Energy-Aware Dynamic Sectorization of Base Stations in Multi-Cell OFDMA Networks

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***Abstract*—In this paper, we propose traffic-sensitive dynamic sectorization of base stations (BSs) for energy savings in OFDMA-based cellular access networks. Under the proposal, following the temporal variation of traffic level, BSs are dynamically reconfigured using fewer sectors. User data rate, service continuity and network coverage are also maintained. A generalized energy saving optimization problem is formulated, which is a challenging combinatorial problem. Therefore, a low complexity greedy style heuristic algorithm is presented. Effectiveness of the scheme is demonstrated using Monte Carlo simulations and compared with the popular BS on/off based energy saving technique.**

***Index Terms*—Dynamic sectorization, energy efficiency, multi-cell networks, OFDMA networks.**

I. Introduction

Due to the recent rapid rise in mobile data traffic, cellular networks are facing an explosive growth in energy utilization. BSs in the cellular access networks are the most dominant energy consuming equipment estimated around 60%-80% [1]-[2]. On the other hand, a high degree temporal-spatial diversity in traffic generation is very common in any cellular network [2] - [3]. However, due to the non-load proportional energy consumption in BSs and the conventional approach of keeping all BSs on irrespective of traffic levels, a significant amount of energy is being wasted in the existing networks. Therefore, in the recent years, the idea of attaining energy efficient cellular networks by switching off the redundant BSs during low traffic periods has gained much attention [1] - [4].

However, practical implementation of dynamic BS switching has many challenging issues [1]. Potential coverage holes, reduced battery life of user equipment (UE), frequent switching in BSs and increased interference from coverage extension are some of the greatest challenges. Thus, it is imperative to have highly intelligent, fast and stringent coordination among network entities. Therefore, in our previous work [5], instead of turning off an entire BS, we investigated an alternate solution with less complexity involving only turning off some sectors, where BSs were considered as like single-cell case.

In this paper, we extensively extend our previous sector on/off based energy saving scheme to multi-cell orthogonal frequency division multiple access (OFDMA)-based cellular networks. By leveraging the temporal-spatial traffic diversity, each BS is dynamically reconfigured with a minimum number of sectors, while qality of service (QoS), namely, user data rate, service continuity and network coverage are maintained. Unlike the system model in [5], a near realistic network environment is captured by considering varying inter-cell interference, antenna radiation patterns and variation of antenna gains with the change of antenna beamwidths. A generalized energy optimization problem is also formulated. Because of its challenging combinatorial nature with exponential complexity, we propose a simpler heuristic algorithm with linear complexity. Simulation results demonstrate a substantial volume of energy savings amounting over 80% at very low traffic.

The rest of the paper is organized as follows. Section II describes the network model. Proposed dynamic sectorization is presented in Section III. Simulation results are explained in Section IV. We then conclude the paper in Section V.

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II. Network Model

This section presents the network model in the context of OFDMA-based long term evolution (LTE) systems, which can also be adopted to worldwide interoperability for microwave access (WiMAX) systems.

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. Same frequency bands are reused among BSs leading to potential inter-cell interference. Each BS assumed to have the capability for dynamically reconfiguring them with various number of sectors.

B. Power Consumption Model of BSs

Operating power of $\mathcal{B}_i$ can be given as [2], $P_i(t) = \sum_{s=1}^{S_{i,ON}(t)} \left[(1-\delta_i)\, L_f^{i,s}(t) P_{i,Op} + \delta_i P_{i,Op}\right]$. Here, $0 \leq L_f^{i,s}(t) \leq 1$ is the load factor (LF) of sector s and $1 \leq S_{i,ON}(t) \leq \mathcal{S}_i$ is the number of active sectors of $\mathcal{B}_i$ at time t. LF is defined as the ratio of the number of resource blocks (RBs) in use to the total available RBs [4]. $P_{i,Op} = g_i P_{i,Tx} + h_i$ is the maximum operating power of a fully utilized sector, $P_{i,Tx}$ is the maximum transmit power per sector, and g_i and h_i are constants [2], [6]. While, the parameter $0 \leq \delta_i \leq 1$ determines the level of dependency of $P_i(t)$ on $L_f^{i,s}$.

C. Session Admission Control (SAC)

We only consider real-time services requiring constant bit rate (CBR). We assume no queuing and the allocated RBs remain dedicated until the end of a session. Let, $\gamma_u^{i,s}$ denotes the received signal-to-interference-plus-noise-ratio (SINR) at the new session requesting u^{th} UE located in sector s of BS $\mathcal{B}_i$. Information on received SINR at UEs can be gathered from the channel state information (CSI) feedback to BSs by UEs, which is supported in both LTE [7] and WiMAX [8] standards. For adaptive modulation and coding (AMC), $\gamma_u^{i,s}$ is then mapped to the spectral efficiency given in bps/Hz [9]

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

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 is estimated by $\beta_u^{i,s} = \left\lceil \frac{R_u^{i,s}}{W_{RB}\psi_u^{i,s}} \right\rceil$. Here, $R_u^{i,s}$ is the required data rate in bps, W_{RB} is the bandwidth per RB in Hz (equal to 180 kHz in LTE), and $\lceil x \rceil$ is the nearest integer equal to or larger than x.

