Energy-Efficient Inter-RAN Cooperation for Non-Collocated Cell Sites with Base Station Selection and User Association Policies

[1]Md. Farhad Hossain, [2]Kumudu S. Munasinghe and [3]Abbas Jamalipour

[1]Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh

[2]Faculty of Education, Science, Technology and Maths, University of Canberra, Australia

[3]School of Electrical and Information Engineering, University of Sydney, NSW 2006, Australia

Email: [1]mfarhadhossain@eee.buet.ac.bd, [2]kumudu.munasinghe@canberra.edu.au, [3]a.jamalipour@ieee.org

Abstract

Conventional planning and optimization of cellular mobile networks for supporting the peak-time user demand leads to substantial wastage of electrical energy. Infrastructure sharing among geographically collocated networks is considered promising for energy efficient operation of future cellular systems. Therefore, this paper proposes a generalized energy-efficient cooperation framework for sharing BSs between two cellular radio-access networks (RANs) serving the same geographical area. Previous works have the constraint of cooperation only among the collocated BSs belonging to different RANs, while the proposed framework is free from such limitation. To the best of our knowledge, this paper is the first for developing cooperation mechanisms among the non-collated BSs. Independent Poisson point process (PPP) is used for modeling the near realistic random locations of both BSs and user equipment (UEs). Under the proposed framework, BSs belonging to different RANs dynamically share each others traffic and thus allow some BSs to switch into low power sleep mode for saving energy. During this BS switching through traffic-sharing, connection continuity (no drop of the existing calls) is maintained throughout the network. A generalized optimization problem for maximizing energy savings is formulated. Due to the high complexity of the optimization problem, heuristically guided algorithms differing in BS selection and UE association policies are proposed. More specifically, two different BSs selection schemes and three separate UE association policies are integrated in the algorithms. Performance of the proposed inter-RAN cooperation framework is evaluated using extensive simulations demonstrating a substantial energy savings and gain in energy efficiency. Impact of different network parameters, such as BS selection and UE association policies, BS and UE densities, BS power profile and SINR requirements for connection continuity on the system performance is thoroughly investigated and analyzed.

Index Terms

Inter-RAN cooperation; energy efficient cellular networks; BS selection; UE association; BS switching

I. INTRODUCTION

In recent years, the world has seen a rapid growth in the number of deployed base stations (BSs) as well as networks operators for meeting the massive demand of subscribers for voice and data applications. This results in an unprecedented increase in energy consumption in cellular mobile networks and emerges as a great concern from both economical and environmental perspectives [1] - [4]. In a cellular system, BSs of its radio access network (RAN) are the most dominant energy consuming equipment amounting around 60-90% of the total consumption [4]-[6], while the accumulated energy usage in user equipment (UE) is approximately 1% [7]. Consequently, designing network architectures and protocols for achieving green cellular networks by reducing energy consumption in access networks, mainly in BSs, has drawn considerable attention of many researchers. On the other hand, with the increasing number of BSs, cell deployment layout of modern cellular networks is becoming more random and thus moving further away from the regular hexagonal pattern. Recent studies also identify that for many existing networks, Poisson point process (PPP) based modeling could capture a more realistic spatial distribution of BSs leading to improved accuracy in performance evaluation [8] - [9].

A high degree temporal-spatial diversity in traffic generation is very common in modern day cellular networks [7], [10] - [12]. However, cellular networks are provisioned based on the peak-traffic time leading to a significant wastage of electrical energy during off-peak periods. Consequently, during the recent years, various proposals for minimizing energy consumption by switching off BSs in a RAN have emerged [5], [7], [13] - [18]. On the other hand, given the future network environment having 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 [6], [19]. A recent studies concludes that despite the technical challenges that might arise in such scenarios, the potential benefits of sharing cellular networks can be as much as €2 billion [20]. A major benefit of such inter-operator cooperation is the obvious reduction in total energy consumption in running the networks [6], [19], [21]. Such cooperation can also lead to better service quality for mobile users and enhanced network performance by providing ubiquitous access, better reliability, fast load balancing, supporting vertical handoffs and facilitating soft handoffs [19]. However, although the principle is simple in theory, MNO cooperation possesses several technical and logistical challenges. Feasible profit division mechanism among the infrastructure sharing MNOs, alteration in signal quality distribution due to handoff of UEs from one RAN to another, compatibility issues among MNOs of heterogeneous technologies, requirement of strong coordination among the access networks as well as the core networks of cooperating RANs, and handset capabilities for multi-RAN connectivity and handoff support are some of the major challenges in implementing such cooperation mechanism.

Several works on the energy savings through cooperation among MNOs are available in literature [22] - [28]. Apart from all the strength and weakness of these works as discussed in Section II, they all suffer from a common, but critical limitation. All the proposed system models and cooperation mechanisms of these works are based on an over simplified assumption that the cooperating BSs are collocated, i.e., BSs belonging to different RANs are placed on the same tower. Moreover, the systems restrict the traffic offloading of a BS only to the other collocated BSs. However, in practice, BSs belonging to different RANs are not collocated having spatial separation of random amount. Consequently, the proposed cooperation mechanisms in [22] - [28] are impractical for real networks. In light of this, this paper proposes a novel energy efficient cooperation framework among two collocated cellular networks, which is free from all the above limitations. Several other improvements are also addressed in this paper. The main contributions of this paper thus can be summarized as below:

• We propose an inter-RAN dynamic cooperation framework at access network level between two geographically collocated cellular networks for reducing energy consumption. The proposed system is a generalized in the sense that it is not essential for cooperating BSs from the two networks to be collocated and thus it is more realistic. To the best of our knowledge, this is the first approach of developing inter-RAN cooperation mechanisms among non-collocated BSs belonging to different RANs. For modeling this spatial separation of cooperating BSs belonging to different RANs, locations of BSs are modeled using independent Poisson point process (PPP) for both the networks. Location of UEs in different RANs are also modeled using independent PPP.

• Under the proposed framework, by leveraging the tempo-spatial traffic diversity, the two RANs cooperate for sharing each others traffic which is regulated by the instantaneous network traffic and other system settings. Thus a set of BSs are selected to switch into low power sleep mode, while the other BSs are left in high power active mode for serving the UEs. Thus, the two RANs are adaptively reconfigured with time using a reduced number of active BSs for achieving energy savings. At the same time, service continuity of the active UEs are guaranteed (i.e., no call drop) by maintaining a minimum signal strength.

• We also formulate a generalized energy saving optimization problem for selecting the optimal set of BSs to switch into sleep mode, which is a challenging combinatorial problem with high computational complexity. Therefore, for the ease of practical implementation, a heuristically guided traffic sharing algorithmic framework incorporating two different BS selection schemes for deciding which BSs to distribute first and three separate schemes for associating the distributed UEs with other BSs are proposed. More specifically, network priority (NP) and traffic priority (TP) are the two schemes proposed for selecting the order of BSs from traffic distribution. On the other hand, the proposed UE association schemes are namely, location-, distance- and signal-based. By combining the BS selection schemes and the UE association policies, we propose and investigate six different algorithms.

• We thoroughly investigate the performance of the proposed energy saving inter-RAN cooperation framework using extensive simulations. Impact of various network parameters including UE and BS densities, BS selection and UE association policies, BS power models and desired signal quality on the degree of energy savings and other system parameters are explored and critically analyzed. Presented results demonstrate that the proposed framework is capable to significantly improve the overall energy efficiency (subject to network settings) of cellular networks.

The rest of the paper is organized as follows. Section II presents a comprehensive study on the related works. Section III describes the network model. Proposed energy saving framework along with the optimization problem is presented in Section IV. Whereas Section V presents the algorithms with the proposed BS selection and UE association policies. Simulation results with a thorough analysis is provided in Section VI. The paper finally concludes in Section VII by summarizing our key findings.

II. Related Works

Due to the ever increasing energy demand in cellular networks, a growing concern has developed among the operators as well as the vendors for implementing techniques in reducing energy consumption [29] - [30]. Out of the proposed schemes by the research community, minimizing energy consumption in a cellular RAN by switching some of its BSs into low-power sleep mode at low-traffic times have emerged as the most popular one [7], [14] - [18], [21], [31] - [33]. On the other hand, an extended form of this scheme, that is the energy-aware cooperation among multiple RANs by sharing BSs among themselves and thus allowing some BSs to switch into sleep mode for saving energy has recently drawn considerable attention [22] - [28].

