $i = i + 1$ and Go to Step 8
34: **End If**
35: **End If**
36: **End for**

the *a*BS for supporting its own and shared UEs are to be within the limits. These conditions are guaranteed by the constrains as stated in (15)-(19).

If *a*BSs are found for all the UEs in *d*BS $\mathcal{B}_1$, it can then be switched into sleep mode. After that $\mathbb{B}_{ON}$ is updated by removing $\mathcal{B}_1$ from the current $\mathbb{B}_{ON}$. If re-association of any one UE of $\mathcal{B}_1$ is not successful, $\mathcal{B}_1$ remains in active mode, i.e., $\mathbb{B}_{ON}$ remains unchanged. The algorithm then continues with the next active *d*BS $\mathcal{B}_2$, updates $\mathbb{B}_{ON}$ and so on. After finishing with all the *d*BSs, final $\mathbb{B}_{ON}$ provides a list of BSs which are left in active mode and the other BSs in $\{\mathbb{B} \setminus \mathbb{B}_{ON}\}$ are switched into sleep mode. For demonstration purpose, pseudo code of the *DAS* algorithm is presented in Table IV.

D. Computational Complexity

We evaluate the computational complexity of all the algorithms. It is found that all the algorithms with *D*-based and *S*-based *c*BS sequencing schemes have a computational complexity of $\mathcal{O}(N_U N_B^2)$. Whereas, the algorithms with *L*-based scheme have comparatively lower computational complexity of $\mathcal{O}(N_U(N_B+N^2))$. Here, $N_B = |\mathbb{B}|$ and $N_U = \sum_{n=1}^{N} N_{n,u}$ are the total number of BSs and UEs of the N cooperating networks respectively. It is to be noted that the computational complexity of the optimal solution by exhaustive search is $\mathcal{O}(N_U 2^{N_B})$ and thus our heuristic algorithms are computationally efficient. On the other hand, signaling overhead is also evaluated, which is found equal to $(N_U + 2N_B)$ for all the algorithms.

VII. Results and Analysis

A. Simulation Setup

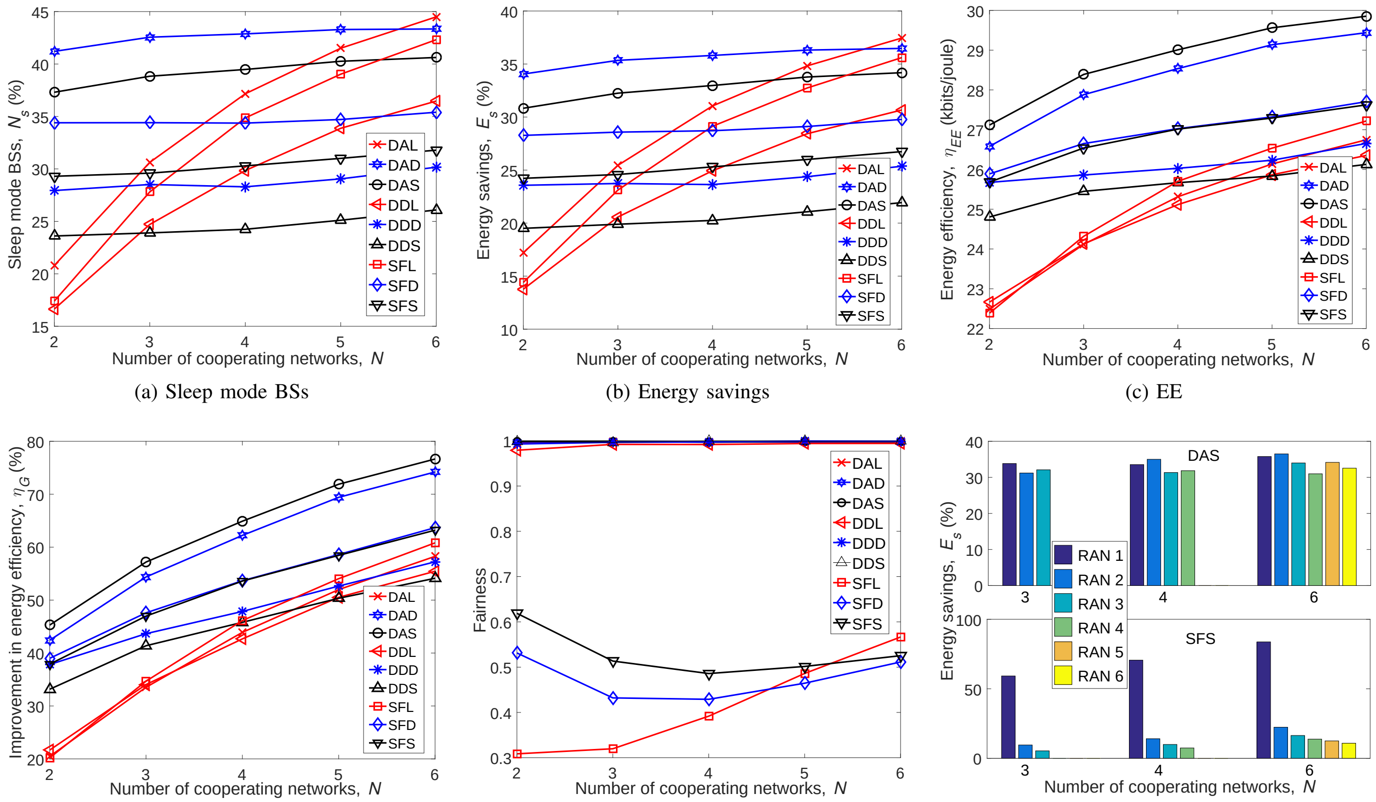
We develop a MATLAB based simulation platform for evaluating the performance of the proposed energy efficient multi-operator cooperation framework. Each data point in the presented results corresponds to the average over a large number of simulations. For the convenience and clarity, we simulate a network area of $10 \times 10\text{km}^2$ covered by N collocated RANs, where the location of BSs and UEs are modeled using independent HCPPs and PPPs respectively. Carrier frequency = 2GHz, channel bandwidth per BS = 5MHz (i.e., 25 RBs), $h_{BS} = 25$m, $h_{UE} = 1.5$m, single TRX chain per BS (i.e., $N_T = 1$), shadow fading standard deviation $\sigma = 8$dB and thermal noise power density = -174dBm/Hz are used. AMC code set parameters $\xi = 0.75$, γ_{min} = -6.5dB, γ_{max} = 19dB and ψ_{max} = 4.8bps/Hz are used in reference to the 3GPP LTE suggestions [48].

