Traffic-Aware Two-Dimensional Dynamic Network Provisioning for Energy-Efficient Cellular Systems

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Abstract—Conventional peak-traffic based provisioning of cellular mobile networks leads to a significant wastage of electrical energy. Therefore, we propose a novel traffic-aware two-dimensional dynamic network provisioning mechanism for enhancing the energy efficiency in OFDMA-based cellular systems. Proposed scheme, named as joint dynamic sectorization and switching of base station (JDSBS), adaptively provisions cellular access networks by switching the redundant BSs as well as sectors into sleep mode. Quality of service (QoS), namely user data rate, service continuity and network coverage are also maintained. Because of the high complexity of the formulated generalized energy optimization problem, the two dimensions (i.e., sector switching and BS switching) are decoupled in time-domain into two sub-problems, each executing its own heuristically guided algorithm. Moreover, a novel exponentially weighted moving average (EWMA)-based load factor estimator is employed for reducing the occurrence of network provisioning. System performance is evaluated using extensive simulations demonstrating substantial energy savings. In addition, impact on the spectral efficiency and resource utilization is presented. Effectiveness of JDSBS is further validated by comparing with the individual application of sectorization and BS switching. Furthermore, for realistic traffic patterns, use of EWMA-estimator achieves over 40% reduction in network provisioning events without compromising energy saving performance.

Index Terms—Energy efficiency, dynamic sectorization, base station switching, EWMA-based estimator, network provisioning.

I. Introduction

Rapid growth in the number of deployed base stations (BSs), subscribers and diverse applications is producing an increasing amount of energy consumption in cellular mobile networks. By constituting a significant portion of network operating expenditure (OPEX) as well as contributing to the global warming, this rising energy utilization has become a great concern from both economical and environmental perspectives [1], [2]. In a cellular system, BSs of its radio access network (RAN) are the most dominant energy consuming equipment adding up to 60%-80% of the total consumption [3], [4], [5]. Whereas, the accumulated energy usage in user terminals can be around 1% [5]. Therefore, most recently, the notion of attaining energy efficient cellular networks by reducing the consumption in BSs has become the focus of many researchers.

A high degree temporal-spatial diversity in traffic generation is very common in modern day cellular networks [5], [6], [7]. However, conventional cellular networks are provisioned

based on the peak-traffic time, where all BSs as well all the sectors in each BS are left in active mode ignoring the variations in traffic demand. Thus, the networks remain over-provisioned (in terms of capacity and power) for most of the time leading to a significant wastage of radio resources, particularly, electrical energy during off-peak periods. Considering this fact, in our previous work [8], we proposed distributed inter-BS cooperation for switching the redundant BSs into sleep mode for saving energy. Proposed distributed cooperation is developed following the principle of ecological self-organization, which functions based on the information of the neighboring BSs. We also proposed an alternative traffic-driven centralized technique for energy savings by adaptively adjusting the number and the beamwidth of sectors of BSs [9]. Unlike the system in [8], this system does not entirely turned off a BS making the implementation of the scheme much easier, yet effective for saving a significant amount of energy.

In this paper, we focus on combining both dynamic sectorization (DS) and dynamic switching of BS (DSBS) for energy efficiency in cellular access networks. At the same time, quality of service (QoS) constraints, namely user data rate, service continuity and network coverage are maintained. Aforementioned limitations of our previous works are also addressed here. Although the proposed technique can be adopted to any cellular standard (viz., 2G, 3G and beyond) with slight modifications, we develop and investigate the proposed scheme under the framework of orthogonal frequency division multiple access (OFDMA)-based cellular systems. Emphasizing on OFDMA-based systems comes from its promise to support higher data rates with better service quality leading to its acceptance as a multiple-access technology for long term evolution (LTE) and worldwide interoperability for microwave access (WiMAX) cellular networks [10], [11]. The main contributions of this paper can be summarized as below:

- We propose a novel traffic-sensitive energy-saving two-dimensional network provisioning mechanism for cellular access networks. Proposed scheme is named as JDSBS under which DS and DSBS are jointly employed for dynamically provisioning cellular access networks by scaling in two different dimensions, namely the number of BSs and the number of sectors in each active BS. To the best of our knowledge, we are the first in investigating the joint application of DS and DSBS schemes for energy savings.
- We formulate a generalized energy saving optimization

problem for JDSBS, which is a challenging combinatorial problem with high computational complexity. Therefore, for the ease of practical implementation, we first decouple the JDSBS problem into two sub-problems in time-domain: DS problem and DSBS problem. Heuristically guided centralized algorithms are then proposed for both the problems, which are executed one after another. Based on the sequence of employing DS and DSBS, two variants of JDSBS, designated as JDSBS-I and JDSBS-II, are investigated.

• A novel exponentially weighted moving average (EWMA)-based estimator is proposed for approximating the load factor (LF) of an entire day from the past data. Network provisioning event at an instance is triggered only when the estimated LF meets a certain criterion. Actual network parameters (e.g., received signal strength and active user data rates) are then used to decide the operating modes of BSs and sectors. This approach prevents infeasible network reconfiguring attempts leading to reduced signaling and computations.

• A near realistic network environment is captured by considering generalized load-dependent power consumption profiles of BSs, variation of antenna gains with the change of transmission beamwidths, average antenna radiation pattern, channel propagation model, and realistic daily traffic patterns with temporal and spatial variations.

• Extensive simulations are carried out for thoroughly investigating the system performance under various traffic levels, user distributions, user data rates, user association policies, BS power models and other design parameters. The evaluation is carried out in terms of percentage of sleep mode BSs and sectors, net energy savings, spectral efficiency and resource utilization. Simulation results demonstrate a substantial volume of energy savings amounting over 90% at very low traffic. Performance of JDSBS is also compared with the individual application of DS and DSBS.

The rest of the paper is organized as follows. A comprehensive discussion on the related works is presented in Section II. Section III describes the network model, while the proposed EWMA-based estimation is detailed in Section IV. System model of the proposed JDSBS mechanism along with the implementation approach is explained in Section V. In Section VI and VII, algorithms for DS and DSBS sub-problems are presented respectively. Simulation results with an insightful discussion is provided in Section VIII. Performance of EWMA estimator is analysed in Section IX. We then conclude the paper in Section X.

II. RELATED WORKS

Cellular network operators and vendors are immensely concerned about the ever increasing cost of energy [12], [13]. Consequently, during the recent years, various proposals for minimizing energy consumption by switching off BSs have emerged [4], [5], [8], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25]. Aiming to leverage the temporal-spatial traffic diversity in cellular networks, LTE proposes turning off evolved node Bs (eNBs) at lower traffic times for

saving energy [15]. However, the standard has left the issue of designing implementation schemes open for further research.

In light of this, we proposed an energy saving cellular access network by employing distributed cooperation among BSs [8]. On the other hand, authors in [16] and [17] employed mutual cooperation among BSs for manually switching BSs. However, the schemes in [16] and [17] are applicable only for regular cell layouts. While, [18] and [19] proposed algorithms for dynamically shutting down BSs, but provided no mechanism for dynamically switching them back ON. In contrast, distributed schemes for dynamically switching on and off BSs using system load as the algorithm initiator were proposed in [21]. However, guaranteed data rate demands from users may significantly affect the load distribution, which is not addressed in this work. On the other hand, concept of cell zooming along with the switching of BSs was introduced in [22]. Whereas, a load-forecasting based centralized BS switching technique for global system for mobile (GSM) and high speed packet access (HSPA) was investigated in [23]. Along with the switching off BSs, scope of heterogeneous cell sizes for energy savings was also investigated in [24]. However, the schemes in [16], [18], [21], [19], [20], [22], [23], [24] failed to capture the load-dependent power utilization in BSs resulting in overestimations. Moreover, many of them presented either very basic algorithms ignoring the actual data rate and locations of users [18], [19], [23] or no algorithm at all [16], [20].

For the networks with non-deterministic traffic patterns, an actor-critic based centralized learning framework for switching BSs into sleep mode was proposed in [25]. Besides, trade-off between energy savings and delay for predefined deterministic traffic patterns was analyzed by formulating cost minimization problems [4]. However, the systems in [4] and [25] do not guarantee user data rates leading to the potential degradation of service quality for the users in sleep mode BSs. On the other hand, a grid-based traffic profiling scheme for selecting the best BSs to turn off was proposed in [5]. This system is designed under the framework of wideband code division multiple access (WCDMA)-based 3G systems. Thus, changes in the system modeling approach is required to make it compatible for next generation OFDMA-based systems.

An alternative way of reducing energy utilization, yet little explored, is to turn off the redundant sectors of the under-utilized BSs [9], [26], [27], [28]. Without considering any antenna pattern, [26] and [27] investigated switching off sectors for energy savings. Incorporating antenna pattern, an adaptive sectorization scheme was presented in [28]. However, change of antenna gain with the beamwidth and load-dependent power consumption in BSs are not taken into consideration in [26], [27], [28]. By considering all of these constraints, our work in [9] proposed a centralized traffic-driven energy saving dynamic sectorization technique for multi-cell OFDMA-based networks.

Proposed JDSBS mechanism presented in this paper, for the first time, investigates the joint application of DS and DSBS for energy efficiency. Thus, JDSBS dynamically provisions

cellular access networks by scaling the number of BSs as well as the number of sectors for meeting the traffic demand. A near realistic system model is also reproduced by considering the actual location of users, various user data rates, non-uniform user distributions, a generalized power consumption model of BSs, antenna gain-beamwidths interrelationship and the antenna radiation pattern. In addition, measure is taken for reducing the number of computations and the system model is developed for OFDMA-based cellular systems.

III. NETWORK MODEL

In this section, we present different aspects of the system model, such as the network layout, admission control policy, traffic model, power consumption profile of BSs, antenna pattern, etc. Network model is presented in the context of OFDMA-based LTE systems, which can also be adopted to WiMAX systems. Although in LTE, BSs are named as eNB, both the terms are used interchangeably throughout the paper.

A. Network Layout

We consider the downlink of a multi-cell cellular network serving by a set of BSs $\mathcal{B} = \{\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_{|\mathcal{B}|}\}$ and covering an area $\mathcal{A} = (\mathcal{A}_1 \cup \mathcal{A}_2 \cup ... \cup \mathcal{A}_{|\mathcal{B}|}) \subset \mathbb{R}^2$. Here, $\mathcal{A}_i$ is the coverage area of BS $\mathcal{B}_i$. Let $\mathcal{S}_i$ denotes the number of sectors of BS $\mathcal{B}_i$, which are allocated orthogonal frequency bands resulting in zero intra-cell interference. However, BSs $\mathcal{B}_i$ and $\mathcal{B}_j$, $i \neq j$, reuse the same frequency bands leading to potential inter-cell interference.