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 request, the session is admitted into the system. Otherwise, the session request is rejected. RBs allocated to UEs are randomly selected from the available RBs, which is an efficient way to limit inter-cell interference. 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.

D. Antenna Pattern

Antenna radiation pattern is given by [9], $A(\theta) = -min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right]$. Here, $-180^0 \leq \theta \leq 180^0$, θ_{3dB} and A_m are the angle between the direction of interest and the antenna boresight, 3dB beamwidth and the maximum attenuation respectively. Omni and three-sector antennas are more popular in practice, and the more recent trend is in developing six-sector antennas [10]. Nevertheless, for investigating all possible configurations, omni to six-sector antennas are considered. Now, with the decrease (increase) of beamwidth, antenna gain roughly increases (decreases) by 3dB [11] - [12]. 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 as, [120 65 55 45 33] deg, [18 20 21 22 23] dB and [13 15 16 17 18] dBi respectively [9], [11] - [12]. For an omni antenna, $A(\theta) = 0$dB and antenna gain = 10dB are taken.

III. Proposed Dynamic Sectorization

In existing cellular networks, irrespective of traffic level, all the sectors in a BS are left always on expecting that during the worst case peak-traffic scenario, all of them would be required for supporting its UEs. Thus, during low traffic times, a substantial amount of energy is being wasted. Under the proposed scheme, based on the instantaneous traffic level, each BS $\mathcal{B}_i, \forall i$ is dynamically reconfigured keeping a minimum number of its $\mathcal{S}_i$ sectors on, while maintaining QoS and thus, energy savings is achieved.

Remarks: Remaining active sectors need to adjust their transmission beamwidth for covering the entire cell area. One of the simple and robust techniques is to use adaptive smart antenna technology employing linear antenna arrays [13]. Through the adjustment of the length and the spacing of the antenna array elements as well as the phase of their input currents, main beam of the array can be steered and shaped as desired and thus, it is possible to cover a sector of desired size. Moreover, recent development of reconfigurable beam antennas for BSs with beam fanning capability backs the proposal as a practically implementable solution [10].

A. Problem Formulation

The objective of the proposed scheme 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. Here, $\mathbf{S}_i = \{s_1, s_2, ..., s_{S_{i,ON}}\}$ is the set of active sectors in $\mathcal{B}_i$. We thus can formulate the following optimization problem:

$$\underset{\mathbf{S}_1,\mathbf{S}_2,....,\mathbf{S}_{|\mathcal{B}|}}{\arg\min} \sum_{i=1}^{|\mathcal{B}|} \sum_{s \in \mathbf{S}_i} \left[(1-\delta_i)\, L_f^{i,s}(t) P_{i,Op} + \delta_i P_{i,Op} \right] \quad (2)$$

$s.t.,$

$$P_{i,b}(t) \leq P_b^{Th}, i = 1, 2, ..., |\mathcal{B}|, \forall t \quad (3)$$

$$P_{i,out}(t) \leq P_{out}^{Th}, i = 1, 2, ..., |\mathcal{B}|, \forall t \quad (4)$$

$$R_u^{(a)}(t) \geq R_u, u = 1, 2, ..., \sum_{i=1}^{|\mathcal{B}|} \sum_{s=1}^{\mathcal{S}_i} U_s(l_i, t), \forall t \quad (5)$$

$$\bigcup_{s \in \mathbf{S}_i} \mathcal{A}_{i,s}(t) = \mathcal{A}_i, i = 1, 2, ..., |\mathcal{B}|, \forall t \quad (6)$$

$$\sum_{u=1}^{U_s(l_i,t)} \beta_u^{i,s}(t) \leq \beta_{Tot}^{i,s}, i = 1, 2, ..., |\mathcal{B}|, \forall s \in \mathbf{S}_i, \forall t \quad (7)$$

$$\sum_{u=1}^{U_s(l_i,t)} P_u^{i,s}(t) \leq P_{i,Tx}, i = 1, 2, ..., |\mathcal{B}|, \forall s \in \mathbf{S}_i, \forall t \quad (8)$$

Here, $P_{i,b}(t)$ and $P_{i,out}(t)$ are the 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 u^{th} 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 (3), (4), (5) and (6) respectively guarantees the session blocking, session outage, UE data rates and the network coverage within acceptable limits. Finally, (7) and (8) imply that the required total number of RBs and total transmit power in BSs can not exceed their respective maximum limits.