Without losing the generality, for the sake of clarity and the convenience of result comparisons among various schemes, we consider homogeneous settings across all the RANs and the BSs. That is, we consider TP $P_{i,n}^{Tx} = 43$dBm, and power profile constants $w_{i,n} = w = 21.45$, $v_{i,n} = v = 354.44$, $\forall i, \forall n$ [50]. Besides, unless otherwise specified, number of collocated networks $N = 3$, thinning radius $h = 0.5$ km, no reserved RBs in BSs for future calls, SINR threshold $\gamma_{th} =$ 0dB, PLP type BSs with $\delta_{i,n} = \delta = 0.7$, sleep mode power $p_{i,n}^s = p_s = 0$, BS denisties $\lambda_{n,b} = \lambda_{BS} = 1/\text{km}^2$ and UE densities $\lambda_{n,u} = \lambda_{UE} = 10/\text{km}^2, \forall i, \forall n$, are used for the simulations. Proposed framework can also be simulated by setting unequal values for these parameters.

B. Impact of Number of Cooperating Networks N

Figures 3(a)-(f) present the variation of the percentage of sleep mode BSs N_s, energy savings E_s, EE η_{EE}, improvement in EE η_G, fairness in cooperation and energy savings in individual networks respectively with the number of cooperating networks N. As shown in the Fig. 3(a), N_s increases with the increase of N for all the algorithms. This is obvious as with the increase of N, *c*BSs for distributing traffic increases resulting in the increased N_s. However, the increment is faster for the algorithms with *L*-based schemes. This is because, under the algorithms using *D*- and *S*-based schemes, all the BSs in the N networks work as *c*BSs for accepting UEs. Thus the number of *c*BSs for lower values of N is already high enough and hence, the increment in N_s with N is not that much. Whereas for the *L*-based case, at best, only $(N-1)$ BSs of the other $(N-1)$ cooperating networks are *c*BSs. Thus, with the increase of N, number of *c*BSs increases linearly and hence, N_s also increases nearly linearly. Similar patterns are also observed in E_s as it is directly related to N_s. Thus all the proposed algorithms are found capable in saving substantial amount of energy though the amounts depend on the network settings and vary among the algorithms. However, E_s is found slightly less than N_s. As for the simulations, BSs are of PLP type with $\delta = 0.7$, when one BS is switched into sleep mode, its UEs are re-associated with other BSs increasing power consumption in those BSs resulting in reduced E_s.

On the other hand, an increasing trend of η_{EE} with N is evident from Fig. 3(c). This is because, under-loaded BSs are less energy efficient and vice versa as the fixed part is the dominating part of the total BS power. With the increase of N, N_s increases and consequently, number of BSs with higher traffic increases resulting in higher EE in BSs. On the other hand, for the convenience of better understanding of EE performance, η_G of the network under the proposed algorithms is also demonstrated in Fig. 3(d), which also increases with the increase of N. It can be seen that all the proposed algorithms are capable to improve EE being as high as $\eta_G = 75\%$ for $N = 6$. Fairness in cooperation among the N networks for saving energy under the proposed algorithms is also presented in Fig. 3(e), which is extremely critical for any multi-operator cooperation. It can be seen that *dynamic* algorithms maintain great fairness in energy savings among the networks, while the fairness is very poor for the *static* algorithms. For the *dynamic* algorithms, *d*BSs are sequenced dynamically based on the instantaneous traffic and hence, BSs from all the N networks get fair chances to be *d*BSs for distributing traffic for saving energy. This results in nearly balanced energy savings across all the networks. On the other hand, for the *static* algorithms, BSs of the networks with higher priorities always save more than others and hence poor fairness is achieved. Figure 3(f) illustrating the energy savings of the individual networks under *DAS* and *SFS* algorithms also supports the balanced and the unbalanced energy savings achieved by the *dynamic* and the *static* algorithms respectively. Therefore, due to poor fairness, we exclude the *static* algorithms from further analysis.