In [23], authors outlined several energy saving cooperation strategies between collocated BSs of two RANs. Using these strategies, namely, equal switching off time periods, equal roaming costs, equal energy gains and maximum energy savings, the traffic of the switched off BS is transferred to the other collocated active BS and thus saves energy. In [22], 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 and the load-dependent power usage in BSs is not considered. On the other hand, authors in [24] introduced a game theory based BS switching off strategy in networks with two RANs. The same authors then extended their work in [25] for generalizing the game theoretic based BS sharing scheme among multiple RANs. 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 [26]. Whereas, a Bayesian game based mechanism for sharing BSs among multiple RANs was presented in [27]. The mechanism also included a strategy for motivating the network operators for cooperating and revealing their private information for maximizing the overall utility through this BS sharing. Furthermore, BS sharing problem among multiple RANs for saving energy was further extended to heterogeneous networks in [28].

However, all the works in [22] - [28] are based on the basic assumption of collocated BSs of all the network operators and thus are not applicable for the network environment having spatial separation among the BSs of cooperating RANs. Furthermore, none of the above papers except [28] 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. Our proposed framework in this paper is free from all the aforementioned limitations and thus more practical. Furthermore, consideration of spatial separation among the BSs of cooperating RANs and modeling this phenomena using PPP add significant novelty to the proposed algorithms.

III. Network Model

This section presents the considered network layout and other system components. The particulars are presented in the context of orthogonal frequency division multiple access (OFDMA)-based long-term evolution system (LTE) systems, which can also be adopted to other cellular systems.

A. Network Layout

We consider the downlink of an environment having $N = 2$ geographically collocated LTE RANs each covering the same area $\mathcal{A} \subset \mathbb{R}^2$ serving their respective UEs through their respective BSs. On the other hand, BSs of the networks are assumed non-collocated, i.e., BSs belonging to the two RANs are placed on their own towers having spatial separation. A view of such an environment having two collocated RANs with their own BSs is shown in Fig. 1. Let $\mathbb{B} = \{\mathbb{B}_1, \mathbb{B}_2\}$ be the set of all BSs in the area. Here, $\mathbb{B}_n = \{\mathcal{B}_{1,n}, \mathcal{B}_{2,n}, ..., \mathcal{B}_{|\mathbb{B}_n|}\}, n = 1, 2,$ is the set of BSs of n^{th} RAN, where $\mathcal{B}_{i,n}$ is the i^{th} BS of n^{th} RAN. Let $\mathcal{A}_{i,n}$ be the coverage area of $\mathcal{B}_{i,n}$ and thus $\cup_{i=1}^{|\mathbb{B}_n|} = \mathcal{A}, \forall n$. For accounting the random locations of BSs and the spatial separation between two cooperating BSs belonging to different RANs, homogeneous PPP is used for modeling the locations of BSs. In practice, the locations of BSs in one RAN is not decided by the locations of BSs in other RANs. Thus, the locations of BSs in the two RANs can be modeled as two independent PPP with intensity $\lambda_{n,b}, n = 1, 2$ [34], which can be denoted as $\Phi_{n,b} = \{(x_{i,n}^b, y_{i,n}^b) : i = 1, 2, ..., |\mathbb{B}_n|\}$, where $(x_{i,n}^b, y_{i,n}^b)$ is the Cartesian coordinate of BS $\mathcal{B}_{i,n}$ in $\mathbb{R}^2$. Similarly, the locations of UEs of the two RANs can also be modeled as two independent PPP with intensity $\lambda_{n,u}, n = 1, 2$ and denoted by $\Phi_{n,u} = \{(x_{i,n}^{k,u}, y_{i,n}^{k,u}) : i = 1, 2, ..., |\mathbb{B}_n|; k = 1, 2, ..., M_{i,n}\}$, where $(x_{i,n}^{k,u}, y_{i,n}^{k,u})$ is the two-dimensional Cartesian coordinate of k^{th} UE of $\mathcal{B}_{i,n}$ denoted as $U_{i,n}^k$ and $M_{i,n}$ is the total number of UE in $\mathcal{B}_{i,n}$. We also denote $N_{n,u} = \sum_{i=1}^{|\mathbb{B}_n|} M_{i,n}$ as the total number of UEs in n^{th} RAN. 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 B has a Poisson distribution with mean $\lambda|B|$ and can be given by [34]

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

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. 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. We also consider one resource block (RB) per UE and equal transmit power for all RBs. Furthermore, it is assumed that the BSs are equipped with omnidirectional antennas, and capable in switching between active mode and sleep mode.

B. Link Model

Received power $P_{Rx}(d)$ in dBm at a UE located at a distance d from the serving BS can be given by

$$P_{Rx}(d) = P_t - P_L(d) + X_\sigma \tag{2}$$

where P_t is the transmit power in dBm, $P_L(d)$ is the total path-loss in dB and X_σ is the amount of shadow fading in dB. Shadow fading X_σ is 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 [35]. Thus the path-loss $P_L(d)$ can be written as

$$\begin{aligned} P_L(d) = (44.9 - 6.55\log_{10} h_{BS})\log(d) \\ + 5.83\log_{10} h_{BS} + 14.78 + 34.97\log_{10} f_c \end{aligned} \quad (3)$$

where the distance d is in meter, f_c is the carrier frequency in GHz and h_{BS} is the height of the BS in meter.

C. Power Consumption Profile of BSs

Power consumption profiles of BSs varies from vendor to vendor. Based on our thorough literature survey on the power consumption profiles of macro-cell BSs, we define three categories. The first kind is the non-load proportional (NLP) type BSs, which consume constant power irrespective of traffic load. The second category is the partialy load proportional (PLP) type BSs for which a load-dependent dynamic power consumption part and a load-independent constant power consumption part together constitute the total operating power. The final type is the fully load proportional (FLP) type BSs whose power consumption is linearly related to the load consuming no power at all with zero traffic to serve. In literature, NLP model [15] - [16], [32], [36] - [42] and PLP power consumption model [7], [14], [17] - [18], [43] - [46] are popularly used. However, FLP macro-cell BSs are not available in practice and it is the optimal target for vendors to manufacture such BSs. In this paper, we adopt a generalized power consumption model, which can capture a wide range of BSs including all three types discussed above.

Let BS $\mathcal{B}_{i,n}$ has total N_T transceiver (TRX) chains. Now, assuming equal maximum operating power $P^m_{i,n}$, equal sleep mode power $p^s_{i,n}$ and equal power-load proportionality constant (PLPC) $\delta_{i,n}$ for all of these N_T chains of $\mathcal{B}_{i,n}$, total instantaneous operating power of $\mathcal{B}_{i,n}$ can be written as below [14], [17] - [18]

$$p_{i,n} = \begin{cases} \sum_{q=1}^{N_T} \Big[(1-\delta_{i,n})L^{(q)}_{i,n}P^m_{i,n} + \delta_{i,n}P^m_{i,n}\Big] & \text{(active)} \\ \sum_{q=1}^{N_T} p^s_{i,n} & \text{(sleep)} \end{cases} \quad (4)$$

where $0 \le L^{(q)}_{i,n} \le 1$ is the load factor (LF) of the q^{th} TRX chain, while the LF of BS $\mathcal{B}_{i,n}$ can be written as $L_{i,n} = \frac{1}{N_T}\sum_{q=1}^{N_T} L^{(q)}_{i,n}$. LF in an LTE system can be defined as the ratio of the number of RBs in use to the total number of available RBs [47] - [49]. On the other hand, $P^m_{i,n} = g_{i,n}P^{Tx}_{i,n} + h_{i,n}$. Here, $P^{Tx}_{i,n}$ is the maximum transmit power of a chain, and $g_{i,n}$ and $h_{i,n}$ are constants [18], [36]. Here, $g_{i,n}P^{Tx}_{i,n}$ is the fraction of maximum operating power $P^m_{i,n}$ that scales with the transmit power rating of a TRX chain. This scaling is required as $P^m_{i,n}$ of a BS varies due to amplifier and feeder losses as well as cooling of sites. The constant $g_{i,n}$ here works as a dimensioning factor. On the other hand, $h_{i,n}$ is another constant representing the fraction of $P^m_{i,n}$ which remains constant irrespective of TRX transmit power rating due to signal processing, battery backup and a part of site cooling. In addition, for considering various sleep mode power of BSs, we model it as $p^s_{i,n} = \delta_{i,n}h_{i,n}$. On the other hand, the PLPC parameter $0 \le \delta_{i,n} \le 1$ determines the level of dependency of $p_{i,n}$ on $L^{(q)}_{i,n}$. Thus, based on the value of $\delta_{i,n}$, we can model various types of BSs, which fall in the above defined three categories - NLP model ($\delta_{i,n} = 1$), FLP model ($\delta_{i,n} = 0$), and PLP model ($0 < \delta_{i,n} < 1$).