B. Power Consumption Model of BSs

Both constant energy consumption (CEC) model [16], [18], [19], [20], [21], [22], [24] [29], [30], [31], [32] and non-energy proportional (NEP) linear power consumption model [4], [5], [17], [25], [27], [33], [34] for BSs are widely used in literature. CEC type BSs consume constant power irrespective of traffic load. Whereas, for NEP type BSs, a load-dependent dynamic power consumption part and a load-independent constant power consumption part together constitute the total operating power. In this paper, we adopt a generalized power consumption model, which can capture a wide range of BSs. For a BS, it is a reasonable assumption that the constant power consumption part scales linearly with the number of sectors [9], [29]. Therefore, the total operating power in $\mathcal{B}_i$ can be given by the following model [4], [9], [25]

$$P_i(t) = \sum_{s=1}^{S_{i,ON}(t)} \left[(1 - \delta_i) L_f^{i,s}(t) P_{i,Op} + \delta_i P_{i,Op} \right] \quad (1)$$

Here, the expression within the square brackets is the operating power of sector s in $\mathcal{B}_i$. Whereas, $0 \leq L_f^{i,s}(t) \leq 1$ and $1 \leq S_{i,ON}(t) \leq \mathcal{S}_i$ are the LF of sth sector and the number of active sectors of $\mathcal{B}_i$ at time t respectively. LF is defined as the ratio of the number of RBs in use to the total number of available RBs [35], [36]. $P_{i,Op} = g_i P_{i,Tx} + h_i$ is the maximum operating power of a fully utilized sector of $\mathcal{B}_i$; where, $P_{i,Tx}$ is the maximum transmit power per sector, and g_i and h_i are constants [4], [29]. While, the parameter $0 \leq \delta_i \leq 1$
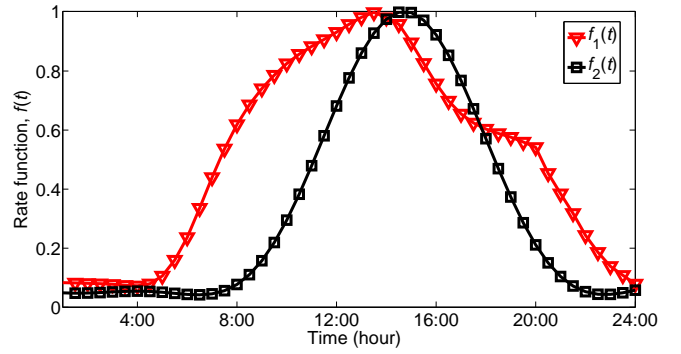

Fig. 1: Rate function [5], [16], [20], [21], [37].

determines the level of dependency of $P_i(t)$ on $L_f^{i,s}$. Thus, based on the value of δ_i, we can model various types of BSs, which fall in three categories - CEC model ($\delta_i = 1$), fully energy proportional (FEP) model ($\delta_i = 0$), and NEP model ($0 < \delta_i < 1$). FEP type does not consume any power at no-load and consumption increases with the load, which is an ideal case and the ultimate target of BS manufacturers.

C. Traffic Model

In this paper, both homogeneous and inhomogeneous traffic generation are considered. In homogeneous case, average traffic generation rate is constant and equal for all BSs. In contrast, traffic generation rate varies both in time and space under inhomogeneous case. We model an inhomogeneous process by multiplying a homogeneous process with a time-varying rate function $0 \leq f(t) \leq 1$ and space varying constant $\alpha_s(l_i) \in [0, 1]$, where $l_i \in \mathcal{A}$ is the location of $\mathcal{B}_i$.

Now, considering a homogeneous traffic generation process with an average rate λ, the rate parameter of the inhomogeneous process for s^{th} sector of $\mathcal{B}_i$ can be written as

$$\lambda_s(l_i, t) = \alpha_s(l_i) f(t - \theta_i) \lambda, \forall i, \forall s \quad (2)$$

In (2), same rate function is assumed for all BSs. Thus, the rate function $f(t)$ changes the time-homogeneous traffic generation process (i.e., the process with parameter λ) into a time-varying time-inhomogeneous process. Two typical rate functions extracted from various articles are shown in Fig. 1 [5], [16], [20], [21], [37]. For mathematically generating the above rate functions, we express these rate functions as a sum of several sinusoidal functions as below

$$f(t) = \sum_{m=1}^{M} c_m sin(d_m t - \tau_m) \quad (3)$$

where c_m, d_m and τ_m are constants, which are determined by using MATLAB curve fitting tool. In this paper, both the rate functions are approximated by the summations of six sinusoids (i.e., $M = 6$). For the sake of brevity, the values of these constants are not presented here.

On the other hand, for a particular sector in a BS, the parameter $\alpha_s(l_i)$ is constant over a day and may vary from weekdays to weekends. Furthermore, by varying the values

of α among the sectors (as well as BSs), both inter-sector and inter-BS space-varying traffic generation can be modeled. Therefore, $\alpha_s(l_i)$ basically scales the rate function $f(t)$, i.e., scales the traffic over an entire day. Also, peak-time and off-peak time variation among BSs can be produced by using different values of $\theta_i \in [0, 24)$ hours for BSs.

D. Resource Block Allocation

Received signal-to-interference-plus-noise-ratio (SINR) at u^{th} UE located in sector s of BS $\mathcal{B}_i$ is given by

$$\gamma_u^{i,s} = \frac{P_{u,Rx}^{i,s}}{\mathcal{I}_{u,intra}^{i,s} + \mathcal{I}_{u,inter}^{i,s} + \mathcal{P}_N} \quad (4)$$

where, $P_{u,Rx}^{i,s}$, $\mathcal{I}_{u,intra}^{i,s}$, $\mathcal{I}_{u,inter}^{i,s}$ and $\mathcal{P}_N$ are the received power, intra-cell interference, inter-cell interference and the thermal noise power respectively. Now, considering adaptive modulation and coding (AMC), received SINR $\gamma_u^{i,s}$ can then be mapped to the spectral efficiency given in bps/Hz [38]

$$\psi_u^{i,s} = \begin{cases} 0 & \text{if } \gamma_u^{i,s} < \gamma_{min} \\ \xi \log_2(1 + \gamma_u^{i,s}) & \text{if } \gamma_{min} \leq \gamma_u^{i,s} < \gamma_{max} \\ \psi_{max} & \text{if } \gamma_u^{i,s} \geq \gamma_{max} \end{cases} \quad (5)$$

where, $0 \leq \xi \leq 1$, γ_{min}, ψ_{max} and γ_{max} are the attenuation factor, minimum SINR, maximum spectral efficiency and the SINR at which ψ_{max} is achieved. Then, the number of required RBs for the UE can be estimated by

$$\beta_u^{i,s} = \left\lceil \frac{R_u^{i,s}}{W_{RB}\psi_u^{i,s}} \right\rceil \quad (6)$$

where, $R_u^{i,s}$ is the required data rate in bps, W_{RB} is the bandwidth per RB in Hz (e.g., 180 kHz in LTE), and $\lceil x \rceil$ is the nearest integer equal to or larger than x.

E. Inter-cell Interference

Due to the network-wide switching and coverage adjustments of BSs as well as the beamwidth alteration in the sectors of each BS and corresponding handover of UEs, inter-cell interference experienced by individual UE may become highly dynamic throughout the network, which is very challenging to keep track. Therefore, for the sake of computational tractability, with the following reasoning, we ignore the dynamic inter-cell interference and consider it as static Gaussian-like noise. Firstly, the time scale of dynamic inter-cell interference is much smaller than the session durations. Secondly, interpreting inter-cell interference as Gaussian-like noise can be considered as the worst case assumption [39], [40]. This assumption is more realistic under the condition when the RBs are randomly assigned to UEs and the information of the assigned RBs to UEs in other BSs is unknown [40]. As explained in Section III-F, we assume no coordination among BSs for RBs assignment to UEs. Moreover, availability of intelligent frequency planning (e.g., fractional and soft frequency reuse, and interference randomization techniques for OFDMA-based systems), which can be accommodated in the system, leads the assumption to a feasible one [4], [25], [42], [43]. Considering

these factors, other energy efficient works also adopted this type of model for inter-cell interference [4], [25], [32], [44][1].

F. Session Admission Control (SAC)

For the analysis of the proposed system, we consider only real-time services requiring constant bit rate (CBR). We assume no queuing and the allocated RBs remain dedicated until the end of a session. As SAC is not our main focus, for the convenience of analysis, a simple first-come/first-served based SAC is adopted in this paper. When a new session request from u^{th} UE arrives in sector s of $\mathcal{B}_i$, based on the data rate requirement and the received power $P_{u,Rx}^{i,s}$ (or SINR $\gamma_{u,Rx}^{i,s}$), number of required RBs $\beta_u^{i,s}$ is estimated using (4)-(6). Information on received signal power at UEs can be gathered from the channel state information (CSI) feedback by UEs, which is supported in both LTE [45] and WiMAX [46] standards. Now, if the number of available RBs in sector s is greater than or equal to $\beta_u^{i,s}$, and at the same time, this sector has sufficient transmit power left for supporting the requested UE, the session is admitted into the system. Otherwise, the session request is rejected. No coordination is considered among BSs for allocating RBs to UEs; which is a low complexity, yet effective technique for limiting the inter-cell interference [41]. Session blocking probability resulting from the unavailability of RBs as well as the session outage probability due to insufficient SINR (i.e., $\gamma_u^{i,s} < \gamma_{min}$) are calculated for guaranteeing QoS requirements.

It is to be noted that although LTE is envisaged to be an all-Internet protocol (IP) network, circuit switch (CS)-type SAC is suitable for analyzing the aforementioned assumed service type. Also, CS-type SCA is widely practised in literatures for evaluating LTE systems [47], [48]. System performance under guaranteed bit rate (GBR) and best effort services is left for our future works. It can be inferred that energy savings for non-CBR services would be higher as UE data rates do not need to be strictly maintained like CBR services. In this sense, use of CBR services in evaluating the system performance can be considered as a conservative approach.

G. Antenna Pattern

Antenna radiation pattern for accounting the attenuation of radio signal due to the non-ideality of antenna can be given as below [38]

$$A(\theta) = -min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right] dB \quad (7)$$

where $-180^0 \leq \theta \leq 180^0$, θ_{3dB} and A_m are the angle between the direction of interest and the antenna boresight, 3dB beamwidth and the maximum attenuation respectively. Omnidirectional and three-sector antennas are more popular

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[1]It is worthwhile to mention that inter-BS coordinated RBs assignments can also be incorporated in the proposed system, which may reduce the inter-cell interference. Consequently, this may result in higher energy savings than that in the non-coordinated case adopted in this paper. Investigation of the system performance under coordinated RB allocations is left for future works.

in practice, and the more recent trend is to develop six-sector antennas [49]. Nevertheless, for investigating all possible configurations, omnidirectional to six-sector antennas are considered. Now, with the decrease (increase) of beamwidth by a factor of two, antenna gain roughly increases (decreases) by 3dB [50], [51]. Thus, for the set of sectors $S = [2\ 3\ 4\ 5\ 6]$, the complete set of θ_{3dB}, A_m and antenna gain can be approximated by, [120 65 55 45 33] deg, [18 20 21 22 23] dB and [13 15 16 17 18] dBi respectively [38], [50], [51]. For an omnidirectional antenna, $A(\theta) = 0$dB [52] and antenna gain equal to 10dBi are taken.

