ENERGY REDUCTION IN LTE ACCESS NETWORK OPERATION AND PLANNING

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Energy consumption in cellular networks is increasingly a concern, due to the rapid growing demand for mobile communications, the necessity of adding new base stations will continue to grow as well as the amount of energy needed to operate the network. This dissertation presents two algorithms to manage the increasing service demand and create possibilities for energy reduction. The novel cell selection algorithms are bandwidth-based (BB) and energy-aware (EA) cell selection. BB balances traffic between two tiers of a LTE heterogeneous network (HetNet) and offloads traffic from high-powered base stations. EA considers the potential energy requirement to serve users and enables turning off base stations during quiet hours. Also, this thesis shows two energy optimization models to minimize the amount of energy consumption in operating LTE HetNets while maintaining levels of customer satisfaction. First, step-dimming (SD) energy reduction technique reduces the transmission power of high-powered base stations according to the levels of traffic demand. Second, resource-based (RE) energy reduction optimization minimizes the spectrum resources required to achieve user service demand level according to the user channel quality indicator (CQI). Last, this dissertation studies benefits of the proposed algorithms in a minimum CAPEX LTE access network in a sample city-like area with time and spatial varying traffic demand.

Keywords: Energy Reduction, HetNet, LTE, Cell Selection.

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1.0 INTRODUCTION

Energy consumption is a critical issue in many fundamental infrastructures. Only recently has energy consumption become a vital focus in cellular networks. Techniques have been proposed and studied to reduce energy consumption and improve energy efficiency in operating the networks. The majority of the techniques focus on tackling the most energy-consuming part of the networks which is the radio access network. For example, switching off base stations or eNodeBs (eNBs) and strategically adding smaller cells. The proposed approaches still have many challenges and constraints, for instance, interference coordination management, providing sufficient coverage, and bandwidth. In this dissertation, we divide the energy consumption challenge into three sections. First, we cope with the rising traffic demand that is the leading cause of the increasing energy requirement. We present two novel cell selection techniques to moderate the impact of high demand and create a potential for energy reduction. Next, we introduce two advanced energy reduction techniques to cut energy requirements in serving user demand. Last, we examine the state-of-the-art cell selection and energy reduction techniques in a simulated network and study a potential impact on optimizing capital expense in expanding a network.

1.1 REDUCING ENERGY CONSUMPTION IN CELLULAR NETWORK

Studies have suggested constant growth of traffic demand in cellular networks, thanks to the rapid increase in popularity of smartphones and tablets. The addition of improved and advanced cellular network facilities will continue to be needed to satisfy increased service demand and enable ubiquitous wireless access [1]. Despite the increase of energy consumed to provide wireless connections in networks, which is estimated to be up to 80% of the total power consumption, it is projected that less than 20% of communication traffic will be wireless in 2020 [2]. It shows that even though the demand in wireless section of a network is light compared to other sections, the energy to serve the demand is significant. Furthermore, [3, 4] report that the access network base station consumes the biggest proportion of energy in cellular networks. In addition, [5] notes that the financial cost of energy is now as large as the personnel cost to operate networks. As a result, there has recently been a focus on *reducing* energy consumption in LTE access networks. The focus is on reducing the energy consumption of the network not the customer mobile devices. This is because the energy consumption of the network is in orders of magnitude larger than the total energy consumed by the users mobile devices [6].

To reduce energy consumption, it is understandable that the simplest way is to turn off the equipment. Recent research has proposed and examined several techniques to switch off unnecessary eNBs during certain periods of time [7–14]. The techniques take advantage of the fact that traffic demand varies over time, and a network is designed and deployed based on peak demand. Therefore, there is a possibility of switching off eNBs when the traffic is lower than the peak. Also, to enhance the chance of turning off an eNB, users connection to the eNB can be maneuvered and handed over to other eNBs. The remaining active eNBs are assumed to take responsibility of providing service to users during the period either by maintaining their regular operation or adjusting according to the added responsibility. Furthermore, research agrees that operating smaller coverage cells can improve energy efficiency and reduce the total network energy consumption. By deploying smaller eNBs, available bandwidth per user is increased, and energy consumed by signal transmission is reduced while providing better received signal strength (RSS) to users.

However, every advancement has its difficulty. In most cases, switching off an eNB would leave an area with poor service from neighboring eNBs or no service at all. Doing so would upset customers in the area or conflict with regulatory emergency localization requirements. Expanding the coverage area of neighboring eNBs to compensate for the coverage hole has been shown in some cases to require even more energy consumption [15]. Although implementing smaller coverage eNBs can ease the issue of poor quality of service

(QoS) after turning off eNBs while saving total energy, dense eNBs deployment requires additional interference management. Last but not least, few works have studied the extra cost of installation the additional eNBs and expansion of the backhaul to support the eNBs.

1.2 PROPOSED ENERGY REDUCTION APPROACH

To tackle the challenges of reducing energy consumption while maintaining or improving the quality of service, we first look at how to manipulate the traffic to enable increased opportunity for reducing the energy. We consider the deployment of smaller cells, picocells or low-powered nodes (LPNs), inevitable to provide more available bandwidth and improve the user experience. Also, we are not concerned about energy consumption in user equipment. One of the challenges in operating a network with the added LPNs is load management. Current research on cell selection techniques mainly aim to improve network performance, and quality of service, by offloading more traffic from high-powered nodes (HPNs) to low-powered-nodes (LPNs). In addition, according to research, HPNs consume significantly higher energy than LPNs when operating at full capacity. More users connecting to LPNs or fewer users associating with HPNs can lessen the necessity of HPNs operating fully and increase the possibility of saving power at the HPNs. Consequently, offloading more traffic to LPNs would create more possibility to reduce energy consumption in HPNs. Therefore, we first propose *Bandwidth-based (BB)* cell selection that shares the number of users fairly among eNBs in an area and lowers the number of users associating with HPNs.

In addition to providing a more balanced network to improve service performance and create opportunities to reduce energy consumption at HPNs, we see more possibility during very light-loaded hours. Depending on the energy required to operate LPNs, running multiple LPNs, in fact, could cause higher energy consumption than the energy saved at the HPNs. In this research, we calculate user spectrum resource requirement based on user service demand and user received signal quality. The required spectrum resource is defined as a percentage of the total spectrum resource at an eNB. We found that during light-load periods, operating HPNs in low-power mode could potentially provide sufficient services to users without any active LPNs and would create lower total network energy consumption. Thus, we present *Energy-aware (EA)* cell selection that keeps LPNs inactive and ensures sufficient services is provided by reduce-powered HPNs.

After managing load demand to produce the potential to reduce energy requirement in eNBs and sufficiently maintain the service quality, we focus on minimizing the energy consumption in HPNs and LPNs. Due to smaller power an LPN transmits, efforts to reduce energy consumption in LPNs may not considerably minimize the total energy consumption. Thus, we concentrate on reducing the energy consumption in HPNs by presenting a *Step-dimming (SD)* mechanism. The transmission power of HPN can be adjusted according to pre-defined steps. The steps are determined based on the number of users and guaranteed achievable data rate. To the furthest possibility, an HPN could transmit a signal at a very low level just to maintain its coverage and provide enough achievable data rate for the control signaling. Next, we advance the consideration of the required spectrum resource and develop a *Resource-based (RE)* energy reduction technique to further minimize the energy consumption in eNBs, both HPNs and LPNs. Depending on user different service demand, each user receives sufficient spectrum resource transmitted to the user at a calculated transmission power from an eNB. This technique further minimizes the obligation for eNBs to transmit signal at high power in both time and frequency domain thus reducing the energy required.

Last, even though adding more eNBs can improve network performance, and quality of service, one drawback of doing so is the increase in the cost of deployment. To the best of our knowledge, very little literature has considered this issue. Therefore, we extend our scope of research to study impacts of our energy reduction mechanisms on network expansion. In a sample city-like area, we divide and categorize the area into five different types of service areas, namely, Business district, Entertainment area, Residential, Highway, and Unoccupied. Each type of service area carries unique variant traffic characteristic. Regarding the different demand characteristic, we present a CAPEX optimization problem to plan a network in the sample area. After the network deployment and extension, we investigate the possibility of energy saving and analyze the potential impact on the capital expenditure. Eventually, the results of anticipated energy saving could influence the modification of network planning.

1.3 RESEARCH CONTRIBUTION

Here, we summarize the contribution in this thesis. The main focus of this thesis is to optimize the total cost of operational expense (OPEX) and capital expenditure (CAPEX) of an LTE access network given a prospective service area with projected time and location dependent traffic.

This research makes contributions in three parts.

1. **Cell Selection:** In Chapter 4, we propose two cell selection algorithms for HetNets to increase the possibility of energy reduction while maintaining the quality of service. Numerical results show that Bandwidth-based cell selection can offload more users to LPNs and create a more a balanced network that has higher possibility to reduce energy consumption and also increases overall user satisfaction. Next, we propose Energy-aware cell selection that is an advanced version of BB cell selection. EA cell selection takes into account the various levels of service demand from users and the quality of user RSS. We found that in many hours of a day, an operator can sufficiently satisfy user demand by operating HPNs in a reduced-power mode that can decrease the requirement of power even further.
2. **Energy Consumption Minimization:** After we manipulate the traffic demand to increase the opportunity to reduce energy consumption, we propose two novel energy optimization approaches in Chapter 5. The Step-dimming (SD) energy reduction approach dynamically reduces the transmission power of HPNs, according to the traffic load. When our cell selection offloads users to LPNs, SD is shown to reduce the power requirement to operate the network considerably and maintain customer satisfaction levels. A second approach called Resource-based energy reduction (RE) further considers the user service levels and RSS quality to determine adequate spectrum resource for each user and transmission power of eNBs. RE decreases the total energy consumption even further than SD and improves the user satisfaction in certain time periods.
3. **OPEX/CAPEX Optimization:** To incorporate energy consumption minimization into the process of planning a network, we propose a optimization problem that considers the cost of deploying the network in Chapter 6. The optimization problem includes

consideration of the base station cost, installation, backhaul transmission and site lease which are different for an HPN and an LPN. With some constraints, we generate a network in a sample area as a result of the optimization problem. The sample area contains five different types of service areas which have various traffic profiles. The types of the service areas are business, entertainment, residential, highway and unoccupied. Next, we examine the energy consumption in the generated network and found that with the amount of operational expense saving from reduced energy consumption the operator can plan to deploy more base stations and satisfy more users.

1.4 THESIS OUTLINE

Table 1.1 summarizes frequently used abbreviations in this thesis. The remainder of this thesis is organized as follows. Chapter 2 provides a literature review on energy reduction techniques in cellular networks, related issues, their limitations and drawbacks and comparison with our proposed techniques. Chapter 3 describes our scope of research. Chapter 4 presents the proposed cell selection techniques and numerical results. Chapter 5 introduces the energy reduction optimization methods, their numerical results, and analysis. Chapter 6 presents CAPEX network design optimization approach and its challenges. Last, Chapter 7 concludes the dissertation with discussion and possible future work.

Table 1.1: List of abbreviations

LTE	Long term evolution
HetNet	Heterogenous Network
HPN	High powered node
LPN	Low powered node
UE	User entity
eNB	eNodeB
RSS	Received signal strength
SINR	Signal to interference plus noise ratio
OPEX	Operating expense
CAPEX	Capital expenditure
QoS	Quality of service
QCI	QoS Class Identifier
CQI	Channel Quality Indicator
MILP	Mixed-integer linear programing
DB	Distance-based cell selection
SB	SINR-based cell selection
BB	Bandwidth-based cell selection
EA	Energy-aware cell selection
SD	Step-dimming energy reduction
RE	Resource-based energy reduction

2.0 LITERATURE REVIEW

In the past five years, energy consumption in cellular networks has received a great deal of research attention, especially in energy-efficient network operation. The majority of the research notes that the access part of a network is taking the most of the energy to provide 24×7 service coverage [3]. Several research directions have been proposed to save energy, for example, switching off base stations [7–14], implementing smaller cells [16–27], and partially turning off service [28–30]. In [7], the authors take advantage of the number of base stations in a dense service area and suggests that one base station in the area can be turned off during light-loaded periods. In [8, 9], the authors partition a service area into responsible smaller areas and congregate traffic demand into fewer base stations. With a pre-set threshold, the lowest loaded base station is switched off. A similar methodology is analyzed in a network-wide scenario in [10]. These techniques all use the assumption that neighboring base stations can expand their coverage and provide services to switched-off base station service area. To be able to cover the area, a physical antenna adjustment has been proposed and analyzed by [11–13, 21]. However, expanding cell coverage has several challenges, for example, increased interference to neighboring service cell, decrease in the amount of available bandwidth per users [31], lower achievable data rate due to lower RSS and higher energy consumption in the system. Also, the study in [32] points out that switching on and off network equipment frequently actually consumes more energy per time unit than keeping it active. Energy required to provide service to an extra area, in fact, grows faster than energy saved by simply turning off base stations [15]. The authors in [21] propose to deploy a sector in a base station using an 800 MHz frequency carrier and takes advantage of its low path loss attenuation. By physical adjustment of the antenna, the solution can provide higher RSS in the expanded area without increasing transmission power. Partially switching off base stations methods have been proposed. Techniques in [28–30] gather remaining traffic during light-loaded time into fewer frequency basebands and switch off unoccupied ones.

To overcome the challenges HPN-only networks present using smaller cell sizes was studied in [16, 18]. Regarding required coverage and transmission power, four strategies of implementing smaller cells and their locations were designed based upon the distance between each base stations in [17]. [19] presents a multi-hop transmission cellular network to divide a link between a base station and a user into shorter links to enjoy lower pathloss and lower necessary transmission power. Most of the research mentioned is developed regarding a single-layer network. Coordinating strategies between base stations or backhaul are proposed in [21–23, 33]. All methods still assume that neighboring base stations can cover the coverage hole left by turning off a base station.

Energy efficiency in multi-tier networks was studied in [20,23,24,34–40]. Initially, HetNet deployment is to improve the spectral efficiency in cellular networks by offloading traffic from HPNs to LPNs. Such deployment leads to an increase in energy requirements due to the additional eNBs installed. Nevertheless, by introducing cell sleeping, HetNets can potentially operate more energy-efficiently than traditional single-tier networks. During peak traffic hours, more energy-efficient LPNs can become active and offload some demand from HPNs. Then, those LPNs are turned to sleep during light traffic hours when the HPNs are capable of maintaining throughput and coverage [34]. [24] conducts a study on LPN deployment with dynamic sleep mode. The deployment shows to improve the coverage of cellular network but consumes more energy when the LPNs do not adapt to traffic load. [34, 35] present similar cross-layer energy optimization models for heterogeneous cellular network. The authors find that certain LPNs are located in the coverage of HPNs. Thus, the main challenge is to associate users with the group of eNBs to minimize the energy consumption after lightly-loaded small cells go to sleep. In [36], the authors use fuzzy set theory to determine frequency reuse and improve spectral and power efficiency. [20] uses stochastic geometry to model a multi-tier HetNet system and optimizes power consumption by statically switching off base stations while [40] adds a layer of smaller base stations to improve energy efficiency with trade-offs of outage probability. [37] switches off small cells when traffic demand is below a threshold and shows that higher traffic offloaded to smaller cells can reduce total energy consumption of the network. [38] proposes a shared baseband unit to be used by multiple base stations. The unit can mitigate inter-cell interference and eventually reduce energy consumption. To maintain coverage of a service area, [39] finds an optimal number of eNBs that can be switched off as a function of coverage radius. However, all of the mentioned works consider only energy reduction by switching off LPNs

At the time of writing, there is no standardized energy efficiency metrics to compare the performance of different energy reduction mechanisms [6, 41]. The main issue is differences among various cellular networks are so significant that comparing their energy performance becomes subjective. The comparison depends highly on benchmark settings and specifications of the measured network i.e. specific models of equipment, types of base stations, the number of tiers in the network, characteristic of the considered coverage area. Many papers measure energy efficiency by achievable data rate per energy unit. The performance can be improved by deploying more base stations simply to increase available capacity [42]. However, having more operating base stations can create higher interference. Simulations have been done assuming all types of base stations, HPNs and LPNs, are operating in the same frequency band. The interference can be caused by transmission signal from either HPNs that act as umbrella cells, neighboring LPNs or from a combination of both [39]. [11, 43] consider interference in an area with densely deployed LPNs while [44] presents impact of inter-tier interference where both tiers are transmitting signal at the same level of power. [11] proposes baseband units that can adaptively switch baseband. By switching the baseband, the network can timely reallocate the baseband to areas where more spectrum is needed to produce more energy efficiency, reduce interference and improve spectrum efficiency.

Widely used metrics to measure the effect of interference are coverage probability, outage probability and achievable data rate. [8] shows that once base stations are turned off, interference is reduced, and coverage probability and achievable data rate are improved. Outage probability is caused by being unable to provide a service to users that experience a SINR below a set threshold or there is no available bandwidth [39]. [45] utilizes outage probability as the result of switching off an eNB as a constraint in optimizing energy consumption. However, the study did not consider service performance for individual users. Some research neglects the impact of interference when LPNs are far away from another [9], located in another macro cell [46] or assumed to not have overlapping coverage [10]. There are studies on the optimization of the number of LPNs to balance the tradeoff between maximum energy efficiency, network performance, i.e., outage probability [39] or user experience (e.g., the number of users per cell [47]). A way to avoid high inter-cell interference is to have a coverage range [38, 48] and number of active base stations per cell [48] that create the least interference. Another way to mitigate interference is to have a frequency reuse strategy. Frequency reuse techniques are presented in [9, 12, 13, 36, 49]. So far, all studies have been conducted on a single frequency band that is shared by both HPN and LPN yielding a high possibility of interference. Several Inter-Cell Interference Coordination (ICIC) techniques have been proposed to reduce the impact of the interference [50–55]. However, to prevent LPN users from interference caused by HPNs, HPN users suffer from deteriorated service. In this thesis, we utilize a dual-frequency scenario where minimum inter-tier interference exists. Two distant frequency bands can operate simultaneously in the same area on different tiers in the HetNet. HPNs, which provide service to a bigger coverage, operate on a lower frequency band. LPNs, which handle smaller coverage, operate on a higher frequency such as the AWS band. Thanks to LTE technology, it allows LPNs to concern only user data traffic or user-plane while leaves responsibility of control signal or control-plane for HPNs [56, 57]. A similar implementation has been conducted in [12,21]. However, the works only reserve the lower frequency band for users during low traffic to expand the coverage after switching off base stations while both frequency bands are deployed at the same eNB in [58]. In addition, these advantages are possible in practice considering that all four major network providers in the USA possess licenses on both low and high frequency bands [59, 60] and additional spectrum bands will continue to be available in 2016 [61].