(a) Sleep mode BSs (b) Energy savings (c) EE

(d) Improvement in EE (e) Fairness (f) Energy savigs of individual networks

Fig. 3: Performance of the proposed framework with the number of cooperating networks N under various algorithms with $\lambda_{BS} = 1$ /km^2, $\lambda_{UE} = 10$ /km^2, $h = 0.5$ km, $\gamma_{th} = 0$ dB, $\delta = 0.7$ and $p_s = 0$.

Finally, it can be identified that generally the *dynamic* algorithms with *ascending* traffic based *dBS* sequencing scheme (i.e., *DAL*, *DAD* and *DAS*) save more as well as are more energy efficient. As explained above, BSs with higher traffic are more energy efficient than the BSs with lower traffic. Under *ascending* based algorithms, lightly loaded *d*BSs distribute traffic first to the heavily loaded *c*BSs making the networks more energy efficient. Therefore, from hereafter, we will present the results of the *dynamic* algorithms with *ascending* traffic based *d*BS sequencing scheme.

C. Impact of Thinning Radius h

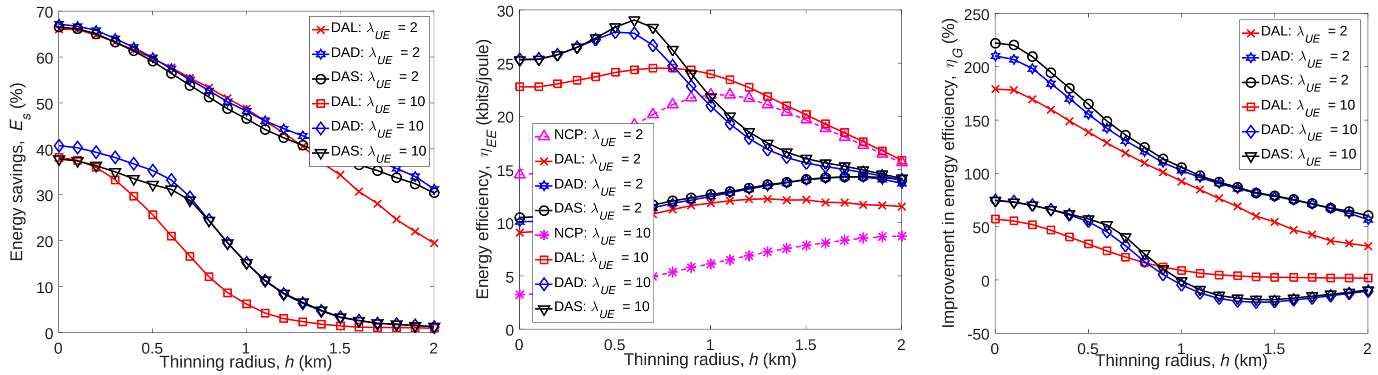
Impact of thinning radius h of HCPPs on the various performance metrics is illustrated in Figs. 4(a)-(c). A decreasing trend of E_s with the increase of h is evident from Fig. 4(a). This is due to the fact that with the increase of h, number of *c*BSs for a *d*BS to distribute its UEs decreases resulting in lower N_s as well as reduced E_s. On the other hand, with the increase of λ_{UE} from 2 /km^2 to 10 /km^2, number of heavily loaded BSs as well as outage in those BSs increases. This results in lower chance for a *d*BS to switch into sleep mode and consequently E_s decreases as seen in the figure.

EE η_{EE} of the original network with no cooperation designated as 'NCP' and the network under the proposed algorithms as demonstrated in Fig. 4(b) shows a peak at a certain value of h (e.g., $h = 0.6$ km for *DAS* algorithm with $\lambda_{UE} = 10$ /km^2). Below this h, there is a higher number of BSs in the networks, i.e., a higher number of lightly loaded BSs leading to lower η_{EE}. For the region beyond this h, a fewer number of BSs are left in the network and consequently, UE-BS distance increases so much that received SINR at the re-associated UEs decreases significantly resulting in lower η_{EE}.

Furthermore, it can be seen that the *DAS* algorithm using *S*-based *c*BS sequencing generally has better η_{EE} as well as higher η_G than that of with *L*-based *DAL* and *D*-based *DAD* algorithms. This is because, *DAS* associates UEs with the *c*BSs providing higher SINR, while *DAL* and *DAD* consider the distance (i.e., location) for association. Smaller distance does not always guarantee the higher SINR due to the presence of shadow fading. Consequently, the higher SINR achieved in *DAS* leads to higher throughput, higher η_{EE} and higher η_G. However, for higher values of h with high user densities (e.g., $\lambda_{UE} = 10$ /km^2), *DAL* algorithm can be more energy efficient. The reason behind this is that with the increase of *h*, BS moves further and further such that after certain value of *h*, SINR at the re-associated UEs under *DAS* and *DAD* decreases so much that η_{EE} and η_G of both algorithms fall below than those of *DAL* algorithm.