D. Energy Savings

Let $s_{i,n} \in \{0,1\}$ be the status parameter indicating the operating mode of BS $\mathcal{B}_{i,n}$, where $s_{i,n} = 1$ designates that $\mathcal{B}_{i,n}$ is in active mode and $s_{i,n} = 0$ represents its sleep mode. Then the percentage of sleep mode BSs for the entire network can be written as

$$N_s = \frac{\sum_{n=1}^{N} \sum_{i=1}^{|\mathbb{B}_n|} (1 - s_{i,n})}{\sum_{n=1}^{N} |\mathbb{B}_n|} \times 100\% \tag{5}$$

On the other hand, total power consumption in BS $\mathcal{B}_{i,n}$ after redistribution of UEs among the BSs in the RANs can be given by

$$\hat{p}_{i,n} = \left[s_{i,n} \sum_{q=1}^{N_T} \left[(1 - \delta_{i,n}) \hat{L}_{i,n}^{(q)} P_{i,n}^{m} + \delta_{i,n} P_{i,n}^{m} \right] + (1 - s_{i,n}) \sum_{q=1}^{N_T} p_{i,n}^{s} \right] \tag{6}$$

where $\hat{L}_{i,n}^{(q)}$ is the new value of $L_{i,n}^{(q)}$ after reassociating UEs. Then the percentage of energy savings of the entire network can be written as below

$$E_s = \left[1 - \frac{\sum_{n=1}^{N} \sum_{i=1}^{|\mathbb{B}_n|} \hat{p}_{i,n}}{\sum_{n=1}^{N} \sum_{i=1}^{|\mathbb{B}_n|} p_{i,n}} \right] \times 100\% \tag{7}$$

E. Energy Efficiency

Received 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

$$\gamma_{i,n}^{k} = \frac{P_{i,n}^{k,Rx}}{\mathcal{I}_{i,n}^{k,intra} + \mathcal{I}_{i,n}^{k,inter} + \mathcal{P}_N} \tag{8}$$

where, $P_{i,n}^{k,Rx}$, $\mathcal{I}_{i,n}^{k,intra}$, $\mathcal{I}_{i,n}^{k,inter}$ and $\mathcal{P}_N$ are the received power, intra-cell interference, inter-cell interference and the thermal noise power respectively. Due to the use of orthogonal frequency bands in a OFDMA-based LTE BS, zero intra-cell interfrence occurs. Now, considering adaptive modulation and coding (AMC), received SINR $\gamma_{i,n}^{k}$ can then be mapped to the spectral efficiency (SE) given in bps/Hz [48]

$$\psi_{i,n}^{k} = \begin{cases} 0 & \textit{if } \gamma_{i,n}^{k} < \gamma_{min} \\ \xi \log_2(1 + \gamma_{i,n}^{k}) & \textit{if } \gamma_{min} \le \gamma_{i,n}^{k} < \gamma_{max} \\ \psi_{max} & \textit{if } \gamma_{i,n}^{k} \ge \gamma_{max} \end{cases} \tag{9}$$

where, $0 \le \xi \le 1$, γ_{min}, ψ_{max} and γ_{max} are the attenuation factor, minimum SINR, maximum SE and the SINR at which ψ_{max} is achieved. Then, the energy efficiency (EE) metric η_{EE} of a system calculated over all UEs, BSs and RANs is defined as the ratio of the network wide total achievable throughput to the total power consumption in all BSs and can be written as

$$\eta_{EE} = \frac{\sum_{n=1}^{N} \sum_{i=1}^{|\mathbb{B}_n|} \sum_{k=1}^{M_{i,n}} W_{RB} \psi_{i,n}^{k}}{\sum_{n=1}^{N} \sum_{i=1}^{|\mathbb{B}_n|} p_{i,n}}, \text{bits/joule} \tag{10}$$

where W_{RB} is the bandwidth per RB in Hz (e.g., 180 kHz in LTE). Using (10), EE of both the original and the proposed networks can be evaluated. Then the EE gain provided by the proposed algorithms denoted as η_G can be defined by

$$\eta_G = \frac{\eta_c}{\eta_o} \tag{11}$$

where η_c is the EE of the reorganized network under the proposed algorithms, and η_o is the EE of the original network having no inter-RAN cooperation and BS switching.

IV. Proposed Energy-Efficient Inter-RAN Cooperation

A. High Level View of the Proposed Cooperation

It is very common that any geographical area is covered by more than one cellular network serving their respective subscribers. This paper proposes an inter-RAN energy saving cooperation framework for sharing BSs between two collocated networks by exploiting the inherent temporal-spatial traffic diversity in cellular systems. Under the proposed framework, a BS serves subscribers of its own RAN as well as share some subscribers from the other RAN under certain conditions. Thus, based on the instantaneous total traffic of both the RANs, a central coordinator determines which BSs of which RANs to remain active and which to switch into sleep mode. Consequently, some of the BSs of the cooperating RANs distribute their traffic to the other BSs and thus the entire network is reorganized (i.e., 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 traffic of these concerned BSs is taken into consideration, while service continuity of active UEs is maintained.

The basic concept of the inter-RAN cooperation between two networks is illustrated in Fig. 2, which is later explained in details with specific cases in Section V. For instance, BS $\mathcal{B}_{1,1}$ of RAN 1 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 BS $\mathcal{B}_{1,1}$ denoted as $U_{1,1}^1 - U_{1,1}^4$ are then associated to the BSs (as shown by the arrows) $\mathcal{B}_{1,2}$, $\mathcal{B}_{2,2}$, $\mathcal{B}_{4,2}$ and $\mathcal{B}_{5,2}$ respectively, and then $\mathcal{B}_{1,1}$ switches into sleep mode. It is considered that after the decision of switching to sleep mode by a BS, no new call is accepted by that BS and the active UEs are forced to handoff by associating them to the respective designated BSs. Proposed traffic offloading from one BS to the others is governed by the UE association policies, traffic of itself and the other BSs, required signal strength and other design parameters.

Traffic redistribution and sharing between the two RANs can be done according to an agreed policy between the network operators, such as, a pre-defined rank of the networks, a dynamic ranking derived from the instantaneous traffic scenario, game theory and utility based approaches, etc. No matter what is the policy, the profit has to be shared between the cooperating networks in a manner such that both the operators are satisfied. On the other hand, it is worthwhile to mention here that in the existing LTE architecture, there is no element assigned to be used as a coordinator for MNO cooperation through BS sharing. The coordinator in the proposed system model needs the access of information from both the operators. Thus, this coordinator can be placed on top of the core networks, where it will work as an umbrella entity for facilitating the proposed cooperation. Alternatively, the coordinator can also be placed between the RANs and the core networks similar to the 3GPP proposed gateway core network (GWCN) configuration proposed for MNO cooperation [50]. In this second approach, both the RANs will access their respective core networks through this coordinator, i.e., it will work as a common gateway node for both the networks.

B. Optimization Problem Formulation

The goal of the proposed inter-RAN BS sharing is to optimize EE calculated over both the cooperating RANs. Thus the objective is to determine an optimum set of active BSs $\mathcal{B}_{ON} = \{\mathbf{B_{ON,1}}, \mathbf{B_{ON,2}}\}$, 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. The active BSs in $\mathcal{B}_{ON}$ must support the service continuity of the active UEs. Thus the optimization problem can be presented as below

$$\arg\max_{\mathcal{B}_{ON}} \frac{\sum_{n=1}^{N} \sum_{i=1}^{|\mathbb{B}_n|} \sum_{k=1}^{M_{i,n}} W_{RB} \psi_{i,n}^{k}}{\sum_{n=1}^{N} \sum_{i=1}^{|\mathbb{B}_n|} p_{i,n}} \tag{12}$$

$$s.t.,$$

$$\gamma_{i,n}^{k} \geq \gamma_{th}, \forall U_{i,n}^{k}, \forall k, \forall i, \forall n \tag{13}$$

$$\bigcup_{i,n} \mathcal{A}_{i,n} = \mathcal{A}, \mathcal{B}_{i,n} \in \mathcal{B}_{ON} \tag{14}$$

$$\sum_{k=1}^{M_{i,n}} R_{i,n}^{k} \leq C_{i,n}, \forall \mathcal{B}_{i,n} \in \mathcal{B}_{ON} \tag{15}$$

$$\sum_{k=1}^{M_{i,n}} P_{i,n}^{k} \leq P_{i,n}^{Tx}, \forall \mathcal{B}_{i,n} \in \mathcal{B}_{ON} \tag{16}$$

Here, γ_{th}, $P_{i,n}^{k}$ and $C_{i,n}$ are the minimum SINR required for continuing effective communication, transmit power per RB required for $U_{i,n}^{k}$ and the capacity of BS $\mathcal{B}_{i,n}$ in terms of RBs respectively. In the above optimization problem, service continuity by maintaining a minimum SINR γ_{th} and coverage are guaranteed by (13) and (14) respectively. On the other hand, (15) and (16) correspond to the limitations of available RBs and transmit power in each BS respectively.