So far in this section, the majority of research aims mainly to meet customer service demand fully and equally among customers. However, the service demand can be categorized into several levels and the service provided can be adequately adjusted without customers noticing, instead of always providing full-service [28]. [47] shows that the different levels of service is experienced even though eNBs transmit at a constant level of power. The levels of service depend on the number of users sharing constant limited bandwidth. Moreover, although a few studies have concerned and suggested the importance of different network planning for various types of service area, no concrete method has been proposed to reflect the difference yet. Note that, [36] suggests that a network needs to be broken down into five typical deployment areas, i.e., dense urban, urban, suburban, rural and unpopulated. Moreover, a day can be divided into five periods, i.e., night, morning, average, high and busy hour. However, the work does not state how to model the differences. [62] points out that traffic profile in smaller areas served by pico cells can be different from one in bigger areas served by HPNs that cover the same wider area. [28] expresses that a cellular network can be divided into four types of service area, Business, Entertainment and Shopping, Highway and Residential. Additionally, energy optimization is more effective when it considers different time-varied patterns of demand and peaks of the demand in particular areas rather than network-wide demand. Moreover, increasing capacity alone will not be enough to improve the network energy efficiency. The capacity needs to be tuned dynamically according to traffic demand that varies by time and locations [63]. Another interesting study shows that the energy saving from switching off base stations is proved to increase when a ratio of the traffic variance over its mean and the density of base stations are high. That means it is more probable to reduce energy consumption in an area where there is high traffic variance between day and night as well as high base station density such as in an urban area [64]

Instead of using total network traffic demand or demand per area which creates an inaccurate average traffic demand, studies utilize the location of users to imitate geographical variations of the traffic. Also, users location is a critical factor in computing their achievable data rate and evaluating the network performance. Two major approaches to user distribution have been assumed. The network could consist of uniformly distributed users location [22–24,37,42,48] where the average of traffic load follows the approximated level of demand per area. Even though the uniform distribution of user can represent the spatial variation of traffic demand in wide areas, it does not present the nature of user concentration in particular areas creating considerably high traffic at certain times. In comparison, the users could gather in specific areas forming dense areas of users or particularly high service demand per area in small regions. The occurrence can be simulated by distributing the users according to a Poisson Point Process (PPP) with specified locations acting as centers of the distribution and hotspots or small areas where there is high demand [20,38–40,47]. However, only PPP does not demonstrate sufficient traffic demand in areas far away from the hotspots. Moreover, [65, 66] show that implementing LPNs can save significant energy when they are where users are gathered, and energy saved increases when traffic is offloaded more to picos. Even though backhaul energy is mentioned, solely first hop connection, microwave link in HPNs and Ethernet terminal in LPNs, is considered. The backhaul energy consumption is assumed to be independent of traffic and location of the eNBs. [67] re-arranges users among coverage cells to enable turning off base stations by re-assigning users in a low loaded base station to a new base station within range. However, the study does not consider the effect of the reassignment on the network performance. A similar idea is experimented in [68] where an optimization model is created to switch off base stations that have no users and maintain required service demand. The model is extended to guarantee no coverage holes in [32].

Energy consumption concern is still not widely included when designing a network. Only very few works have presented studies on the potential of minimizing operation energy cost by including consideration of future energy consumption. The ability to minimize energy consumption depends highly on network layout. Crucial constraints that limit the energy reduction are coverage guarantee, the location of eNBs relevant to the user location, adaptation of the mechanism in regards to traffic profiles. [69] presents a possible network deployment approach where the entire traditional HPN-only network is replaced by LPNs to reduce the transmission power and the total network energy consumption. However, the number of eNBs required to cover entire coverage area is extremely high and would cost a considerable amount of capital to deploy the high number of LPNs and their backhaul connections. Another study includes QoS, coverage and capacity constraints in an optimal selection of eNBs locations [70]. The results show that a network will mainly consist of a vast number of LPNs to achieve the most energy efficiency. Also, there is a trade-off between network deployment cost and level of efficiency in energy management. A constraint of full coverage requirement limits the energy savings when the traffic level is low if there is no specific energy reduction implemented at the remaining eNBs. In [71], the initial investment in building a network is considered as an extra objective in the energy optimization. However, the considered investment cost includes only a cost of installation. A cost of connection from eNBs to the backhaul that varies by the distance from the eNBs to the backhaul is still to be studied.

However, this work does not include distant frequency bands into the planning.

In summary, the current literature has considered mainly on how to improve the energy efficiency of the network or cut down energy requirement by switching off equipment. The approaches lack respects to causes of energy consumption increase and effects of energy reduction. One of the causes that require growing energy demand is the rising service demand. The service demand, when is handled by a standard load management, can limit the probability to reduce the network energy consumption. In this work, we propose two cell selection techniques to create further opportunities to save energy while maintaining the quality of service. Moreover, besides switching off equipment, we present two energy saving approaches that generate additional detailed energy reduction to the system. The two approaches reduce energy requirement more specifically to the user service demand and most importantly creates no coverage hole. Last, studies on energy saving in a cellular network are based on results from simulations that assume either static traffic demand or universal dynamic traffic demand that varies by only time or locations. In the last chapter of this thesis, we evaluate our proposed energy saving mechanism in a city-like area where traffic demand varies in both time and locations.

3.0 SYSTEM MODEL AND SCOPE OF RESEARCH

In this chapter, we define the research problem and depict our research model and scope of the research on LTE HetNet cell selection, energy consumption, network planning, service demand as well as evaluation metrics.

The ultimate goal of this research is to determine a methodology for operating an LTE access network with minimized energy requirement. The general problem is: *given a prospective service area and predicted time- and location-dependent traffic demand, determine a strategy to operate and deploy eNBs in LTE access network that optimizes the operator's OPEX and CAPEX.* We tackle the problem by dissecting the problem into three parts; load management by cell selection, energy consumption and network planning.

Table 3.1 presents variables used in the following two sections and their definitions.

3.1 CELL SELECTION IN LTE HETNET

In a LTE HetNet, the traditional cell selection aims for UEs to connect to an eNB that offers the highest SINR, which leads to the possible highest achievable data rate.

Consider a LTE network consisting of N^{eNB} eNBs supporting N^{UE} users. In traditional cell selection UE_i, where $i \in \{1, \ldots, N^{UE}\}$ connects to eNB_j having the highest SINR, where $j \in \{1, \ldots, N^{eNB}\}$. Thus, the base station eNB_j^i selected by UE_i is given by:

$$eNB_j^i = max_j\{SINR_j^i\} \tag{3.1}$$

where $SINR_j^i$ is the SINR level measured by UE_i from base station j. In HetNets, the eNBs have various levels of transmission power with the HPNs operating at high power and the

Table 3.1: Variables and definitions.

Variable	Definition
N^{UE}	Total number of users
UE_i	User equipment i when $i \in \{1, 2, 3, \ldots, N^{UE}\}$
N^{eNB}	Total number of eNodeBs
eNB_j	eNodeB j when $j \in \{1, 2, 3, \ldots, N^{eNB}\}$
N^{HPN}	Total number of HPNs: $hpn = \{1, 2, 3, \ldots, N^{HPN}\}$
N^{LPN}	Total number of LPNs: $lpn = \{1, 2, 3, \ldots, N^{LPN}\}$
E^{hpn}	Energy hpn when $hpn \in \{1, \ldots, N_{HPN}\}$
E^{lpn}	Energy lpn when $lpn \in \{1, \ldots, N_{LPN}\}$
T	Total number of time periods: $t = \{1, 2, 3, \ldots, T\}$
E_t	Network energy requirement at time t
SE	Supporting equipment energy factor
AC	Heating ventilation and air conditioning factor

LPNs at low power. If the standard cell selection technique is used the UEs tend to connect to the HPNs, leaving the LPNs underutilized. To better exploit LPNs, *CRE* techniques have been proposed by adding an offset value $offset_j$ to the SINR from LPNs This results in the UE_i selecting the eNB with the largest $SINR^i_j$ plus $offset$ as given by

$$eNB^i_j = max_j\{SINR^i_j + offset_j\}. \tag{3.2}$$

The $offset_j$ value is zero for HPNs and is typically selected in the range of 2 - 20 dB for LPNs [53]. Note that the $offset_j$ can be different among LPNs. As presented in Fig. 3.1, adding an offset value increases the geographic coverage range of LPNs, and, therefore, more UEs connect to LPNs. As the number of UEs connecting to LPNs increases, the network bandwidth efficiency and overall data rate increases. However, such an improvement depends on the offset values selected. If the offset value is too small, most UEs will still select the

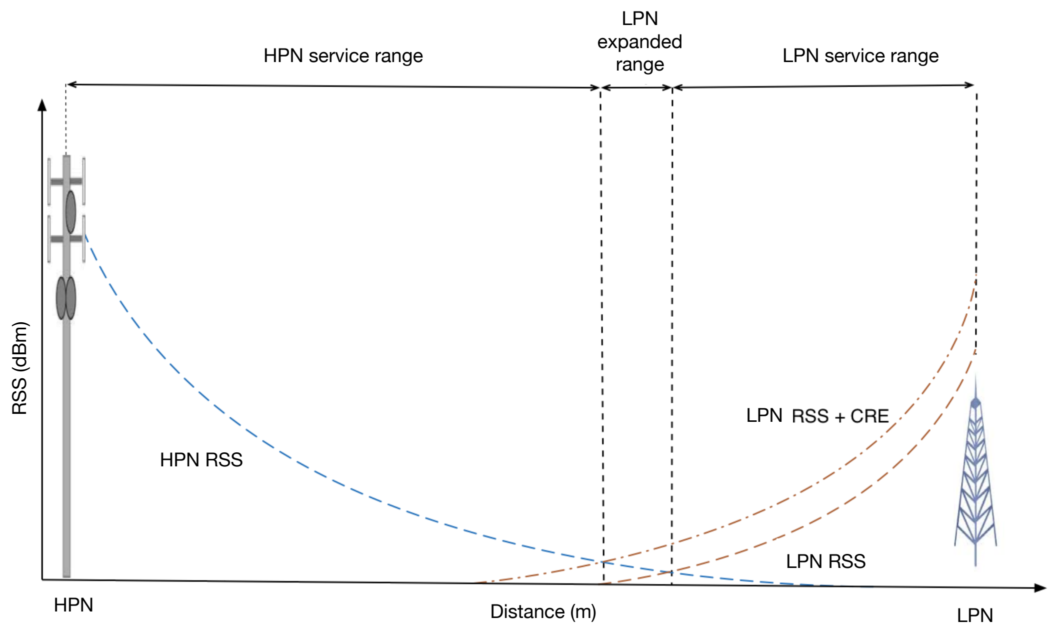

Figure 3.1: Expanded LPN service range.

HPNs, thus leading to a low offloading performance. On the other hand, when the offset value is too high, UEs will select LPNs even though they have a poor SINR and the performance will suffer.

Because the cause of increasing energy consumption is the growing traffic demand, cell selection or load management is critical to promote energy saving. We consider that HPNs generally consume significantly higher energy than LPNs due to the high transmit power. The HPNs are required to transmit at a high power because they cover a much wider area and need to provide services to a greater number of users than LPNs. Due to the rapidly growing mobile communication, additional deployment of LPNs is inevitable. Assuming that LPNs obtain the same amount of bandwidth as HPNs, the LPNs can provide services to as many users as HPNs. With more users offloaded to LPNs, we can reduce the HPNs transmit power. In Chapter 4, we first develop a cell selection to mitigate the problem of users congestion in HPNs caused by the standard cell selection. The first technique, Bandwidth-based (BB) cell selection (Section 4.1), considers the number of users in each eNBs in addition to the

SINR. BB can solve the problem of user congestion in HPNs during normal hours and create opportunities for HPNs to reduce the power consumption. However, during quiet hours, we found a disadvantage of the BB cell selection. The cell selection balances the load between HPNs and LPNs regardless of the total demand. In some occasions, the total demand can be so low that it does not require LPNs to be active. All users can particularly connect to HPNs and receive satisfying services. We consider that HPNs are needed to operate at all times to avoid coverage hole despite the traffic demand. The network can save more energy by keeping LPNs inactive. Therefore, we develop the second cell selection techniques, Energy-aware (EA) cell selection (Section 4.2), to generate further energy saving during the quiet hours. EA maintains users with the HPNs as long as the HPNs operate at the lowest power and satisfy users demand. Although the cell selection techniques improve the quality of service in many cases, we do not prioritize the improvement in this work. Given the opportunities to save power in eNBs by BB and EA cell selection, we proceed to focusing on mechanisms to reduce the energy consumption.

3.2 ENERGY CONSUMPTION IN LTE HETNET

Because the majority of energy requirement in an LTE network is from the access network [3], specifically, transmission equipment in eNBs [72]. Note that, we consider only the access network of a HetNet. Power requirement and operation limits in the core network and the user terminal are not in the scope of this research. According to [73], energy consumption in the core network contributes to a low percentage of the total network energy consumption. Meanwhile, energy requirement in user equipments has received great improvement for the last two decades. Current user equipment requires more than 97% less power than one in 1990s. The advancement has made the energy consumption in user equipment negligible when compared to the consumption in eNBs [6].

Consider a HetNet access network that consists of N^{HPN} HPNs and N^{LPN} LPNs. We divide a day into a set T of non-overlapping time periods $t = \{1, 2, 3, \ldots, T\}$. Note that the time periods need not be equally long. Let E_t represents the total energy consumption in a LTE HetNet in time interval t. For a given eNB, we define the energy requirement based on dependent and independent traffic demands [73]. The traffic dependent energy requirement includes the transmission power and energy required for signal processing. The other supporting equipment, including the power supply and controlling signal processor, are assumed to be independent of the amount of traffic but require electric power when the eNB is operating. Moreover, HPNs, which are, in general, installed in a dedicated building or room, needing supplemental heating ventilation and air conditioning (HVAC). In contrast, LPNs typically do not need. As a result, the total energy consumption in the network in time interval t can be expressed as follows:

$$
\begin{aligned}
E_t = &\sum_{lpn=1}^{N^{LPN}} x_t^{lpn} \cdot \left(El_t^{lpn} + SE \right) + \\
&\sum_{hpn=1}^{N^{HPN}} y_t^{hpn} \cdot \left(Eh_t^{hpn} + SE \right) + N^{HPN} \cdot AC,
\end{aligned} \tag{3.3}
$$

where El_t^{lpn} and Eh_t^{hpn} are the varying traffic dependent energy in LPNs and HPNs at time t. The variables x_t^{lpn} and y_t^{hpn} are binary decision variables equal to 1 when the particular eNB is providing service and 0 otherwise. However, in this thesis, as we require all HPNs to stay active at all time to avoid coverage hole, y_t^{hpn} alway equals to 1. We let SE and AC represent the energy consumption of the supporting equipment and HVAC respectively.

In this research, we focus on reducing the total energy consumption in the network. To do so, there can be two ways according to Eq. 3.3. First is limiting the number of operating LPNs by having as many x_t^{lpn} equal to zero as possible. To limit the number of active LPNs, we adopt widely-studied switching off LPNs method. By switching off LPNs, we can let x_t^{lpn} in Eq. 3.3 equal to 0. Second, in Chapter 5, we focus on reducing the El_t^{lpn} and Eh_t^{hpn} in Eq. 3.3 based on the traffic demand. The variables are power consumption required in transmission of the respective eNBs. In this thesis, we assume that the traffic demand consists of the number of users in the network and their service demand levels. According to the traffic demand, we propose reducing the power consumed by lowering the level of HPN transmit power based on the number of users (Section 5.1), lowering operating spectrum resource based on the user service levels or both (Section 5.2). (Section 3.4 discusses the relation between the energy requirement and the spectrum resource requirement.) We analyze the fundamental Shannon capacity equation, $C = Blog_2(1 + SINR)$ where C is user achievable data rate, B is available bandwidth and $SINR$ is signal to interference plus noise ratio. Once there are fewer users in the system, available bandwidth per user, B, increases. As a result, $SINR$ can be lower without decreasing C. Lower required $SINR$ yields a possibility to reduce transmission power. We apply this principle and propose Step-dimming energy reduction method in Section 5.1. On the other hand, when a user receives high $SINR$, an eNB can restrict the user to a smaller B or spectrum resource and retain the user data rate, C. In Section 5.2, we present an optimization model to calculate a required amount of B for users according to their $SINR$.

3.3 NETWORK PLANNING

Improving the network performance by network planning is not one of our goals in this thesis as there exists plenty of literature covering the topic. However, current literatures on network planning still lack consideration of energy consumption. One of the challenges is incorporating energy consideration into network planning creates a significantly greater optimization problem. The extremely large problem for planning a city-wide network could become an NP-hard problem. Another issue in the current literature regarding network planning for energy optimization is traffic demand consideration. A literature assumes uniform traffic demand across the area [71]. In a large area, it is highly likely that the trend of traffic demand varies greatly both spatially and in time. In this work, we include the diversity of the demand into consideration. Moreover, existing cellular networks show a slowly increasing expansion rate in the last few years. The saturation of cellular penetration rate [74] indicates that there is a less likelihood that an operator needs to plan and build a greenfield network, especially in an urban area [72]. Hence, to examine our energy reduction in a sample network with minimum CAPEX that is as realistic as we can, we present a network planning optimization problem in Section 6.1. The problem is to generate a sample existing HPN-only network that requires additions of LPNs to serve the increasing demand. The problem focuses on coverage-driven network planning with minimum CAPEX to provide full coverage of an area and service-driven network planning for additional demand in high-demand spots. The additional high-demand spots represent the increase of service demand that requires an expansion of the network in certain areas. We define a high-demand spot as a small area where users gather and create a cluster of users that require high capacity in a small area. A similar two-step method to plan a network is proposed in [75]. However, the work considers a uniform traffic demand peak in planning the network expansion. A one-step model that combines both concerns of coverage and service is presented in [71]. However, the authors explain that the network performance or service quality part in the model does not produce any influence on the results. Also, even though the optimization includes a variation of traffic demand for determination of power requirement, the traffic demand does not contain spatial variation in the coverage area. After comparing the results in a similar scenario of the one-step model [71] and the two-step method [75], we found no significant advantage of the one-step model over the other in terms of total expense. In this thesis, due to the size of the planning problem and deficiency of computational resources, we decide to adopt a two-step approach. Besides CAPEX, the two models also include energy consumption due to traffic demand and network performance into the network planning models. Nevertheless, in the two studies, the authors consider only switching on and off eNBs to reduce energy demand. In Chapter 5, we show that our proposed energy minimization can reduce a significant amount of energy requirement in network operation. The amount of saving is considerably greater than simply turning off eNBs. Therefore, we apply the CAPEX minimization network planning and the OPEX minimization or energy reduction separately. In this work, we further take into account cost of eNB equipment, site installation, backhaul transmission equipment and radio network controller equipment in the CAPEX calculation. The costs could impact the placement of eNBs location.

Furthermore, to our knowledge, no previous work has studied the benefit of reduced OPEX on network planning. In Chapter 6, we create a city-like network for the purpose of evaluating our proposed energy reduction methodology and analyzing the benefit of the energy saving on network planning. The simulated city-like network represents a dense urban and suburban area where traffic demand always exists. At the lowest, there is sufficient demand to enforce eNBs to stay active and provide services. At the highest, the demand is so overwhelming that the available bandwidth of the eNBs in the area cannot satisfy all the users. There are two reasons for this assumption. First is reducing energy consumption by switching off equipments is likely not possible during busy hours in a dense area. Given the demand, we can examine how our cell selection and energy reduction perform in such a demanding scenario. Second, we do not consider a rural area where service demand is sparse and minimal. Although we believe our energy reduction methods can accomplish in the type of area, the methods will not be tested applicable with high demand. We formulate the network planning optimization solely to construct a city-like sample network on which we can examine our cell selection and energy reduction techniques. To an extent, the scale of such optimization platform can be advanced in the future and used for broader purposes.

3.4 SERVICE LEVELS AND SPECTRUM RESOURCE

One main constraint in reducing energy consumption in a cellular network is guaranteeing a quality of service (QoS) to customers. The quality of service can be classified into multiple levels of service depending on the operator and the area of service. In 3GPP LTE standard release 13 [76], QoS is classified into 13 categories represented by the QoS class identifier (QCI). Seven QCI categories are best-effort-like services, and the rest are guarantee-bit-rate (GBR) services. The categories can also be grouped into video service, real-time service, TCP-based service, and voice service. Since we focus only on high level user data rates, we use 5 QoS categories to represent different service levels. They are FullHD video (1080p), HD video (720p), SD video (480p), TCP and voice service. The services require data rates of 10 Mbps, 4-7 Mbps, 500 kbps - 3 Mbps, 700 kbps [77] and 48 kbps for the Super Wideband Adaptive Multi-Rate (SWB-AMR) voice codec [78] respectively. In this thesis, we let the minimum required data rate for the service levels to be 10 Mbps, 5 Mbps, 3 Mbps, 700 kbps and 50 kbps, respectively.