B. Algorithm

The objective function in (2) is convex in $L_f^{i,s}, \forall i, \forall s$ for a given $\mathbf{S}_{ON}$. However, for variable $\mathbf{S}_{ON}$, it becomes nonconvex. Thus, (2) is a challenging combinatorial problem

TABLE I: Algorithm for dynamic sectorization

1:	Initialize: $\mathbf{S}_i = \mathbf{S}_{i,all} = \{1, 2, ..., \mathcal{S}_i\}, n_i = \|\mathbf{S}_i\|$
2:	**If** $L_i < (n_i - 1)/\mathcal{S}_i$
3:	Find $\mathbf{S}_i^* = \{s_1^*, s_2^*, ..., s_{n_i}^*\}$ reordering $\mathbf{S}_i$ *s.t.*, $L_m^* \geq L_n^*, m > n$
4:	Set $q = 1$
5:	Associate all $U_{s_q^*}(l_i, t)$ UEs with the other sectors $\mathbf{S}_i \setminus \{s_q^*\}$ and calculate $\mathbb{U}_i(t)$
6:	**If** Conditions (3)-(8) are met and $\mathbb{U}_i(t) < \eta$,
7:	Set $\mathbf{S}_i = \mathbf{S}_i \setminus \{s_q^*\}$ and $n_i = n_i - 1$
8:	**Else** Set $q = q + 1$
9:	**If** $q <= n_i$, Go to Step 5, **End If**
10:	**End If**
11:	**If** $n_i > 1$, Go to Step 2
12:	**Else** Stop the algorithm, **End If**
13:	**End If**

with an exponentially increasing search space $\mathcal{O}(2^{\sum_{i=1}^{|\mathcal{B}|} \mathcal{S}_i})$. Therefore, in this paper, we propose a centralized greedy style heuristic algorithm with linear complexity.

Proposed 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 on. Let, $L_i(t)$ be the 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 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 $\mathcal{S}_i$ 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 $\mathbb{U}_i(t) = P_i^{(s-)}(t)/P_i^{(s+)}(t)$ 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 (3)-(8) are met and $\mathbb{U}_i(t) < \eta$ ($\eta \in [0, 1]$), then sector s is removed from $\mathbf{S}_i$. Here, $\mathbb{U}_i(t) < 1$ implies potential energy savings from switching off sector s.

Iteration continues as long as $L_i(t) < (n_i - 1)/\mathcal{S}_i$, where n_i is the number of on sectors from the last iteration. Sectors in the final $\mathbf{S}_i$ are kept on with essential beamwidth adjustments. Other sectors in $\mathbf{S}_{i,all} \setminus \mathbf{S}_i$ are switched off. 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 algorithm for BS $\mathcal{B}_i$ is presented in Table I.

C. Inter-Cell Interference

One way of calculating inter-cell interference is to keep track whether the same RB is simultaneously assigned in the interfering BS(s). Thus, the central coordinator needs to have the access to a RB allocation database maintained for each BS, which may create a large overhead on the system. Therefore, for reducing the overhead, we evaluate inter-cell interference using a RB collision based model [14]. In the collision based model, only LF information of each sector is required. Let, $L_f^{i,s}$ and $L_f^{j,c}$ be the LFs of two interfering sectors from $\mathcal{B}_i$ and $\mathcal{B}_j$ respectively. Considering that the RBs are randomly assigned among UEs, then the upper bound of the probability of collision between two RBs becomes $P_C(L_f^{i,s}, L_f^{j,c}) = L_f^{i,s} L_f^{j,c}$ [14]. Total inter-cell interference in $\mathcal{B}_i$ then equals to $\sum_{c=1}^{\mathcal{C}} P_C(L_f^{i,s}, L_f^{j,c}) P_{u,Rx}^{(c)}$, where, $\mathcal{C}$ is the number of colliding sectors, and $P_{u,Rx}^{(c)}$ is the received power at u^{th} UE in $\mathcal{B}_i$ from the colliding sector c.

IV. Results and Discussion

A. Simulation Setup

We evaluate the proposed scheme using Monte Carlo simulations. For each data point, we average the simulation results from 500 iterations. Simulated network covers roughly an area of 8×8 km^2 served by 64 BSs deployed with hexagonal layout having an inter-site distance equal to $\sqrt{3} \times 500$m. 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 with path loss $P_L = 138.4 + 35.74 log_{10}(d)$ is considered [15]. Shadow fading parameter $\sigma = 8$dB, penetration loss 10dB [16] 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 [9]. Antennas are configured according to the parameters discussed in Section II-D.