V. Proposed Algorithm with BS Selection and UE Association Policies

The optimization problem defined in (12) is a highly challenging combinatorial problem with a large search space $\mathcal{O}(2^{|\mathbb{B}|})$. Therefore, to reduce the computational complexity, we propose a heuristically guided algorithmic framework for finding out a set of BSs to switch into sleep mode for saving energy. The search for the set of sleep mode BSs is proposed to be carried out periodically in every T time over a day, while the parameter T is adjustable. Under the framework, two different BS selection schemes for determining the priority order of traffic distributing BSs and three different policies for associating a UE from its original BS to another BS are proposed. Combining the proposed BS selection schemes and the UE association policies, this paper proposes and investigates six different inter-RAN cooperation algorithms for saving energy.

A. BS Selection Schemes

In the proposed framework, BSs are allowed one after another to re-associate their current active UEs to the other BSs. Therefore, the first step for redistributing traffic among the cooperating RANs is to select the order in which the BSs are sequentially allowed for distributing corresponding UEs. This paper proposes two different schemes for selecting the order of BSs as presented below.

1) NP-based Scheme: In an NP-based scheme, a certain pre-defined ranking of RANs is used. This ranking has to be based on certain agreed policies to be designed through mutual agreement among the network operators. Development and integration of such RAN ranking mechanism is beyond the scope of this paper and left for future works. Without losing the generality, this paper considers that the RANs are ranked according to the network index. Thus for a geographical area served by two networks, RAN 1 has the higher priority. Now, this paper considers that the BSs of a RAN can distribute traffic only to the BSs of lower ranked RANs. This implies that the BSs of RAN 1 can only distribute traffic to those of RAN 2, while RAN 2 have no chance to distribute its traffic. On the other hand, within RAN 1, the network operator also uses a predefined priority order of its own BSs for allowing them to distribute their traffic sequentially. Once again, without losing the generality, this paper considers the original indexes of BSs as the priority order. For instance, among the $|\mathbb{B}_1|$ BSs of RAN 1, $\mathcal{B}_{1,1}$ has the highest priority, while $\mathcal{B}_{|\mathbb{B}_1|}$ is of the lowest priority for distributing its traffic.

2) TP-based Scheme: Unlike the NP-based scheme, this one uses a dynamic mechanism for selecting BSs to distribute traffic. Under the TP-based scheme, based on the instantaneous total traffic $L_{i,n}, \forall i, \forall n$, all the $|\mathbb{B}| = \sum_{n=1}^{N} |\mathbb{B}_n|$ BSs of all the cooperating RANs are sorted in an ascending order. That is a modified set of $\mathbb{B}$ denoted as $\mathbb{B}^* = \{\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_{|\mathbb{B}|}\}$ such that $L_i <= L_j, j > i$ is found, where L_i is the LF of BS $\mathcal{B}_i$. Then the BS with the lowest traffic, i.e, $\mathcal{B}_1$ is allowed to distribute its traffic first, then the BS with the next lower traffic $\mathcal{B}_2$ and so on.

B. UE Association Policies

After the selection of a BS to redistribute its traffic, active UEs of this BS are re-associated with other BSs using a UE association policy. We assume no partial redistribution of traffic of a BS. This implies that a BS can switch into sleep mode only after re-associating all of its UEs. Otherwise, the BS remains in active mode and continues to serve all the active UEs. This paper proposes and investigates three different UE association policies for the proposed inter-RAN cooperation, which are explained as below.

1) Location (L)-based: Proposed L-based policy utilizes the location information of a UE for associating it with one of the BSs. The k^{th} UE $U_{i,n}^k$ of BS $\mathcal{B}_{i,n}$ located at $(x_{i,n}^{k,u}, y_{i,n}^{k,u}) \in \mathcal{A}_{i,n}$ can only be associated with another BS $\mathcal{B}_{r,s}$ if the UE is within its Voronoi cell, i.e., $(x_{i,n}^{k,u}, y_{i,n}^{k,u}) \in \mathcal{A}_{r,s}$. Fig. 2 demonstrates the basic principle of L-based UE association policy. As shown, BS $\mathcal{B}_{1,1}$ of RAN 1 currently has four active UEs $U_{1,1}^1 - U_{1,1}^4$, which are to be distributed. As $U_{1,1}^1$ is located in the coverage area of BS $\mathcal{B}_{1,2}$ of RAN 2, i.e., $(x_{1,1}^{1,u}, y_{1,1}^{1,u}) \in \mathcal{A}_{1,2}$, UE $U_{1,1}^1$ is associated with $\mathcal{B}_{1,2}$. Using the same principle, UE $U_{1,1}^2$, $U_{1,1}^3$ and $U_{1,1}^4$ are associated with BS $\mathcal{B}_{2,2}$, $\mathcal{B}_{4,2}$ and $\mathcal{B}_{5,2}$ of RAN 2 respectively.

2) Distance (D)-based: Under this proposed D-based policy, the objective is to associate a UE $U_{i,n}^k$ located at $(x_{i,n}^{k,u}, y_{i,n}^{k,u}) \in \mathcal{A}_{i,n}$ to the nearest available active BS. To do so, Euclidean distances between the location of $U_{i,n}^k$ and all the active BSs to which $U_{i,n}^k$ can be associated are calculated first and then these available BSs are sorted in an ascending order of the calculated distances. Then $U_{i,n}^k$ is first tried to be associated with the nearest available BSs. If $U_{i,n}^k$ can't be associated with the nearest BS, then the attempt is moved to associate with the next nearer BS and continued to the other BSs until all the active BSs are tried. If $U_{i,n}^k$ can't be associated with any of the available BSs, it remains associated with $\mathcal{B}_{i,n}$.

3) Signal (S)-based: The focus of the proposed S-based policy is to associate a UE $U_{i,n}^k$ located at $(x_{i,n}^{k,u}, y_{i,n}^{k,u}) \in \mathcal{A}_{i,n}$ to the active BS providing better signal quality (i.e., SINR) in the downlink. Therefore, the active BSs are ordered according to the descending order of received SINR. Then $U_{i,n}^k$ is first tried to be associated with the BS providing the highest SINR. If $U_{i,n}^k$ can not be associated with this BS, then the attempt is moved to associate with the BS providing the next higher SINR and continued to the other BSs until all the active BSs are tried. If association of $U_{i,n}^k$ with any of the active BSs fails, it remains associated with $\mathcal{B}_{i,n}$.

An example of the order of available four active BSs at which they are approached for associating the UE $U_{i,n}^k$ of BS $\mathcal{B}_{i,n}$ under the above described UE association policies is demonstrated in Table I. The distances and the SINR values used in the example are chosen randomly.

C. Algorithms

By combining the two BS selection schemes and the three UE association policies, this paper proposes and investigates six different algorithms for inter-RAN energy efficient cooperation. The algorithms are named as *NP-L*, *NP-D*, *NP-S*, *TP-L*, *TP-D* and *TP-S*. For example, NP-L algorithm employs NP-based BS selection scheme and L-based UE association policy.

Now for deciding on a BS whether to switch into sleep mode, proposed algorithms start with the initialization $\mathcal{B}_{ON} = \mathbb{B}$ and sorts the BSs according to a BS selection scheme as proposed in Section V-A. It then takes the first active BS (say $\mathcal{B}_{i,n}$) at a time and then using one of the UE association policies as proposed in Section V-B, all UEs of $\mathcal{B}_{i,n}$ one by one are attempted to be distributed by associating them with the other BSs. For an association attempt of a UE (say $U_{i,n}^k$) to be successful, several conditions are to be met. Firstly, the intended BS to which a UE to be associated (say $\mathcal{B}_{i,n}^{k,p}$) is in active mode. This avoids the ping-pong effect of switching of a BS several times between active and sleep modes. Secondly, the received SINR at UE $U_{i,n}^k$ from BS $\mathcal{B}_{i,n}^{k,p}$ is equal to or greater than γ_{th}. Finally, the total transmit power and the total number of required RBs of $\mathcal{B}_{i,n}^{k,p}$ for supporting its own and shared UEs is within the limits. These conditions are guaranteed by the four constrains as stated in (13)-(16).

If the association of all the UEs in $\mathcal{B}_{i,n}$ with other BSs is successful, $\mathcal{B}_{i,n}$ can be switched into sleep mode. After that $\mathcal{B}_{ON}$ is updated by removing $\mathcal{B}_{i,n}$ from the current $\mathcal{B}_{ON}$. The algorithm then continues with the next active BS determined before using a BS selection scheme, updates $\mathcal{B}_{ON}$ and so on. After finishing with all BSs, final $\mathcal{B}_{ON}$ provides the list of BSs, which are left in active mode and the other BSs in $\{\mathbb{B} \setminus \mathcal{B}_{ON}\}$ are switched into sleep mode.