Additionally, the LTE standards utilize a Channel Quality Indicator (CQI). CQI is defined to represent discrete levels of signal quality reception or SINR. The quality of the channel can be depicted by levels of SINR ranges [79–83]. The levels are determined by the operator to suit its services. A CQI level indicates a specific modulation and coding scheme (MCS) and transport block size (TBS) for transmitting data to the users. With MCS and TBS, one can estimate a user achievable data rate by using the information and the number of resource blocks (RB) assigned to the user. Here, we simplify the estimation by disregarding the complexity of MAC layer scheduling and physical layer modulation and coding process. Instead, we adopt an LTE-specific modified Shannon capacity formula from [84] to estimate the users achievable data rate. Therefore, we only need the discrete CQI levels in considering the quality of the channel when determining the required amount of spectrum resources for a user. To estimate and guarantee the minimum achievable data rate for a UE, we can consider the lowest SINR of user's reported CQI level and calculate the estimated throughput. The CQI levels and their minimum SINR requirement are presented in Table 3.2 which is taken from [83].

Next, based on the users CQI levels, we determine a minimum amount of spectrum resource that satisfies the users demand and minimizes the energy requirement. In LTE, spectrum is distributed over both time domain and frequency domain. The smallest unit that can be assigned to a user is a resource block (RB) spans over 0.5 ms in time and 180kHz in frequency [85]. Assuming constant transmit power in all RBs, an eNB either providing services in fewer RBs or smaller frequency band can result in less energy consumption [86, 87]. The relationship between energy consumption and resource usage in the time domain (duration of transmission) and frequency domain (operating bandwidth) is discussed in [86, 87]. In frequency domain, 3GPP LTE standard limits bandwidth availability of an eNB to be 1.4, 3, 5, 10, 15 and 20 MHz [88]. To establish energy saving, an eNB can execute discontinuous transmission (DTX) and bandwidth adaptation [87, 89] which is to limit the total number of active RBs. Figure 3.2 illustrates the standard LTE resource block and examples of DTX and bandwidth adaptation. For example, the energy requirement in signal transmission reduces to 60% when an eNB operates on 15 MHz bandwidth (out of a total of 20 MHz) for 80% of the total working time. In other words, the reduced bandwidth of 15 MHz requires 75% of energy. When an eNB transmits 15 MHz bandwidth for 80% of the time, the total energy requirement decreases to 60%. An eNB can achieve the same amount

Table 3.2: CQI levels and minimum SINR requirement

CQI level	Minimum SINR (dB)
1	-7
2	-5.0714
3	-3.1429
4	-1.2143
5	0.7143
6	2.6429
7	4.5714
8	6.5000
9	8.4286
10	10.3571
11	12.2857
12	14.2143
13	16.1429
14	18.0714
15	20

of energy saving by operating at full bandwidth (20 MHz) but only 60% of the time. As different operating configurations can yield the same level of power saving, we disregard when the discontinuous transmission happens and the specification of the operating bandwidth. Instead, we determine *Resource Unit (RU)* as the spectrum resource usage in percentage both in time and frequency domain. Considering the modified Shannon capacity formula $C = 0.75 \times B \times log(1 + SINR/1.25)$ where B is the full bandwidth [84], we define a resource

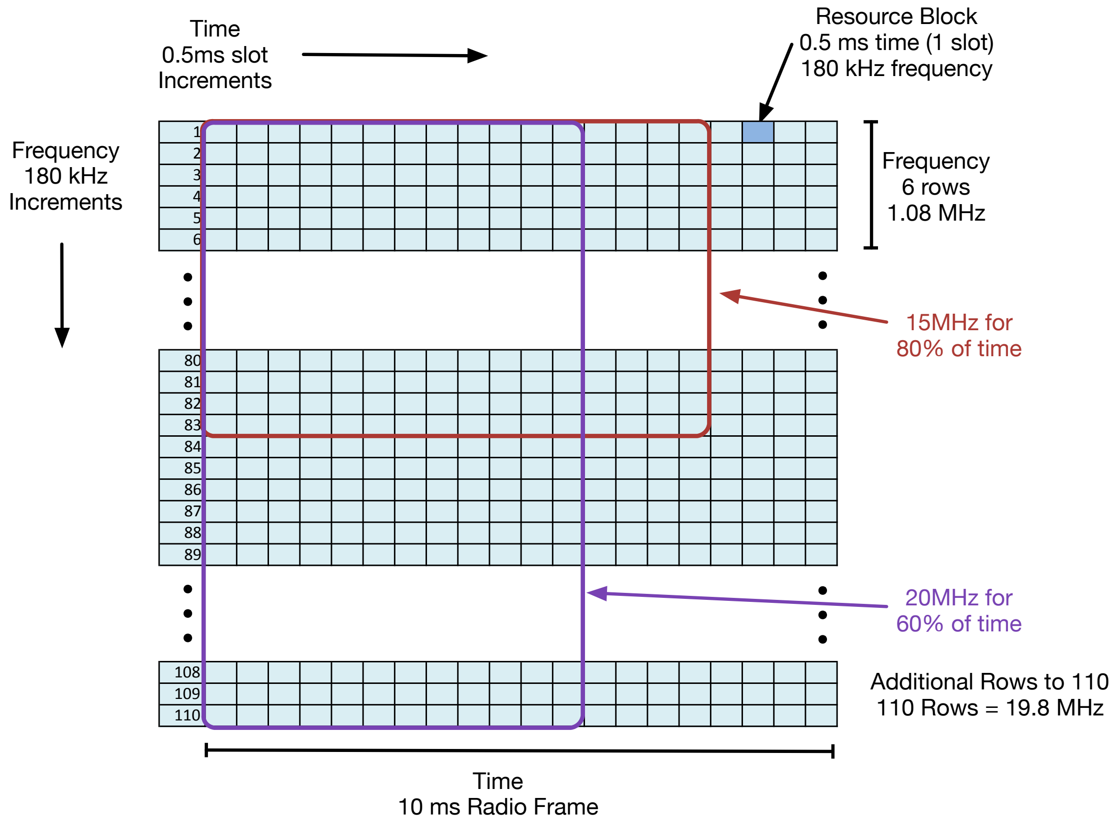

Figure 3.2: Spectrum Resource with DTX and Bandwidth Adaptation

unit (RU) as

$$RU = \frac{reqC}{(0.75 \times B \times log(1 + \frac{SINR}{1.25})} \tag{3.4}$$

$RU = \frac{reqC}{(0.75 \times B \times log(1+\frac{SINR}{1.25})}$ in percentage; where $reqC$ is the requested achievable data rate of a user service demand.

3.5 RESOURCE MANAGEMENT

According to [90], several resource management techniques and scheduling techniques have their advantages and disadvantages making them suitable for certain particular situations and operator's preferences. In this work, we divide the resource management strategy into three main situations namely: quiet hours, normal hours and busy hours. The distinction of the situations is the amount of required bandwidth to support the service demand. During the quiet hours, the resource availability is sufficient to meet all users demand regardless of their service level. During normal hours, the available resource is enough to satisfy only some of the demand but not all. Depending on users arrival to the network, their service level could be degraded to a lower level. Busy hours or overload scenarios are when the operator may be able to meet some users demand but can only guarantee a minimum requirement of QoS or voice call.

Here, to describe how to incorporate adaptive resource management to various levels of QoS, we discuss principles of resource management strategy used in this research. To provide various levels of QoS, we distinguish services into guaranteed-bit-rate (GBR) services and non-GBR or Best-effort (BE) services as mentioned in the previous section. An operator first needs to prioritize and meet the demand of GBR users then provide the rest of the resource to BE users. To implement fairness among GBR users, an eNB considers the different levels of QoS the users demand and the users CQI. The eNB then determine a necessary amount of resource to dedicate to each user. Assuming all users have the same channel condition and duration of a connection, users with higher guaranteed rate should receive a greater amount of resources. For example, a user that requests FullHD video (1080p) service, which we assume require 10 Mbps rate, would require twice as much RU than a user that demands HD video (720p) service of 5 Mbps. However, users do not necessarily have the same channel conditions. Using CQI feedback, an eNB has knowledge of the channel conditions. Users with the same type of demand will occupy more resource if they have a lower CQI level than others to compensate the inferior channel condition. In other words, a user at cell-edge would receive more spectrum resource than a user at cell center when they demand the same level of QoS. Moreover, we set a maximum threshold of resource for BE users. The threshold is a percentage of the total available resource. The threshold allows the eNB to have unused radio resource and creates energy reduction opportunities. Also, when the resources are heavily used, the available resource for BE users could be the only unused resource from GBR users which, in this case, is less than the threshold. For example, the threshold of BE users resource is 25% of the total resource. When the GBR users require 60% of the total available spectrum resource, all the BE users can enjoy the resource up to 25% of the total resource. This case the eNB can save the energy of 15% given that the eNB is transmitting at the maximum power. On the contrary, if the GBR users require 80%, all BE users will receive 20% of the total resource and the eNB needs to operate at full capacity.

During normal hours, when the service demand increases and the available spectrum resource can meet only a portion of the demand, we consider a first-come-first-serve scheduling strategy in addition to QoS levels. A BE user who connects to the network during the hours may receive the minimum achievable data rate of 50 kbps which is sufficient to make a voice call. Note that we consider the data rate for voice call as the lowest constraint for all users in the network. Furthermore, when a GBR user requests a connection to an eNB that already utilize full spectrum resource, the resource allocated to the latest connected BE user will be reduced to meet only the minimum requirement. Later, when the demand increases further and all connected BE users already receiving the minimum resource, the resource of the latest GBR user will get reduced to a lower level. This procedure ensures to provide service to every users according to their service demand and to minimize the possibility of access failure. During the busy hours, the available resource is not enough to provide the minimum guaranteed service to all the users. We assign the amount of resource to users proportionally to their service demand and do not consider their CQI level to simplify the calculation for the extremely high number of users. A GBR user with demand of 10 Mbps would receive twice the resources a 5 Mbps-demanding user and so on. This assignment could potentially satisfy a portion of the users.

3.6 EVALUATION METRICS

In this research we apply three particular evaluation metrics. We measure the performance of energy reduction methods by comparing the amount of energy consumption saved by the energy minimization mechanisms. To calculate user achievable data rates, we utilize a LTE-specific modified Shannon's achievable data rate formula [84]. Also, we allow users to experience adverse effect of energy reduction; lower data rate. Therefore, to examine the impact, we define *customer satisfaction* metric which compares the percentage of users that receive data rate higher than required data rate according to the levels of service.

When doing research on energy optimization, very often researchers measure the performance and analyze the results using certain general metrics, for instance, data rate, SINR and coverage probability. However, it is understandable that in doing an experiment, there are certain variables and constraints that substantially affect the format of the measurement and correspondingly the intuition of network or optimization performance [6]. For example, an increased data rate, higher coverage probability or greater data transferred per energy unit can lead to a conclusion of better network performance. However, the improvement of the results could be achieved by only deploying more base stations that consequently cause an additional amount of energy consumption. Therefore, we focus mainly on the amount of energy consumption as the goal of optimizing the network operation.

3.6.1 Customer Satisfaction

Measuring the performance based on only the general metrics can also mislead the analysis of optimization results. Lower system performance after performing an energy reducing process does not always represent an inferior mechanism for energy saving. For example, during a light load time, because there are fewer users demanding the service at the time, as long as the users receive the service they expect, the energy saving technique should be considered successful. However, the results of the general metrics could reveal otherwise. Therefore, to evaluate the service performance of the system in this research, we do not take into account various defined QoS measurement metrics, coverage probability, and outage probability as in [20, 38]. We suggest adhering an achievable data rate, and we propose *customer satisfaction* as a further performance metric for more informative results.

An optimization decision is often made solely based on the general measurements. With the same reason previously discussed, discarding firm constraints on the general metrics could lead to more opportunities to reduce energy consumption. Therefore, our work concentrates primarily on lessening amount of energy and allows users to experience an occasional adverse effect of degraded resource availability and QoS. *Customer satisfaction* is a percentage of the number of satisfied users and the number of total users in the system. We assume that users are satisfied when they experience a higher data rate than their respective request and are not satisfied when the received achievable data rate is lower. Thus, a user can only be either satisfied or not satisfied. The percentage can present the drawbacks of power cutting and provide an informative comparison of the user experience before and after the power reduction procedure.

In this work, we define the *customer satisfaction* according to the traffic demand assumption in each scenario. In principle scenarios (Section 4.1) where we assume users receive equal bandwidth, we define a minimum baseline requirement of data rate to be 695.4 kbps. The minimum baseline is the average user data rate in a traditional HPN-only cellular network before the demand of mobile communication steeply increased. We assume that after network expansion or the addition of LPNs, users should receive a better service; higher data rate than the minimum baseline. See Appendix for calculation of the baseline. Furthermore, in scenarios where we apply various QoS levels, the customer satisfaction rate is a percentage of users that receive an achievable data rate that is higher than their respective service. We consider GBR users satisfied when they receive a data rate that is higher than 700 kbps which is the minimum guaranteed data rate for VDO services. Similarly, satisfied BE users are BE users who achieve a data rate higher than 50 kbps which is the guaranteed data rate for voice call. A similar customer satisfaction metric is mentioned in [91] to compare the performance of different energy reduction methods in terms of energy per satisfied users. However, no computational work was shown.

4.0 CELL SELECTION

In this chapter, we present our two cell selection techniques, namely; Bandwidth-based (BB) and Energy-aware (EA) cell selection. The two techniques are our first part of the process to minimize the energy consumption in LTE access network. The purpose of the two approaches is to manipulate the traffic load to create the maximum possibility of reducing power requirement in operating eNBs while maintaining the quality of service for users.

It is widely known that the majority of energy consumed in an access cellular network is at HPNs. Research often displays that the amount of energy that can be saved depends highly on how a system handles the traffic demand. Studies show more power can be reduced when traffic demand or users are moved to particular desired eNBs in order to enable other eNBs to switch off. However, after LTE technology has been deployed, LTE-based *cell selection* mechanisms have been proposed and implemented, thus far no cell selection techniques have taken into consideration energy consumption yet. Besides, current researchers believe that offloading more traffic from high-powered nodes (HPNs) to low-powered nodes (LPNs) that provides smaller coverage can improve overall service quality. However, that is not always necessary. With the typical technique, too many users could be connecting to the same eNB yielding small available bandwidth for each user. Many agree the network needs a cell selection technique that aims to balance the number of users in HPNs and LPNs. One considerable challenge making the network imbalance is significantly different RSS users experience from HPN and LPN. [50, 53, 92, 93] present *Cell Range Expansion (CRE) with Offset Value* by adding a logical offset value to cell selecting decision, making UEs connect to LPNs regardless of the stronger signal from HPNs. As a result, the traffic is offloaded to LPNs, bandwidth is more utilized and spectral efficiency increases. However, the improvement depends greatly on the determination of the offset value. If the value is too small, most UEs will remain with HPNs leaving lower network performance for most UEs. On the other hand, when the offset value is too high, LPN UEs that are far away from the node will experience much interference due to the farther distance from the connecting LPN. [93–96] show a method using an adaptive offset value based on the time varied UE distribution and traffic requirement. Nevertheless, the proposed CRE with offset techniques still cannot achieve a well-balanced HetNet that evenly utilizes the available bandwidth from both HPNs and LPNs. Therefore, we propose additional considerations to the cell selection techniques. In order to maintain the levels of service, we consider both the network performance in terms of UEs achievable data rate and the possibility to reduce the energy required. Note that a HetNet implementation is assumed inevitable in this dissertation.

Here we discuss two *cell selection* techniques; *Bandwidth-based* and *Energy-aware*, their possibility of reducing the total energy consumption and their effect on the overall UEs experience in the dual-frequency system. The result of analysis in this chapter will be used in later chapters when we consider reducing energy consumption.

4.1 BANDWIDTH-BASED CELL SELECTION

Studies have shown that standard cell selection techniques fail to promote a well-balanced HetNet where available bandwidth in both HPNs and LPNs is shared equally. Using only specific cell range [14] or SINR, even with a CRE offset [14] and [20], to choose eNBs, in most cases, still leaves the majority of UEs connecting to the HPNs. This is because of the bigger area covered by the HPNs and the stronger transmit signal strength from the HPNs. Since HPNs consume the majority of the network energy, we would like to create more opportunities to reduce the energy requirement in operating HPNs. To do so, we want to push more UEs to LPNs and leave fewer UEs demanding service from HPNs. Therefore, we propose *Bandwidth-based* cell selection to share the available resource in HetNet more evenly and create more possibility to minimize traffic load in HPNs and, as a result, lower energy consumption.

Note that using SINR as the decisive factor can cluster UEs into one or a few eNBs the bandwidth in a eNB is shared among UEs. The connecting UEs may suffer from decreased available bandwidth and achievable data rate. Also, it requires the eNBs to operate at full capacity. Because there are UE-congested eNBs, there must be other eNBs that have a more available bandwidth that at the moment is shared by fewer UEs. The concept of a Self-organizing Network (SON) [97] proposes that eNBs, both HPNs and LPNs, in the same service area communicate and exchange their network conditions. The advancement enables a system to act collectively to save energy by redistributing traffic and sharing traffic information among eNBs [98, 99]. Our goal here is to move UEs from the congested eNBs to the ones that are less congested in order to benefit from more available bandwidth and produce feasibility for HPNs not to operate at full capacity. To focus on the number of users offloaded and average performance of the network, at this stage of the research, we consider all UEs receive the equal amount of bandwidth and the same type of service. The performance of the network and the quality of service is measured by comparing the user achievable data rate to the average data rate of user when there are only HPNs operating, $\boldsymbol{BaseC}$ (see Section 3.6).

A diagram showing the process is presented in Figure 4.1. A UE_i searches for the strongest $SINR$ from all eNB and initially requests to connect to the eNB that provides the highest SINR ($eNB_k, k = 1$). The eNB grants the request and establishes the connection if the number of connected UEs (N_k^{UE}) does not exceed a threshold (TL). TL is set to equal to the total number of UE in the service area divided by the number of eNBs (N_{UE}/N_{eNB}). Then, the selected eNB_k updates its number of connected users N_k^{UE}. If the UE_i is excessive, the UE_i will try to connect the eNB that provides the next strongest $SINR$; $eNB_k, k = 2$. Moreover, the process repeats until k surpasses α in case the second eNB is also too crowded according to the same threshold. In the end, if all the choices are crowded, the eNBs ($eNB_k; k = 1, 2, ...\alpha$) will decide according to the number of their existing UEs and connect UE_i to the eNB that can provide the most available bandwidth; fewest connected users ($\min_k(N_k^{UE})$). An example of connections between UEs and eNBs with *Bandwidth-based* cell selection in a cell of 500 meter radius, with the total of 200 UEs, one HPN and 18 LPNs distributed 50 meters to the cell edge is presented in Figure 4.2. Blue circles and lines represent HPN UEs and connections to the HPN while red represents LPNs, their UEs and

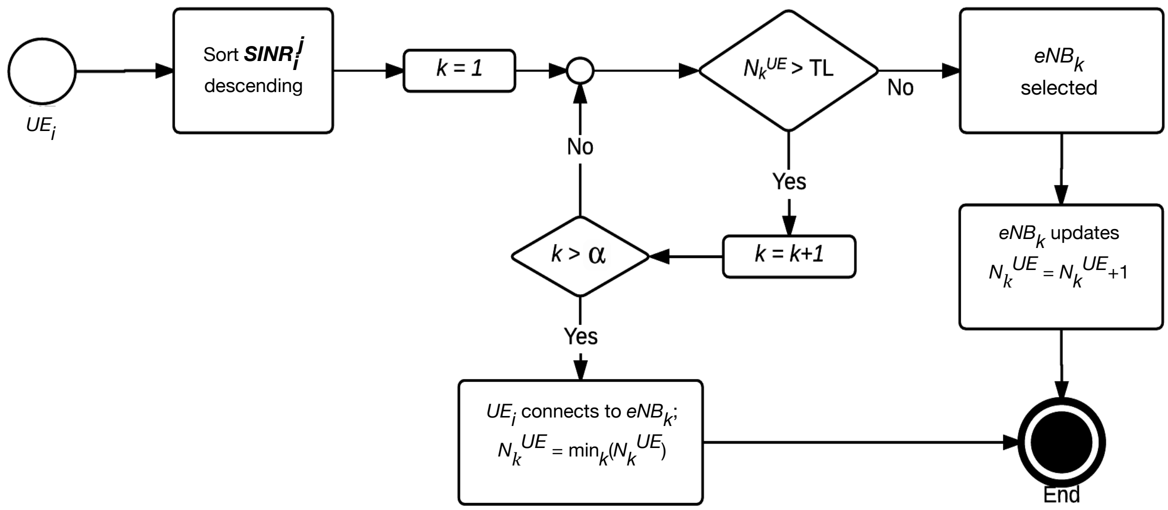

Figure 4.1: Bandwidth-based cell selection mechanism

their connections. An immediate observation shows that, because of the cell selection, UEs that would have connected to the HPN due to HPN stronger SINR connect to LPNs.

