

Network Cooperation for Energy Saving in Green Radio Communications

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Abstract

Financial and environmental considerations have motivated a trend in wireless communication network design and operation to minimize the amount of energy consumption. Such a trend is referred to as green radio communications. In this article, network cooperation is investigated as a means of energy saving. Networks with overlapped coverage can cooperate to reduce their energy consumption by alternately switching on and off their resources according to the traffic load conditions. We present an optimal resource on-off switching framework that adapts to the fluctuations in the traffic load and maximizes the amount of energy saving under service quality constraints, in a cooperative networking environment. For the system model under consideration, unlike the existing solutions in literature, the proposed technique can achieve energy saving while avoiding an increase in the transmission power. Numerical results demonstrate the validity of the proposed technique.

INTRODUCTION

In green radio communications, a main network design objective is to reduce the amount of energy consumption while maintaining satisfactory quality of service (QoS). Two motivations are behind such design criterion. One is the service provider's financial considerations. Almost half of a mobile service provider's annual operating expenses is for energy costs [1]. Each base station (BS), in cellular networks, roughly consumes upto 2.7 KWH of electrical power [2]. With densely deployed BSs to achieve wide area coverage, high energy is consumed per annum. Such high energy consumption results in a significant environmental impact due to the associated CO₂ emissions. This gives the other motivation behind green radio communications network design criterion, which is environmental considerations. Currently, the telecommunication industry is responsible for about 2 percent of CO₂ emissions, and given the industry's growth it could increase to 4 percent by 2020 [3]. As a result, political initiatives start to put requirements on operators to lower the CO₂ emissions of communication networks [4]. In Europe, companies such

as Orange (France), Ericson (Sweden) and Vodafone (UK) aim to reduce their CO₂ emissions by 50-80 percent by 2020 [5]. Hence, the reduction of energy consumption in the telecommunication industry sector will result in a positive impact both on the environment and on the operators' profit [1].

In literature, there has been several proposals for designing an energy aware infrastructure in wireless communications networks. In the following, energy saving techniques at the network level are discussed. The limitations of the existing techniques are pointed out. We investigate network cooperation as a means of energy saving in green radio communications. The objective is to develop a framework that enables networks with overlapped coverage in a given geographical region to cooperate among each other to achieve energy saving.

ENERGY SAVING AT NETWORK LEVEL

Energy awareness in wireless communication networks has been studied for a long time on the mobile devices and wireless sensors, due to their limited power capabilities. Recently, such awareness has been extended to include the cellular network BSs, due to financial and environmental considerations. Three categories of solutions can be defined to provide an energy aware infrastructure in wireless communications networks. These are discussed in the following.

RENEWABLE ENERGY SOURCES

From an environmental perspective, the objective of green radio communications is to reduce the CO₂ emissions [6]. This can be achieved by using renewable energy sources at the BSs, such as locally generated wind and solar power. This can reduce the amount of electrical power consumption taken from the grid. Also, it can complement the fossil fuel power generators in the off-grid sites. Moreover, air cooling and cold climates can be used to cool the electronic devices in the BSs [6]. However, the renewable energy sources cannot replace the traditional energy sources in the BSs, due to their required high reliability, since any power shortage will disturb the wireless network's service provision.

HETEROGENEOUS CELL SIZES

Traditionally, macro cells have been used to provide large area coverage and to better handle user mobility in cellular networks. However, as the coverage area increases, more transmitted

power is required to provide an acceptable signal quality for cell edge users, which increases the overall BS energy consumption. Recently, femto cells have been deployed to enhance in-building coverage and provide higher data rates. Due to their small coverage area, femto cells require much less transmission power than a macro cell, and hence their BSs consume less energy. However, a deployment with only small cells would require a large number of BSs. This increases the handoff rates of mobile users among adjacent cells and also may degrade the overall energy efficiency of the network. A joint deployment of BSs with different cell sizes is desired. A balance of different cell sizes is required for most energy efficient layout [4].