IV. EWMA-BASED LF ESTIMATION

In this paper, we utilize the aggregate network LF as an indicator in triggering the network provisioning operations for distributing traffic. Either the instantaneous or an estimated LF can be used for this purpose. Let N_d be the number of instances per day at which traffic distribution is planned to be attempted. Use of instantaneous LF implies the necessity of gathering network parameters and attempting to distribute traffic at all these N_d instances, which may impose a significant signalling and computational burden. In contrast, from the estimated envelope, it is possible to eliminate a subset of N_d instances *a priori* at which provisioning procedure is not feasible. Thus, unnecessary attempts of network reconfiguring event can be avoided resulting in reduced number of computations. This approach can be more effective under closely correlated traffic patterns in the consecutive days, which is the case in typical cellular mobile networks [5], [6]. In light of this, in this paper, we propose an EWMA-based technique for estimating the LF envelope of an entire day in advance from the historical LF data of the past days. Since, the traffic level differs much from weekdays to weekends, we estimate the weekday (weekend) LF from the weekday (weekend) data. It is to be noted that the estimated LF is used for deciding whether to initiate the traffic distribution event. Whereas, the actual traffic environment (e.g., data rate, locations and received SINR of UEs) is used for the traffic distribution.

Let we want to estimate the LF of the total network for $(N+1)^{th}$ day from the given LF matrix $\mathbf{L} = [\mathbf{L}_1; \mathbf{L}_2; ...; \mathbf{L}_N]$, where $\mathbf{L}_n, n = 1, 2, ..., N$ is a row vector containing the samples of LFs taken over n^{th} day. For achieving the smooth version of LF data by reducing the abruptness, we then apply a robust version of local regression technique using weighted linear least squares on each day [53], which is given as $\widetilde{\mathbf{L}} = [max(\mathbf{L}_1, Sm(\mathbf{L}_1)); max(\mathbf{L}_2, Sm(\mathbf{L}_2)); ...; max(\mathbf{L}_N, Sm(\mathbf{L}_N))] = [\widetilde{\mathbf{L}}_1; \widetilde{\mathbf{L}}_2; ...; \widetilde{\mathbf{L}}_N]$. Here, $Sm(.)$ does the smoothing operation and $max(\mathbf{L}_n, Sm(\mathbf{L}_n))$ takes the sample-wise maximum between $\mathbf{L}_n$ and $Sm(\mathbf{L}_n)$, which increases the probability of not underestimating the envelope. Overestimation can decrease the potential energy savings. However, it is a conservative approach for suppressing the potential false triggering of load distribution procedure at infeasible instances. Then, the moving average $\overline{\mathbf{L}}_{N+1}$, the standard deviation $\overline{\sigma}_{N+1}$ and the estimated LF $\widehat{\mathbf{L}}_{N+1}$ for
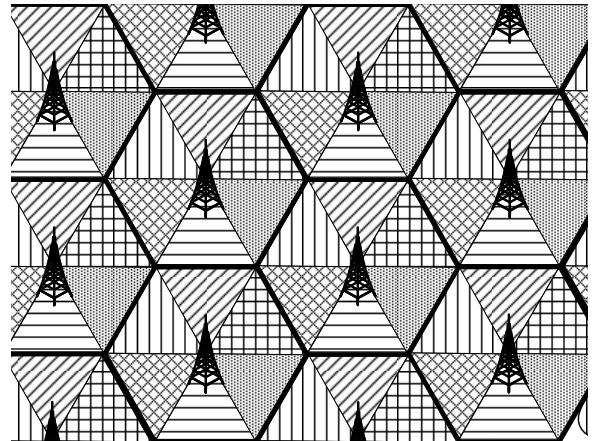
$(N + 1)^{th}$ day are given by [5], [54]

$$\overline{\mathbf{L}}_{N+1} = (1 - \beta)\overline{\mathbf{L}}_N + \beta\widetilde{\mathbf{L}}_N \tag{8}$$
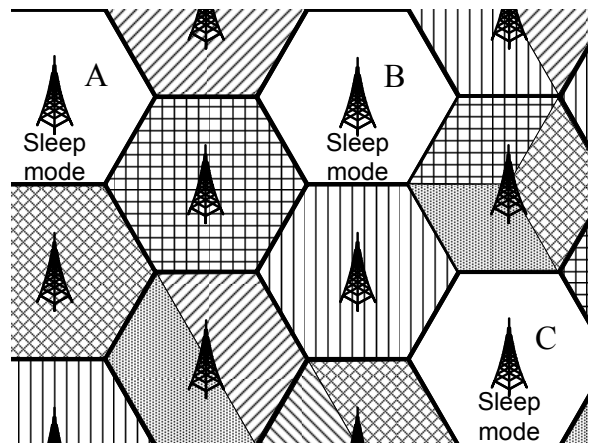
$$\overline{\sigma}_{N+1} = (1 - \gamma)\overline{\sigma}_N + \gamma|\overline{\mathbf{L}}_N - \widetilde{\mathbf{L}}_N| \tag{9}$$

$$\widehat{\mathbf{L}}_{N+1} = \overline{\mathbf{L}}_{N+1} + \xi\ \overline{\sigma}_{N+1} \tag{10}$$

where, $0.2 \leq \beta, \gamma \leq 0.3$ are smoothing constants [54]. In this paper, $\beta = \gamma = 0.2$ are used. Here, ξ is another constant usually taken equal to 3 [54]. At the end of each day, LF database used for estimation is updated by appending the actual LF data of the day and deleting that of the oldest day.

(a) Peak traffic time. All BSs and sectors are in active mode.

(b) Low traffic time. Some BSs (A, B and C) and sectors are in sleep mode.

Fig. 2: Concept of two-dimensional network provisioning. Each pattern corresponds to an orthogonal frequency band.

V. PROPOSED TWO-DIMENSIONAL NETWORK PROVISIONING MODEL

Despite the inherent high degree temporal-spatial diversity in traffic generation, existing cellular networks are provisioned based on the peak-traffic time and all RAN equipment is left into active mode for all time. In conjunction with this provisioning approach, non-load proportional energy consumption

in contemporary BSs leads to a significant waste of electrical energy. Therefore, the energy-efficient two-dimensional dynamic network provisioning JDSBS mechanism is proposed in this paper. Proposed scheme adaptively adjusts the number of BSs as well as the number of sectors in each BS for maximizing energy savings[2].

The basic concept of the network operation under JDSBS technique is illustrated in Fig. 2. The patterns shown in the figure represent the coverage areas of sectors corresponding to the different orthogonal frequency bands. In this example, it is assumed that the original network is provisioned to have $\mathcal{S}_i = 6, \forall i$ sectors. As shown, during peak traffic times, all BSs and all the six sectors in each BS are in active mode. On the other hand, during low traffic period, several BSs (e.g., A, B and C) are switched into sleep mode, while most of the active BSs are operated with only one or two sectors and thus, energy savings is achieved. Under DS scheme, the total coverage area of a BS does not change (i.e., the cell radius is left unchanged), rather the antenna transmission beamwidth of the remaining active sectors are expanded to cover the sleep mode sectors. In contrast, in case of DSBS, the transmission beamwidth of the sectors are left unchanged. Whereas, the coverage distance of the corresponding sectors are extended (not shown in the figure for clarity) for covering the area of the neighboring sleep mode BSs.

BSs are assumed to be capable in switching between active mode and sleep mode. An active mode BS has the full functionality as of conventional BSs. In contrast, a sleep mode BS neither carries any user traffic nor performs any control signaling. However, a sleep mode BS can intercept any wake-up request upon receiving which it can switch to active mode. We further assume that each BS is equipped with the apparatus and control circuitry for dynamically reconfiguring them with various number of sectors and transmission ranges. Sharing of RBs and transmit power among the active sectors of a BS is also considered. In addition, users are assumed stationary for the duration of network provisioning procedures. Also, downlink power allocation is considered to maintain minimum signal strength at the user terminals for service continuity.

A. Problem Formulation

Proposed network provisioning is carried out periodically in every T time units, while T is an adjustable parameter. However, the initialization of this provisioning process depends on the estimated LF of the total network. Let $\widehat{L}_{net}(t)$ be the estimated LF at time t. In every T time, $\widehat{L}_{net}$ is checked against a certain LF threshold L_{th}. If $\widehat{L}_{net}(t) < L_{th}$, only after then the network provisioning is initiated. Now, the goal of JDSBS is to maximize the energy savings by minimizing both the number of active BSs and the number of sectors in these BSs. Therefore, we have to evaluate two optimal sets: the set of active BSs $\mathcal{B}_{ON} = \{\mathcal{B}_1^*, \mathcal{B}_2^*, ..., \mathcal{B}_{|\mathcal{B}_{ON}|}^*\} \subseteq \mathcal{B}$ and

the set of active sectors $\mathbf{S}_{ON} = \{\mathbf{S}_1, \mathbf{S}_2, ..., \mathbf{S}_{|\mathcal{B}_{ON}|}\}$. Here, $\mathbf{S}_i = \{s_1, s_2, ..., s_{|\mathbf{S}_i|}\} \subseteq \mathbf{S}_{i,all} = \{1, 2, ..., \mathcal{S}_i\}$ is the set of active sectors in $\mathcal{B}_i$. Thus, we can formulate the following optimization problem

$$\underset{\substack{\{\mathcal{B}_1^*, \mathcal{B}_2^*, ..., \mathcal{B}_{|\mathcal{B}_{ON}|}^*\} \\ \{\mathbf{S}_1, \mathbf{S}_2, ..., \mathbf{S}_{|\mathcal{B}_{ON}|}\}}}{\arg\min} \sum_{i \in \mathcal{B}_{ON}} \sum_{s \in \mathbf{S}_i} \Big[(1 - \delta_i) L_f^{i,s}(t) P_{i,Op}$$
$$+ \delta_i P_{i,Op} \Big] \quad (11)$$

$s.t.,$

$$P_{i,b}(t) \leq P_b^{Th}, \forall i \in \mathcal{B}_{ON}, \forall t \quad (12)$$

$$P_{i,out}(t) \leq P_{out}^{Th}, \forall i \in \mathcal{B}_{ON}, \forall t \quad (13)$$

$$R_u^{(a)}(t) \geq R_u, u = 1, 2, ..., \sum_{i=1}^{|\mathcal{B}|} \sum_{s=1}^{\mathcal{S}_i} U_s(l_i, t), \forall t \quad (14)$$

$$\bigcup_{i \in \mathcal{B}_{ON}} \bigcup_{s \in \mathbf{S}_i} \mathcal{A}_{i,s}(t) = \mathcal{A}, \forall t \quad (15)$$

$$\sum_{s \in \mathbf{S}_i} \sum_{u=1}^{U_s(l_i, t)} \beta_u^{i,s}(t) \leq \sum_{s \in \mathbf{S}_i} \beta_{Tot}^{i,s}(t), \forall i \in \mathcal{B}_{ON}, \forall t \quad (16)$$

$$\sum_{s \in \mathbf{S}_i} \sum_{u=1}^{U_s(l_i, t)} P_u^{i,s}(t) \leq \sum_{s \in \mathbf{S}_i} P_{i,Tx}, \forall i \in \mathcal{B}_{ON}, \forall t \quad (17)$$

Here, $P_{i,b}(t)$ and $P_{i,out}(t)$ are session blocking and session outage probabilities in $\mathcal{B}_i$ respectively; P_b^{Th} and P_{out}^{Th} are the target blocking and outage probabilities respectively; $R_u^{(a)}(t)$ and R_u are the uth UE's achievable data rate and the required data rate respectively; $\mathcal{A}_{i,s}$ is the coverage area of sector s; $P_u^{i,s}(t)$ is the downlink transmit power for u^{th} UE; and $U_s(l_i, t)$ and $\beta_{Tot}^{i,s}$ are the total number of UEs and RBs in sector s of $\mathcal{B}_i$ respectively. Constraints (12) and (13) respectively guarantee the session blocking and outage probabilities are within QoS limits; while, (14) and (15) ensure the data rate for UEs and the network coverage respectively. Finally, (16) and (17) correspond to the constraints that the required total number of RBs and total transmit power in BSs can not exceed their maximum limits.