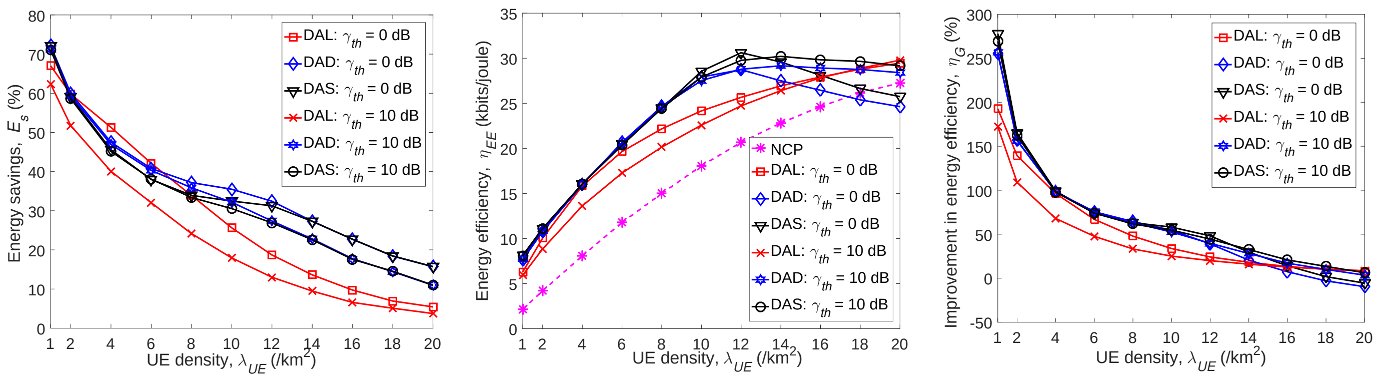
D. Impact of UE Density λ_{UE} and BS Density λ_{BS}

Figures 5(a)-(c) present the variation in E_s, η_{EE} and η_G respectively with λ_{UE} under the proposed *DAL*, *DAD* and



(a) Energy savings (b) EE (c) Improvement in EE

Fig. 4: Performance of the cooperation framework with thinning radius h for $N = 3$, $\lambda_{BS} = 1$ /km^2, $\lambda_{UE} = \{2, 10\}$ /km^2, $\gamma_{th} = 0$ dB, $\delta = 0.7$ and $p_s = 0$.



(a) Energy savings (b) EE (c) Improvement in EE

Fig. 5: Performance of the cooperation framework with UE density λ_{UE} for $N = 3$, $h = 0.5$ km, $\lambda_{BS} = 1$ /km^2, $\gamma_{th} = \{0, 10\}$ dB, $\delta = 0.7$ and $p_s = 0$..

DAS algorithms with two different γ_{th}, namely, 0 dB and 10 dB. With the increase of λ_{UE}, number of UEs in all the BSs increases and consequently fewer number of UEs can be re-associated with *c*BSs leading to reduced N_s and reduced E_s as shown in Fig. 5(a). It is also found that with the increase of γ_{th} from 0 dB to 10 dB, E_s decreases. A higher γ_{th} implies that fewer number of UEs can be re-associated with *c*BSs resulting in lower N_s and reduced E_s as well.