For demonstration purpose, pseudo code of the TP-D algorithm is presented in Table II. Proposed TP-D algorithm has a computational complexity $\mathcal{O}(N_U N_B^2)$ in place of $\mathcal{O}(N_U 2^{N_B})$ of the optimal solution by exhaustive search. 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 cooperating networks respectively. On the other hand, signaling overhead of the TP-D algorithm is equal to $(N_U + 2N_B)$. Pseudo code, computational complexity and the signaling overhead of the other algorithms can be written in a similar way, which are not presented here for the sake of clarity.

VI. Results and Analysis

A. Simulation Setup

A MATLAB based simulation platform is developed for evaluating the performance of the proposed energy saving inter-RAN cooperation framework. We perform extensive simulations and each data point 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 two collocated RANs, where the location of BSs and UEs are modeled using independent PPPs. 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, we consider same BS power profile parameters for all the BSs of all RANs. That is, we consider transmit power $P_{i,n}^{Tx} = 43$dBm, and power profile constants $g_{i,n} = 21.45$, $h_{i,n} = 354.44$, $\forall i, \forall n$ [36]. Unless otherwise specified, SINR threshold $\gamma_{th} = 0$dB, PLPC = 0.7 and zero sleep mode power for all BSs (i.e., $\delta_{i,n} = 0.7$ and $p_{i,n}^{s} = 0, \forall i, \forall n$ respectively), and equal BS denisties and equal UE densities for both the networks (i.e., $\lambda_{n,b} = \lambda_{BS}$ and $\lambda_{n,u} = \lambda_{UE}, \forall n$ respectively) are used for the presented results. Moreover, assuming inbuilt signalling facilities in the networks and optical fiber backhaul link from BSs to the central coordinator requiring a very low energy requirement ($\sim$1pJ/bit/m [51]), we ignore the signaling energy cost compared to that of the total network.

B. Impact of UE Densities

Figures 3(a)-(d) present the variation of the percentage of sleep mode BSs, percentage of energy savings, EE and the gain in EE respectively with the UE density λ_{UE} under the proposed algorithms. Simulations are performed considering BS density $\lambda_{BS} = 1$ per km^2, $\gamma_{th} = 0$dB, PLPC = 0.7 and sleep mode power equal to zero. As shown in the Fig. 3(a), percentage of sleep mode BSs decreases with the increase of UE density for all the algorithms. This is obvious as with the increase of λ_{UE}, number of UEs in all the BSs increases and consequently fewer number of UEs can be shared from other BSs leading to reduced number of sleep mode BSs. Similar patterns are also observed in the percentage of energy savings as it is directly related to the number of sleep mode BSs. However, from comparison between Fig. 3(a) and 3(b), it can be seen that the percentage of savings is less than the percentage of sleep mode BSs and this difference increases with the increase of UE density. These two quantities would have been equal if BSs were of NLP type (i.e., PLPC = 1). As for the simulations, BSs are of PLP type with PLPC = 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 energy savings.

Further investigation of Fig. 3(a) and 3(b) identifies that for lower λ_{UE}, the algorithms with the TP-based BS selection performs better producing higher energy savings, while the NP-based algorithms are found better for higher traffic density scenarios. This can be explained as follows: When λ_{UE} is low, many BSs have lower traffic and hence a BS has many other BSs to whom its UEs can be distributed. Thus for lower λ_{UE}, TP-based BS selection by sorting BSs with respect to traffic level increases the probability of BSs to switch into sleep mode by distributing their fewer UEs. On the contrary, for higher λ_{UE}, most of the BSs are relatively heavily loaded and hence a BS with lower traffic obtained from TP-based BS selection has other BSs to share its traffic which already have higher traffic than this one. Consequently the probability of distribution of traffic of this BS to the other BSs with relatively higher traffic level decreases.

On the other hand, an increasing trend of EE with UE density λ_{UE} of the original network as well as the network under the proposed algorithms is evident from Fig. 3(c). 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. The line corresponding to 'No-Coop' represents the EE of the original network, i.e., no inter-RAN cooperation for saving energy. From the figure, it is clear that all the proposed inter-RAN cooperation algorithms can significantly improve the EE of the original network. For the convenience of better understanding of the EE performance, gain in EE of the network under the proposed algorithms is also demonstrated in Fig. 3(d) which decreases with the increase of λ_{UE}. As with the increase of λ_{UE}, the rate of increase in EE of the original network with no cooperation is much faster than the network under the proposed algorithms, gain in EE is found decreasing. Finally, it can be seen that under a particular BS selection scheme, the algorithm with S-based UE association have better EE as well as higher EE gain than those of with D-based UE association. This is because, S-based algorithms tries to associate UEs with the BSs providing higher SINR, while D-based algorithms considers the smaller distance for association. However, smaller distance does not guarantee the higher SINR due to the presence of shadow fading. The higher SINR achieved from S-based UE association leads to higher throughput, higher EE and higher EE gain.

C. *Impact of BS Densities*

Impact of BS density λ_{BS} on the energy savings, EE and gain in EE under the proposed algorithms is demonstrated in Figs. 4(a)-(c). As the pattern of percentage of sleep mode BSs is similar to the energy savings as observed in Fig. 3, we omit the former one here. For the simulations, UE density $\lambda_{UE} = 10$ per km^2, $\gamma_{th} = 0$dB, PLPC = 0.7 and sleep mode power equal to zero are used. As seen in Fig. 4(a), an increasing trend in energy savings with λ_{BS} is evident though the amount significantly varies among the algorithms. With the increase of λ_{BS} for a fixed λ_{UE}, BSs are being increasingly lightly loaded and thus higher number of BSs can switch into sleep mode saving more energy. Furthermore, for lower values of λ_{BS}, savings by TP-based algorithms is smaller than that by NP-based counterparts. However, with the increase of λ_{BS}, BSs are being increasingly lightly loaded and thus the energy savings gap between NP-based and TP-based algorithms diminishes and then after certain values of λ_{BS}

in the range of 4-5 per km^2, TP-based algorithms outperforms the NP-based algorithms. This is because, for the given $\lambda_{UE} = 10$ per km^2, lower values of λ_{BS} imply relatively higher traffic level in the BSs than in the region with higher values of λ_{BS}. Consequently, savings by TP-based algorithms for smaller λ_{BS} is lower than that by NP-based algorithms and converse is true for higher λ_{BS}, which is also supported by Figs. 3(a)-(b).

On the other hand, with the increase of λ_{BS}, BSs become increasingly lightly loaded and consequently turning to be less energy efficient as the fixed part of BS power consumption become more dominant. Thus the overall EE of the network decreases as evident from Fig. 4(b). Furthermore, for a given λ_{UE}, decrease in EE with λ_{BS} in the original network is faster than the proposed networks and hence the gain in EE improves under all the algorithms as demonstrated in Fig. 4(c). In addition, for the same reason as explained for Fig. 3, S-based algorithms outperform the D-based algorithms.

D. *Impact of BS Power Profile*

Figures 5(a)-(c) and 6(a)-(c) illustrate the impact of BS power consumption profile parameter PLPC $\delta_{i,n}$ considering sleep mode power equal to zero and $\delta_{i,n}h_{i,n}, \forall i, \forall n$, respectively. Simulations are conducted using $\lambda_{UE} = 10$ per km^2, $\lambda_{BS} = 1$ per km^2 and $\gamma_{th} = 0$dB. As seen from Fig. 5(a) and Fig. 6(a), energy savings increases with the increase of PLPC. The constant PLPC = 0 implies a FLP type BS in which power consumption increases linearly with traffic level and consumes no power with zero traffic. Consequently, By switching BSs into sleep mode generates no energy savings. On the other hand, with the increase of PLPC, 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, PLPC = 1 implies a NLP type BS that consumes constant power irrespective of traffic load 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 PLPC, the fixed part of BS power consumption increases. Consequently, BSs become increasingly less energy efficient and hence the overall EE of the network decreases being the minimum at PLPC = 1 as seen in Fig. 5(b) and Fig. 6(b). In addition, decrease in EE in the original network with no cooperation is much faster than the network under the proposed algorithms. Consequently, an increasing trend in EE gain is observed under all the proposed algorithms as evident from Fig. 5(c) and Fig. 6(c).

Furthermore, impact of sleep mode power other than zero can be visualized by comparing Fig. 5 and Fig. 6. With the increase of sleep mode power, overall energy savings, EE and gain in EE should decrease as the savings is offset by the sleep mode power consumption, which is also evident from careful examination of the curves presented in these figures. For example, energy savings of NP-S algorithm with PLPC = 1 decreases from 50% to 27% when the sleep mode power is increased from zero to $\delta_{i,n}h_{i,n}$.

E. *Impact of SINR Requirement*

Performance variation with the threshold SINR (γ_{th}) requirement for continuing an active connection when re-associated with another BS is demonstrated in Fig. 7. The network is simulated using $\lambda_{UE} = 10$ per km^2, $\lambda_{BS} = 1$ per km^2, PLPC = 0.7 and zero sleep mode power. Significant variation in performance with γ_{th} as well as among the algorithms is evident from the figure. As shown in Fig. 7(a), energy savings decreases with the increase of γ_{th}.