DYNAMIC PLANNING

The traffic load in a wireless network can have spatial and temporal fluctuations due to user mobility and activities [7]. An example is in a city scenario, where the traffic load in daytime of weekdays is heavy in office areas and light in residential areas, while the opposite happens in the evening. In literature, researchers propose to exploit such traffic load fluctuations, by switching off some of the available resources when the traffic load is light. This is known in literature as dynamic planning. On one hand, these resources can be the radio transceivers of active BSs [8]. However, when a BS is in its active mode, power supply, processing circuits, and air conditioning take up to 60 percent of the total energy consumption [7]. Hence, significant energy saving can be achieved if the entire BS is switched off when the traffic load is light [5 and references therein].

While BS on-off switching can avoid resource overprovision in a low traffic load condition and hence achieve energy saving, the radio coverage and service provision for the off cells face some challenges. Since most of the dynamic planning solutions are limited to the operation of a single network, the proposed solutions for service provision for the off cells rely on the active resources of such network. As a result, an increase in the transmission power of the active BSs is required to increase its cell radii in order to provide radio coverage for the off cells. This also may result in coverage holes if the maximum allowed transmission power of the remaining active BSs cannot achieve radio coverage for the switched off cells, and as a result service disruption is expected in these areas. Also, an increase in the transmission power may result in inter-cell interference in a case that more than one active BS tries to achieve radio coverage for the switched off cells, and as a result additional interference management schemes are needed.

Two solutions are proposed in literature to avoid the aforementioned shortcomings of dynamic planning. One relies on the mobility of relay nodes to migrate traffic from the off BSs to the active ones [9]. However, such solution is not reliable in case of delay sensitive applications such as voice telephony. The other solution exploits the cooperation between two cellular operators to achieve energy saving by allowing the traffic to be carried on for one operator's off BSs through the other operator's active BSs [10]. However, the proposed solution assumes that the traffic profile can be expressed in terms of a deterministic function that varies with time. This cannot accurately capture the random behavior of traffic arrivals and traffic load fluctuations.

The dynamic planning solutions in literature whether focus on switching off some of the BSs or switching off some of the resources of the BSs. It is more beneficial to combine both strategies and not only switch off some BSs but also switch off some of the resources of an active BS to further improve the amount of energy saving. Also, with the existence of different wireless networks with different overlapped coverage areas, network cooperation can achieve energy saving and avoid the dynamic planning shortcomings. In this article, we aim to provide an optimal resource on-off switching framework that captures the random behavior of traffic arrivals, adapts to the fluctuations of the traffic load, and maximizes the amount of energy saving under service quality constraints, in a cooperative networking environment.

For a better insight to the benefits of cooperative networking, the next section provide some discussion of the future heterogeneous wireless access environment and the potentials of cooperative networking.

THE POTENTIALS OF NETWORK COOPERATION

Currently, there exist different wireless networks that offer a variety of access options. Such wireless access networks include the 3G cellular systems, the IEEE 802.11 WiFi networks, and the IEEE 802.16 WiMAX systems. These networks have complementary service capabilities. For example, the IEEE 802.11 networks can support high data rate services in hot spots, whereas the 3G cellular networks and the IEEE 802.16 networks can offer broadband wireless access over long distances and serve as a backbone for hot spots. In spite of fierce competition in the wireless service market, these successful wireless networks will coexist. In such a heterogeneous wireless access environment, cooperative networking will lead to better service quality to mobile users and enhanced performance for the networks.

From the perspective of mobile users, cooperative networking solutions for heterogeneous wireless networks enable the mobile users to enjoy an always best connection. The always best connection is facilitated by inter-network vertical handoffs, which can be based on service cost, coverage, transmission rate, QoS, information security, and user preference. Taking advantage of cooperation activities among multiple access networks, the inter-network vertical handoffs can be supported in a seamless and fast manner. Hence, a reliable end-to-end connection at the transport layer can be provided to preserve service continuity and to minimize disruption. Also, the future mobile terminals (MTs) will be equipped with multiple radio interfaces for network access. Multi-homing techniques maintain multiple simultaneous associations of an MT with different radio access networks. Facilitated by the cooperation across different network domains, multi-homing can support applications with high required bandwidth through bandwidth aggregation [11], provide ubiquitous access, facilitate soft handoff, and enhance reliability.