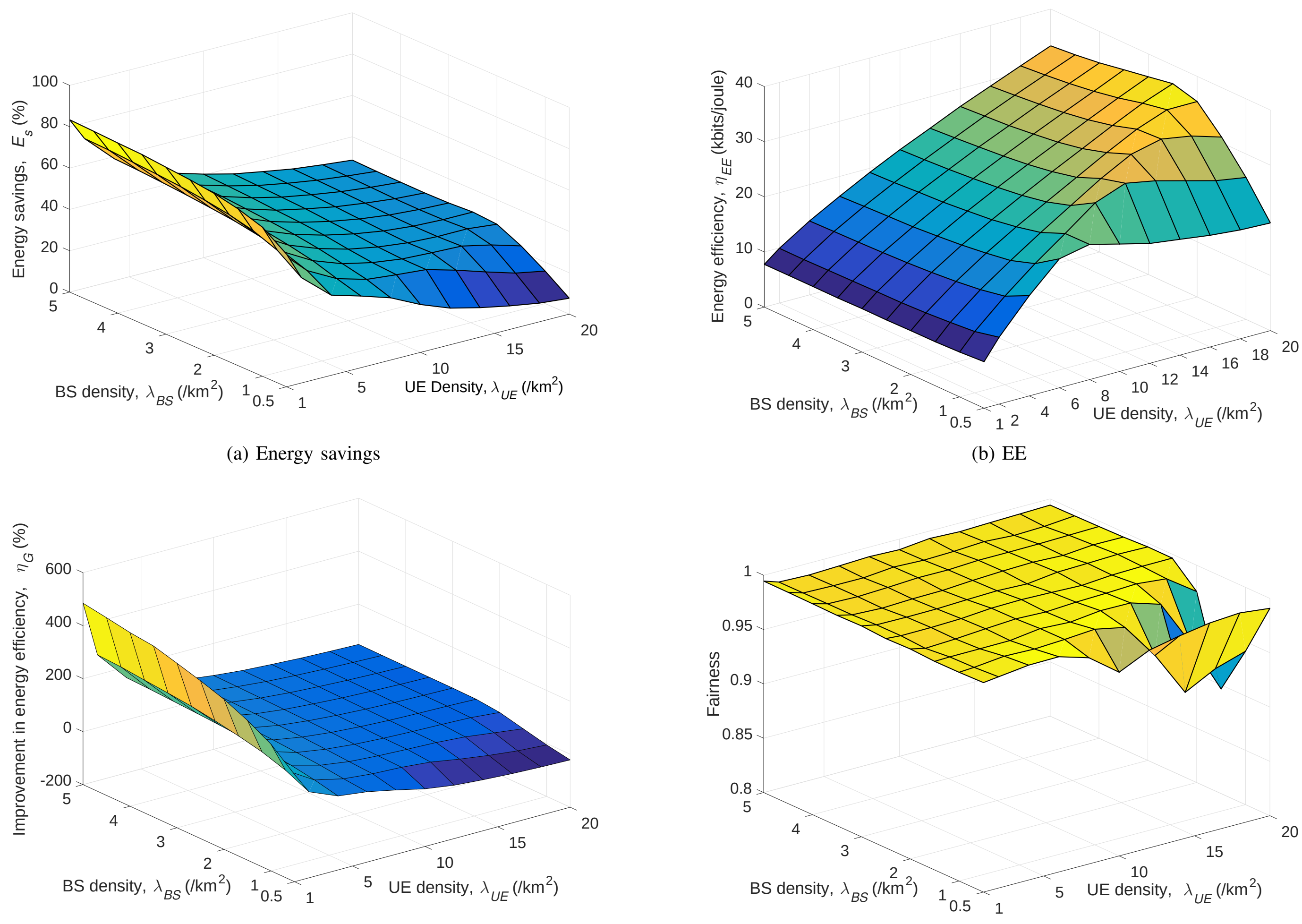
On the other hand, an increasing trend of η_{EE} with λ_{UE} of the original network as well as the network under the proposed algorithms is evident from Fig. 5(b). This is because, under-loaded BSs are less energy efficient as the fixed part is the dominating part of the total BS power. With the increase of traffic, the dynamic part varying with LF becomes increasingly dominating leading to the higher energy efficient operation of BSs. It is to be noted that if λ_{UE} continues to increase, for the same reason as explained in Section VII-C, η_{EE} and η_G of both *DAS* and *DAD* algorithms can fall below that of *DAL* algorithm as evident from the figure. Furthermore, as with the increase of λ_{UE}, the rate of increase in η_{EE} of the networks with no cooperation is much faster than the networks under the proposed algorithms, η_G is found decreasing as shown in Fig. 5(c).

Whereas, 3D figures of E_s, η_{EE}, η_G and fairness for a wide range of λ_{UE} and λ_{BS} under the proposed *DAS* algorithm only are also demonstrated in Figs. 6(a)-(d). For a given λ_{UE}, E_s is found to be increasing with the increase of λ_{BS}, which is more evident at higher λ_{UE} regions. This is because, with the increase of λ_{BS}, BSs are being increasingly lightly loaded and thus higher number of BSs can switch into sleep mode for saving more energy. On the other hand, for logical reasons, an increasing trend in η_{EE} is found for lower values of λ_{UE} and vice versa. Furthermore, a decreasing trend in η_G is evident for the same reason as explained for Fig. 5(c). On the other hand, for higher λ_{UE} at lower λ_{BS} regions, a degradation in fairness is seen in Fig. (d). However, the degraded fairness is still quite high with the minimum value around 90%.

E. Impact of Call Blocking Limit P_b^{th}

Figures 7(a)-(c) present the bar charts of E_s, η_{EE} and η_G with various P_b^{th} for $\lambda_{UE} = \{2, 10\}$ /km^2. The decreasing trends of E_s, η_{EE} and η_G with the decrease of P_b^{th} can readily be identified, which is more evident for higher λ_{UE}. With the decrease of P_b^{th}, a higher number of RBs in each BS are left reserved for new calls and thus *c*BSs can accept fewer

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TGCN.2018.2890041, IEEE Transactions on Green Communications and Networking



(a) Energy savings

(b) EE

(c) Improvement in EE

(d) Fairness

Fig. 6: Performance of the cooperation framework under *DAS* algorithm in 3D with UE density λ_{UE} and BS density λ_{BS} for $N = 3$, $h = 0.5$ km, $\gamma_{th} = 0$ dB, $\delta = 0.7$ and $P_s = 0$.