B. Solution Approach

For given sets $\mathcal{B}_{ON}$ and $\mathbf{S}_{ON}$, the objective function in (11) is convex in $L_f^{i,s}, \forall i, \forall s$. However, for variable $\mathcal{B}_{ON}$ and $\mathbf{S}_{ON}$, it turns to be nonconvex becoming a highly challenging combinatorial problem with a large search space $\mathcal{O}(2^{\sum_{i=1}^{\mathcal{B}_i} \mathcal{S}_i})$. Moreover, by reducing any instance of the minimal dominating set (MDS) problem to the above optimization problem, it can be proved that the problem is NP-hard with a computational complexity of $\mathcal{O}(N_U 2^{N_B N_S})$ [55]. Here, N_B, N_S and N_U are the number of BSs, sectors in each BS and UEs of the network respectively. For the sake of brevity, we omit the detailed proof.

For reducing the complexity, a sequential approach is taken under which the JDSBS problem is divided into two sub-problems by decoupling DS and DSBS in time-domain. This implies that at every instance of network provisioning, either

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[2]It is to be noted that the proposed two-dimensional network provisioning technique is developed independent of underlying network settings, such as network layout, traffic model, BS power model, SAC policy, interference model, LF estimation technique, etc.

TABLE I: Algorithmic framework for JDSBS

1:	Set $\mathcal{B}_{ON} = \mathcal{B}$ and $\mathbf{S}_{ON} = \left\{ \mathcal{S}_{1,all}, \mathcal{S}_{2,all}, ..., \mathcal{S}_{|\mathcal{B}|,all} \right\}$
2:	**For JDSBS-I scheme:**
3:	Perform DSBS $\forall \mathcal{B}_i \in \mathcal{B}$ and update $\mathcal{B}_{ON}$
4:	Perform DS $\forall \mathcal{B}_i \in \mathcal{B}_{ON}$ and update $\mathbf{S}_{ON}$
5:	**For JDSBS-II scheme:**
6:	Perform DS $\forall \mathcal{B}_i \in \mathcal{B}$ and update $\mathbf{S}_{ON}$
7:	Perform DSBS $\forall \mathcal{B}_i \in \mathcal{B}$ and update $\mathcal{B}_{ON}$

of these DS and DSBS is carried out first for the entire network followed by the other. Computational complexity of the proposed JDSBS algorithm is $\mathcal{O}(N_U N_B N_S^2)$ (algorithms for both DS and DSBS sub-problems are presented in the following sections). Now, based on the sequence in which DS and DSBS are applied, following two variants of JDSBS are investigated. The algorithmic framework for JDSBS problem is also presented in Table I.

1) JDSBS-I: At every instance when the network is provisioned, first DSBS is applied to reconfigure the network with minimum number of BSs. Then, DS is employed for switching the redundant sectors in the active BSs into sleep mode.

2) JDSBS-II: The order of applying DSBS and DS is opposite to that in JDSBS-I. That means, first DS is employed followed by DSBS.

Instead of sequential approach, an integrated approach can also be used. In this alternative approach, for each BS, both DS and DSBS have to be executed first. Then, the same procedure has to be repeated for the next BS until the last one. Investigation of this integrated approach has been left for future works. Moreover, an iterative procedure, where DS and DSBS will be executed repeatedly until convergence occurs, can be worth investigation. Studies for both of these approaches are left for future works.

VI. DS PROBLEM

In this section, we present a DS technique, which aims at minimizing energy utilization by adaptively adjusting the number of active sectors in each BS with the time and space varying traffic generation. When a sector is switched off, transmission beamwidth of the remaining active sectors are widened to prevent any coverage hole and vice versa. Necessary power adjustments are made in the active sectors, while they are also allowed to share their unused power among each other. In addition, since the power in a sector now radiates over a larger area, antenna gain is decreased accordingly as discussed in Section III-G.

Without specifying a particular technique for implementing DS, here below we discuss the potential solutions. A simple and robust technique for implementing DS is to use adaptive smart antenna technology employing linear antenna arrays [56]. Main beam of this antenna array can be steered and shaped as desired for covering a sector of desired size by adjusting the length and the spacing of the array elements as well as the phase of their input currents. However, with the state of the art antenna technology, it may not be feasible

to achieve fast enough dynamic adjustments of the length and the spacing of the array elements. Alternatively, BSs can be equipped with multiple sets of antennas, where each set corresponds to a certain number of sectors. Based on the required sector configuration, corresponding set can be activated leaving others inactive. The benefit of energy savings from this technique will come at the expense of additional cost for installing various sets of antennas. On the other hand, the most recent development of reconfigurable beam antennas for BSs with beam panning (shifting of antenna beam to a targeted direction) and beam fanning (shrinking or expanding beamwidth) capability also backs the proposed DS as a practically realizable scheme [49].

A. Problem Formulation

The objective of the DS problem is to employ the optimum set of sectors in all BSs $\mathbf{S}_{ON} = \{\mathbf{S}_1, \mathbf{S}_2, ..., \mathbf{S}_{|\mathcal{B}|}\}$ resulting a minimum operating power (i.e., maximum energy savings), while maintaining QoS. Therefore, following optimization problem can be formulated

$$\underset{\mathbf{S}_1, \mathbf{S}_2, ..., \mathbf{S}_{|\mathcal{B}|}}{\arg\min} \sum_{i=1}^{|\mathcal{B}|} \sum_{s \in \mathbf{S}_i} \left[(1 - \delta_i) L_f^{i;s}(t) P_{i,Op} + \delta_i P_{i,Op} \right] \quad (18)$$

$s.t.,$

$$P_{i,b}(t) \leq P_b^{Th}, i = 1, 2, ..., |\mathcal{B}|, \forall t \quad (19)$$

$$P_{i,out}(t) \leq P_{out}^{Th}, i = 1, 2, ..., |\mathcal{B}|, \forall t \quad (20)$$

$$R_u^{(a)}(t) \geq R_u, u = 1, 2, ..., \sum_{i=1}^{|\mathcal{B}|} \sum_{s=1}^{\mathcal{S}_i} U_s(l_i, t), \forall t \quad (21)$$

$$\bigcup_{s \in \mathbf{S}_i} \mathcal{A}_{i,s}(t) = \mathcal{A}_i, i = 1, 2, ..., |\mathcal{B}|, \forall t \quad (22)$$

$$\sum_{s \in \mathbf{S}_i} \sum_{u=1}^{U_s(l_i,t)} \beta_u^{i,s}(t) \leq \sum_{s \in \mathbf{S}_i} \beta_{Tot}^{i,s}, i = 1, 2, ..., |\mathcal{B}|, \forall t \quad (23)$$

$$\sum_{s \in \mathbf{S}_i} \sum_{u=1}^{U_s(l_i,t)} P_u^{i,s}(t) \leq \sum_{s \in \mathbf{S}_i} P_{i,Tx}, i = 1, 2, ..., |\mathcal{B}|, \forall t \quad (24)$$

B. DS Algorithm

Once again, due to the variable $\mathbf{S}_{ON}$, above optimization problem in (18) is nonconvex combinatorial problem having $\mathcal{O}(2^{\sum_{i=1}^{|\mathcal{B}|} \mathcal{S}_i})$ possible cases. Number of cases increases exponentially with the number of BSs and their sectors, becoming very big, specially when the number of BSs and sectors are large. Therefore, in this paper, we propose a low complexity centralized greedy style heuristic algorithm.

Proposed DS algorithm employs a two-level triggering to initialize the traffic distribution process for associating UEs with the reduced number of sectors. First, if $\widehat{L}_{net}(t) < L_{th}$, the network initializes the event. Thereafter, each BS uses its own criterion for initializing the event for itself. The algorithm takes one BS at a time, say, $\mathcal{B}_i = \mathcal{B}_1$ and assumes that all $\mathcal{S}_i = \mathcal{S}_1$ sectors are active, i.e., $\mathbf{S}_i = \mathbf{S}_{i,all}$. Let $L_i(t)$ be the actual LF of $\mathcal{B}_i$ at time t. Now, if $L_i(t) < (\mathcal{S}_i - 1)/\mathcal{S}_i$, traffic distribution by associating UEs with the reduced number of

1:	**If** $\widehat{L}_{net}(t) < L_{th}$
2:	**For** $i = 1$ to $|\mathcal{B}|$
3:	Initialize: $\mathbf{S}_i = \mathbf{S}_{i,all}, n_i = |\mathbf{S}_i|$
4:	**If** $L_i(t) < (n_i - 1)/\mathcal{S}_i$
5:	Find $\mathbf{S}_i^* = \{s_1^*, s_2^*, ..., s_{n_i}^*\}$ reordering $\mathbf{S}_i$
	s.t., $L_m^* \geq L_n^*, m > n$
6:	Set $q = 1$
7:	Associate all $U_{s_q^*}(l_i, t)$ UEs with the other
	sectors $\mathbf{S}_i \setminus \{s_q^*\}$ and calculate $U_{i,DS}(t)$
8:	**If** (19)-(24) are met and $U_{i,DS}(t) < \eta_{DS}$
9:	Set $\mathbf{S}_i = \mathbf{S}_i \setminus \{s_q^*\}$ and $n_i = n_i - 1$
10:	**Else** Set $q = q + 1$
11:	**If** $q <= n_i$, Go to Step 7, **End If**
12:	**End If**
13:	**If** $n_i > 1$, Go to Step 4, **End If**
14:	**End If**
15:	**End For**
16:	**End If**

sectors is triggered. At first, $\mathcal{S}_i$ sectors of $\mathcal{B}_i$ are ordered in the ascending order of their LFs. Then the algorithm iteratively eliminates sectors from $\mathbf{S}_i$ one-by-one starting from the sector with the lowest LF. This policy of imposing the higher priority to the sectors with lower LFs in distributing traffic reduces the number of intra-cell handoffs. Each time the algorithm is successful in associating UEs of one sector (say, sector s), utility function $U_{i,DS}(t) = P_i^{(s-)}(t)/P_i^{(s+)}(t)$ is evaluated, where $P_i^{(s+)}$ and $P_i^{(s-)}$ are the operating power of $\mathcal{B}_i$ with and without sector s respectively. Now if (19)-(24) are met and $U_{i,DS}(t) < \eta_{DS}$ ($\eta_{DS} \in [0,1]$), then sector s is removed from $\mathbf{S}_i$. Here, $U_{i,DS}(t) < 1$ implies a potential of saving energy from switching sector s into sleep mode.