On the other hand, service providers can take advantage of network cooperation to enhance network performance. Multiple heterogeneous networks can cooperate to provide a multi-hop backhaul connection in a relay manner. This can increase the coverage area of such networks. Moreover, cooperation among different networks can provide load balancing among these networks. As a result, traffic overload situations in one network can be avoided. Also, network cooperation can be exploited to save energy in green radio communications. For geographical regions where two or more networks have an overlapped coverage, cooperation among the networks can achieve energy saving and avoid the dynamic planning shortcomings. Such networks can alternately switch on and off their resources according to the traffic load conditions, and the traffic is carried on by the remaining active resources. In such a case, an optimal resource on-off switching framework is required to adapt the available resources to the traffic load fluctuations and to maximize the amount of energy saving under service quality constraints.

NETWORK COOPERATION FOR ENERGY SAVING

In this section, we investigate the application of network cooperation as a means of energy saving. First, we present the system model under consideration. Then, we discuss the challenges in the resource on-off switching decision making problem. Based on the challenges, an optimal resource on-off switching framework is presented.

SYSTEM MODEL

Consider an integrated cellular/ WiMAX system for wireless services over an area. The cellular network covers the whole service area. In regions with a high service demand, WiMAX BSs are also deployed to provide additional capacity. Let \mathcal{N} denote the set of cellular network cells covered by a WiMAX network BS, $\mathcal{N} = \{1, 2, \dots, N\}$ as shown in Figure 1. An MT in the overlapped coverage can be served by either of the two networks. It is possible that an MT can obtain service from both networks simultaneously, which is not discussed here for clarity of presentation. Let C denote the number of channels available in a cellular network BS, while the WiMAX network BS has M channels. Each channel has a fixed bandwidth B . For simplicity of illustration, assume that a call requires one channel from one of the networks for its service. A network BS working mode, x_n for the cellular network BS where $n \in \mathcal{N}$ and x_{N+1} for the WiMAX network BS, is represented by a binary digit “0” to indicate an inactive (off) BS or “1” to indicate an active (on) BS. There is always at least one active network in the overlapped coverage area to guarantee service provision in the area. Let $X = [x_1 x_2 \dots x_{N+1}]$ denote a vector of BS working modes in the overlapped coverage area. The total power consumption for a given BS, given by P_w (P_c) for WiMAX (cellular) network, has two components. One is a fixed component which accounts for the BS power supply and air conditioning, given by P_{wo} (P_{co}) for WiMAX (cellular) network. The other component depends on the number of active channels in the BS, and accounts for the power amplifier, feeder loss and transmitted power, given by P_{wv} (P_{cv}) for WiMAX (cellular) network. The number of active channels in cell n is given by k_{wn} (k_{cn}) for WiMAX (cellular) network, $n \in \mathcal{N}$. The power consumption of an inactive WiMAX (cellular) network BS is given by P_{wf} (P_{cf}). When a BS changes its working mode from inactive to active, an additional energy is required in order to startup the BS power supply, circuits, and air conditioning. This switching cost is represented by an additional power consumption β of the BS fixed power component. It is assumed that there is a central decision maker that controls the BS working mode and the number of active channels based on the optimization framework presented in the next section.