4.2 ENERGY-AWARE CELL SELECTION

The purpose of the Bandwidth-based cell selection is to draw more UEs to LPNs so that HPNs need to provide service to fewer users and require less energy. However, from our study, we found a disadvantage of the cell selection during light load periods. Because BB pushes more UEs to LPNs creating a possibility to reduce energy consumption at HPNs, LPNs need to operate for a longer period to serve the offloaded users. Depending on the number of LPNs installed in the network, the higher number of operating LPNs could adversely generate more energy consumption than the energy saved at load-reduced HPNs. Also, we assume that HPNs act as umbrella eNBs that handle communication of the control signal. As a result, HPNs need to maintain their operation at a certain level at all time regardless of

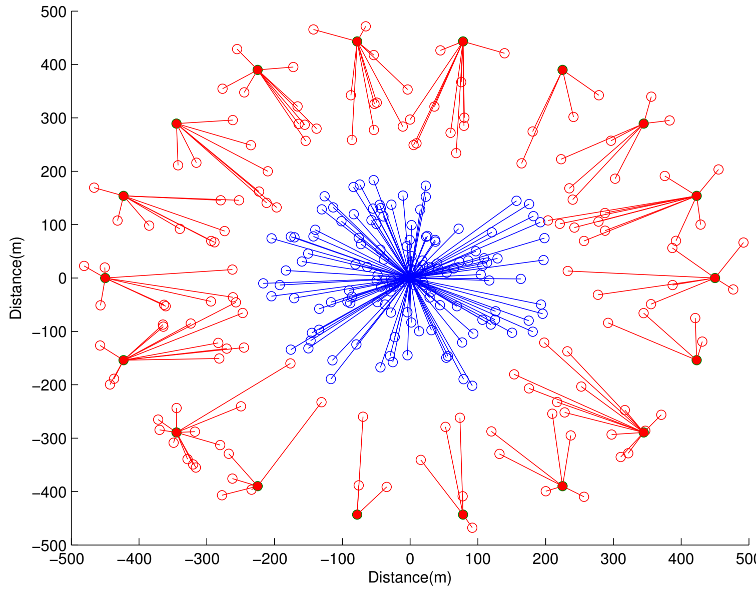

Figure 4.2: Connection example of bandwidth-based cell selection

the amount of traffic. The level of operation can be at the minimum energy-consuming stage. Consider a low load period when few users are sharing the HPN bandwidth, a significant amount of resource can be dedicated to the users. The vast amount of resource then lessens the necessity of high transmit power from HPNs. Hence, at the minimum energy-consuming stage, HPNs can provide service for the low number of users with their minimum transmit power. Also, on such occasions, we can have the LPNs inactive and reduce the total energy consumption of the network. Here, we propose *Energy-aware (EA)* cell selection that aims to create a maximum possibility to reduce the total energy consumption by keeping the LPNs off as long as possible and providing the sufficient service to UEs by only the HPNs.

Consider a HetNet that contains eNB_j when $j \in [1, N^{eNB}]$ and N^{eNB} is the total number of eNBs in the HetNet. The HetNet contains one central eNB which is an HPN, $N^{HPN} = 1$. We let eNB_1 represent the HPN and eNB_j when $j \in [2, N^{LPN}+1]$ given N^{LPN} is the number of LPNs represent LPNs. At time t, there are UE^i when $i \in [1, N_t^{UE}]$. According to Eq. 3.4, the required RU for UE^i is RU^i when the requested service requires an achievable data rate of $reqC^i$ and SINR of $reqSINR^i$. When performing EA cell selection, the HPN decides to connect and provide the service to all the users when two conditions are met. The conditions are 1) the HPN (eNB_1) must be able to provide the service to all users, $\sum_i^{N_t^{UE}} RU^i < 100\%$, and 2) the SINR that all users receive from the HPN minimum transmit power must be equal or greater than the requirement, $SINR_1^i \geq reqSINR^i$. When either of the conditions is not met, the HPN decides to switch to BB cell selection and turn on the neighboring LPNs. When all UEs connect to the HPN due to EA cell selection, we can have all LPNs switched off and let $x_t^{lpn} = 0, \forall\ lpn$ to minimize the total energy consumption according to Eq. 3.3. Furthermore, due to the main purpose of cell selection is to hold the total energy consumption at the minimum. According to Eq. 3.4, the operator could lower the QoS ($reqC^i$) for some users to keep the transmit power of HPN at the minimum. The HPN would need to increase its transmit power to increase $SINR_1^i$ in order to compensate with the limited RU when the number of users increases. Also, by lowering the QoS, the system can maintain the total of RU ($\sum_i^{N_t^{UE}} RU^i$) under 100% and refrain LPNs from switching on.

A similar cell selection technique has been very recently proposed in [100]. Although the work does prove that users would have the best experience receiving services when the load is well balanced between the tiers, the proposed technique does not consider energy consumption in the network. The proposed technique solely aims to improve the quality of service by utilizing adaptive CRE and traditional SINR-based cell selection to balance the traffic load between an HPN and LPNs. Even though the authors consider switching off LPNs, there is no possibility of energy reduction in terms of optimizing resource utilization in eNBs involved (see Section 5.2). Besides, the criteria to start offloading from an HPN is a solid pre-determined percentage of load regardless of energy requirement and service levels. Also, the authors assume that the traffic load in an area increases gradually creating a slight necessity to switch on several LPNs at the same time. The assumption contradicts to our traffic profile that we received from a real network measurement [101]. In our data, the traffic demand rises sharply from a quiet hour to a busy hour. The sudden increase makes switching to BB more suitable. Nevertheless, in a future work, we can improve EA cell selection by ensuring HPNs remain operating at close to 100% resource at the minimum energy even after switching on LPNs. Doing so would restrain additional LPNs from starting to provide service and save more energy during this transition time. However, in this work, due to sharp increase in general traffic demand and brief time of the transition that we conceive, we decide that the potential amount of extra energy saving would not worth the additional concern and calculation.

Figure 4.3 and Figure 4.4 show an example of connections between UEs and eNBs with *Energy-aware* cell selection in a cell of 500 meter radius on a quiet hour with the total of 56 UEs and on a busy hour with the total of 200 UEs. The example has one HPN and 18 LPNs distributed 50 meters to the cell edge. Blue circles and lines represent HPN UEs and connections to the HPN while red represents LPNs, their UEs and their connections. Figure 4.3 shows that during quiet hours, all UEs connect to the HPN while Figure 4.4 presents similar UE-eNB connections to BB cell selection.

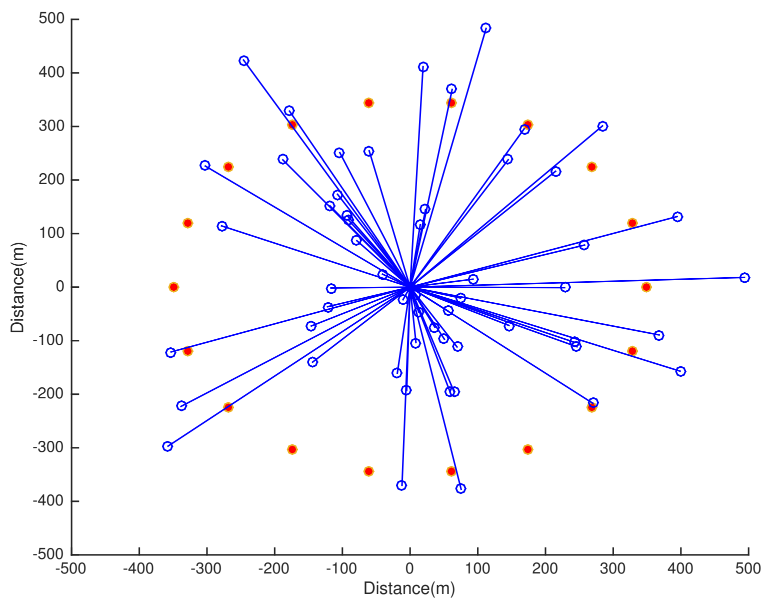

Figure 4.3: Connection example of energy-aware cell selection during quiet hours

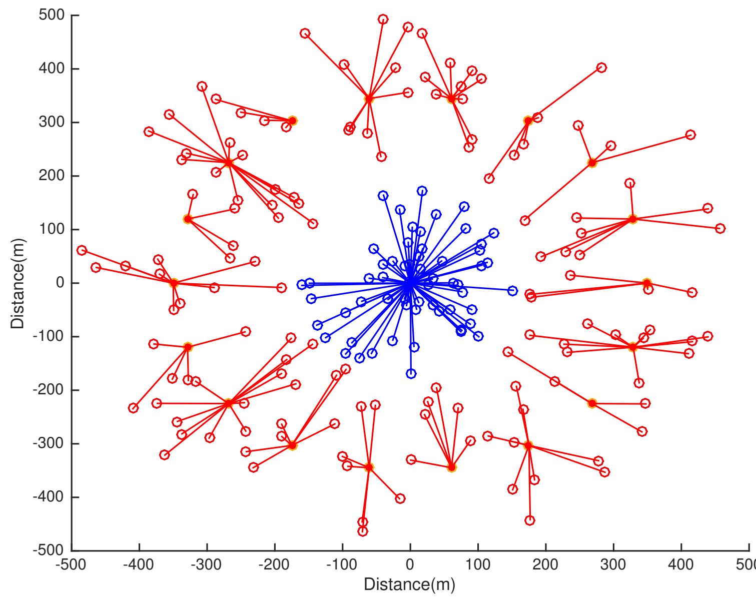

Figure 4.4: Connection example of energy-aware cell selection during busy hours

4.3 NUMERICAL RESULTS

To evaluate the performance of our proposed cell selection techniques, we compare the techniques with two simplified cell selection techniques, namely, Distance-based (DB) and SINR-based (SB). When the system utilizes DB, UEs connect to LPNs whenever they are within a pre-determined geographical distance from the LPNs regardless of the distance from the HPN and SINR [14]. This LPN coverage is assumed be an effective cell radius of the LPNs. This number can vary by scenarios. Figure 4.5 shows an example of a service cell of 500 meter radius, with 200 total UEs connecting to eNBs according to *DB* cell selection. The effective cell radius of the LPNs in the example is 50 meters. Blue circles and lines represent HPN UEs and connections to the HPN while red represents LPNs, LPN UEs and their connection. Also, a UE performing *SINR-based* cell selection chooses to connect to an eNB that can provide the highest SINR regardless of physical distance between the UE and eNBs [14, 20]. Because an HPN transmits signal at a considerably higher power level than

LPNs, usually by selecting an eNB based on only the SINR, the majority of UEs will concentrate into the HPN. CRE offset value has been introduced into this technique to increase the logical level of the LPNs signal strength. Doing so allows signal strength from LPNs to be more comparable and draws more UEs to the LPNs making the network more balanced. As a result, UEs that connect to the LPNs can enjoy more available bandwidth and thus higher achievable data rate. Figure 4.6 shows an example of UEs with connection to eNBs using *SINR-based* cell selection with offset value of zero. Blue color represents HPN UEs and their connection and red color represents LPNs, LPN UEs and their connection.

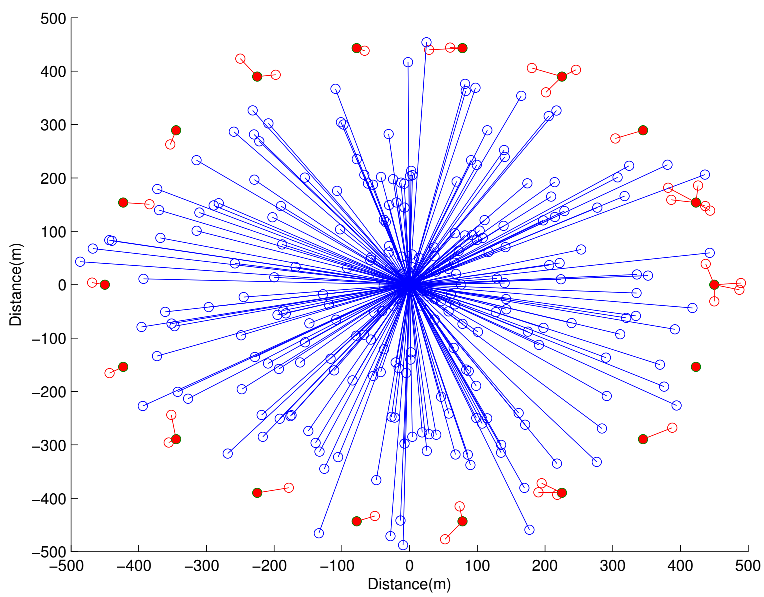

Figure 4.5: Connection example of distance-based cell selection

Next, we explain a sample HetNet on which we evaluate our proposed cell selection techniques. We assume that the service area of this work contains three service cells covered by three HPNs. The HPNs operate as umbrella eNBs with coverage of 500 meters in radius. Each service cell has 18 LPNs providing services at high-demand spots within the HPN

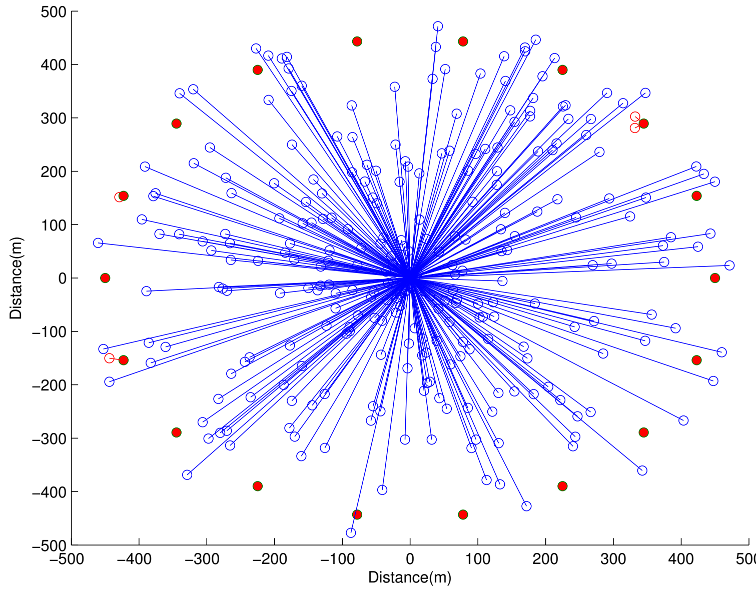

Figure 4.6: Connection example of SINR-based cell selection when offset = 0 dB

coverage. LPNs are deterministically distributed around their HPN with equal angular distance [17, 102]. Six LPNs are deployed 200 meters away from the HPN, and 12 LPNs are 350 meters away to form two rings of coverage that can cover the service cell. Figure 4.7 shows the service area with blue dots represent HPNs, and red dots represent LPNs.

In this chapter, we examine the performance of the cell selection techniques on various traffic load. We define two types of users, namely, general users and HS users. We vary the number of general users from 20 to 240 users and assume that each high-demand spots generates an additional 10% of the general users to the total load. For instance, when there are 100 users in the general area of the service cell, each high-demand spot will have an addition of 10 users. The total number of users in the service cell becomes 280 users $(100 + (0.1 \times 100 \times 18) = 280)$. General users location is uniformly distributed throughout the service cell while the additional high-demand spot users are uniformly distributed around the location of the LPNs. We determine a user location by a distance from the center of the distribution (d) and angle of the vector to the UE location (θ). Thus, a user location

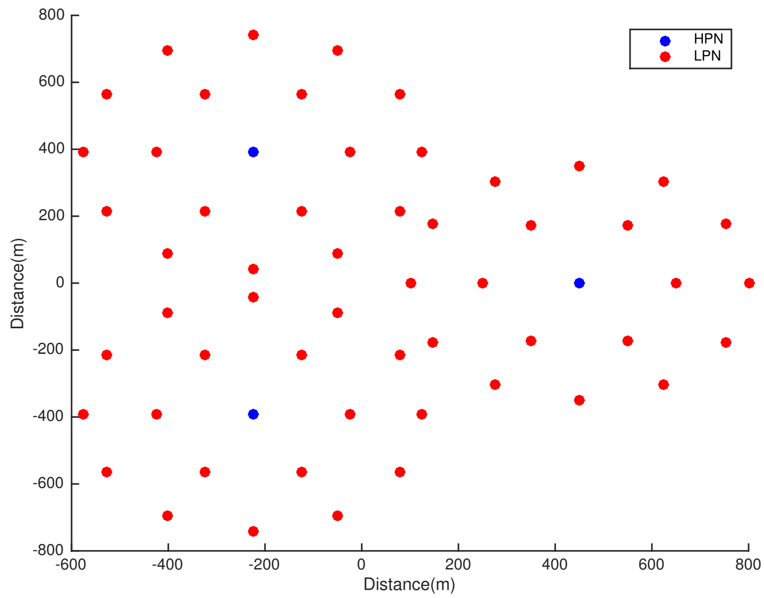

Figure 4.7: eNBs location

coordinate is determined by $(d\cos\theta, d\sin\theta)$, as shown in Figure 4.8, where d is uniformly random from 0 – 500 meters for general users and 0 – 150 meters for high-demand spot users and θ is uniformly random from 0 – 360 degrees. To learn the impact of load, we vary the number of general users from 20 to 240. We conduct each scenario for 1,000 iterations to simulate the variation of users location and order of network entry. Particularly, in Energy-aware cell selection when we start to consider various levels of service demand, we define minimum data rate requirements of 10 Mbps, 5 Mbps, 3 Mbps, 700 kbps and 50kbps, for FullHD video, HD video, SD video, TCP and voice service, respectively. Probability for a user to request for each type of service equals to 0.05, 0.15, 0.25, 0.25 and 0.3 for FullHD video, HD video, SD video, TCP and best-effort. Note that best-effort users are users who receive a guarantee for only voice service that requires 50 kbps but initially we aim to provide higher data rate, "baseline" mentioned in Section 3.6.1, to satisfy the users.