Iteration continues as long as $L_i(t) < (n_i - 1)/\mathcal{S}_i$ and $n_i > 1$, where n_i is the number of active sectors from the last iteration. Sectors in the final $\mathbf{S}_i$ are kept active with essential beamwidth adjustments. Other sectors in $\mathbf{S}_{i,all} \setminus \mathbf{S}_i$ are switched to sleep mode. The algorithm then proceeds to the next BS $\mathcal{B}_{i+1}$, evaluates $\mathbf{S}_{i+1}$ and continues to the last BS. Pseudo code of the DS algorithm is presented in Table II.

VII. DSBS Problem

This section presents a mechanism for the DSBS sub-problem, which performs the dynamic energy efficient provisioning of cellular networks by switching BSs between active and sleep modes. Depending on the instantaneous traffic level, the locations and the number of sleep mode BSs are adjusted adaptively. Remaining active BSs adjust their coverage for providing service to UEs located in the sleep mode BSs. Power adjustments are made in the corresponding sectors for maintaining the extended coverage. Once again, power sharing is allowed among the sectors of an active BS.

A. Problem Formulation

The goal of DSBS problem is to evaluate the optimum set of active BSs $\mathcal{B}_{ON} = \{\mathcal{B}_1^*, \mathcal{B}_2^*, ..., \mathcal{B}_{|\mathcal{B}_{ON}|}^*\} \subseteq \mathcal{B}$ consuming a minimum operating power. QoS is also guaranteed by the active BSs. The optimization problem is presented as below

$$\underset{\{\mathcal{B}_1^*, \mathcal{B}_2^*, ..., \mathcal{B}_{|\mathcal{B}_{ON}|}^*\}}{\arg \min} \sum_{i \in \mathcal{B}_{ON}} \sum_{s=1}^{\mathcal{S}_i} \left[(1 - \delta_i) L_f^{i,s}(t) P_{i,Op} \right.$$
$$\left. + \delta_i P_{i,Op} \right] \quad (25)$$

$s.t.,$

$$P_{i,b}(t) \leq P_b^{Th}, \forall i \in \mathcal{B}_{ON}, \forall t \quad (26)$$

$$P_{i,out}(t) \leq P_{out}^{Th}, \forall i \in \mathcal{B}_{ON}, \forall t \quad (27)$$

$$R_u^{(a)}(t) \geq R_u, u = 1, 2, ..., \sum_{i \in \mathcal{B}_{ON}} \sum_{s=1}^{\mathcal{S}_i} U_s(l_i, t), \forall t \quad (28)$$

$$\bigcup_{i \in \mathcal{B}_{ON}} \mathcal{A}_i(t) = \mathcal{A}, \forall t \quad (29)$$

$$\sum_{s=1}^{\mathcal{S}_i} \sum_{u=1}^{U_s(l_i,t)} \beta_u^{i,s}(t) \leq \sum_{s=1}^{\mathcal{S}_i} \beta_{Tot}^{i,s}(t), \forall i \in \mathcal{B}_{ON}, \forall t \quad (30)$$

$$\sum_{s=1}^{\mathcal{S}_i} \sum_{u=1}^{U_s(l_i,t)} P_u^{i,s}(t) \leq \sum_{s=1}^{\mathcal{S}_i} P_{i,Tx}, \forall i \in \mathcal{B}_{ON}, \forall t \quad (31)$$

B. DSBS Algorithm

Using the similar logic as in JDSBS, the objective function in (25) is nonconvex for a variable $\mathcal{B}_{ON}$. Thus, the optimization becomes a combinatorial problem with a large search space $\mathcal{O}(2^{|\mathcal{B}_{ON}|})$. Therefore, we again propose a centralized greedy style heuristic algorithm. Same as DS, proposed algorithm for DSBS also utilizes a two-level triggering. Once again, if $\widehat{L}_{net}(t) < L_{th}$, the network itself triggers the network provisioning procedure followed by another triggering operation by each BS in its turn.

1) BS Switching Policy: For deciding on a BS whether to switch to sleep mode, proposed algorithm starts with the initialization $\mathcal{B}_{ON} = \mathcal{B}$. It then takes one BS at a time (say, $\mathcal{B}_i$) and checks its $L_i(t)$. If $L_i(t) < L_{th}$, $\mathcal{B}_i$'s UE distribution process is triggered. Using one of the policies explained below in Section VII-B2, all UEs of $\mathcal{B}_i$ is distributed by associating them with the neighboring BSs. Following utility function is then evaluated

$$U_{i,BS}(t) = \sum_{l=1}^{\mathcal{L}} P_l^{(+)}(t) / \left\{ P_i(t) + \sum_{l=1}^{\mathcal{L}} P_l(t) \right\} \quad (32)$$

where, $\mathcal{L}$ is the number of BSs to which UEs of $\mathcal{B}_i$ would be associated, and $P_l(t)$ and $P_l^{(+)}(t)$ are the total operating power of lth neighbors before and after this association respectively. If utility $U_{i,BS}(t) < \eta_{BS}$ ($\eta_{BS} \in [0,1]$ is a constant) and (26)-(31) are met at the same time, then we set new $\mathcal{B}_{ON} = \mathcal{B}_{ON} \setminus \{\mathcal{B}_i\}$. Here, $U_{i,BS}(t) < 1$ implies potential energy savings from switching $\mathcal{B}_i$ into sleep mode. The algorithm continues with the next BS, updates $\mathcal{B}_{ON}$ and so on. After finishing with all BSs, final $\mathcal{B}_{ON}$ provides the list of BSs,

TABLE III: DSBS algorithm

1:	**If** $\widehat{L}_{net}(t) < L_{th}$
2:	Initialize: $\mathcal{B}_{ON} = \mathcal{B}, i = 1$
3:	**If** $L_i(t) < L_{th}$
4:	Associate all UEs of $\mathcal{B}_i$ with BSs in $\mathcal{B}_{i,a}^*$
5:	Calculate $U_{i,BS}(t)$ for $\mathcal{B}_i$
6:	**If** (26)-(31) are met and $U_{i,BS}(t) < \eta_{BS}$
7:	Set $\mathcal{B}_{ON} = \mathcal{B}_{ON} \setminus \{\mathcal{B}_i\}$ and $i = i + 1$
8:	**Else** Set $i = i + 1$
9:	**End If**
10:	**If** $i \le |\mathcal{B}|$, Go to Step 3
11:	**Else** Stop the algorithm
12:	**End If**
13:	**End If**
14:	**End If**

which are kept in active mode and the other BSs $\mathcal{B} \setminus \mathcal{B}_{ON}$ are switched into sleep mode.

2) UE Association Policy: Let $\mathcal{B}_{i,a} = \{\mathcal{B}_{i,1}, \mathcal{B}_{i,2}, ..., \mathcal{B}_{i,N}\}$ be the set of neighboring active BSs of $\mathcal{B}_i$, where N is the number of active neighbors. For the sequence of neighbors in $\mathcal{B}_{i,a}$ following which they are approached for associating a UE of $\mathcal{B}_i$, various BS selection schemes can be investigated [57]. For the sake of brevity, following two schemes are considered:

● *SINR-based:* Under this scheme, a UE is associated with the BS providing the highest SINR. The BS has to have available RBs and transmit power for supporting the UE, otherwise the BS with the next highest SINR is approached and so on. Thus, if $\mathcal{B}_{i,a}^* = \{\mathcal{B}_{i,1}^*, \mathcal{B}_{i,2}^*, ..., \mathcal{B}_{i,N}^*\}$ is the resequenced $\mathcal{B}_{i,a}$, then $SINR_{i,p}^* \ge SINR_{i,q}^*, p < q$. Here, $SINR_{i,p}^*$ is the received SINR at the UE from BS $\mathcal{B}_{i,p}^*$.

● *Sequence-based:* In this case, $\mathcal{B}_{i,a}$ is reordered in the ascending order of operator-predefined BS IDs. That means, BSs with the lower ID is given a higher priority for associating a UE, i.e., $\mathcal{B}_{i,p}^* > \mathcal{B}_{i,q}^*, p > q$.

Remarks: It is worth noting that in LTE, primary synchronization channel (P-SCH) and secondary synchronization channel (S-SCH) signals are used by a UE to carry out cell search for detecting its serving BS ID as well as the neighbor BSs' IDs [10]. We assume that a UE is capable to detect the IDs of its serving as well as the adjacent BSs, and feedbacks to the central coordinator via its serving BS. Many cell searching algorithms are available in literature [58], discussion of which is beyond the scope of this paper. Also, as stated earlier, the CSI feedback facility in LTE [45] and WiMAX [46] standards can be used for collecting SINR data at UEs.

VIII. RESULTS AND DISCUSSIONS

A. Evaluation Setup

We evaluate the proposed JDSBS mechanism through extensive simulations. For each data point, we average the simulation results from 300 iterations. Although the technique is applicable for any cell layout, for the convenience of creating a benchmark for comparison with other similar works,

hexagonal layout is chosen for simulations. Simulated network is served by 64 BSs having an inter-site distance equal to $\sqrt{3} \times 500$m, while the cells are approximated by circles. BSs are arranged in eight rows each having eight BSs, which are numbered along each row incrementing from left to right, then continuing along the next row and so on. Thus, the BS in the left top corner is indexed as 1, while the one in the right bottom has the index 64. Carrier frequency = 2GHz, channel bandwidth per sector = 5MHz (i.e., 25 RBs) and BS transmit power per sector = 40dBm are assumed. WINNER+ non-line-of-sight (NLOS) urban macro-cell channel model is adopted, which gives a path loss $P_L = 138.4 + 35.74 log_{10}(d)$ with antenna height $h_{BS} = 25$m and $h_{UE} = 1.5$m for BS and UE respectively [59]. Shadow fading parameter $\sigma = 8$dB, penetration loss 10dB [60] 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; noise figure = 9dB (5dB) for UE (BS) are chosen in reference to the 3GPP LTE suggestions [38].

We consider three classes of real-time services of data rates equal to 512kbps, 768kbps and 1024kbps, which include packet headers and payloads. LTE Frequency division duplexing (FDD) frame structure is considered. New sessions arrive following a Poisson process with arrival rate λ. For a fair comparison and without losing the generality, a constant session duration equal to 3 minutes is used for all classes. Both uniform and Gaussian distribution of UEs in the cells are considered, while in the second case, more UEs are concentrated near the BS. Unless otherwise specified, $P_b^{th} = 1\%, P_{out}^{th} = 1\%, L_{th} = 1, \eta_{DS} = \eta_{BS} = 1,$ $\alpha_s(l_i) = 1, \delta_i = 0.7, \mathcal{S}_i = 6, \{g_i = 21.45, h_i = 354.44\}$ [29], $\forall i = 1, 2, ..., |\mathcal{B}|, \forall s$, uniformly distributed UEs, *SINR-based* scheme for UE associations and homogeneous session generation are used for the presented results. Also, instead of calculating $A(\theta)$ for each UE explicitly, an approximate average value equal to -3dB is used for multi-sector antennas. Other antenna parameters are configured as discussed in Section III-G. Sleep mode power consumption in BSs is considered insignificant. Moreover, due to the use of the inbuilt signalling facilities in the networks and the provision of optical backhaul link from BSs to the central coordinator having a very low energy requirement (~1pJ/bit/m [61]), signaling energy cost compared to that of the total network is assumed negligible.