This is because, increase in SINR requirement implies that a lower number of UEs can achieve this target leading to reduced number of UEs re-associated with the other BSs. Consequently fewer number of BSs can switch to sleep mode resulting in reduced amount of energy savings. On the other hand, gain in EE as illustrated in Fig. 7(b) also shows a similar decreasing trend with the increase of γ_{th}. Here, the EE figure is omitted as it has the same pattern as of gain in EE except a multiplication by the EE of the original network, which is constant irrespective of the value of γ_{th}. With the increase of γ_{th}, increasingly lower number of BSs are switched into sleep, higher number of BSs remain in active mode and hence as explained above, BSs are operated with lower traffic resulting in overall lower EE. Furthermore, the performance gap among the algorithms is higher for lower γ_{th} values and decreases with the increase of γ_{th}, which is also due to the increasingly lower number of sleep mode BSs.

VII. Conclusion

This paper has proposed an inter-RAN cooperation framework for BS sharing between two geographically collocated cellular access networks for improving overall EE. For avoiding the high complexity, six different heuristic algorithms integrating two BS selection schemes and three different UE selection policies have been developed for selecting BSs to switch into sleep mode for saving energy. Proposed framework has removed the restriction of previous works of traffic sharing among only the collocated BSs belonging to different RANs. For facilitating the development of the cooperation mechanisms for non-collocated BSs, PPP has been used for modeling the locations of BSs. Extensive simulations have been carried out for evaluating the performance of the proposed inter-RAN cooperation framework. Performance has been investigated in terms of sleep mode BSs, energy savings, EE and gain in EE. Impact of BS and UE densities, BS selection schemes, UE association policies, BS power profile and SINR requirement on the performance has been thoroughly investigated and critically analyzed. It has been found that depending on the network settings, performance of the proposed algorithms differs significantly. For lower UE density, energy saving performance has been found better for TP-based algorithms, while the converse is true for NP-based algorithms. On the other hand, higher energy saving algorithms have not always been found to be higher energy efficient. In general, algorithms with the S-based UE association have demonstrated better EE as well as improvement in EE compared to the D-based counterparts. Performance of the proposed algorithms have shown substantial variation with the BS power profile parameters, such as PLPC and sleep mode power. In addition, increase in SINR requirement has shown negative effect on both the energy savings and the gain in EE. In summary, apart from the observed high dependency of performance on the network settings, all the proposed algorithms have demonstrated the substantial capability in saving energy as well as improving the EE of the networks as a whole.

In Section I, we have identified several open challenges in implementing MNO cooperation, which we will address in our future research. For instance, we will focus on the development of generalized cooperation mechanisms among any number of networks. In addition, impact of this cooperation on both the RANs and the core networks of the involved operators will be investigated. Our work will also include the development of efficient coordination mechanisms among the concerned network components belonging to different MNOs for optimal benefit from such cooperation.

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TABLE I: Demonstration of attempt order of four available BSs $\mathcal{B}_{i,n}^{k,1} - \mathcal{B}_{i,n}^{k,4}$ for associating the UE $U_{i,n}^{k}$ of BS $\mathcal{B}_{i,n}$. Here, $\mathcal{B}_{i,n}^{k,p}$ is the p^{th} available active BS for associating $U_{i,n}^{k}$. It is assumed that $(x_{i,n}^{k,u}, y_{i,n}^{k,u})$ falls in the coverage area of $\mathcal{B}_{i,n}^{k,2}$

Available BS	$\mathcal{B}_{i,n}^{k,1}$	$\mathcal{B}_{i,n}^{k,2}$	$\mathcal{B}_{i,n}^{k,3}$	$\mathcal{B}_{i,n}^{k,4}$
Distance (m)	500	300	100	600
SINR (dB)	-2	10	5	8
L-based	Never	I	Never	Never
D-based	III	II	I	IV
S-based	IV	I	III	II

TABLE II: Pseudo code of TP-D algorithm for the proposed energy efficient inter-RAN cooperation

1:	Initialize: $\mathcal{B}_{ON} = \{\mathbb{B}_1, \mathbb{B}_2\}$, $L_{i,n}, (x^b_{i,n}, y^b_{i,n}),$ $(x^{k,u}_{i,n}, y^{k,u}_{i,n}), \gamma^k_{i,n}, \forall i, \forall n, \forall k$
2:	Sort BSs to determine $\mathbb{B}^* = \{\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_{\lvert\mathbb{B}\rvert}\}$ s.t., $L_i <= L_j, j > i$, L_i is the LF of $\mathcal{B}_i \in \mathbb{B}^*$
3:	**for** $i = 1 : \lvert\mathbb{B}\rvert$
4	**If** $L_i = 0$
5	Set $\mathcal{B}_{ON} = \{\mathcal{B}_{ON} \setminus \mathcal{B}_i\}$
6	**Else**
7:	**for** $k = 1$:Number of UEs in BS $\mathcal{B}_i$
8:	Calculate distance $d_{k,i}$ between k^{th} UE in $\mathcal{B}_i$ and all other BSs in $\mathbb{B}_r = \{\mathcal{B}_{ON} \setminus \mathcal{B}_i\}$
9:	Sort BSs in $\mathbb{B}_r$ in an ascending order of $d_{k,i}$ and denote as $\mathbb{B}^s_r = \{\mathcal{B}^s_{r,1}, \mathcal{B}^s_{r,2}, ..., \lvert\mathbb{B}_r\rvert\}$
10:	**for** $d = 1$:$\lvert\mathbb{B}_r\rvert$
11:	Find the received SINR at k^{th} UE from $\mathcal{B}^s_{r,d}$
12:	Calculate call blocking rate, total transmit power requirement and total RB requirement in $\mathcal{B}^s_{r,d}$
13:	**If** constraints (13)-(16) are met,
14:	Associate k^{th} UE with BS $\mathcal{B}^s_{r,d}$
15:	Set $k = k + 1$ and Go to Step 8
16:	**Else**
17:	Set $d = d + 1$ and Go to Step 11
18:	**End If**
19:	**End for**
20:	Set $k = k + 1$ and Go to Step 8
21:	**End for**
22:	**If** association of all UEs of BS $\mathcal{B}_i$ is successful,
23:	Set $\mathcal{B}_{ON} = \{\mathcal{B}_{ON} \setminus \mathcal{B}_i\}$
24:	Set $i = i + 1$ and Go to Step 7
25:	**Else**
26:	Set $i = i + 1$ and Go to Step 7
27:	**End If**
28:	**End If**
29:	**End for**

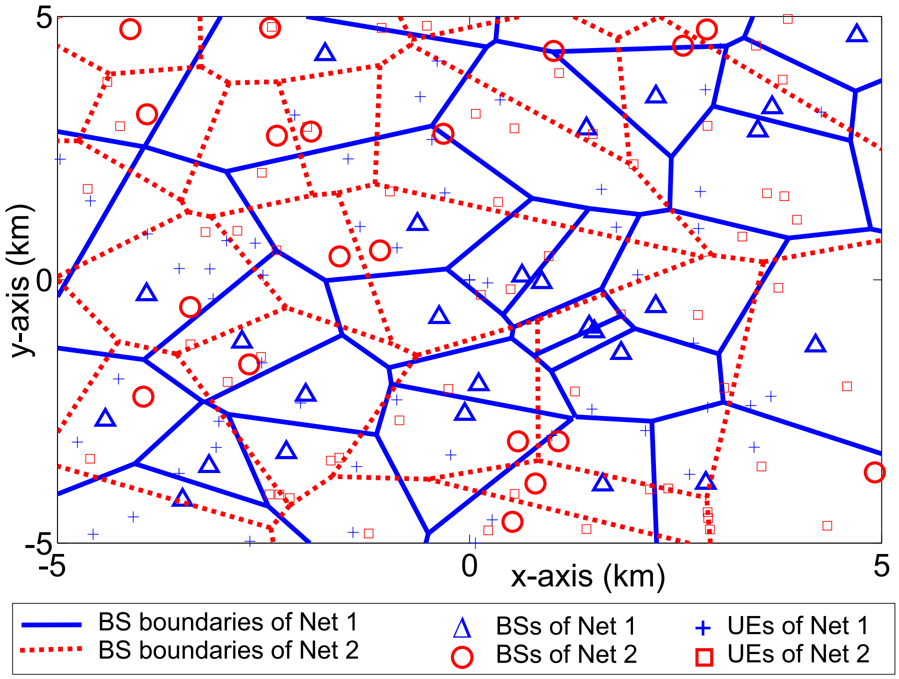


Fig. 1: A snapshot of the network layout with two geographically collocated RANs serving their respective UEs.