The HPN transmits a signal at the power of 46 dBm on 800 MHz band while the LPNs are operating on 2.1 GHz band with the transmit power of 30 dBm. We use Okumura-Hata

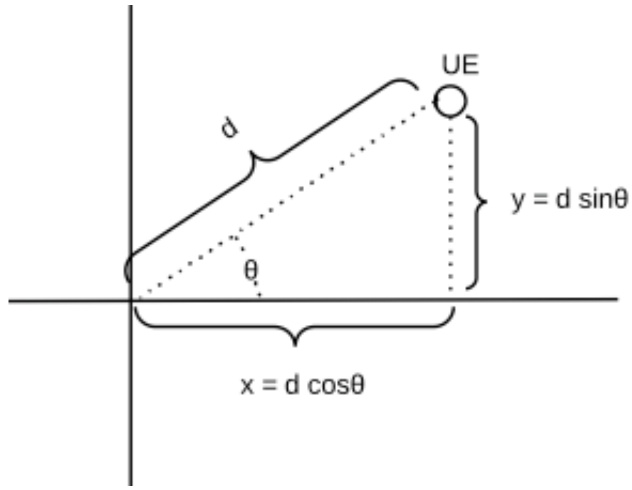

Figure 4.8: Determining UEs location

urban model [103] to calculate pathloss for HPN signal; $L_p = 69.55 + 26.16log(f) - 13.82 * log(hb) - a(hm) + (44.9 - 6.55log(hb))log(d)$. The factor a is $3.2(log(11.75hm))^2 - 4.97$. L_p is pathloss in dB, f is frequency which is 800MHz, hb is the height of them, d is distance between the HPN and the UE in km. For LPN pathloss, we calculate according to "3GPP heterogeneous system simulation baseline parameters for outdoor/Hotzone", model 1 for 2 GHz Pico to UE, $L_p = 140.7 + 36.7log_{10}(d)$ [104]. Each eNB obtains 10 MHz bandwidth (B). A user achievable data rate, C, is calculated according to the LTE-specific modified Shannon's formula [84], $C = 0.75Blog_2(1+SINR/1.25)$, where B is the available bandwidth, $SINR$ is the RSS of the UE, I is the interference which is equal to the combination of signal strength from all eNBs operating on the same frequency band and we assume no inter-tier interference. Noise (N) is set -92 dBm. Table 4.1 summarizes the system parameters.

Figure 4.9 - 4.13 show numerical results of all cell selection techniques. Black solid lines present results for Distance-based (DB) cell selection. Red solid lines present results for SINR-based (SB) cell selection. Pink solid lines show results for Bandwidth-based (BB) cell selection. Blue solid lines represent results for Energy-aware (EA) cell selection and blue dash lines are for EA when the load is significantly low (the number of general users is two to 20). We present the offloading rate in Figure 4.9. When compared to SB, both BB and

Table 4.1: System parameters

HPN cell radius, R_{HPN}	500 m
LPN cell radius, R_{LPN}	150 m
Transmission power, P_t	46 dBm (HPN)
	30 dBm (LPN)
Carrier frequency, f	800 MHz (HPN)
	2.1 GHz (LPN)
Bandwidth, B	10 MHz
Pathloss model	L_p (HPN)$= 69.55 + 26.16log(f) - 13.82 * log(hb)$
	$-a(hm) + (44.9 - 6.55log(hb))log(d)$;
	$a = 3.2(log(11.75hm))^2 - 4.97$
	L_p (LPN)$= 140.7 + 36.7log_{10}(d)$
Achievable data rate, C	$C = 0.75Blog_2(1 + SINR/1.25)$
Interference, I	$\sum RSS_{neighboring\ eNB}$
Noise, N	-92 dBm

EA have a significantly higher percentage of LPN users. The higher portion of LPN users produces the considerably high opportunity to reduce energy consumption in HPNs because the HPNs need to provide service to fewer users. Also, we can see an effect of EA when the traffic load is very small. There are no LPN users. The HPNs can provide service to all users in the service area until the number of general users increases over 20 (the total number of users is over 56).

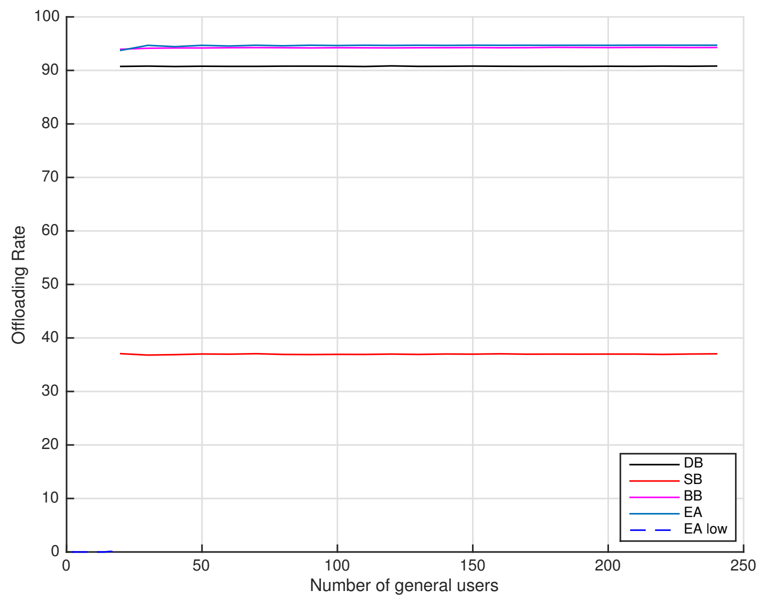

Figure 4.9: Percentage of LPN user

Next, we observe the effect of cell selection techniques on overall user achievable data rate. Figure 4.10 shows that user data rate reduces when the load rises. Moreover, the Figure presents the result of keeping users connect to HPNs. The average data rate of users decreases by the number of users until the system switches from EA to BB.

Figure 4.10 shows that the overall user data rate when the network operates on SB is higher than our techniques. However, we can see from the Figure 4.11 that the majority

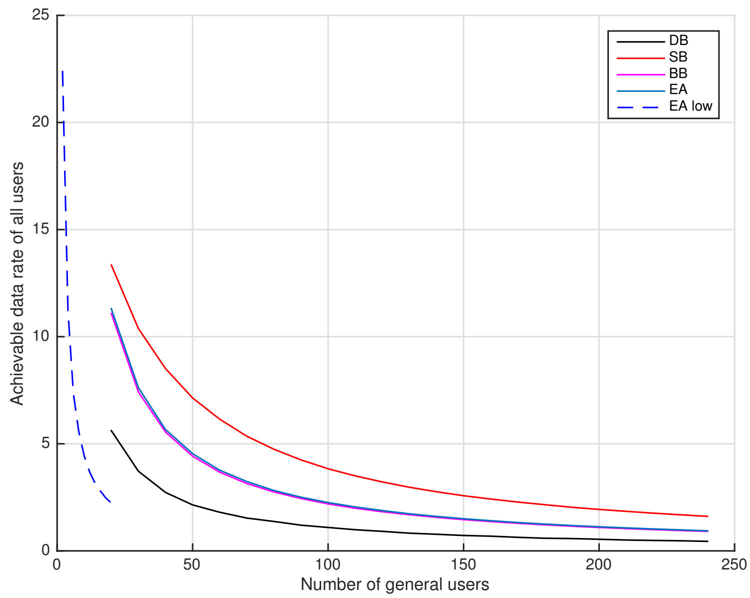

Figure 4.10: Achievable data rate of all users

of users which connect to the HPNs suffer tremendously. The data rate of most users is extremely low because they share a limited HPN bandwidth with the great number of users at HPNs. Figure 4.12 confirms the reason of studies that want to offload more users to LPNs. With typical SB cell selection, there is considerably more radio resource available in LPNs. Whereas, our BB cell selection produces an extremely comparable data rate for all users, both HPN and LPN users.

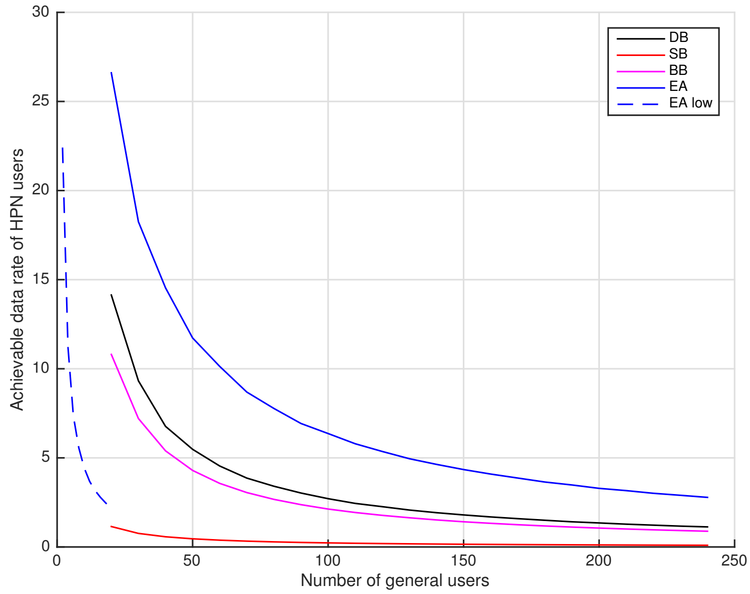

Figure 4.11: Achievable data rate of HPN users

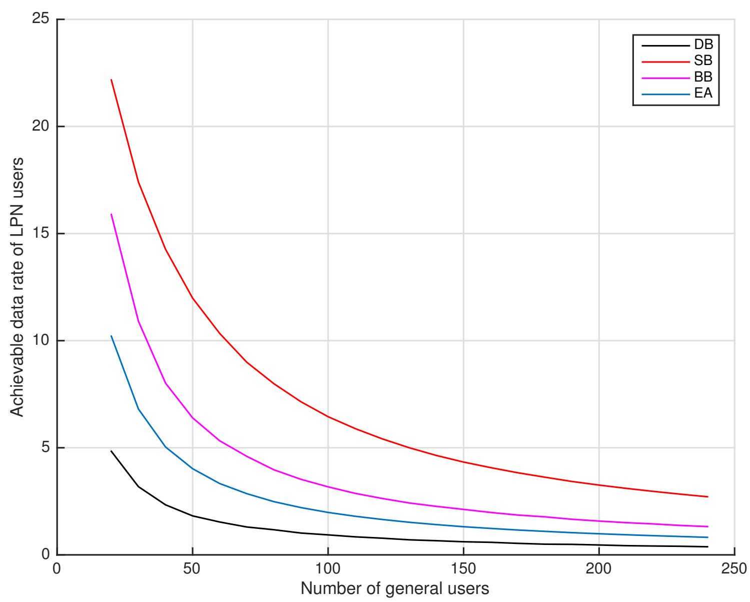

Figure 4.12: Achievable data rate of LPN users

In addition, we present customer satisfaction rate of the users in Figure 4.13. Figure 4.10 shows that the average achievable data rate of all users is the highest when the system uses SB. However, according to Figure 4.13, the percentage of users that enjoy the services is significantly lower than the two proposed techniques. That is because the majority of users connect to HPNs and suffer from a shortage of available bandwidth. On the other hand, BB and EA result in lower overall data rate but more users are satisfied. It is because the network is more balanced, and the available resource is shared more evenly than when the system uses SB. All the results show that, with our proposed cell selection, an operator can accomplish a great possibility of energy reduction in the network while improving the service quality as well.

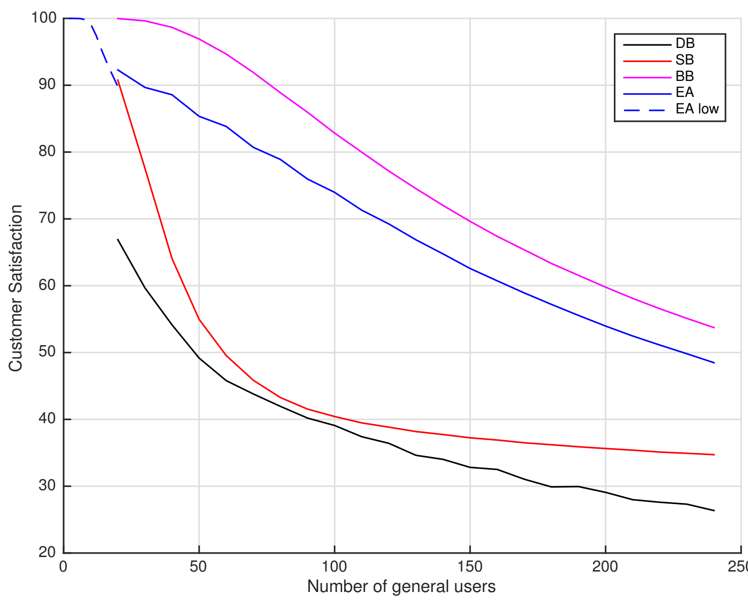

Figure 4.13: Customer satisfaction

Last, we vary the number of LPNs underlaying the HPNs to see the impact of the number of LPNs on the network performance. We further consider when the system has 6, 12 or 24 LPNs per HPN instead of 18. The location of the eNBs are shown in Figure 4.14 - Figure 4.16. Figure 4.17 and Figure 4.18 present offloading rate and customer satisfaction rate when the system has different number of LPNs. Figure 4.17 shows that when the network has 18 and 24 LPNs per HPN the system can offload the highest number of users to LPNs. However, when the network consists of 24 LPNs per HPN, the network can satisfy significantly fewer users as illustrated in Figure 4.18. The reason is because when there are 24 LPNs per HPN, the LPNs become congested in the area and create high interference to neighboring LPNs. Therefore, with the considered network, the ratio of 18 LPNs per HPN can produce the highest possibilities to reduce energy reduction and customer satisfaction rate.

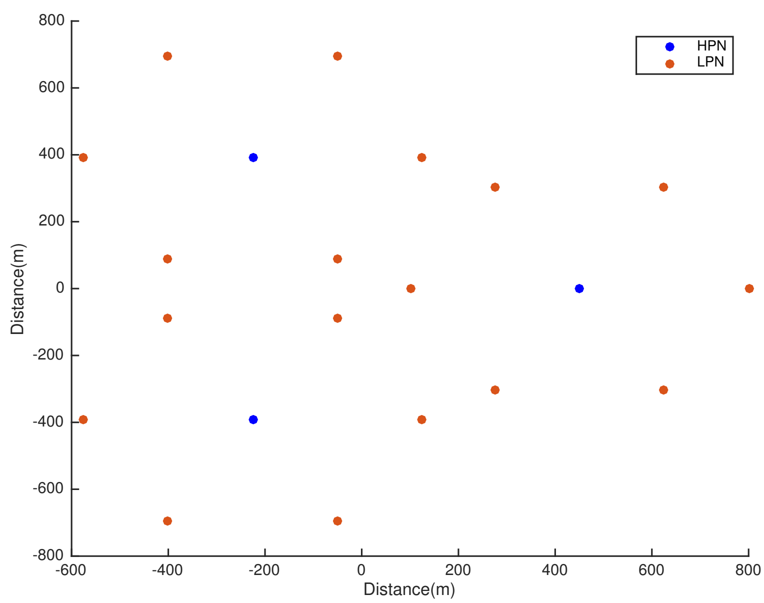

Figure 4.14: eNBs location with 6 LPNs per HPN

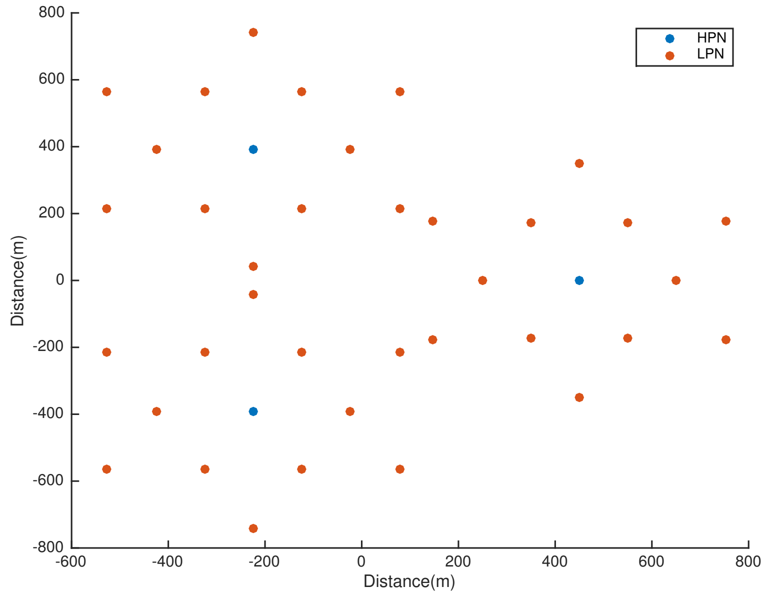

Figure 4.15: eNBs location with 12 LPNs per HPN

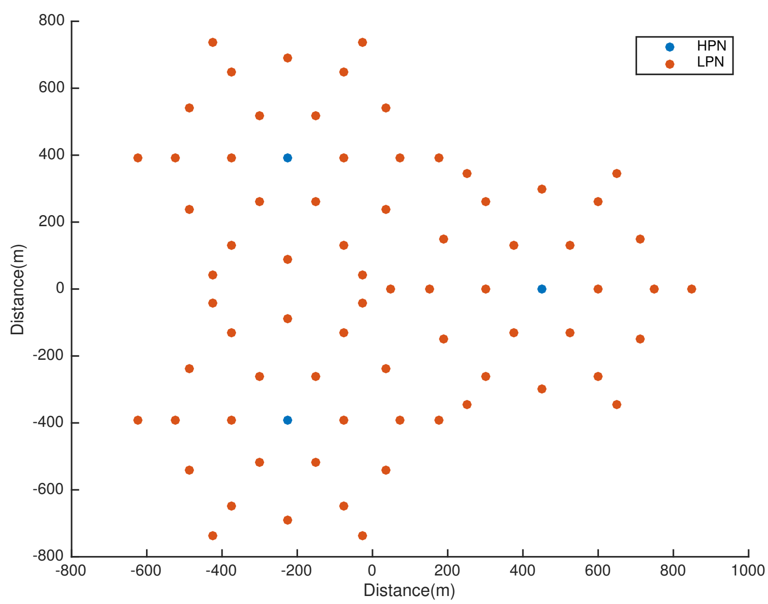

Figure 4.16: eNBs location with 24 LPNs per HPN

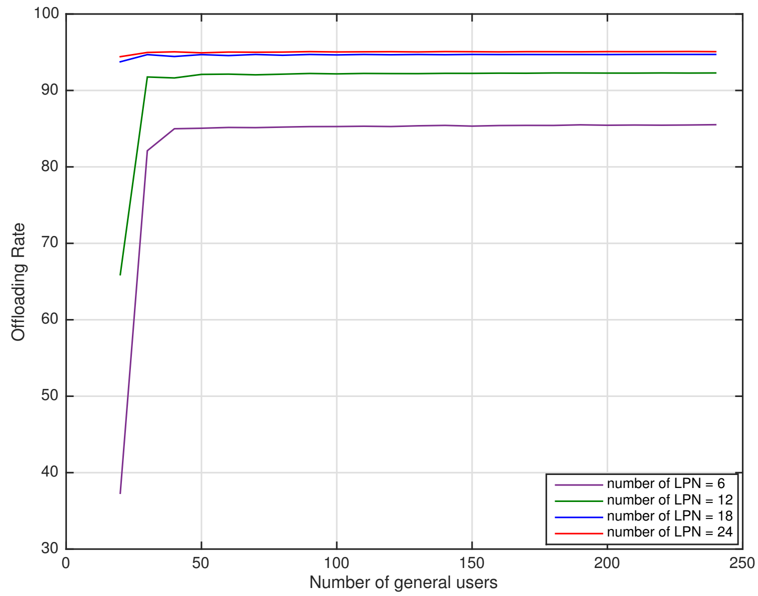

Figure 4.17: Percentage of LPN user with different numbers of LPNs

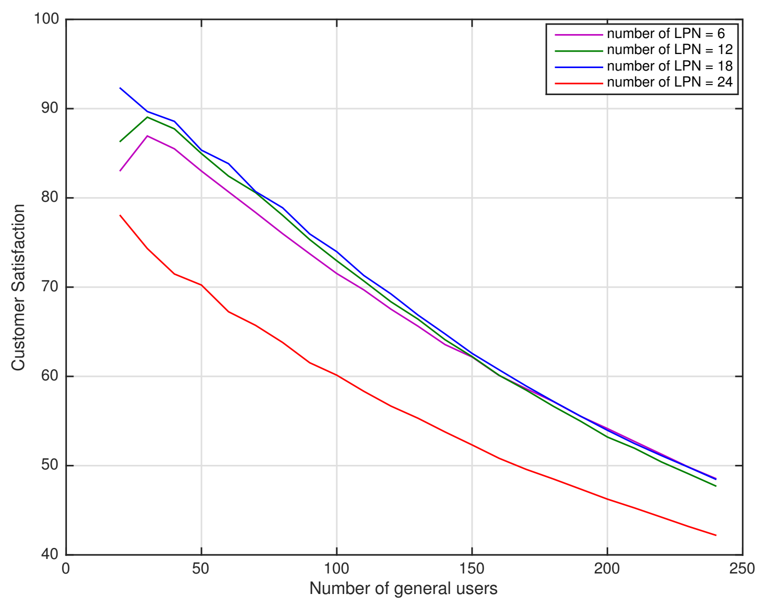

Figure 4.18: Customer satisfaction with different numbers of LPNs

5.0 ENERGY REDUCTION

In this chapter we present two energy reduction models, namely, *Step-dimming*(SD) and *Resource-based*(RE) Energy optimization. After we succeed manipulating traffic demand to promote the most possibility to reduce network energy consumption by cell selection techniques, we now present models to minimize the energy consumption while maintaining the service quality and customer satisfaction. Energy reduction cooperation among eNBs has become a standard by the introduction of 3GPP TS 32.521 technical specification [97]. The technical specification introduces Telecommunication management, Self-Organizing Networks (SON), and Policy Network Resource Model (NRM). The standard adds automatic network management and intelligent features to the system. Thus, it improves performance and increases flexibility of the cellular system through network optimization and reconfiguration processes. SON enables the eNBs to adjust their configurations when necessary without human intervention. Thus, more operations such as timed sleep mode are possible [98, 99]. Sleep mode is one of the various applications of SON, where eNBs are enabled to act collectively to save energy by redistributing traffic and sharing traffic information among eNBs. In this chapter, we present *Step-dimming* energy reduction that reduces transmit power of HPNs according to the number of connecting users. The numerical results of the model are discussed in Section 5.1.1. Last, based on our resource management (see Section 3.5) and various service demand levels, we propose *Resource-based* energy optimization in Section 5.2 and discuss its experimental results in Section 5.2.1.