B. Impact of UE Association Policies

First, we examine the impact of the outlined UE association policies on the system performance. Fig. 3 presents the percentage of sleep mode BSs and sectors under the JDSBS-I scheme. It is identified that in the low traffic region (e.g., $\lambda < 0.025$), lower number of BSs can switch to sleep mode in *SINR-based* policy than that in the predefined *sequence-based* policy, while vice versa for the case of sleep mode sectors. This can be explained as below: *SINR-based* policy has the higher probability in associating UEs with all the surrounding BSs resulting in reduced chance for many of the neighbors to
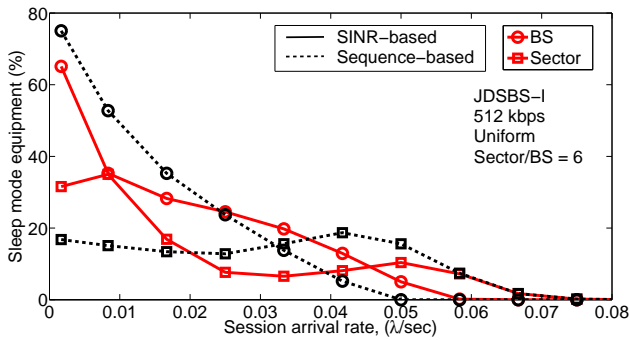
Fig. 3: Sleep mode equipment with user association policies.

Fig. 4: Energy saving performance with user association policies.

Fig. 5: Energy saving performance with user distributions.

switch into sleep mode. On the other hand, *sequence-based* policy associates UEs based on the neighbor ID. Therefore, it has the higher probability to associate UEs to a smaller subset of neighbors leading to a higher probability for the other neighbors in switching into sleep mode. However, for the higher traffic region, this subset of neighbors can be equal to the set of the neighboring active BSs and correspondingly, the difference between the two policies diminishes with the increase of λ. In contrast, for higher λ region, *SINR-based* policy is benefited from the fact that for higher received SINR, lower number of RBs (and hence lower transmit power) is required for supporting UEs leading to the requirement of fewer active BSs, i.e., higher number of BSs in sleep mode.

In JDSBS-I, DSBS is carried out first leading to the increase of traffic in the remaining active BSs. Therefore, the opportunity to switch sectors into sleep mode from the subsequent application of DS is reduced. Thus, the higher the number of sleep mode BSs, the lower the number of sleep mode sectors, which is also evident from the figure. Notably, a slight increase in the sleep mode sectors is observed in the higher traffic region followed by a slow drop to zero. This is due to the fact that during high traffic times, fewer BSs can switch into sleep mode leaving slightly higher unused capacity, which is used by DS for switching more sectors into sleep mode.

Despite the large disparity between the two UE association policies in terms of sleep mode BSs and sectors over the entire range of λ, overall energy savings from both these policies are very close as shown in Fig. 4. From Fig. 3, it is clearly seen that for both the policies, lower number of sleep mode sectors is compensated by a higher number of sleep mode BSs and vice versa. Consequently, the two policies generate almost equal energy savings.

C. Impact of UE Distribution and Data Rates

Energy saving performance of the system with both the uniform and the Gaussian distributed UEs is illustrated in Fig. 5. For the comparison purpose, savings by DS and DSBS alone are also included in the figure. The observed better energy saving performance of DS over DSBS is the direct consequence of better spatial granularity of DS. On top of this, as DS redistributes UEs to the other sectors of the same BS requiring nearly equal radio resources (i.e., RBs and transmit
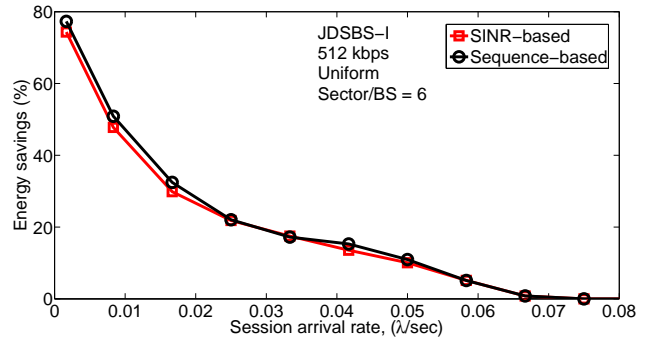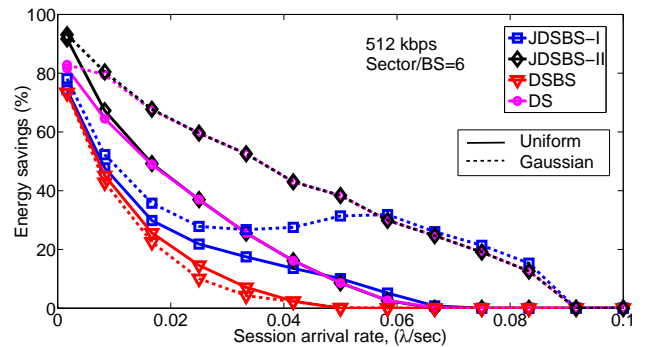
power) of the original sector, a higher number of TRX chains can be switched off leading to higher energy savings than in DSBS.

Now, from the figure, it is found that except DSBS scheme, other three schemes can extract higher energy savings having the Gaussian distributed UEs than that of with uniform distribution. In case of Gaussian distribution, higher number of UEs are located near BSs, which experience lower path loss. Therefore, under DS, many UEs require less amount of radio resources and thus, satisfactory QoS can be provided by fewer active sectors leading to a higher savings than that in uniform distribution case. However, for DSBS scheme, UEs of the switched off BSs are associated with BSs further than the original serving BSs. Thus, in a Gaussian case, as more UEs are concentrated near BSs, a higher amount of radio resources is required than that in uniform distribution case. The consequence is the reduced number of sleep mode BSs and less energy savings under Gaussian case. Despite these two opposing facts, because of the dominance of DS over DSBS, JDSBS generates higher savings under both the uniform and Gaussian distributed cases.

On the other hand, diminishing energy savings with the rise of λ is observed in all the cases except JDSBS-I scheme. The slight increase of energy savings in the higher traffic region for JDSBS-I under Gaussian distribution is due to the increase in the number of sleep mode sectors as explained in Fig. 3. It is also identified that DS can achieve nearly equal savings of
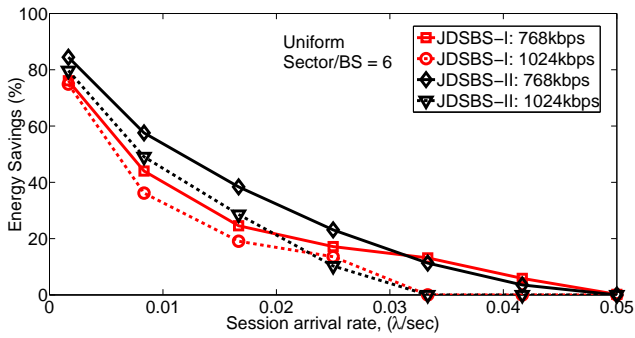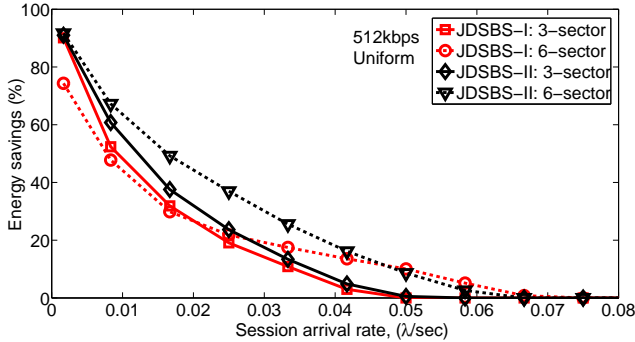
Fig. 6: Energy saving performance with data rates.

Fig. 8: Energy saving performance with BS power profile.

Fig. 7: Energy saving performance with number of sectors.
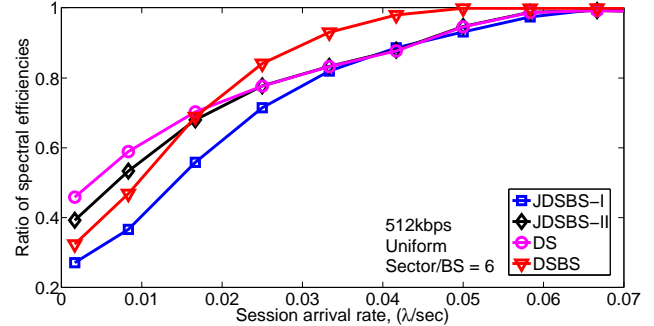
Fig. 9: Ratio of the spectral efficiency under the proposed mechanism to that of the original network.

JDSBS-II except the very low traffic region. This is because, in JDSBS-II, DS is carried out first and thus, the remaining active sectors become nearly fully loaded for $\lambda > 0.01$, beyond which almost no BS can switch into sleep mode. It is also clear from the figure that the proposed JDSBS-II mechanism can outperform the individual application of DS and DSBS schemes.

Fig. 6 demonstrates the impact of UE data rates on the achievable energy savings. It is evident that higher savings is possible for a network having UEs with lower data rate requirement. For example, at $\lambda = 0.02$, JDSBS-I can achieve around 28% (Fig. 4), 22% and 17% energy savings for 512kbps, 768kbps and 1024kbps respectively. For higher data rates, higher number of RBs and thus, higher amount of transmit power are required. These two constraints together increase the session blocking and outage probabilities, and hence, more BSs as well as more sectors are required to keep in active mode for maintaining QoS resulting in reduced energy savings.

D. Impact of the Number of Sectors and Power Profile of BSs

Energy saving performance for a network having 3-sector BSs is presented in Fig. 7. For the convenience of visualizing the impact of the number of sectors per BS, energy savings from 6-sector BSs is also repeated in this figure. Higher number of sectors provide higher number of options for associating UEs to the other sectors and BSs, which increases the probability of switching sectors as well as BSs into sleep
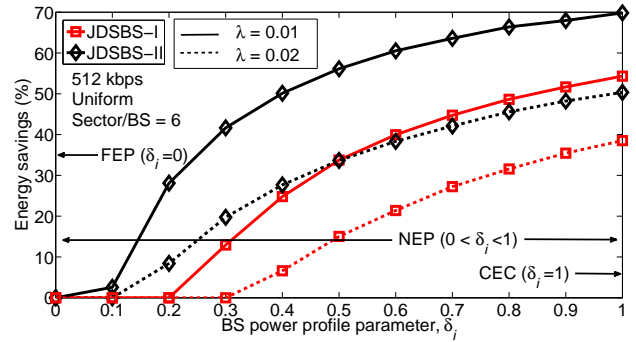
mode. Thus, with the increase of number of sectors per BS, energy savings increases. For instance, at $\lambda = 0.02$, energy saving from JDSBS-II is equal to 32% and 44% for 3-sectored and 6-sector BSs respectively.