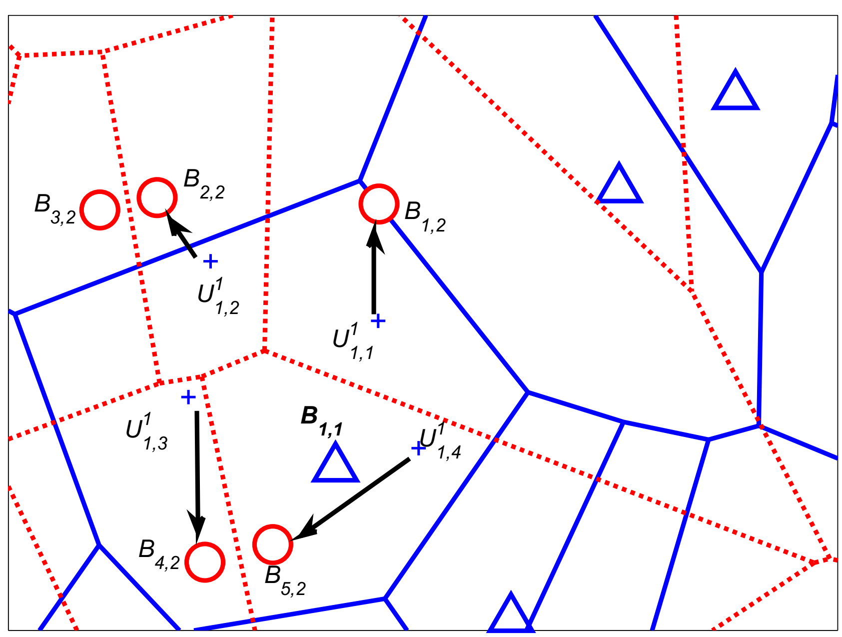
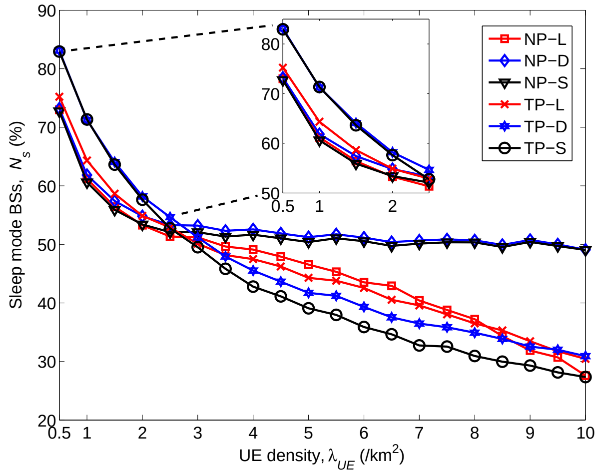
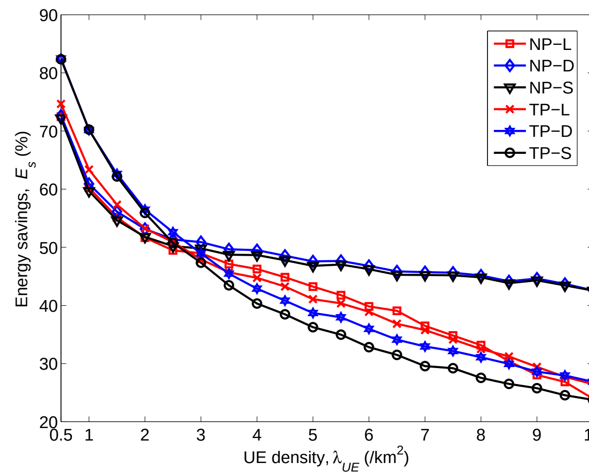


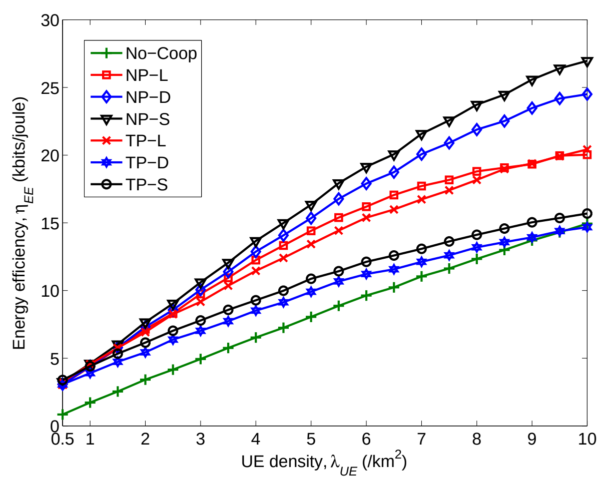
Fig. 2: UE distribution of BS $\mathcal{B}_{1,1}$ using location based association policy. UEs are marked using plus ('+') symbols.



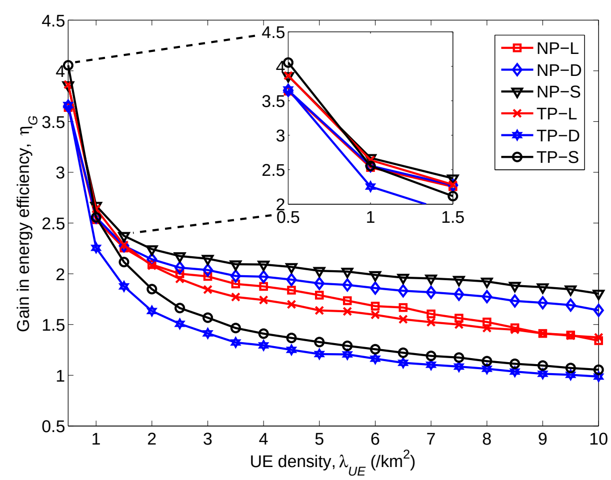
(a) Sleep mode BSs



(b) Energy savings

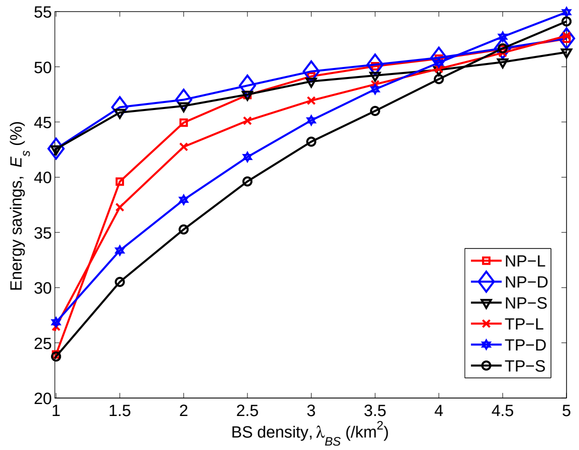


(c) Energy efficiency

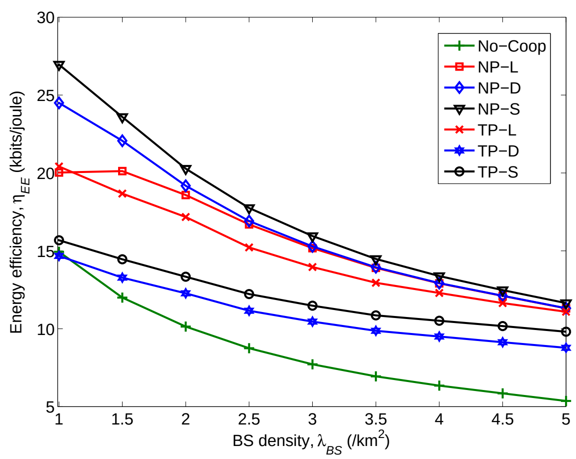


(d) Gain in energy efficiency

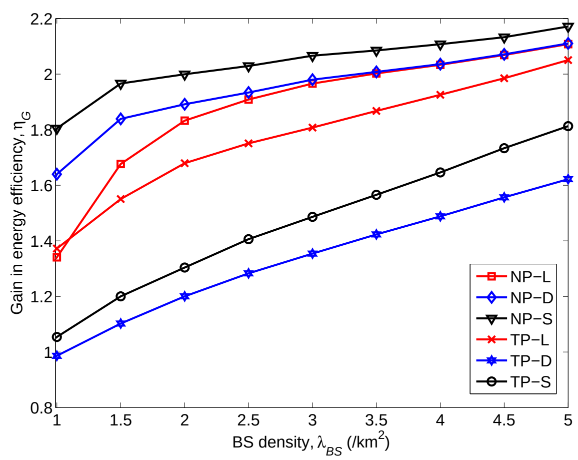
Fig. 3: Percentage of sleep mode BSs, energy savings, EE and gain in EE with UE density λ_{UE} under various algorithms with $\lambda_{BS} = 1$ per km^2, $\gamma_{th} = 0$dB, PLPC = 0.7 and zero sleep mode power in BSs.