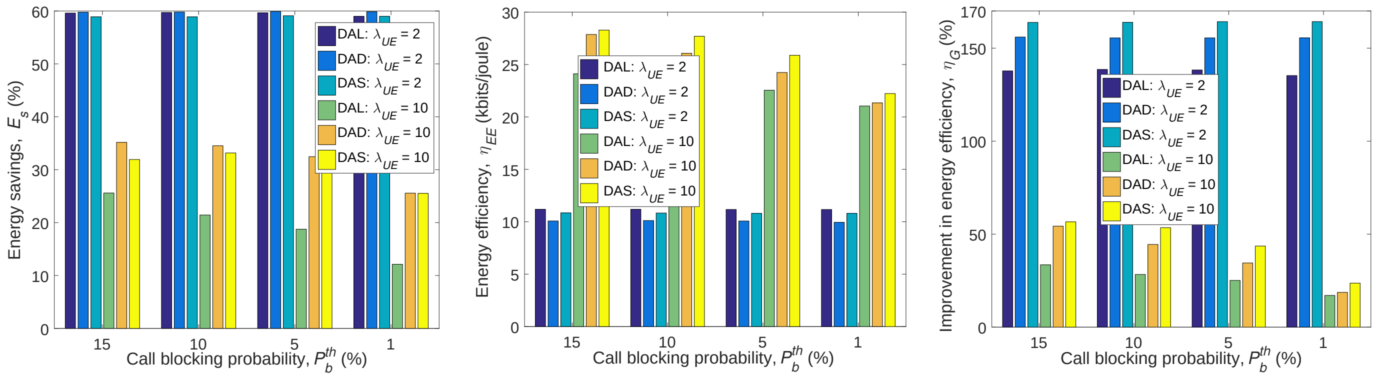
UEs from *d*BSs for allowing them to switch into sleep mode. For $\lambda_{UE} = 2$, as the BSs are originally very lightly loaded, reservation of more RBs does not affect N_s noticeably resulting in insignificant changes in the above parameters. With the increase of λ_{UE}, N_s and consequently the performance metrics are affected by the number of reserved RBs as shown in the figures. Furthermore, it is once again observed that *DAS* algorithm provides better η_{EE} and η_G compared to the other twos.

F. Impact of BS Power Profile

Figures 8(a)-(c) illustrate the impact of BS power profile parameter *PLPC* δ for two different sleep mode power p_s. As seen from Fig. 8(a), E_s increases with the increase of δ. Here $\delta = 0$ implies a FLP BS in which power consumption increases linearly with LF and consumes no power with zero traffic. Consequently, no energy savings is achieved by switching BSs into sleep mode. On the other hand, with the increase of δ, BSs increasingly deviate from the ideal case consuming more and more power with no traffic. Thus, switching a BS into sleep mode results in higher savings. Whereas, $\delta = 1$ implies a NLP BS that consumes constant power irrespective of LF and hence the maximum savings can be achieved for a network deployed using such type of BSs. On the other hand, with the increase of δ, the fixed part of BS power consumption increases. Consequently, BSs become increasingly less energy efficient and hence the overall η_{EE} of the network decreases being the minimum at $\delta = 1$ as seen in Fig. 8(b). In addition, decrease in η_{EE} of the original networks with no cooperation is much faster than the network under the proposed algorithms. Consequently, an increasing trend in η_G is observed under all the considered algorithms as evident from Fig. 8(c). Furthermore, with the increase of p_s from 0 to δv, overall E_s, η_{EE} and η_G decrease as the savings is offset by the amount of p_s, which is also evident from the figures.

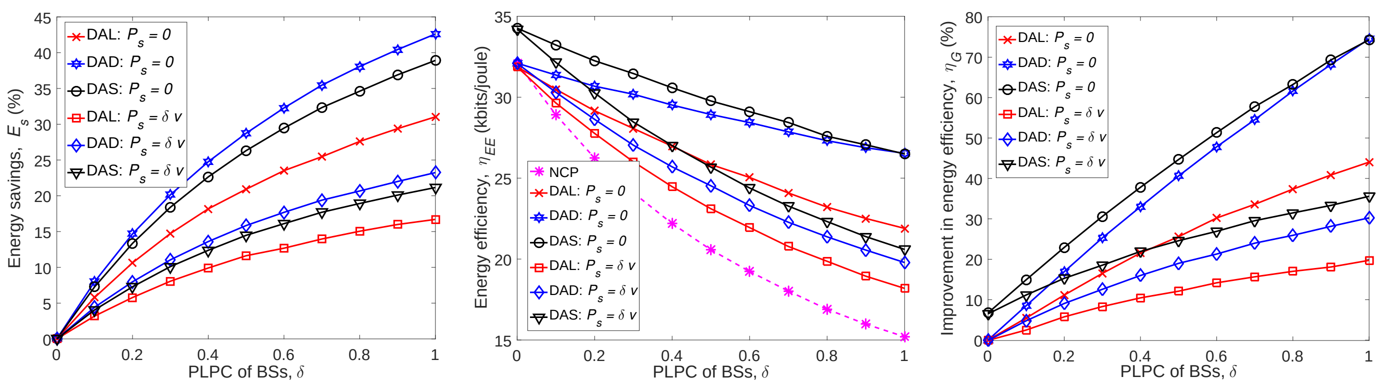
G. Comparisons

For further validation of the proposed framework, we also compare the EE performance of our proposed framework with



(a) Energy savings (b) EE (c) Improvement in EE

Fig. 7: Performance of the cooperation framework with call blocking limit P_b^{th} under various algorithms for $N = 3$, $h = 0.5$ km, $\lambda_{BS} = 1$ /km^2, $\lambda_{UE} = \{2, 10\}$ /km^2, $\gamma_{th} = 0$dB, δ = 0.7 and $P_s = 0$.