The following traffic and mobility assumptions are made: A1) New calls arrive to the coverage area of cell n according to a Poisson process with mean arrival rate ν_n ; A2) Handoff calls from adjacent cells arrive to cell n according to a Poisson process with mean rate ν_n ; A3) The dwell

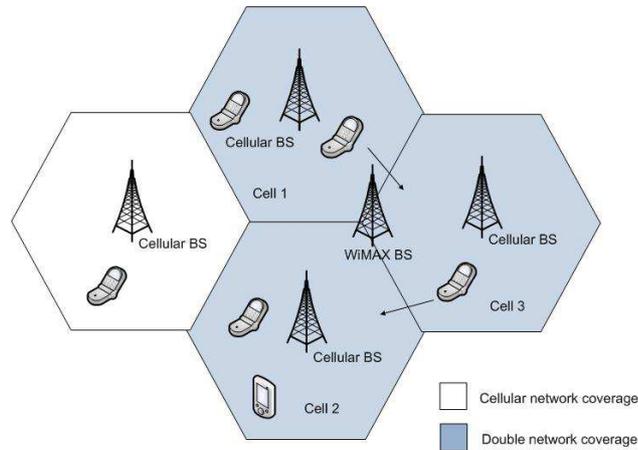


Fig. 1. The network coverage areas

time of an MT in a cell is exponentially distributed with mean $1/\eta$, where η is the average cell boundary crossing rate; A4) The call duration follows an exponential distribution with mean $1/\mu$.

THE PROPOSED ENERGY SAVING STRATEGY

Network cooperation in green radio communications exploits the temporal fluctuations in the traffic load to save energy. This is achieved by alternately switching on and off the available resources from BSs of different networks in regions with overlapped coverage, according to the traffic load condition. In general, two types of traffic load fluctuations can be distinguished. One is a large scale fluctuation, in which the traffic load varies significantly from one period to another along the day. The other is a small scale fluctuation, in which the traffic load varies slightly around some average value. Hence, we partition the time into a set of periods, $\mathcal{T} = \{1, 2, \dots, T\}$, of constant duration τ hours that can capture the large scale fluctuations in the traffic load along the day, $T = 24/\tau$. Each period $t \in \mathcal{T}$ is further partitioned into a set of $\mathcal{D} = \{1, 2, \dots, D\}$ smaller periods, each of duration Λ , to capture the small scale fluctuations of the traffic load during that period, $D = \tau/\Lambda$. The large scale fluctuations in the traffic load can be exploited to turn off some BSs in a light load condition and transfer the traffic load to the remaining active network to save energy. On the other hand, the small scale fluctuations can be exploited to switch off some of the channels in each active BS to further reduce the amount of energy consumption.

Decisions on the BS working mode are made at the initial moment of each period t . While BS on-off switching can save energy, a switching action that is not compatible with the traffic load during a given period will result in a high call blocking probability. An appropriate switching decision should maximize the amount of saved energy during that period and, at the same time, achieve acceptable service quality such as in terms of call blocking probability. Also, it is desirable to minimize the frequency at which a BS changes its working mode from inactive to active, in order to avoid the switching cost due to the additional energy consumption required for the BS startup. From Assumptions A1) and A2), the aggregate traffic arrivals to the cell are modeled by a Poisson process with mean rate $\lambda_n = \nu_n + v_n$. The aggregate traffic arrival rate for each period is estimated using the data of traffic arrivals observed in previous days, as the traffic load in general follows a repeating pattern everyday. The channel holding time in the cell is the minimum of the user cell dwell time and the call duration. From Assumptions A3) and A4), the channel holding time is exponentially distributed with parameter $\mu_u = \mu + \eta$. Hence, the call blocking probability can be calculated using the Erlang B loss model. The optimal BS on-off switching decision for a given period t can be obtained using the following optimization problem

$$\max_{S_n > 0, J, X} \left\{ \alpha \left[\sum_{n=1}^N (P_c - P_n) + (P_w - P_{N+1}) \right] - (1 - \alpha) \left[\sum_{n=1}^N \Delta P_n + \Delta P_{N+1} \right] \right\} \quad (1)$$

$$s.t. \quad \frac{(\lambda_n / \mu_u)^{S_n} / S_n!}{\sum_{s=1}^{S_n} ((\lambda_n / \mu_u)^s / s!)} \leq \epsilon \quad \forall n \in \mathcal{N} \quad (2)$$

$$x_{N+1} = \begin{cases} 1, & \exists S_n > C, n \in \mathcal{N} \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

$$\sum_{n=1}^N x_n = \begin{cases} N, & x_{N+1} = 0 \\ J, & x_{N+1} = 1, \sum_{n=1}^N S_n \leq M + JC. \end{cases} \quad (4)$$