Impact of BS power profile parameter δ_i on net energy savings for two different settings of λ is depicted in Fig. 8. Parameter $\delta_i = 1$ corresponds to CEC BSs requiring constant power irrespective of traffic level resulting in highest wastage of energy. Proposed mechanism thus extracts the highest energy savings as illustrated in the figure. Then, as δ_i moves toward zero, BS hardware tends to be more and more energy proportional and thus, decreasing amount of energy is wasted. Therefore, achievable energy savings also diminishes with the decrease of δ_i. For example, with $\lambda = 0.02$, savings from JDSBS-II decreases from 48% at $\delta_i = 1$ to 0% for $\delta_i \leq 0.1$. In addition, with the increase of λ (i.e., network loading), drop in energy savings as well as rise in the value of δ_i below which no savings is feasible are identified from the figure.

E. Impact on the Spectral Efficiency and the RB Requirement

Impacts on the spectral efficiency and the RB requirement per UE under JDSBS are explained here. Ratio of the achievable spectral efficiency under the proposed technique to that of the original network is illustrated in Fig. 9. Under DS, BSs with the decreased number of sectors have lower antenna gains. This leads to lower SINR resulting in lower spectral efficiency. On the other hand, under DSBS, UEs in the sleep
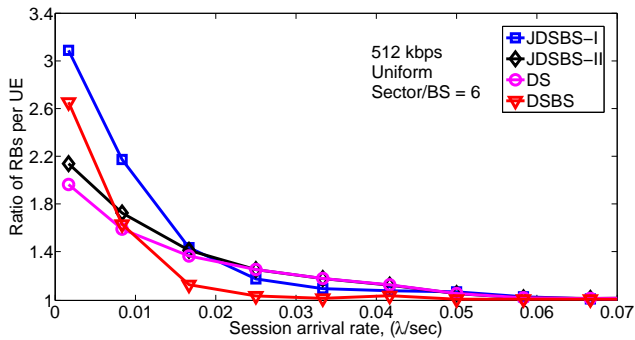
Fig. 10: Ratio of the required number of RBs per UE under the proposed mechanism to that of the conventional network.
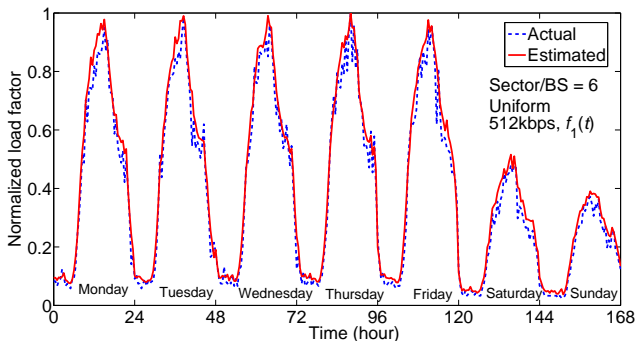

Fig. 12: Daily energy savings and percentage of network provisioning instances.

Fig. 11: LF envelope estimation using the proposed EWMA-based estimator.

used for estimating the LF envelope for the following week as presented in Fig. 11. During the estimation, weekday and weekend data are separated for estimating the envelope for the corresponding days. From the figure, it is clear that the estimated values are close and almost always higher than the actual data. At few instances, the envelope is overestimated by relatively higher amount. This might decrease the energy savings by not allowing the network to trigger the provisioning events.

On the other hand, effectiveness of using the estimated LF and L_{th} in reducing the network provisioning events under JDSBS-II mechanism is demonstrated in Fig. 12. Sampling interval equal to 30 minutes, $\theta_i = 0, \forall i$, and $\alpha_s(l_i) = 1, \forall i, \forall s$ are chosen. It is evident that use of a higher value for L_{th} results in a higher percentage of instances at which network provisioning occurs. The figure also includes the achievable net energy savings per day, which exhibits an increasing trend with L_{th}. Comparing these two groups of curves, an optimal value for L_{th} can be found. The minimum value of L_{th} for maximum energy savings is defined as the optimal value of L_{th}. From the figure, we can evaluate this value around $0.6 \sim 0.7$ and $0.5 \sim 0.6$ for $f_1(t)$ and $f_2(t)$ respectively. At this settings, extracted energy savings per day becomes 36% and 52% for $f_1(t)$ and $f_2(t)$ respectively. Whereas, the network provisioning events are reduced by 43% and 29% respectively, which in turn reduces the amount of feedback to the central coordinator. Other existing algorithms presented in [4], [17], [18], [19], [20], [21], [25] as shown in the figure require feedback for all N_d instances.

mode BSs are located at a higher distance from the serving BSs and thus, received SINR at UEs decreases causing reduced spectral efficiency. These two reasons combinedly contribute to the reduction in spectral efficiency under JDSBS and hence, the ratio is always less than or equal to 1. With the increase of network load, reduced number of BSs and sectors are switched to sleep mode, and consequently, the ratio approaches to 1 for higher λ.

On the other hand, Fig. 10 demonstrates the ratio of the required number of RBs per UE under the proposed network to that of the original network. A rise in the required number of RBs per UE is evident as the ratio is always higher than or equal to 1. As explained above, due to the reduced spectral efficiency, higher number of RBs per UE is required for guaranteeing the required data rate. Consequently, number of utilized RBs for the same number of UEs is higher under the proposal. Once again, the ratio decreases to 1 with the increase of λ due to the diminishing number of sleep mode BSs and sectors.

IX. PERFORMANCE OF THE EWMA-BASED ESTIMATOR

For evaluating the performance of the proposed LF estimation technique, time-inhomogeneous LF data for four weeks is first generated by using the traffic model in (2). It is considered that the network has only 512kbps UEs, while the rate function $f_1(t)$ shown in Fig. 1 is used for achieving the time-varying traffic pattern. Then, the generated LF data is
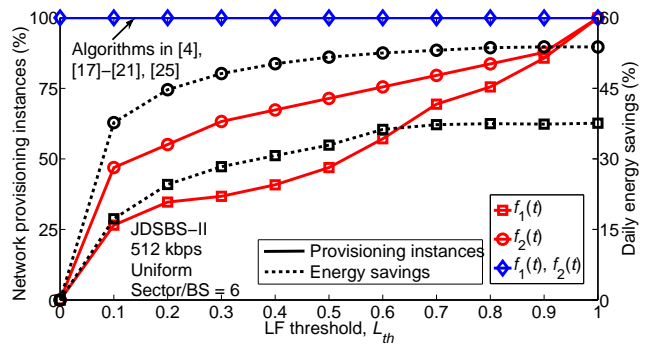
X. CONCLUSION

A novel traffic-sensitive two-dimensional network provisioning mechanism for energy efficiency in OFDMA-based cellular networks has been proposed in this paper. Proposed JDSBS mechanism performs dynamic network provisioning by adjusting the number of active BSs as well as the number of sectors in each BS. For avoiding the high computational complexity of generalized optimization problem, JDSBS problem is decomposed into DS and DSBS sub-problems in time-domain. Centralized low complexity greedy style heuristic algorithms are developed for both the sub-problems, which are

applied sequentially. Extensive simulations over a wide range of network settings have been carried out for evaluating the system performance demonstrating a potential of substantial energy savings amounting over 90% at very low traffic times. JDSBS-I and JDSBS-II are identified to outperform each other during the higher and lower traffic times respectively. It is found that the sequence of DS and DSBS implementation, user association policies, BS power profiles, user data rates, user distributions and original network configurations have significant impact on different system parameters. Reduction in spectral efficiency leading to the requirement of higher number of RBs per user for maintaining the data rates than that in the original network is also identified. Moreover, proposed novel EWMA-based LF predictor used in conjunction with the JDSBS algorithm has demonstrated its effectiveness in reducing the network provisioning event by over 40%. Furthermore, proposed JDSBS has shown its capability in outperforming the individual application of DS and DSBS.

In future, we will focus on the analytical modeling of the proposed mechanism for generalized stochastic geometry based cellular networks. Tradeoffs among energy savings, delay and network throughput using more complex utility functions will also be investigated. Furthermore, non-CBR type traffic, and the impact on UEs in terms of energy consumption and handoff statistics will be considered.

REFERENCES

[1] A. Fehske, G. Fettweis, J. Malmodin and G. Biczok, "The Global Footprint of Mobile Communications: The Ecological and Economic Perspective," *IEEE Communications Magazine*, vol. 49, no. 8, pp. 55-62, Aug 2011.

[2] Z. Hasan, H. Boostanimehr and V. K. Bhargava, "Green Cellular Networks: A Survey, Some Research Issues and Challenges," *IEEE Communications Surveys and Tutorials*, vol. 13, no. 4, pp. 524-540, 2011.

[3] R. Bolla, R. Bruschi, F. Davoli and F. Cucchietti, "Energy Efficiency in the Future Internet: a Survey of Existing Approaches and Trends in Energy-Aware Fixed Network Infrastructure," *IEEE Communications Surveys and Tutorials*, vol. 13, no. 2, pp. 223-244, 2011.

[4] S. Kyuho, K. Hongseok, Y. Yung and B. Krishnamachari, "Base Station Operation and User Association Mechanisms for Energy-Delay Tradeoffs in Green Cellular Networks," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 8, pp. 1525-1536, Sep 2011.

[5] C. Peng, S. Lee, S. Lu, H. Luo and H. Li, "Traffic-Driven Power Saving in Operational 3G Cellular Networks," *Proc. International Conference on Mobile Computing and Networking (MobiCom)*, Nevada, USA, pp. 121-132, Sep 2011.

[6] U. Paul, A. P. Subramanian, M. M. Buddhikot and S. R. Das, "Understanding Traffic Dynamics in Cellular Data Networks," *Proc. IEEE International Conference on Computer Communications (INFOCOM)*, pp. 882-890, China, Apr 2011.

[7] M. Z. Shafiq, L. Ji, A. X. Liu and J. Wang, "Characterizing and Modeling Internet Traffic Dynamics of Cellular Devices," *Proc. ACM SIGMETRICS*, pp. 305-316, Jun 2011.

[8] M. F. Hossain, K. S. Munasinghe and A. Jamalipour, "Distributed Inter-BS Cooperation Aided Energy Efficient Load Balancing for Cellular Networks," *IEEE Transactions on Wireless Communications*, vol. 12, no. 11, pp. 5929-5939, Nov 2013.

[9] M. F. Hossain, K. S. Munasinghe and A. Jamalipour, "Energy-Aware Dynamic Sectorization of Base Stations in Multi-Cell OFDMA Networks," *IEEE Wireless Communications Letters*, vol. 2, no. 6, pp. 587-590, Dec 2013.

[10] 3GPP TR 25.814 V.7.1.0 Rel. 7, "Technical Specification Group Radio Access Network; Physical Layer Aspects for Evolved Universal Terrestrial Radio Access (UTRA)," *Technical Report*, Sep 2006.

[11] WMF-T23-001-R010v09, "Mobile System Profile," *WiMAX Forum Air Interface Specifications*, Sep 2010.

[12] T. Edler and S. Lundberg, "Energy Efficiency Enhancements in Radio Access Networks," *Ericsson Review*, 2004.

[13] Huawei White Paper, "Improving Energy Efficiency, Lower CO2 Emission and TCO," pp. 1-16, 2011.

[14] T. Han and N. Ansari, "On Greening Cellular Networks via Multicell Cooperation," *IEEE Wireless Communications*, vol. 20, no. 1, pp. 82-89, Feb 2013.