(a) Energy savings (b) EE (c) Improvement in EE

Fig. 8: Performance of the cooperation framework with BS *PLPC* δ under various algorithms for $N = 3$, $h = 0.5$ km, $\lambda_{BS} = 1$ /km^2, $\lambda_{UE} = 10$ /km^2, $\gamma_{th} = 0$ dB and $p_s = \{0, \delta v\}$.

three other state-of-the-art works presented in [23], [32], [34]. Compared schemes are: (1) *R-bal* [32] , (2) *E-bal* [32] , (3) *R-to*-1 [23], (4) *GTIS* with $\alpha = \{0.1, 0.5\}$ [34], where α is the roaming cost. In *R-bal*, RANs switch the operation mode of BSs in a way to balance their roaming costs, while the objective of *E-bal* scheme is to balance the energy savings of the cooperating RANs. In both *R-bal* and *E-bal* schemes, user from a RAN can be re-associated with any other RANs. In contrast, *R-to*-1 proposed that the RAN with the highest traffic serves the total traffic, while the other RANs switch off their BSs during the entire low traffic period. On the other hand, the *GTIS* scheme in [34] proposed a game-theory based BS sharing mechanism with a roaming cost. All the systems including ours are simulated considering collocated BSs of N = 4 RANs for a night-zone (1:00 am to 9:00 am) traffic profile as presented in [34]. Traffic load ratio (TLR) of each RAN, which is the fraction of the maximum traffic of a RAN for the respective hours, is set similarly as in [34]. Our framework is simulated considering the *DAS* algorithm.

Average improvement in EE (i.e., η_G) over the baseline approach of no cooperation computed for the entire duration of the night-zone and the fairness index are taken as the metrics for the comparison as presented in Fig. 9. As evident, the proposed *DAS* algorithm always have substantially higher η_G than the *R-bal* scheme. On the other hand, compared to the other schemes, the *DAS* algorithm is found to have lower η_G for lower values of TLR. However, with the increase of TLR, η_G of the *DAS* algorithm relatively improves and eventually outperforms all the schemes. Interestingly, in terms of fairness as shown in the figure, proposed *DAS* algorithm always outperforms the *GTIS* scheme having superior η_G for lower roaming cost. Thus, the proposed *DAS* algorithm is apparently a better choice for the scenarios with moderately unbalanced to highly balanced traffic load among the cooperating networks.

H. Selection of Appropriate Algorithm

As discussed above, all the proposed algorithms are capable to substantially enhance the EE of the cooperating networks compared to the no cooperation scenario. However, the following brief guideline can be used to select an algorithm for a particular scenario. Firstly, *S*-based algorithms can generally provide the best EE in most of the scenarios. On the other hand, EE performance of *L*-based algorithms (namely, *DAL*, *DDL* and *SFL*) is inferior for the case of lower number of

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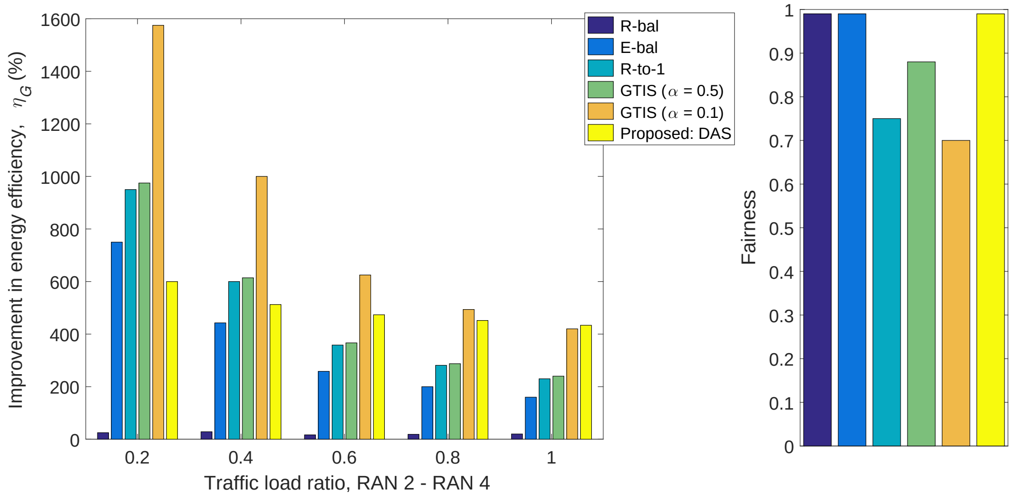

Fig. 9: Performance comparison with the other cooperation schemes for a scenario of $N = 4$ collocated homogeneous networks and TLR = 1 for RAN 1.

cooperating networks, while comparable to or sometimes even better than that of *S*-based and *D*-based algorithms for the scenario with higher number of networks and/or very high UE densities. Secondly, if fairness in energy savings is taken into account, static algorithms (namely, *SFL*, *SFD* and *SFS*) have the worst performance. In contrast, all the other six algorithms with *dynamic d*BS sequencing have demonstrated excellent fairness. Finally, considering the requirement of lower computational complexity, *L*-based algorithms are the better options. Thus, the most appropriate algorithm among the proposed can be chosen based on the joint consideration of the required EE performance, expected fairness, number of cooperating networks, and the densities of UEs and BSs.