5.1 STEP-DIMMING ENERGY REDUCTION

We believe that the majority of the energy consumption in LTE HetNets is at HPNs, which operators deploy to provide wide area coverage. At an HPN, when there are fewer users, the available bandwidth per user increases. The increase of available bandwidth for each user requires lower SINR to achieve the same level of data rate. Hence, it is possible for an HPN to transmit signal at lower power strength and maintain the quality of service.

Consider the energy required by each eNB at time t discussed in Section 3.2 and the number of attached users to LPNs and HPNs, Nl_t^{lpn} and Nh_t^{hpn}, result from the cell selection in Chapter 4. At this stage we consider the number of users as the load of the eNBs. We assume that LPNs operate at low power and can only be turned on or off, $x_t^{lpn} \in \{0, 1\}$. Therefore, when operating, $Nl_t^{lpn} > 0$ and $x_t^{lpn} = 1$, an LPN transmits at Tx^{LPN} constantly and consumes an extra SE percent of Tx^{LPN} for supporting equipment regardless of the demand level. As a result, $\sum_{lpn=1}^{N^{LPN}} x_t^{lpn} \cdot \left(El_t^{lpn} + SE\right)$ in Eq. 3.3 becomes $\sum_{lpn=1}^{N^{LPN}} x_t^{lpn} \cdot (1 + SE) \cdot Tx^{LPN}$ in Eq. 5.1a. Meanwhile, HPNs require energy for signal transmission, supporting equipment and HVAC. An operator can determine variation of transmission power depending on the current traffic. We assume a set of possible transmission power levels for HPNs, $\boldsymbol{Tx^{HPN}} = [30, 31, 32, \ldots, MaxTx^{HPN}]$ dBm. Thanks to increased available bandwidth per users during light-loaded periods, the transmission power of HPNs can be lowered and users can achieve expected data rate. Depending on the operator network planning, *baseline* targeted data rate is defined in matrix $\boldsymbol{BaseC}$(Figure A1). The matrix contains expected achievable data rate when an HPN has $\boldsymbol{Nh^{hpn}} = [10, 15, 20, \ldots, 250]$ and transmits at $\boldsymbol{Tx^{HPN}}$. Calculation of $\boldsymbol{BaseC}$ can be found in the Appendix. Binary matrix $\boldsymbol{n_t^{hpn}}$ and $\boldsymbol{p_t^{hpn}}$ are created to specify the current condition of HPNs at time t such that the number of HPNs users $Nh_t^{hpn} \leqslant \boldsymbol{Nh^{hpn}} \times [\boldsymbol{n_t^{hpn}}]^t$; $\sum \boldsymbol{n_t^{hpn}} = 1$ and the HPNs transmission power $Tx_t^{HPN} = \boldsymbol{Tx^{HPN}} \times [\boldsymbol{p_t^{hpn}}]^t$; $\sum \boldsymbol{p_t^{hpn}} = 1$. As a result, the traffic dependent energy at HPNs $Eh_t^{hpn} = [\boldsymbol{Tx^{HPN}}] \times [\boldsymbol{p_t^{hpn}}]^t$ in Eq. 5.1a. Moreover, we define supporting equipment, SE, and air-conditioning, AC, energy requirement as percentage of the maximum transmission power, $MaxTx^{HPN}$. The supporting equipment consumes energy only when the HPNs are transmitting signal, $y_t^{hpn} = 1$, while the air-conditioning is needed to be on at all time. Even though the supporting equipment and air-conditioning consume varying power due to the amount of traffic processed and heat generated by the equipment, the varying portion is marginal [105]. We assume the varying portion is included in the transmission power consumption.

Given the definitions above, we seek to minimize the total energy consumption $\sum_{t=1}^{T} E_t$ by turning off LPNs when there are no users ($Nl_t^{lpn} = 0$) and optimize the HPNs transmission power according to the current number of HPNs users (Nh_t^{hpn}). A linear integer programming optimization is formulated as follows:

$$\begin{aligned}
\min \; & \sum_{t=1}^{T} \sum_{lpn=1}^{N^{LPN}} x_t^{lpn} \cdot (1 + SE) \cdot Tx^{LPN} \\
& + \sum_{t=1}^{T} \sum_{hpn=1}^{N^{HPN}} y_t^{hpn} \cdot \left[\boldsymbol{Tx^{HPN}}\right] \times \left[\boldsymbol{p_t^{hpn}}\right]^t \\
& + \sum_{t=1}^{T} \sum_{hpn=1}^{N^{HPN}} \left(y_t^{hpn} \cdot SE \cdot MaxTx^{HPN}\right) \\
& + T \cdot N^{HPN} \cdot AC \cdot MaxTx^{HPN}
\end{aligned} \tag{5.1a}$$

s.t.

$$Nl_t^{lpn} \cdot x_t^{lpn} \geq Nl_t^{lpn} \tag{5.1b}$$

$$Nh_t^{hpn} \cdot y_t^{hpn} \geq Nh_t^{hpn} \tag{5.1c}$$

$$\left[\boldsymbol{n_t^{hpn}}\right] \times [\boldsymbol{BaseC}] \times \left[\boldsymbol{p_t^{hpn}}\right]^t \geq ExpC \tag{5.1d}$$

$$x_t^{lpn}, y_t^{hpn} \in \{0, 1\} \tag{5.1e}$$

The objective of the model is to minimize the total network energy consumption over time T. Eq. 5.1a consists of energy requirement from LPNs, HPNs transmission, HPNs supporting equipment and HPNs HVAC respectively. Eq. 5.1b and 5.1c assure eNBs are switched on when there are users connected. Constraint Eq. 5.1d determines HPNs transmission power regarding the number of HPN users and expected achievable data rate, $ExpC$.

A similar concept is mentioned in [102]. However, the work does not include any optimization model nor various traffic profile.

5.1.1 Numerical Results

To evaluate the power optimization model, we simulate a sample HetNet system similar to the one in Section 4.3. Three HPNs are operating on 800 MHz frequency band and able to transmit a signal at the maximum of 46 dBm. The HPNs transmit power can vary depending on the load (Nh_t^{hpn}), $\boldsymbol{Tx^{HPN}} = \{30, 31, 32, \ldots, MaxTx^{HPN}\}$. LPNs are operating on 2100 MHz frequency band and transmit a signal at 30 dBm constantly when active. The locations of the eNBs are identical to Figure 4.7. According to [73], we define energy requirement for supporting equipment, SE, and air-conditioning, AC, to be 27% of regarding eNB maximum transmission power. Table 5.1 presents our simulation parameters. We simulate the traffic load by using a measured traffic profile from an area in Northern California [101]. The profile contains mean and variance of traffic demand in areas. The average of demand is normalized to represent the percentage of system capacity in an area. Figure 5.1 shows the normalized average network traffic demand in each hour. In our sample HetNet, we assume that the maximum number of general users is 200 users, and each high-demand spot adds 10% of the number of users. We use the same random method of generating users location as in Section 4.3. To simulate the variation of users location and the order of network entry, we conduct each scenario for 500 iterations. Moreover, we continue to analyze results when DB and SB cell selection is used along with our proposed cell selections, BB, and EA, to learn the impact of various cell selections. DB cell selection presents a reference when a fixed cell coverage of LPNs is strictly enforced. SB cell selection represents current standard cell selection technique.

When considering the effectiveness of energy optimization, an analysis is typically based on general metrics such as an impact on the data rate of users, coverage probability and efficiency of energy usage. However, in practice, there are more variables and constraints that substantially affect the measurement and the evaluation. For example, an operator could conclude that an increased data rate, higher coverage probability, or greater data transferred per energy unit lead to an improved network performance. However, the improvement can be achieved by only deploying more base stations that consequently causes additional energy consumption. Therefore, to measure the performance we focus on the actual amount of

Table 5.1: Simulation parameters

Parameter	**Configuration**
HPN cell radius, R_{HPN}	500 m
LPN cell radius, R_{LPN}	150 m [106]
Max. transmission power, $MaxTx$	46 dBm (HPN) [107, 108], 30 dBm (LPN) [106, 107]
Carrier frequency, f	800 MHz (HPN), 2.1 GHz (LPN)
SE energy factor, SE	27% of $MaxTx$ [73]
AC energy factor, AC	27% of $MaxTx$ [73]
Bandwidth, B	10 MHz [107, 108]
Pathloss model	L_p (HPN)$= 69.55 + 26.16log(f) - 13.82 * log(hb)$
	$-a(hm) + (44.9 - 6.55log(hb))log(d)$;
	$a = 3.2(log(11.75hm))^2 - 4.97$ [103]
	L_p (LPN)$= 140.7 + 36.7log_{10}(d)$ [104]
Achievable data rate, C	$C = 0.75Blog_2(1 + SINR/1.25)$ [84]
Interference, I	$\sum RSS_{neighboring\ eNB}$
Noise, N	-92 dBm
Time periods, T	24 hours

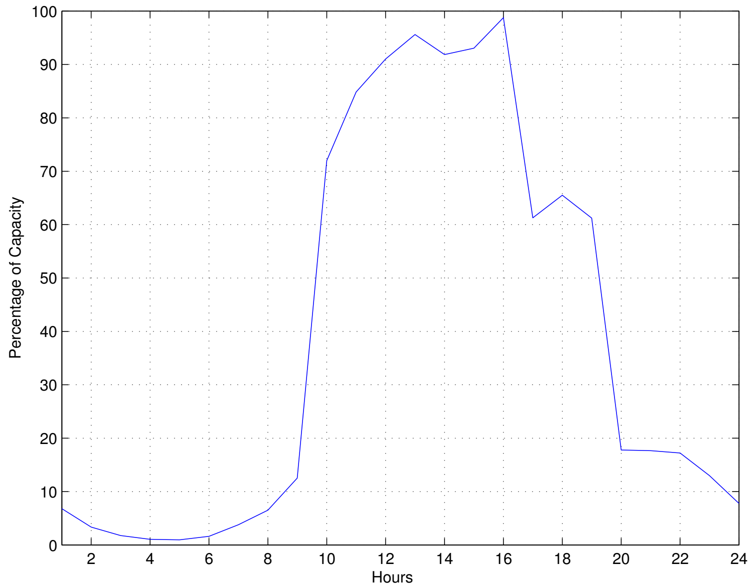

Figure 5.1: Normalized network traffic demand

energy consumption and measure the improvement in terms of percentage of the energy required after optimization. Also, we do not limit the maximum data rate of users who receive high SINR. On the other hand, we allow users to experience descended services caused by an adverse effect of degraded signal quality as a trade-off of lower energy consumption. We only consider data rate required for a voice call, 50kbps, as the minimum requirement.

Firstly, we present Table 5.2. The table shows the percentage of energy requirement after performing energy reduction mechanisms. The percentage is a percentage of full operation energy consumption when there is no energy reduction performed. Results in each scenario contain two numbers. The first is the percentage of energy consumed after performing *Step-dimming (SD)* energy reduction. The second is the percentage of energy consumption when the system only operates widely-proposed switching on-off eNB technique. The difference is that, in our proposed method, we also optimize the transmit power of HPNs in addition to solely switching off zero-loaded eNBs. The table presents the percentage of the energy consumption in the network (Total), HPNs and LPNs. In the table, BB represents proposed

Table 5.2: Total energy consumption in percentage of full operation energy requirement when using Step-dimming compared to switching on and off eNBs only (SD/no dimming)

	BB	EA	DB	SB
Total	36.67%/95.24%	32.98%/91.54%	36.70%/95.26%	57.81%/91.97%
HPNs	19.60%/100%	19.60%/100%	19.60%/100%	53.09%/100%
LPNs	82.46%/82.46%	68.84%/68.84%	82.56%/82.56%	70.45%/70.45%

BB:Bandwidth-based, EA:Energy-aware, DB:Distance-based, SB: SINR-based cell selection

Bandwidth-based cell selection, EA stands for *Energy-aware* cell selection, DB and SB are *Distance-based* and *SINR-based* respectively. According to the table, we can reduce the total energy consumption considerably with the proposed energy optimization technique, Step-dimming model. The network requires as low as 32.98% of full operation requirement when the system uses EA cell selection and SD energy reduction model. The optimization method can also reduce the energy consumption when the system uses the typical SB cell selection to 57.81%. Though, the power consumption is considerably higher than the system uses BB and EA, which requires 36.67% and 32.98% respectively. The reason is that the SB congests a larger number of users at the HPNs, which consume significantly more power than the LPNs. When there are a significant number of users at HPNs, it is less possible to reduce the transmit power at HPNs. As a result, the energy requirement at the HPNs, 53.09%, is significantly higher than when the network uses other cell selection techniques, 19.60%. Moreover, EA results in the lowest energy requirement regardless of the energy optimization methods. The main reason is that the cell selection creates the most opportunities for LPNs to switch off. EA results in LPNs consuming energy at 68.84% of when they are always active.

Next, Figure 5.2 - 5.7 present further numerical results in each hour period. In the figures, black lines with ‘x’ markers present results for Distance-based (DB) cell selection. Red lines with ‘□’ markers present results for SINR-based (SB) cell selection. Pink lines with ‘△’ marker show results for Bandwidth-based (BB) cell selection. Blue lines with ‘○’

markers represent results for Energy-aware (EA) cell selection. Also, dash lines and solid lines demonstrate results before and after performing energy reduction. First, we analyze the system power consumption by hours to see the effect of the variation in traffic load. Figure 5.2 shows that the difference in power consumption between EA and other cell selection techniques is apparent during low-load periods. Figure 5.3 shows that during those periods LPNs consume significantly smaller amount of energy on average or become inactive while Figure 5.4 shows that the cell selection does not increase power consumption at HPNs during that time. On the other hand, SB requires the highest amount of power during the busy hours (10 - 20) due to the significant number of users congesting in the HPNs.

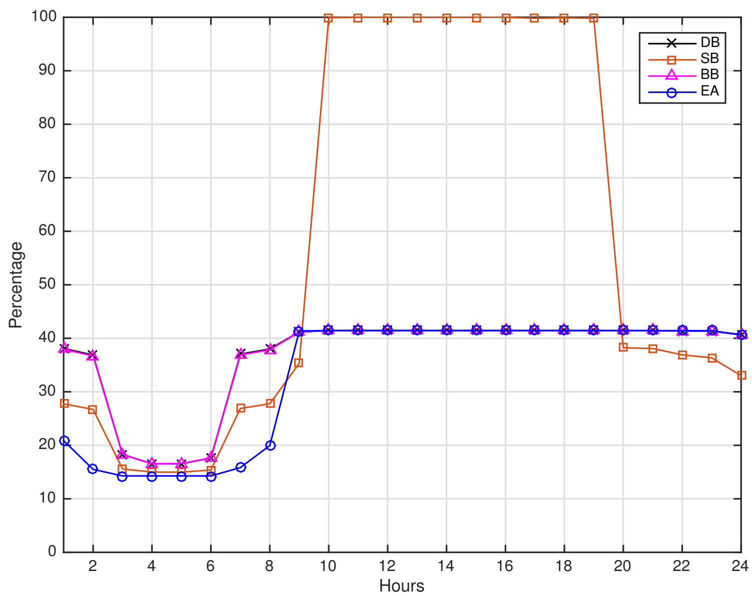

Figure 5.2: Total energy consumption in percentage of full operation after using Step-dimming

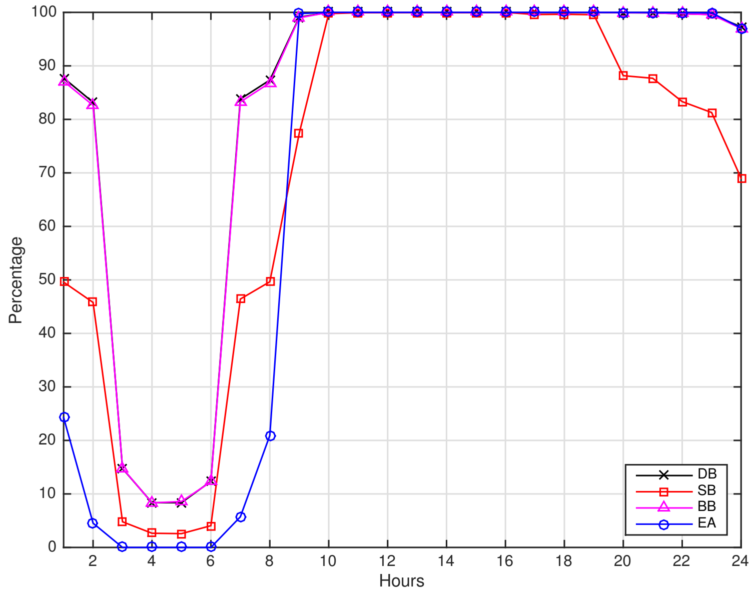

Figure 5.3: LPN energy consumption in percentage of full operation

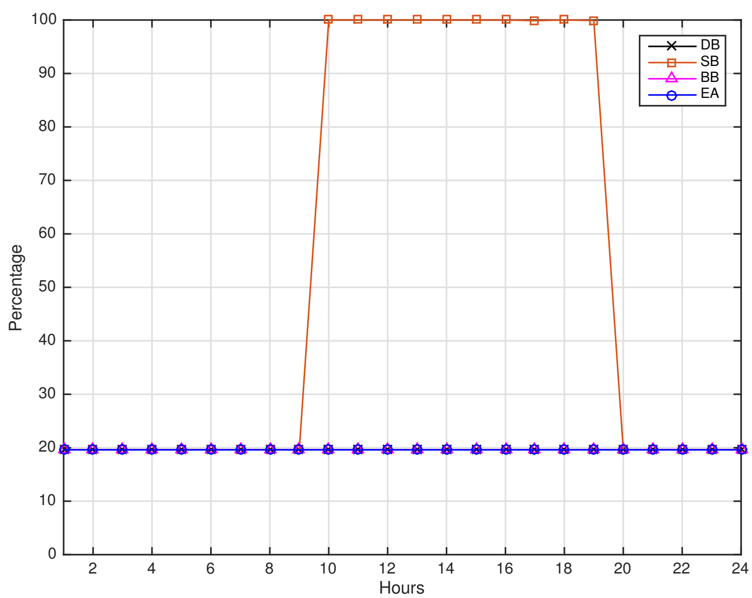

Figure 5.4: HPN energy consumption in percentage of full operation after using Step-dimming

Figure 5.5 shows customer satisfaction before and after applying SD (Dim). DimDB, DimSB, DimBB and DimEA represent the results after applying SD when DB, SB, BB and EA cell selection is applied, respectively. The figure demonstrates that the optimization technique can relatively maintain the level of satisfaction after reducing energy consumption regardless of cell selection schemes. Moreover, when the system provides equal services to all users, BB can provide the highest customer satisfaction rate. When measuring the customer satisfaction based on equal services, EA receives lower customer satisfaction rate because of the spectrum resource management we adopt. The resource management procedure ensures that high-service users demand occupy more resource than low-service users. The lower user demand then receives spectrum resource that could be insufficient to achieve their expectation. Therefore, we also measure the customer satisfaction rate according to the users service level. Because we apply different services to the scenario of EA only, the figure shows EAServ and DimEAServ as the results before and after performing SD energy reduction with EA. When we measure the satisfaction according to the different service demand, EA gains considerably high satisfaction rate. Note that even though we do not measure the satisfaction rate by the other cell selection techniques, we can interpret the result. The satisfaction rate of BB would not be considerably different from EA due to EA utilizes BB during peak time periods. On the other hand, the satisfaction rate of SB would be significantly lower. Because of the significant number of users connecting to the HPNs, the extremely high number of the HPN users would receive discounted services yielding lower satisfaction rate.