[15] 3GPP TR 36.902 ver. 9.3.1 Rel. 9, "Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Self-Configuring and Self-Optimizing Network (SON): Use Cases and Solutions," *Technical Report*, 2011.

[16] M. A. Marsan, L. Chiaraviglio, D. Ciullo and M. Meo, "Optimal Energy Savings in Cellular Access Networks," *Proc. Workshop on Green Comm. in conjunction with IEEE ICC*, Dresden, Germany, pp. 1-5, Jun 2009.

[17] F. Han, Z. Safar, W. S. Lin, Y. Chen and K. J. R. Liu, "Energy-Efficient Cellular Network Operation via Base Station Cooperation," *Proc. of Int. Conf. on Comm. (ICC)*, pp. 5885-5889, Ottawa, Canada, Jun 2012.

[18] E. Oh and B. Krishnamachari, "Energy Savings Through Dynamic Base Station Switching in Cellular Wireless Access Networks," *Proc. IEEE Global Communications Conf. (GLOBECOM)*, pp. 1-5, Dec. 2010.

[19] S. Zhou, Gong J, Z. Yang, Z. Niu, P. Yang, "Green Mobile Access Network with Dynamic Base Station Energy Saving," *Proc. ACM International Conference on Mobile Computing and Networking (MobiCom)*, Beijing, China, pp. 1-3, Sep 2009.

[20] E. Oh, B. Krishnamachari, X. Liu and Z. Niu, "Toward Dynamic Energy-Efficient Operation of Cellular Network Infrastructure," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 56-61, Jun 2011.

[21] E. Oh, K. Son and B. Krishnamachari, "Dynamic Base Station Switching-On/Off Strategies for Green Cellular Networks," *IEEE Transactions on Wireless Communications*, vol. 12, no. 5, pp. 2126-2136, May 2013.

[22] Z. Niu, Y. Wu, J. Gong and Z. Yang, "Cell Zooming for Cost-Efficient Green Cellular Networks," *IEEE Communications Magazine*, vol. 48, no. 11, pp. 74-79, Nov 2010.

[23] S. Morosi, P. Piunti and E. D. Re, "Sleep Mode Management in Cellular Networks: A Traffic Based Technique Enabling Energy Saving," *Transactions on Emerging Telecommunications Technologies*, vol. 24, no. 3, pp. 331-341, Apr 2013.

[24] K. Son, E. Oh and B. Krishnamachari, "Energy-Aware Hierarchical Cell Configuration: From Deployment to Operation," *Proc. IEEE INFOCOM Workshop on Computer Communications*, pp. 289-294, China, Apr 2011.

[25] R. Li, Z. Zhao, X. Chen and H. Zhang, "Energy Saving through a Learning Framework in Greener Cellular Radio Access Networks," *Proc. IEEE Global Communications Conference (GLOBECOM)*, pp. 1574-1579, Anaheim, USA, 2012.

[26] L. G. Hevizi and I. Godor, "Power Savings in Mobile Networks by Dynamic Base Station Sectorization," *Proc. IEEE Personal Indoor and Mobile Radio Communications (PIMRC)*, pp. 2415-2417, Budapest, Hungary, Sept 2011.

[27] G. Micallef, P. Mogensen and H. O. Scheck, "Cell Size Breathing and Possibilities to Introduce Cell Sleep Mode," *Proc. IEEE European Wireless Conference (EW)*, pp. 111-115, Lucca, Italy, Apr 2010.

[28] Y. Qi, M. A. Imran and R. Tafazolli, "Energy-Aware Adaptive Sectorisation in LTE Systems," *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pp. 2402-2406, Toronto, Canada, Sep 2011.

[29] F. Richter, A. J. Fehske, and G. P. Fettweis, "Energy Efficiency Aspects of Base Station Deployment Strategies for Cellular Networks," *Proc. IEEE Vehicular Technology Conference (VTC)*, pp. 1-5, USA, Sep 2009.

[30] O. Arnold *et al.*, "Power Consumption Modeling of Different Base Station Types in Heterogeneous Cellular Networks," *Proc. of Future Network and Mobile Summit*, Florence, Italy, Jun 2010.

[31] L. M. Correria *et al.*, "Challenges and Enabling Technologies for Energy Aware Mobile Radio Networks," *IEEE Communications Magazine*, vol. 48, no. 11, pp. 66-72, Nov 2010.

[32] A. S. Alam, L. S. Dooley and A. S. Poulton, "Energy Efficient Relay-Assisted Cellular Network Model using Base Station Switching," *Proc. IEEE Global Communications Conference (GLOBECOM)*, pp. 1-6, Anaheim, USA, Dec 2012.

[33] M. Deruyck, W. Joseph and L. Martens, "Power Consumption Model for Macrocell and Microcell Base Stations," Transactions on Emerging Telecommunications Technologies, Aug 2012, doi: 10.1002/ett.2565.

[34] L. Xiang, X. Ge, C. Wang, F. Li and F. Reichert, "Energy Efficiency Evaluation of Cellular Networks Based on Spatial Distributions of Traffic Load and Power Consumption," *IEEE Transactions on Wireless Communications*, vol. 12, no.3, pp. 961-973, March 2013.

[35] H. Wang, L. Ding, P. Wu, Z. Pan, N. Liu and X. You, "Dynamic Load Balancing and Throughput Optimization in 3GPP LTE Networks," *Proc. ACM International Wireless Communications and Mobile Computing Conference (IWCMC)*, pp. 939-943, Caen, France, Jun-July 2010.

[36] A. Lobinger, S. Stefanski, T. Jansen and I. Balan, "Load Balancing in Downlink LTE Self-Optimizing Networks," *Proc. IEEE Vehicular Technology Conference (VTC)*, Munchen, Germany, pp.1-5, May 2010.

[37] M. A. Marsan and M. Meo, "Energy Efficient Management of Two Cellular Access Networks," *GreenMetrics Workshop in Conjunction with ACM SIGMETRICS*, Washington, USA, pp. 1-5, Jun 2009.

[38] 3GPP TR 36.942 Ver. 11.0.0 Rel. 11, "Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) system scenarios," *Technical Report*, Sep 2012.

[39] C. Seol and K. Cheun, "A statistical Inter-Cell Interference Model for Downlink Cellular OFDMA Networks Under Log-Normal Shadowing and Multipath Rayleigh Fading," *IEEE Trans. on Commun.*, vol. 57, no. 10, pp. 3069-3077, Oct 2009.

[40] S. Shamai and A. D. Wyner, "Information-Theoretic Considerations for Symmetric, Cellular, Multiple-Access Fading Channels-Part I," *IEEE Transactions on Information Theory*, vol. 43, no. 6, pp. 1877-1894, Nov 1997.

[41] A. Racz, *et al.* "On the Impact of Inter-Cell Interference in LTE," *IEEE GLOBECOM*, pp. 1-6, LA, USA, Nov-Dec 2008.

[42] K. Son, S. Chong and G. Veciana, "Dynamic Association for Load Balancing and Interference Avoidance in Multi-Cell Networks," *IEEE Transactions on Wireless Comm.*, vol. 8, no. 7, pp. 3566-3576, July 2009.

[43] T. D. Novlan, R. K. Ganti, A. Ghosh and J. G. Andrews, "Analytical Evaluation of Fractional Frequency Reuse for OFDMA Cellular Networks," *IEEE Transactions on Wireless Communications*, vol. 10, no. 12, pp. 4294-4305, Dec 2011.

[44] D. Cao, S. Zhou, C. Zhang and Z. Niu, "Energy Saving Performance Comparison of Coordinated Multi-Point Transmission and Wireless Relaying," *Proc. IEEE Global Communications Conference (GLOBECOM)*, Beijing, China, pp.1-5, Dec 2010.

[45] 3GPP TS 36.213 V11.1.0 Rel 11, "Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures," *Technical Report*, Dec 2012.

[46] WMF-T32-001-R021v02, "Architecture Tenets, Reference Model and Reference Points: Base Specifications," *WiMAX Forum Network Architecture*, Mar 2013.

[47] S. Chung and Y. Chen, "Performance Analysis of Call Admission Control in SFR-Based LTE Systems," *IEEE Communications Letters*, vol. 16, no.7, pp.1014-1017, July 2012.

[48] M. Qian, Y. Huang, J. Shi, Y. Yuan, L. Tian and E. Dutkiewicz, "A Novel Radio Admission Control Scheme for Multiclass Services in LTE Systems," *Proc. IEEE Global Communications Conference (GLOBECOM)*, Hawaii, USA, pp. 1-6, Nov-Dec 2009.

[49] White Paper, "MIMO and Smart Antennas for Mobile Broadband Systems," *4G Americas*, pp. 1-138, Oct 2012.

[50] R. Stegen, "The Gain-Beamwidth Product of an Antenna," *IEEE Transactions on Antennas and Propagation*, vol.12, no.4, pp. 505- 506, Jul 1964.

[51] 3GPP TR 25.996 V.11.0.0 Rel. 11, "Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Spatial channel model for Multiple Input Multiple Output (MIMO) simulations," *Technical Report*, Sep 2012.

[52] K. Dufkova, M. Popovic, R. Khalili, L. Boudec, J. Yves, M. Bjelica and L. Kencl, "Energy consumption comparison between macro-micro and public femto deployment in a plausible LTE network," *Proc. of ACM International Conference on Energy-Efficient Computing and Networking*, pp. 67-76, New York, USA, May- Jun 2011.

[53] W. S. Cleveland, "Robust Locally Weighted Regression and Smoothing Scatterplots," *Journal of the American Statistical Association*, vol. 74, no. 368, pp. 829836, 1979.

[54] J. S. Hunter, "The Exponentially Weighted Moving Average," *Journal of Quality Technology*, vol. 18, no. 4, pp. 203-207, 1986.

[55] M. R. Garey and D. S. Johnson. *Computer and Intractability: A Guide to the Theory of NP-Completeness*. New York, USA: W. H. Freeman and Company, 1979.

[56] Z. Zhang, M. F. Iskander, Z. Yun and A. H. Madsen, "Hybrid Smart Antenna System Using Directional Elements - Performance Analysis in Flat Rayleigh Fading," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 10, pp. 2926-2935, Oct 2003.

[57] D. Amzallag, R. B. Yehuda, D. Raz, and G. Scalosub, "Cell Selection in 4G Cellular Networks," *IEEE Transactions on Mobile Computing*, vol. 12, no. 7, pp. 1443-1455, July 2013.

[58] Y. Shen, T. Luo and M. Z. Win, "Neighboring Cell Search for LTE Systems," *IEEE Transactions on Wireless Communications*, vol. 11, no. 3, pp. 908-919, Mar 2012.

[59] Wireless World Initiative New Radio WINNER+, "D5.3: WINNER+ Final Channel Models," Jun 2010.

[60] IEEE 802.16m-08/004r5: IEEE 802.16m Evaluation Methodology Document (EMD), *IEEE Standard 802.16m*, Jan 2009.

[61] A. V. Krishnamoorthy, *et al.*, "Progress in Low-Power Switched Optical Interconnects," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 17, no. 2, pp. 357-376, Mar-Apr 2011.