VIII. Conclusions

In this paper, we have proposed a generalized energy efficient multi-operator cooperation framework for sharing spatially separated BSs belonging to N number of collocated cellular RANs. By combining the proposed *d*BS and *c*BS sequencing schemes, nine different heuristic algorithms for cooperation have been developed to dynamically re-associate UEs from *d*BSs to *a*BSs allowing some BSs to switch into sleep mode for improving EE. For emulating the spatially separated BSs belonging to different RANs, independent HCPPs with a thinning radius have been used for modeling the locations of BSs in each RAN. In brief, all the proposed algorithms have shown great capability in saving energy as well as in improving EE of the networks. However, substantial impacts of the system parameters including *d*BS and *c*BS sequencing schemes, number of cooperating networks, thinning radius, BS and UE densities, call blocking limits, SINR requirements and BS power profile on the network performance have been noticed. More specifically, the crucial requirement of extremely high fairness in cooperation has been achieved only by the algorithms with *dynamic d*BS sequencing. On the other hand, higher EE has been observed under the algorithms with *ascending* traffic based *dynamic d*BS sequencing. To narrow down further, algorithms involving the SINR based (i.e., *S*-based) *c*BS sequencing for user re-association generally have better EE. However, the *L*-based algorithms, which also have comparatively lower computational complexity, can offer the best EE under some extreme cases of higher number of cooperating networks and/or relatively higher user densities. Furthermore, comparison with the other works under the joint consideration of fairness and EE performance, the proposed *DAS* algorithm can be considered as a strong candidate for practical applications.

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Md. Farhad Hossain (S'10–M'14) received his Ph.D. in Electrical and Information Engineering from the University of Sydney, Australia in 2014. He completed his B.Sc. and M.Sc. in Electrical and Electronic Engineering from Bangladesh University of Engineering (EEE) and Technology (BUET), Dhaka, Bangladesh in 2003 and 2005 respectively. Currently, he holds a position of Associate Professor in the Department of EEE. He also works as an electrical and electronic engineering consultant. Dr. Hossain has published over 60 refereed articles in highly prestigious journals and conference proceedings. He was the recipient of Best Paper Award in three international conferences and the Student Travel Grant in IEEE Global Communications Conference (GLOBECOM), Anaheim, CA, USA, 2012. His research interests include green cellular networks, underwater communications, smart grid communications, sensor networks, network architectures and protocol designs, etc. He has been serving as TPC member, and reviewer in many international journals and conferences.

Kumudu Munasinghe (S'03–M'08) received his Ph.D. degree in telecommunications engineering from the University of Sydney, NSW, Australia, in 2008. Currently, he is with the Faculty of Education, Science, Technology and Maths, The University of Canberra, Canberra, ACT, Australia, as a Senior Lecturer/Assistant Professor. He also acts as an Editorial Board Member and Reviewer for several prestigious international journals. His research interests include next-generation mobile networks, biologically and ecologically inspired networks, cloud networking, green communication systems, and smart grid communications. Dr. Munasinghe has been successful in securing several prestigious research grants and awards such as ARC APD Fellowship (2010), ARC DP Grant (2010), USYD ECRS Grant (2012), and USYD Bridging Support Seed Grant (2013) and Industrial Grants. He was the recipient of many research awards including an IEEE Paper Award at the 50th Anniversary Global Communications Conference, Washington DC, USA, 2007. He has undertaken TPC Chairing responsibilities in a number of IEEE's flagship conferences.

Abbas Jamalipour (S'86–M'91–SM'00–F'07) is the Professor of Ubiquitous Mobile Networking at the University of Sydney, Australia, and holds a PhD in Electrical Engineering from Nagoya University, Japan. He is a Fellow of the Institute of Electrical, Information, and Communication Engineers (IEICE) and the Institution of Engineers Australia, an ACM Professional Member, and an IEEE Distinguished Lecturer. He has authored nine technical books, eleven book chapters, over 450 technical papers, and five patents, all in the area of wireless communications. Dr. Jamalipour is an elected member of the Board of Governors, Executive Vice-President, Chair of Fellow Evaluation Committee, and the Editor-in-Chief of the Mobile World, IEEE Vehicular Technology Society. He was the Editor-in-Chief IEEE Wireless Communications, Vice President-Conferences and a member of Board of Governors of the IEEE Communications Society, and has been an editor for several journals. He has been a General Chair or Technical Program Chair for a number of conferences, including IEEE ICC, GLOBECOM, WCNC and PIMRC. He is the recipient of a number of prestigious awards such as the 2016 IEEE ComSoc Distinguished Technical Achievement Award in Communications Switching and Routing, 2010 IEEE ComSoc Harold Sobol Award, the 2006 IEEE ComSoc Best Tutorial Paper Award, as well as 15 Best Paper Awards.