Objective function (1) represents the total power saving in the overlapped coverage area. The variables P_n and P_{N+1} denote the BS power consumption for the cellular and WiMAX network respectively, which depends on the BS working mode. Hence, $P_n = P_c$ if $x_n = 1$ and $P_n = P_{cf}$ otherwise. Similarly, $P_{N+1} = P_w$ if $x_{N+1} = 1$, and $P_{N+1} = P_{wf}$ otherwise. The variables ΔP_n and ΔP_{N+1} denote the additional power consumption required for the BS to startup. Hence,

$\Delta P_n = \beta \cdot P_{co}$ if the cellular network BS changes its working mode from inactive to active, and $\Delta P_n = 0$ otherwise. Similarly, $\Delta P_{N+1} = \beta \cdot P_{wo}$ if the WiMAX BS changes its working mode from inactive to active, and $\Delta P_{N+1} = 0$ otherwise. From the objective function definition, there exists a tradeoff between the amount of energy saving achieved by switching on-off different BSs and the switching cost due to the additional energy consumption required for a BS to startup when its working mode changes from inactive to active. The parameter α is a weighting factor to give relative importance between energy saving and the BS startup switching cost. The variable S_n gives the required number of channels in cell $n \in \mathcal{N}$, $\sum_{n=1}^N S_n \leq M + NC$. Constraint (2) guarantees an acceptable service quality in terms of call blocking probability not larger than a required upper bound ϵ , where the value of λ_n for a given t is the largest aggregate traffic arrival rate over \mathcal{D} in that t . The WiMAX BS working mode rule is given in (3), while the number of required active BSs from the cellular network is given in (4), with $J = \{0, 1, \dots, N\}$. The rules of (3) and (4) are designed to satisfy the service demand in each cell for a given λ_n and ensure radio coverage in the overlapped area. Hence, the problem in (1)-(4) results in the optimal BS working mode for the WiMAX and cellular network in the geographical region that maximizes the amount of energy saving during some period t , limits the frequency at which BSs change their working mode, and provides a satisfactory call blocking probability. Due to the simple structure of the optimization problem in (1)-(4), a search algorithm can be used to solve it. In this case, the values of S_n which violate the service quality constraint of (2) are excluded from the search space. Different working mode vector X values can be composed from the feasible S_n values using the rules of (3) and (4). Hence, the working mode vector X which maximizes the objective function value of (1) can be found. If the large scale optimization problem results in more than one optimal BS working mode vector X , the working mode vector X is chosen from these optimal vectors such that the cells with the lowest traffic loads are switched off.

For each active BS, we can further exploit the small scale fluctuations in the traffic load to find the optimal number of active channels that maximizes the percentage energy saving for the active BS and achieves an acceptable call blocking probability. This is calculated at the beginning of each period $d \in \mathcal{D}$ using the following optimization problem

$$\max_{S_n > 0} \{x_n \cdot [P_c - (P_{co} + k_{cn}P_{cv})] + x_{N+1} \cdot [P_w - (P_{wo} + k_{wn}P_{wv})]\}, \quad \forall n \in \mathcal{N} \quad (5)$$