(a) Energy savings

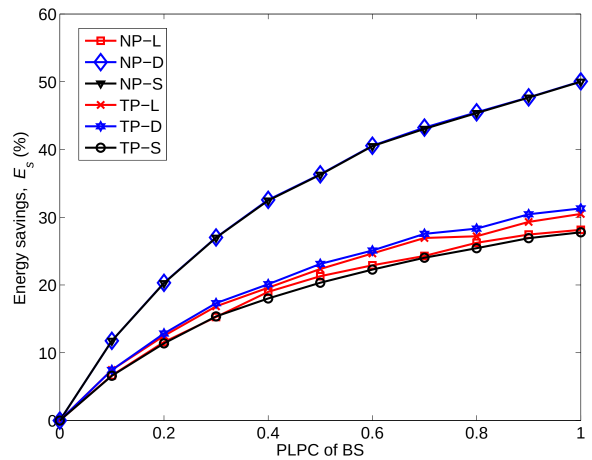


(b) Energy efficiency

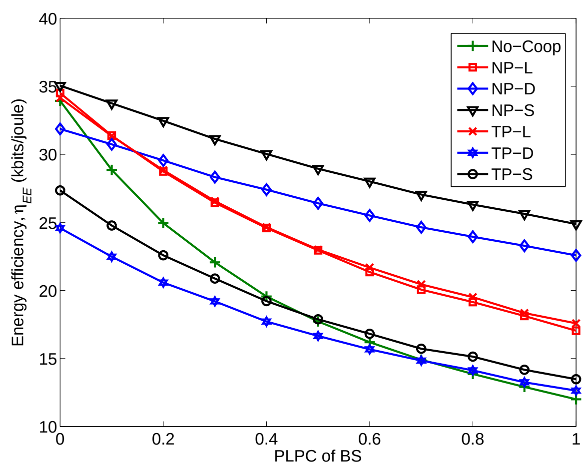


(c) Gain in energy efficiency

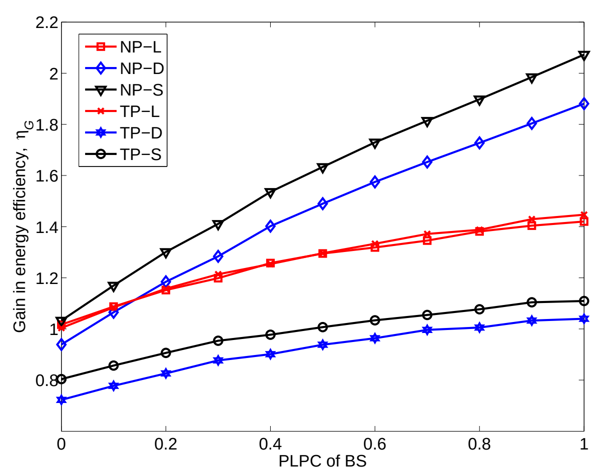
Fig. 4: Percentage of energy savings, EE and EE gain with BS density λ_{BS} under various algorithms with $\lambda_{UE} = 10$ per km^2, $\gamma_{th} = 0$dB, PLPC = 0.7 and zero sleep mode power in BSs.



(a) Energy savings

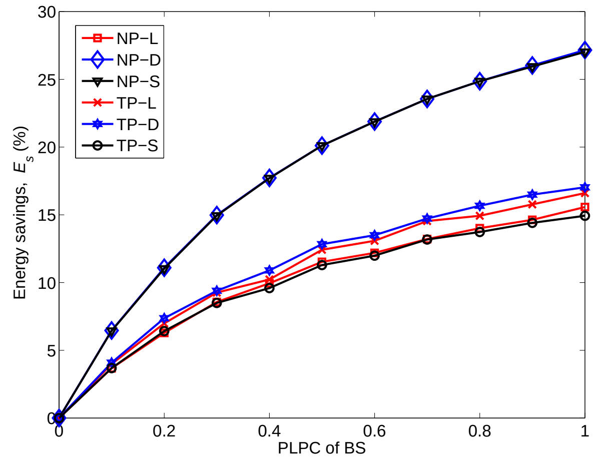


(b) Energy efficiency

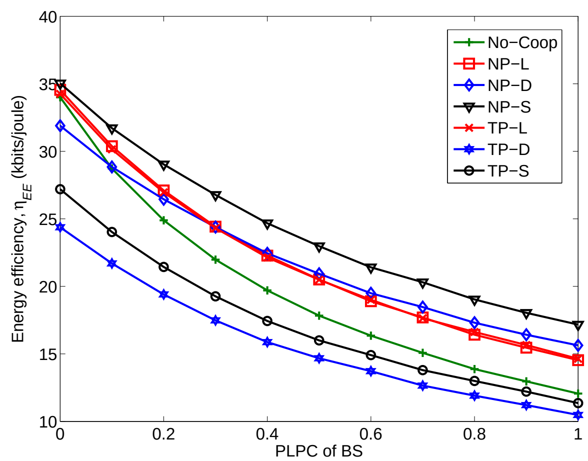


(c) Gain in energy efficiency

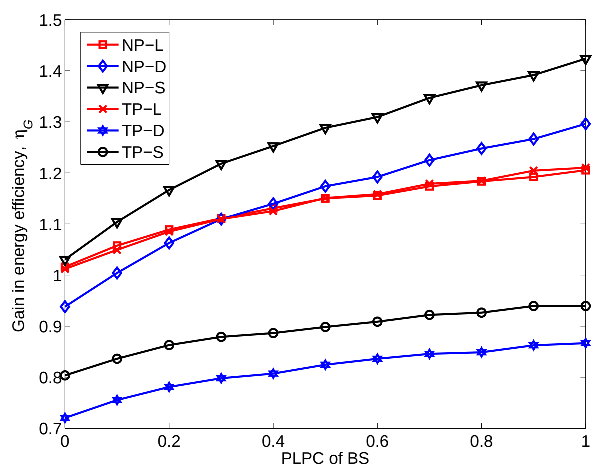
Fig. 5: Percentage of energy savings, EE and EE gain with BS power profile parameter PLPC under various algorithms with $\lambda_{UE} = 10$ per km^2, $\lambda_{BS} = 1$ per km^2, $\gamma_{th} = 0$dB and zero sleep mode power in BSs.



(a) Energy savings

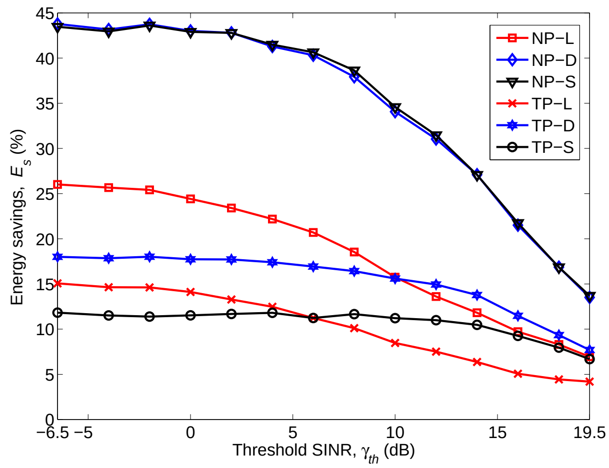


(b) Energy efficiency

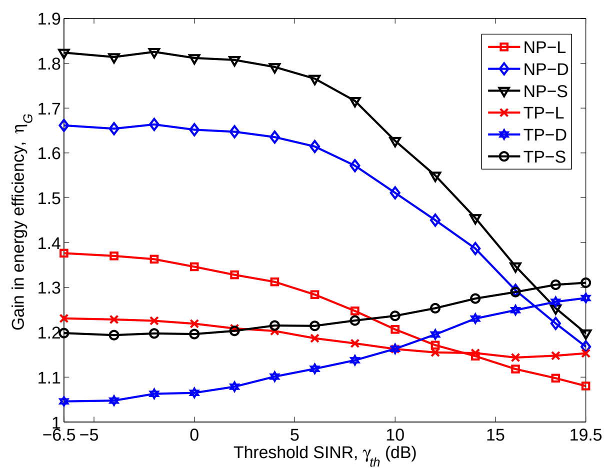


(c) Gain in energy efficiency

Fig. 6: Percentage of energy savings, EE and gain in EE with BS power profile parameter PLPC under various algorithms with $\lambda_{UE} = 10$ per km^2, $\lambda_{BS} = 1$ per km^2, $\gamma_{th} = 0$dB and BS sleep mode power = $\delta_{i,n} h_{i,n}, \forall i, \forall n$.



(a) Energy savings



(b) Gain in energy efficiency

Fig. 7: Percentage of energy savings, EE and gain in EE with threshold SINR γ_{th} under various algorithms with $\lambda_{UE} = 10$ per km^2, $\lambda_{BS} = 1$ per km^2, PLPC = 0.7 and zero sleep mode power in BSs.