We consider CBR services of data rates equal to 512kbps, 768kbps and 1024kbps, which include packet headers and payloads. LTE Frequency division duplexing (FDD) frame structure is chosen. New sessions arrives following a Poisson process with arrival rate λ. For the convenience of 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. Unless otherwise specified, $P_b^{th} = 1\%, P_{out}^{th} = 1\%, \eta = 1$, $\delta_i = 0.7$, $\mathcal{S}_i = 6$, $\{g_i = 21.45, h_i = 354.44\}$ [6], $\forall i$ and uniformly distributed UEs are used for simulations.

B. Numerical Results

Percentage of energy savings along with the 95% confidence intervals is presented in Fig. 1. With the increase of λ, higher number of sectors are required for serving UEs and hence, lower savings is achieved as evident from the figure. In case of multi-cell scenario, inter-cell interference can reduce the SINR at UEs leading to the requirement of higher number of RBs. Consequently, less number of sectors are allowed to switch off and less savings is achieved. As seen, in a single-cell case, higher energy savings is achieved due to the absence of inter-cell interference. Furthermore, 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 sectors are required to keep active for maintaining QoS resulting in reduced energy savings. For example, at $\lambda = 0.05$ of

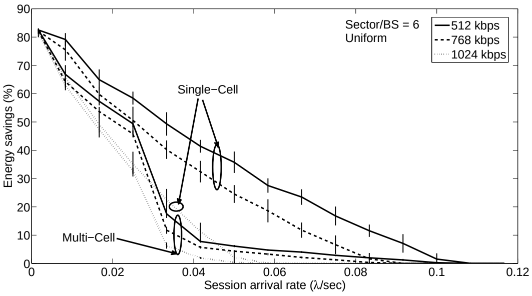

Fig. 1: Energy saving performance.

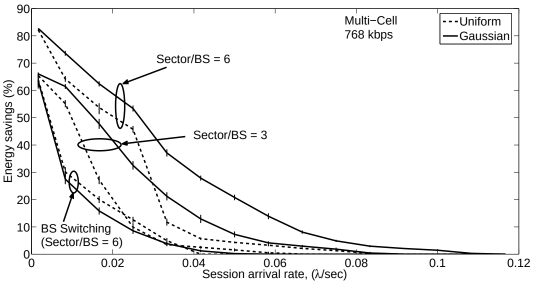

Fig. 2: Impact of user distribution and number of sectors.

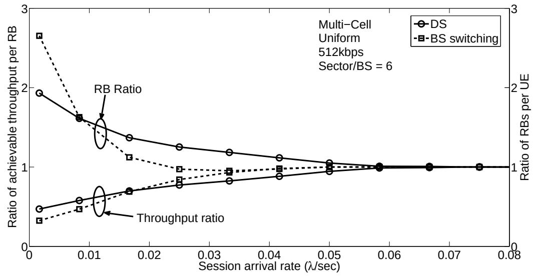

Fig. 3: Throughput and RB utilization.

single-cell case, around 35%, 25% and 3% energy savings are achieved for 512kbps, 768kbps and 1024kbps respectively.

Fig. 2 illustrates that a network having Gaussian distributed UEs in BSs saves much more than that of having uniformly distributed UEs. In case of Gaussian distribution, higher number of UEs are located near BSs, which experience lower path loss. Therefore, many UEs require less number of RBs and thus, satisfactory QoS can be provided by keeping fewer sectors on leading to higher savings. On the other hand, BSs with the higher number of sectors provide higher number of options for associating UEs to the other sectors, which increases the turning off probability of sectors as well as the energy savings. For comparison, energy savings from centralized BS switching on/off technique employing optimal exhaustive search is also included in the figure. Under BS on/off scheme, UEs of the switched off BSs are associated with the nearest BSs. As evident from the figure, proposed scheme clearly outperforms the BS switching scheme.

Ratios of the achievable throughput per RB and the required RBs per UE in the proposed scheme to those in the original network are illustrated in Fig. 3. For smaller λ, many sectors are turned off, which results in lower antenna gains and higher inter-cell interference leading to lower throughput per RB than that in the original network. Consequently, higher number of RBs per UE is required for maintaining user data rates. However, with the increase of λ, the ratios approach to 1 due to the diminishing number of switched off sectors.

V. Conclusion

In this paper, a traffic-aware dynamic sectorization technique is proposed for energy efficiency in multi-cell OFDMA-based cellular networks. For the ease of implementation, a low complexity greedy style heuristic algorithm is developed. Numerical results have demonstrated the potential of the scheme in substantially reducing the total energy consumption, being over 80% at very low traffic times. User data rates, user distributions and original network configurations have shown large impact on the savings. Proposed scheme is also compared with the counterpart BS on/off based scheme. Our future work will focus on the analytical modeling of the scheme encompassing non-CBR type traffic as well as flow level QoS.

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