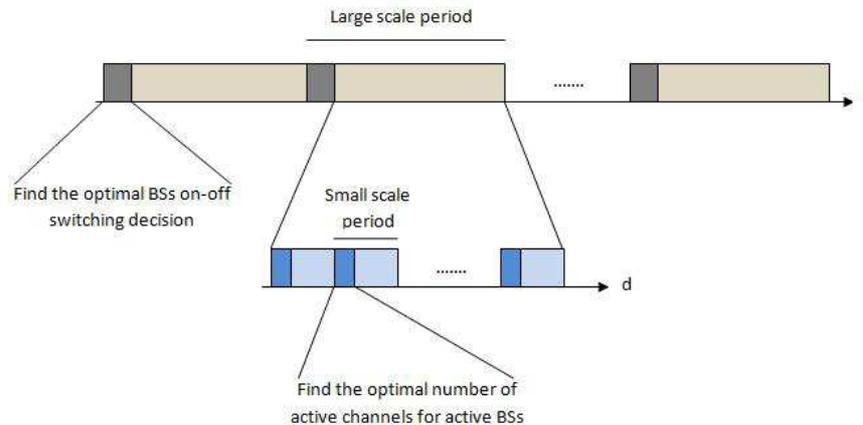


Fig. 2. Time sequence of optimization events for the network cooperation energy saving framework

where x_n and x_{N+1} are obtained from the solution of (1)-(4). The optimization problem of (5) is subject to the service quality constraint of (2), where λ_n is defined for each $d \in \mathcal{D}$. With a larger coverage area of the WiMAX BS, it is assumed that the power consumption of each on channel in the WiMAX BS is not less than that of a cellular network BS (i.e. $P_{wv} \geq P_{cv}$). In this case, to further improve the amount of energy saving, when the BSs of both networks are on, more channels from the cellular network are utilized. As a result, we let $k_{cn} = C$ and $k_{wn} = S_n - C$ when BSs from both networks are on, otherwise the active number of channels from the on BS is equal to S_n . The time sequence of optimization events is illustrated in Figure 2.

PERFORMANCE EVALUATION

In this section, we evaluate the performance of network cooperation for energy saving using the framework given in (1)-(5). The geographical region under consideration is given in Figure 1 with the coverage of 3 cellular networks BSs that overlaps with the coverage area of a WiMAX BS. It is assumed that the initial BS working mode vector is $X = 1111$. The system parameters are given in Table I. The number of available channels in the cellular network and WiMAX BSs are chosen in a way that reflects the higher capacity of a WiMAX BS. The total number of available channels in the region are determined such that the peak traffic load do not violate the target level of the call blocking probability. The different power components of the WiMAX BS

TABLE I
SYSTEM PARAMETERS

Parameter	Value	Parameter	Value	Parameter	Value
C	10	P_c	400 W	τ	1 hour
M	72	P_{co}	250 W	Λ	15 minutes
P_w	1500 W	P_{cf}	10 W	α	0.5
P_{wo}	400 W	$1/\eta$	4 mins	β	0.1
P_{wf}	30 W	$1/\mu$	6 mins	ϵ	0.01

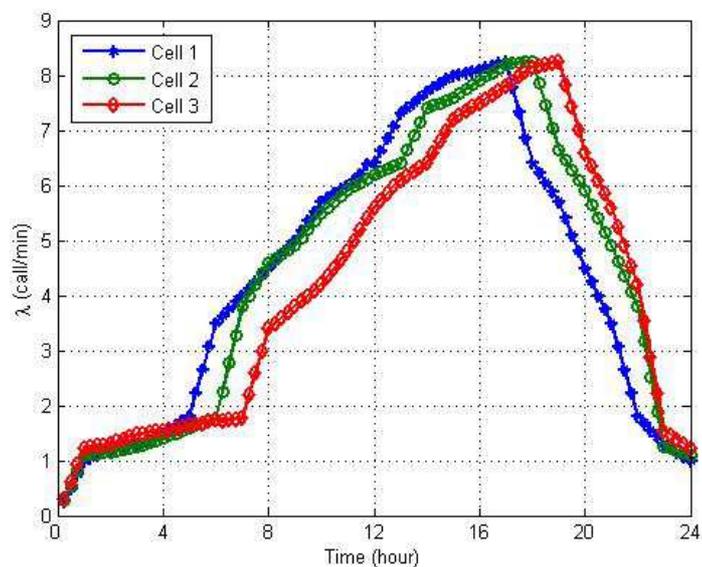


Fig. 3. The aggregate traffic mean arrival rate in each cell

are chosen such that it is larger than that of a cellular network BS, in order to reflect the fact that a WiMAX BS has more channels and covers a larger area than that of a cellular network BS. The value of α gives equal importance for maximizing the amount of energy saving and reducing the BSs on-off switching cost.