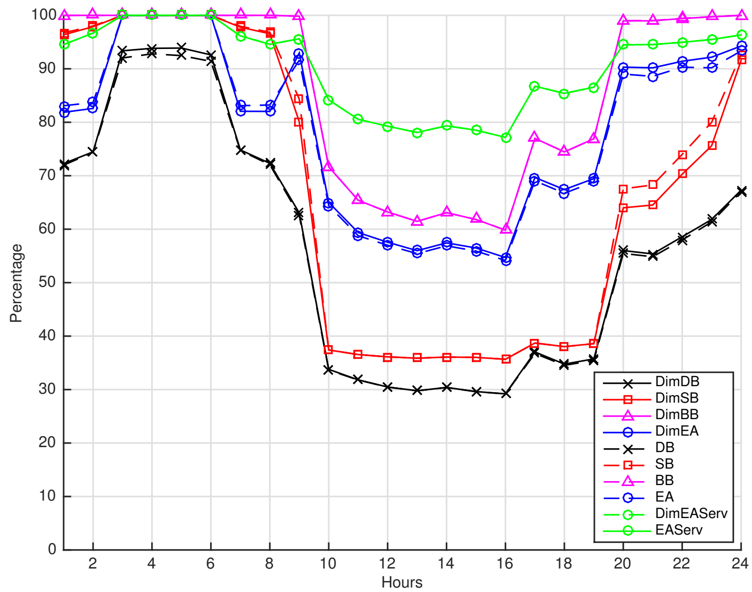

Figure 5.5: Customer satisfaction

As mentioned, we focus on creating a possibility to lower the energy requirement and reducing the amount of power consumption. We believe that by allowing users to experience the decreased quality of service, we can minimize the energy consumption while maintaining users satisfaction. According to Figure 5.5, the proposed energy reduction model can considerably maintain the customer satisfaction. Figure 5.6 shows the outcome of reducing energy consumption. The figure presents the achievable data rate of HPN users in the network. HPN users are the only users affected by the minimized transmit power. Solid lines represent the data rate after dimming the HPNs transmit power and dash lines represent the rate before dimming. With most cell selection techniques, it is apparent that the energy reduction decreases the data rate of users. Especially during light-loaded periods, the deduction is more evident than during busy time. However, when we consider the energy that we save, Figure 5.7 shows that the ratio of the HPN users achievable data rate per energy consumption increases significantly by the energy reduction mechanism.

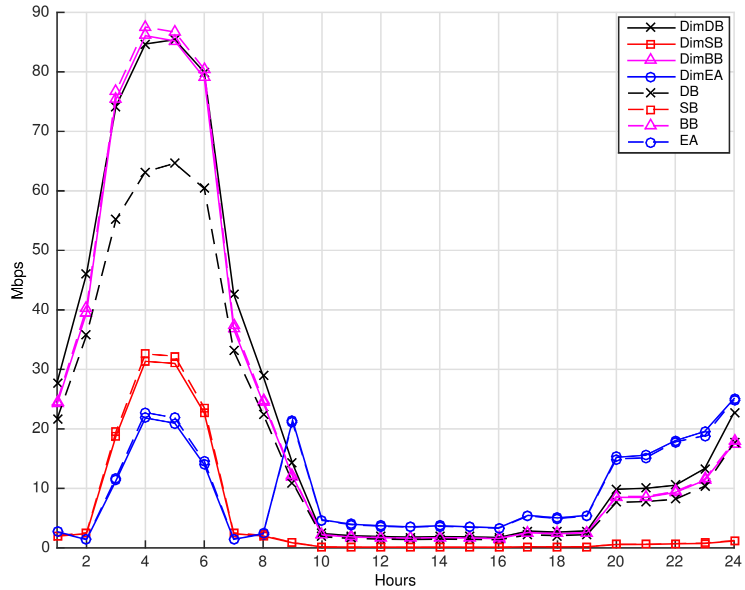

Figure 5.6: HPN users achievable data rate before and after using Step-dimming

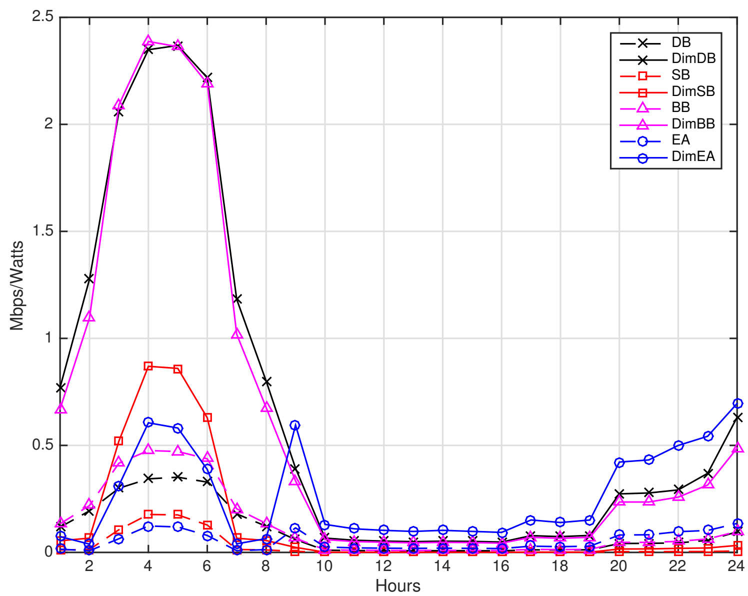

Figure 5.7: HPN achievable data rate and energy consumption ratio

5.2 RESOURCE-BASED ENERGY OPTIMIZATION

In telecommunication, one valid way to quantify the quality of service a user experiences is to evaluate the user achievable data rate. The aim of our work is to save the network total power consumption. Therefore, associating the achievable data rate with power consumption can certainly bring us an insight of how to manage a network energy efficiently while satisfying users. Consider Shannon capacity equation, ($C = Blog_2(1 + SINR)$), the equation provides a straightforward view of relations between critical network parameters. In the previous section, we reduce the transmit power at HPNs by allocating a minimized amount of power to all RBs that ensures the resulting SINR meet a user's requirement. The process enables us to minimize the total energy consumption of HPNs and hence the network. In this section, we further deploy relations between bandwidth and transmit power. We exploit advanced LTE resource management to limit the energy consumption by minimizing the number of resource blocks an eNB allocates to a user. As discussed in Section 3.4, the number of resource blocks can be restricted because different users demand various levels of service. The resource blocks that an eNB assigns to provide lower levels can be transmitted at relatively low transmit power level. In contrast, those users who require high-level services could require the resource blocks to have higher transmit powers. With the concept, we propose Resource-based (RE) energy optimization to minimize the spectrum resource usage and the transmit power required to satisfy users.

In 5.1, we focus on reducing the total energy consumption by minimizing HPN transmission power only. The procedure concerns the number of users in the system. No different QoS levels are considered in the energy reduction. User achievable data rate depends mainly on the quality of the received SINR. Several satisfied users could, in fact, receive a widely different quality of service depending on their SINR. Some could achieve data rate that is considerably higher than their demand due to proximity to the connected eNBs. The extra resource that yields the high achievable data rate to the users would cause unnecessary energy consumption and therefore potentially leads to a further possibility of energy reduction. In this section, we exploit additional energy saving of transmission in radio resource. Due to CQI technology and advanced antennas, we can further reduce the total energy required to provide services by optimizing the amount of spectrum resource and minimizing the transmission power to guarantee various QoS levels.

Resource-based energy reduction optimization aims to reduce the total energy consumption at all eNBs, both HPNs and LPNs, by minimizing the amount of spectrum resource allocated to each user as well as minimizing the HPN transmit power. We formulate the model to execute in each time period, t, independently. Although the value of variables change in every time period, we let all variables in the model represent their value at time t without subscription for simplicity and ease of understanding.

Consider a HetNet containing of N^{eNB} eNBs which include both LPNs and HPNs. At an eNB enb when $enb = [1, N^{eNB}]$, there are Ne^{enb} UEs connected as a result from a cell selection scheme. A UE, i when $i = [1, Ne^{enb}]$, maps its SINR to a CQI value (CQI has 15 values, $N^{CQI} = 15$, each corresponds to a certain range of SINR [79–83]) then reports the CQI value, q when $q = [1, N^{CQI}]$, to the associated eNB. Based on the service level the user demands ($reqC^i$), the eNB optimizes an amount of spectrum resource for the user ($\sum_{q=1}^{N^{CQI}} ru^{i,q}$) and minimizes the user's required CQI level ($cq^{i,q}$). $ru^{i,q}$ is an amount of spectrum resource in percentage allocated to a user i when the user receives a CQI level q. $cq^{i,q}$ is a binary variable that equals to one when the user i receives the corresponding CQI level q. Note that to achieve a certain degree of service demand, an eNB can vary its transmit power that consequently changes the users SINR (CQI level q) and alters the amount of spectrum resource for users ($ru^{i,q}$). The range of transmit power an eNB can perform depends on an operators requirement. Also, an eNB could assign up to 100% of resource to a user. However, the minimum of provided resource depends on the type of the eNB. In our work, because LPNs can be switched off when there is no active user connecting to the LPNs, the LPNs can reduce their total assigned resource to zero percent ($\sum_{i=1}^{Ne^{enb}} \sum_{q=1}^{N^{CQI}} ru^{i,q} = [0, 1]$). In contrast, because we set HPNs to cover service area at all time, the HPNs cannot provide zere assigned resource to the area. We determine that the minimum amount of resource the HPNs require providing be the lowest amount of resource in the frequency domain that is 1.4 MHz at all time. 1.4 MHz is the minimum bandwidth an eNB can operate according to an LTE standard. Thus, the minimum amount of resource an HPN can operate would be 14% when the full bandwidth of the HPNs is 10 MHz ($\sum_{i=1}^{Ne^{enb}} \sum_{q=1}^{N^{CQI}} ru^{i,q} = [0.14, 1]$).

The goal of the problem is to optimize the total resource ($\sum_{i=1}^{Ne^{enb}} \sum_{q=1}^{N^{CQI}} ru^{i,q}$) used at an eNB which leads to the energy consumption. The total energy consumption at an eNB is proportional to the amount of resource allocated to all users at the eNB and the transmit power. To satisfy a user service requirement, the eNB can allocate more resource if the transmit power is low and increase the transmit power when only a limited amount of resource is available. In the optimization problem, an eNB takes into account the minimum required SINR of each CQI level and the user demanded achievable data rate ($reqC^i$)to obtain the optimized amount of resource for a user. We adopt 15 levels of CQI based on levels of SINR and 10% block error ratio (BLER) from Vienna LTE Simulators [83]. The minimum SINR of each CQI level, $reqSINR^{i,q}$, is presented in Table 5.3. With the minimum SINR, the eNB can approximate the achievable data rate of the user i using the modified Shannon capacity equation [84] ($C^i = ru^{i,q} * 0.75 * B * log_2(1 + reqSINR^{i,q}/1.25)$). Because the available spectrum resource at an eNB cannot exceed 100%, the summation of the resource allocated to all users must be less or equal to 1 ($\sum_{i=1}^{Ne^{enb}} \sum_{q=1}^{N^{CQI}} ru^{i,q} \leq 1$). Furthermore, to enable energy reduction, an eNB also tries to minimize the users received CQI level that reduces the necessary eNB transmit power. To do so, an eNB tries to provide the lowest CQI level to a user as long as it meets the service requirement. With the information of minimum SINR requirement for each CQI level shown in Table 5.3, an eNB can assure the user achieve its expected achievable data rate until the user reports a change in its CQI level.

Given the consideration above, we create an optimization model that considers different service demand levels, user CQI levels and transmission power at each eNB and time period. The first stage is to determine the necessary amount of resource and required CQI level for each user in order to achieve their expected data rate. Next, we calculate the required transmission power strength of the eNB for each user based on the users required CQI level result from the first stage.

$$\min \sum_{i=1}^{Ne^{enb}} \sum_{q=1}^{N^{CQI}} \left\{ \left[\boldsymbol{RU} | \boldsymbol{CQ} \right] \times \begin{bmatrix} \boldsymbol{Sf} \\ \boldsymbol{F} \end{bmatrix} \right\} \tag{5.2a}$$

s.t.

$$\sum_{q=1}^{N^{CQI}} \left[\boldsymbol{RU} \times \boldsymbol{S}\right] \geq reqC^{i} \qquad \forall\, i \tag{5.2b}$$

$$\sum_{q=1}^{N^{CQI}} \boldsymbol{CQ} = 1 \qquad \forall\, i \tag{5.2c}$$

$$\sum_{i=1}^{Ne^{enb}} \sum_{q=1}^{N^{CQI}} \boldsymbol{RU} \leq 1 \tag{5.2d}$$

$$\boldsymbol{RU} \leq \boldsymbol{CQ} \qquad \forall\, i, q \tag{5.2e}$$

when

$$\boldsymbol{RU} = [ru^{1,1}\;\; ru^{1,2}\; \ldots\; ru^{1,N^{CQI}}\;\; ru^{2,1}\; \ldots\; ru^{Ne^{enb},N^{CQI}}] \tag{5.2f}$$

$$\boldsymbol{CQ} = [cq^{1,1}\;\; cq^{1,2}\; \ldots\; cq^{1,N^{CQI}}\;\; cq^{2,1}\; \ldots\; cq^{Ne^{enb},N^{CQI}}] \tag{5.2g}$$

$$\boldsymbol{Sf} = \boldsymbol{S} \odot \boldsymbol{F} \tag{5.2h}$$

$$\boldsymbol{S} = \left[\boldsymbol{s} \,|\, \boldsymbol{s} \,|\, \cdots \,|\boldsymbol{s}\right]^{T}_{1\times Ne^{enb}}; \boldsymbol{s} = [s_1\;\; s_2\;\; s_3 \ldots s^{N^{CQI}}] \tag{5.2i}$$

$$\boldsymbol{F} = \left[\boldsymbol{f} \,|\, \boldsymbol{f} \,|\, \cdots \,|\boldsymbol{f}\right]^{T}_{1\times Ne^{enb}}; \boldsymbol{f} = [f_1\;\; f_2\;\; f_3 \ldots f_{N^{CQI}}] \tag{5.2j}$$

$$i \in \{1,\;\; 2, \ldots, Ne^{enb}\} \tag{5.2k}$$

$$q \in \{1,\;\; 2, \ldots, N^{CQI}\} \tag{5.2l}$$

$$ru^{i,q} \in \boldsymbol{RU}\;,\;\; cq^{u,q} \in \boldsymbol{CQ}\;,\;\; s_q \in \boldsymbol{s}\;,\;\; f_q \in \boldsymbol{f} \tag{5.2m}$$

$$ru^{i,q} \in [0,1]\;,\;\; cq^{i,q} \in \{0,1\} \tag{5.2n}$$

The objective of the first stage optimization (Eq. 5.2a) is to minimize the total operating spectrum resource and users CQI level at an eNB, enb. Each element of $\boldsymbol{RU}$, $ru^{i,q}$, represents the percentage of eNB resource within a time period that is dedicated for a user, i, with a particular CQI level, q (Eq. 5.2f). If the considered eNB is an LPN, $ru^{i,q}$ can vary from 0 to 1 (Eq. 5.2n). If the eNB is an HPN, $ru^{i,q}$ can vary from 1.4MHz (HPN minimum bandwidth) to 1. $cq^{i,q}$ in $\boldsymbol{CQ}$ is a binary variable indicating CQI level of a user (Eq. 5.2g). $cq^{i,q}$ is 1 when user i has CQI level q and 0 otherwise. $\boldsymbol{Sf}$ is a Hadamard product or entry-wise product of $\boldsymbol{S}$ and $\boldsymbol{F}$ (Eq. 5.2h). From Eq. 5.2i, $\boldsymbol{S}$ is an array of row matrix $\boldsymbol{s}$ containing, s_q. s_q is a constant representing a part of the modified Shannon's achievable data rate equation ($log_2(1+SINR/1.25)$) [84] with the minimum $reqSINR^{i,q}$ in each determined CQI levels as shown in Table 5.3. The value of s_q depends on determination of received SINR range for each CQI levels. For example, a user, $i = 1$, will report a CQI level 2 ($q = 2$) if it receives SINR between -5.0714 and -3.1429 dB from its associating eNB. From the table, $s_2 = log_2(1 + (-5.0714dB) = 0.3206$. Consequently, in Eq. 5.2c, $cq^{1,2} = 1$ and $cq^{1,q} = 0; q \neq 2$. In Eq. 5.2j, f_q is a constant factoring in the difference of transmit power required to provide the minimum SINR to achieve each CQI levels. The product of s_q and f_q for each CQI or $\boldsymbol{s} \odot \boldsymbol{f}$ is presented in Table 5.3. $\boldsymbol{F}$ is utilized in the objective to favor providing resource with lower CQI requirement over higher CQI levels. The optimization problem concerns that the achievable data rate provided must be greater or equal to user demand, $reqC^i$ (Eq. 5.2b). The guaranteed minimum achievable data rate a user receives is calculated from the percentage of resource dedicated to a user, $ru^{i,q}$, and s_q associated to the particular CQI level. Also, there can only exist one CQI level for each user (Eq. 5.2c). Eq. 5.2d ensures that the portion of resource dedicated to all users at one eNB is less or equal to 100%. Constraint Eq. 5.2e is a condition such that $cq^{i,q}$ needs to be one if $ru^{i,q}$ has a value.