Figure 3 shows the aggregate traffic mean arrival rate over the 24 hrs of the day for each cell. The λ values capture the traffic load fluctuations during the day. The λ value has the peak value in the middle of the day, while it has a small value in the early morning and late night.

The optimal decisions regarding the BS working mode for different periods are given in Table II. The BS working mode vary according to the traffic load fluctuations in each cell, such that the

TABLE II
BS WORKING MODE

Period	1 - 5	6 - 12	13 - 14	15 - 19	20	21 - 23	24
X	1110	0001	1001	1101	0101	0001	1110

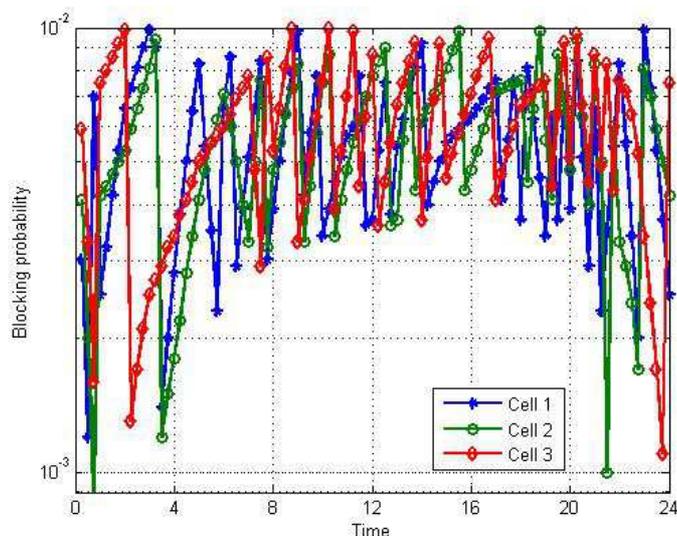


Fig. 4. Call blocking probability in each cell with the optimal number of active channels from the on BSs

optimal number of BSs which maximizes the amount of energy saving and provides a satisfactory service quality level are on.

The daily percentage of energy saving when all channels are active for the WiMAX BS is 24.5%, while for the cellular network BSs in cells 1,2 and 3 are 44.68%, 48.75% and 73.13% respectively. With the number of channels being optimized, the daily percentage of energy saving for the WiMAX BS is 34.45%, and for the cellular network BSs in cells 1,2 and 3 are 46.33%, 50.31% and 74.06% respectively. This shows that the small scale optimization problem significantly improves the amount of energy saving for the WiMAX BS.

Figure 4 shows the call blocking probability in each cell when the number of channels are optimized. The call blocking probability in each cell has a desired maximum value of $\epsilon = 10^{-2}$.

CONCLUSION

In this article, network cooperation as a means of energy saving in green radio communications is investigated. For the system model with overlapped coverage from different networks, the proposed technique can achieve energy saving without increasing the transmission power. It relies on the cooperation among different networks to save energy on two scales. On a large scale, networks with overlapped coverage alternately switch on and off their BSs according to the long term fluctuations in the traffic load. On a small scale, each active BS switches on and off its channels according to the short term fluctuations in the traffic load. Numerical results demonstrate a satisfactory service quality in terms of call blocking probability and a large percentage of energy saving for each network. In the proposed framework, the service quality constraints can be extended to include other metrics than call blocking probability, such as the minimum achieved throughput for data applications, delay and delay jitter for video streaming applications.

In general, while cooperation in wireless communication networks results in performance gain, it incurs some overhead. Specifically, for our framework, this cooperation overhead includes the synchronization required among the cooperating BSs of different networks. The importance of this synchronization is due to the fact that an unsynchronized switching action among different BSs can significantly degrade system performance in terms of call blocking for example. Such a synchronization can be achieved through control signaling among the cooperating BSs.

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