The first stage of the optimization model (Eq. 5.2) results in the amount of spectrum resource ($ru^{i,q}$) an eNB (enb) needs to reserve for a user (i) and their required CQI levels (q) to guarantee their achievable data rate ($reqC^i$). To guarantee that each UE receives SINR within a specific range according to the required CQI levels ($SINR^i \geq reqSINR^{i,q}$) while minimizing transmit power of the eNB, we apply a heuristic optimization to minimize transmit power in HPNs (Eq. 5.3). We consider an HPN with possible transmit power levels $\boldsymbol{Tx^{HPN}} = \{30, 31, \ldots, 46\}$ dBm. The HPN knows its users required achievable data rate ($reqC^i$), their minimized CQI level (q) and the minimum SINR of the CQI level ($reqSINR^{i,q}$). The HPN then heuristically reduces its transmit power (Tx^{HPN}) for a user starting from the maximum. The process continues until the calculated SINR of the user is lower than the minimum SINR requirement of the user CQI required level. The HPN then concludes to transmit at one power level above to the user.

In contrast, because LPNs already transmit at a very low level of power, we assume it is not worth to concern the transmit power reduction for LPNs. Due to this consideration,

Table 5.3: Resource-dimming Energy Reduction factors

CQI level (q)	$reqSINR^{i,q}$ (dB)	$\boldsymbol{s}$	$\boldsymbol{f}$	$\boldsymbol{s} \odot \boldsymbol{f}$
1	-7.0000	0.2137	1.0000	0.2137
2	-5.0714	0.3206	1.5590	0.4998
3	-3.1429	0.4730	2.4305	1.1496
4	-1.2143	0.6825	3.7891	2.5859
5	0.7143	0.9583	5.9072	5.6609
6	2.6429	1.3046	9.2094	12.0148
7	4.5714	1.7190	14.3574	24.6805
8	6.5000	2.1933	22.3852	49.0929
9	8.4286	2.7162	34.8955	94.7814
10	10.3571	3.2759	54.4020	178.2131
11	12.2857	3.8621	84.8128	327.5543
12	14.2143	4.4667	132.2231	590.6039
13	16.1429	5.0838	206.1358	1047.9516
14	18.0714	5.7091	321.3657	1834.7137
15	20.0000	6.3399	501.0091	3176.3225

the first stage of the optimization model(Eq. 5.2) needs an additional constraint to secures particular $cq^{i,q}$ of LPNs users in (Eq. 5.2g) to 1. The constraint affirms that the CQI level every users receives cannot be adjusted in the next stage. However, LPNs are still able to operate at a reduced power level by minimizing the assigned amount of spectrum resource.

$$\min \sum \left[\boldsymbol{Tx^{HPN}}\right] \times \left[\boldsymbol{p^{hpn,i}}\right]^{T} \tag{5.3a}$$

s.t.

$$\left[\boldsymbol{Tx^{HPN}}\right] \times \left[\boldsymbol{p^{hpn,i}}\right]^{T} \geq reqPt^{i} \qquad \forall\, i \tag{5.3b}$$

From (Eq. 5.3a), the objective of the problem is to minimize the transmit power of an HPN. $\boldsymbol{p^{hpn,i}}$ is a state matrix representing the transmit power level an HPN, hpn, is transmitting to a user i. A member of the matrix is a binary variable that equals to one when a represented level of transmit power is chosen and equals to zero otherwise. $\boldsymbol{Tx^{HPN}}$ contains applicable levels of transmit power determined by the operator. The only constraint in the problem is the transmit power must not be lower than a require transmit power ($reqPt^{i}$) that yields a greater SINR than the $reqSINR^{i,q}$ obtained from the previous stage of the problem.

Until the time of writing, there are few works that present energy efficiency in LTE network utilizing discontinuous transmission (DTX) in either frequency domain [109] or time domain [110, 111]. None has proposed the energy reduction considering both time and frequency domain collectively.

5.2.1 Numerical Results

In this section, we evaluate the performance of Resource-based (RE) energy optimization model by applying the model to similar scenarios as ones in Section 5.1.1. The sample network contains three HPNs and 54 LPNs. The locations of the eNBs are shown in Figure 4.7. We maintain the same value of simulation parameters presented in Table 5.1. The mean traffic percentage of capacity follows Figure 5.1. The maximum number of general users is 200 users, and each high-demand spot creates additional 10% of users. We randomly generate users location similarly to Section 4.3. All cell selection schemes (DB, SB, BB, and EA) are applied and examined here. Moreover, we simulate the variation of users location and order of network entry in each hour by conducting each scenario for 500 iterations.

We continue to define service levels and their minimum achievable data rate as follows; FullHD video, HD video, SD video, TCP and voice service have the minimum data rate requirement of 10 Mbps, 5 Mbps, 3 Mbps, 700 Mbps, and 50 kbps, respectively. We determine the probability of a user service demand to be 5%, 15%, 25%, 25% and 30% for FullHD, HD video, SD video, TCP, and best-effort, respectively. Note that best-effort users receive a guarantee for only voice service that requires 50 kbps. However, the BE users are satisfied when achieving at least 695.4kbps (customer satisfaction baseline). To manage the spectrum resource regarding various levels of service demand, we apply the resource management explained in Section 3.5. The maximum amount of resource that can be allocated to BE users is set to 25% of resource assigned to GBR users.

Table 5.4 presents the comparison of energy saving results when the system performs Resource-based(RE) energy optimization and the Step-dimming(SD) energy reduction. Note that in RE, we adopt the principles of SD during the second stage of the optimization. Overall, the results show that RE can reduce a significant amount of energy. The network requires as low as 33.63% of the full capacity when operates EA cell selection. However, the network requires more energy than when the network implements SD energy reduction and EA cell selection (32.98%). The main reason is our input on consideration of different service levels. In SD, we consider meeting a considerable lower rate to users (695.4kbps). In RE optimization, 70% of the users, on average, demand a higher achievable data rate.

Table 5.4: Total energy consumption in percentage of full operation energy requirement after Resource-based(RE) energy optimization compared with Step-dimming energy reduction(SD) (RE/SD)

	BB	EA	DB	SB
Total	37.33%/36.67%	33.63%/32.98%	46.37%/36.70%	66.37%/57.81%
HPNs	25.84%/19.60%	24.73%/19.60%	38.73%/19.60%	80.32%/53.09%
LPNs	60.45%/82.46%	57.51%/68.84%	66.86%/82.56%	28.95%/70.45%

BB:Bandwidth-based, EA:Energy-aware, DB:Distance-based, SB: SINR-based cell selection

50% of the demand requires extremely higher services (3-10 Mbps). Understandably, the network needs more energy to provide faster data rates. Consider the significant increase of required data rate (314.93% increase on average) and the extra number of high-level service users (45%), the additional amount of energy is acceptable. The table further shows that the extra power consumption occurs in the HPNs. When the system performs EA, HPNs require 24.73% of full operation energy while they require 19.60% with SD. Obviously, it is because HPNs need to increase their transmit power. Due to the demand for the higher service levels, HPNs need to allocate more amount of spectrum resource to the users. The amount of resource then becomes more limited. To compensate the decreased amount of resource for users, the HPNs need to transmit the signal at a higher level to meet the users expected achievable data rate. On the other hand, LPNs, which do not adjust their transmit power, benefit from our RE optimization. LPNs can save more energy consumption by optimizing their spectrum resource in addition to switching off when not necessary. When operating EA, LPNs require 57.51% of energy to operate using RE compared to 68.84% when using SD.

Next, Figure 5.8 - 5.15 present further numerical results in each hour period. In the figures, black lines with ‘x’ markers present results for Distance-based (DB) cell selection. Red lines with ‘□’ markers present results for SINR-based (SB) cell selection. Pink lines with '△' marker show results for Bandwidth-based (BB) cell selection. Blue lines with '○' markers represent results for Energy-aware (EA) cell selection. Also, dash lines and solid lines demonstrate results before and after performing Resource-based energy reduction. Considering the energy consumption in each time periods, we can see from Figure 5.8 that the system requires energy the most during peak hours (10-19 hour) and the least during quiet hours (3-6 hour). BB and EA cell selection creates the most energy saving. The effect of RE is most apparent by comparing energy consumption when SB is used with SD and RE. SB represents a standard LTE network that has the majority of the users congested in HPNs. The considerable congestion at the HPNs restrict the HPNs to reduce their power consumption forcing the HPNs to operate at full capacity (see Figure 5.4). Also, SB requires all LPNs to stay operating to provide service at high-demand spots as shown in Figure 5.3. Because RE can optimize LPNs spectrum resource and eliminate unnecessary energy consumption, the system that operates SB can produce energy reduction during the peak hours. We can also see different impacts of BB and EA during quiet hours in Figure 5.8. As EA keeping LPNs inactive by gathering users into HPNs only, energy saving by EA is present during the hour of 1-2 and 7-8.

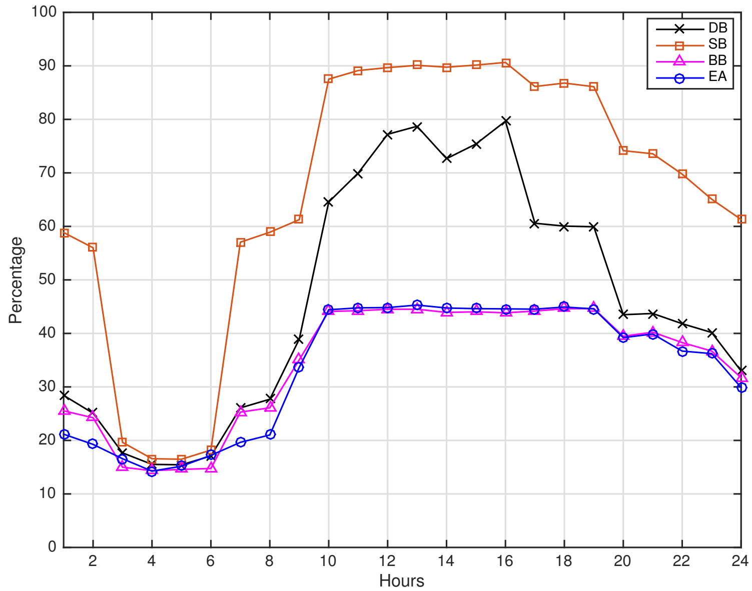

Figure 5.8: Total energy consumption in percentage of full operation after Resource-based energy optimization

To continue observing the impact of EA when operating RE optimization, we present Figure 5.9 and Figure 5.10. Because EA gathers all users into HPNs to allow LPNs to stay off during quiet hours, HPNs require higher energy to satisfy the higher number of users than when the system uses BB. On the other hand, EA can save LPN energy consumption by stopping the LPNs from operating during the hour of 3-6 that contributes considerably to the total energy reduction. Further, we can see a level of energy saving in LPNs due to RE optimization during the hours of 17-20 in Figure 5.10. Also, RE optimization successfully reduces the energy requirement at HPNs to the minimum during the peak hours as shown in Figure 5.9.

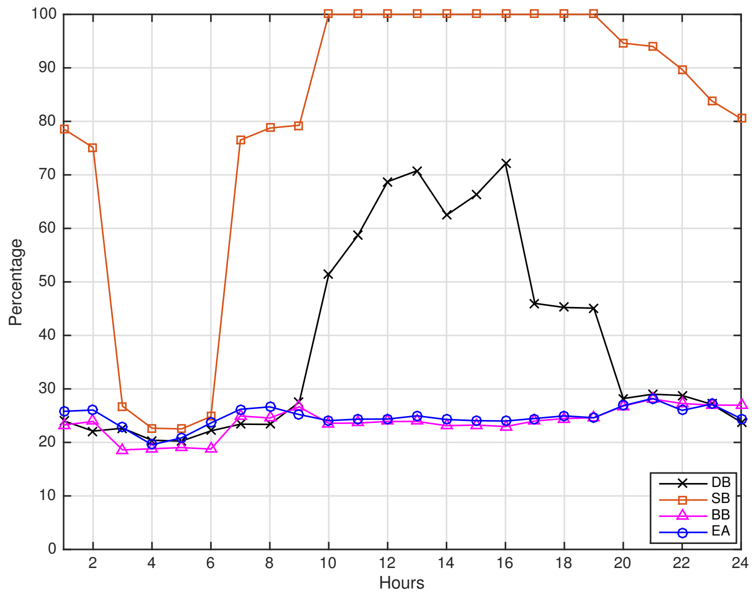

Figure 5.9: HPN energy consumption in percentage of full operation after Resource-based energy optimization

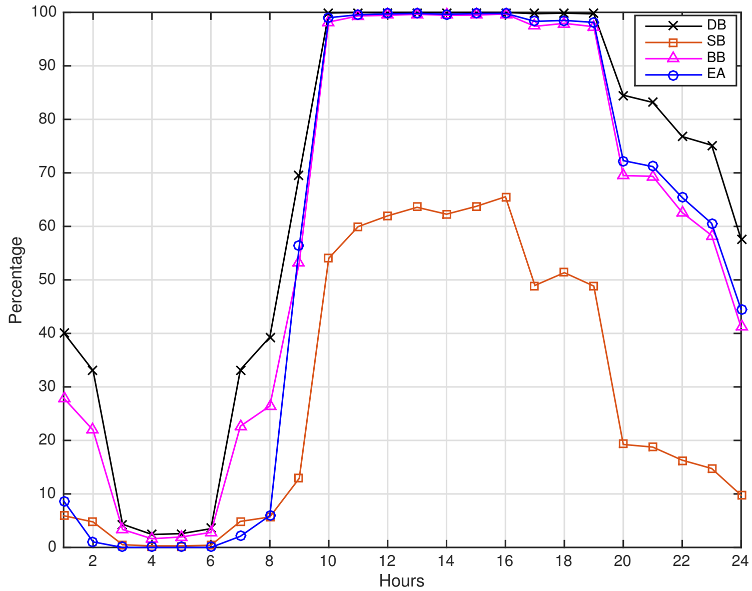

Figure 5.10: LPN energy consumption in percentage of full operation after Resource-based energy optimization

Considering customer satisfaction, in this section we measure the customer satisfaction according to the user demand service levels. Figure 5.11 shows that RE commits to maintaining the customer satisfaction rate at all time regardless of cell selection scheme. When we view the results during quiet hours, we observe that the system with EA can satisfy users demand by running only HPNs. In contrast, the scenario where BB is used, a certain number of users do not receive their expected service. The reason is that the users connect to LPNs due to BB. The LPNs users suffer from interference from nearby “unnecessarily” active LPNs. Also, because EA congests users into HPNs when possible, the HPN users suffer from the limited available resource. We can see the impact of the limited resource that dissatisfies users by comparing the satisfaction rate when the system utilizes BB and EA during busy hours from 7 to 24. The figure also shows that our optimization succeeds in reducing the energy requirement and maintaining the users satisfaction at a high level when compared to users satisfaction when the system performs SD in Figure 5.5.

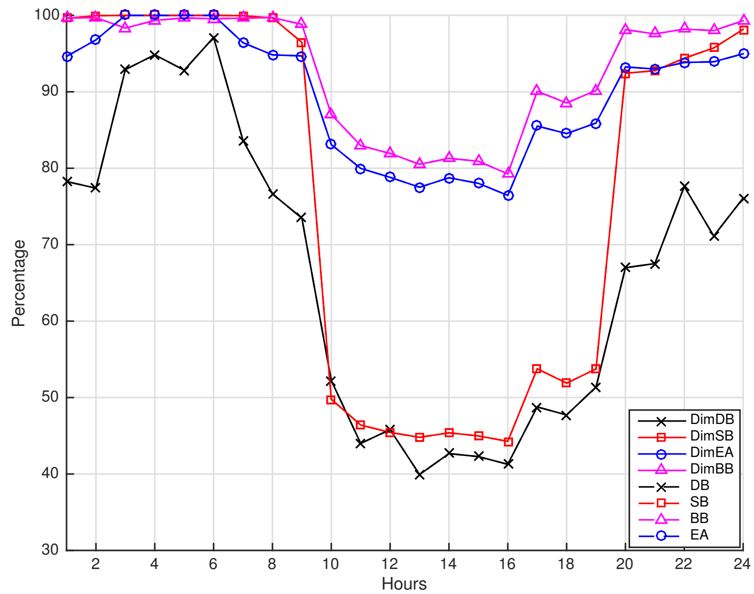

Figure 5.11: Customer satisfaction

Next, we examine the impact of the optimization model on users achievable data rate. Presumably, reducing allocated resource and transmit power decreases users data rate. Both Figure 5.12 and Figure 5.13 show that user achievable data rate is considerably lower during light load periods. The lower data rate is a confirmation of concrete possibility of energy saving. Even though the user data rate decreases, the system can satisfy all the users according to their various service demand levels. Especially, when there are only HPNs operating during the quiet time, the HPNs can optimize their spectrum resource and transmit power while meeting users expectation favorably.

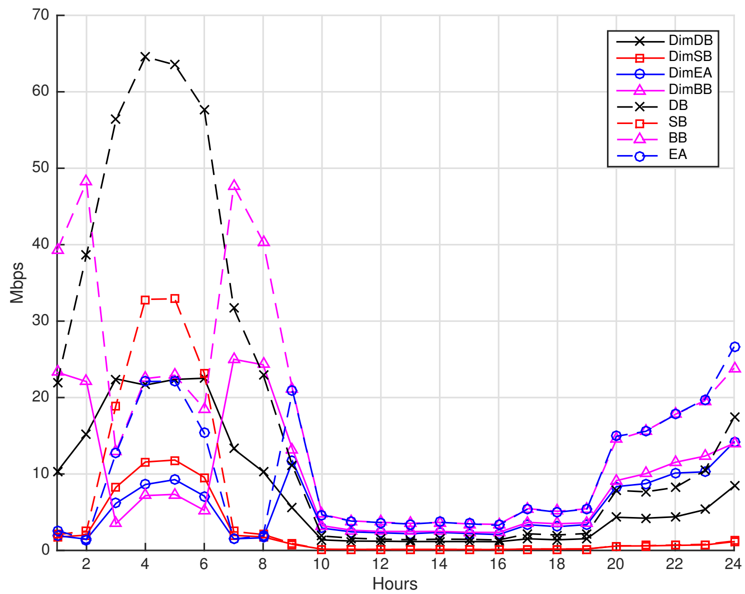

Figure 5.12: HPN users achievable data rate before and after Resource-based energy optimization

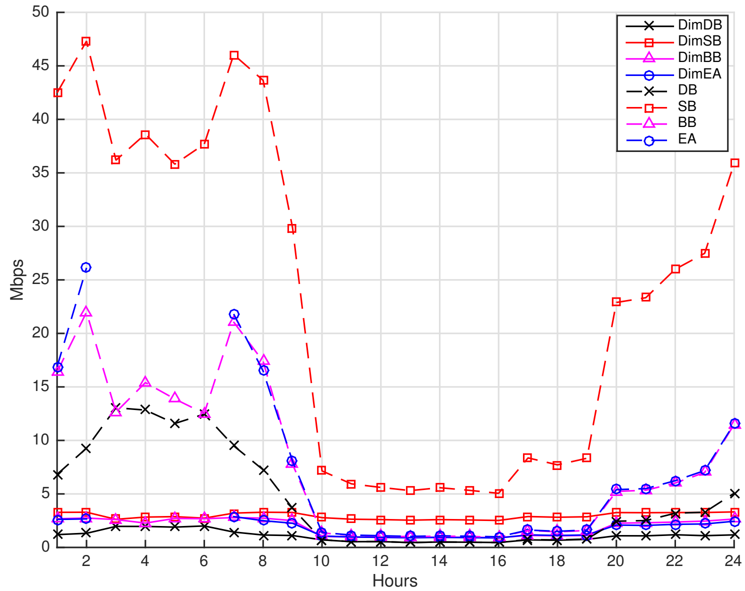

Figure 5.13: LPN users achievable data rate before and after Resource-based energy optimization

Figure 5.14 and Figure 5.15 show ratios of user achievable data rate and energy consumption at HPNs and LPNs, respectively. Note that Figure 5.15 is cropped to present a better view of the graphs. The ratio of DimSB is approximately 14 Mbps/Watts at time 3-6. The results show consistent trends of improved bits per energy consumption similar to ones with SD. Regardless of cell selection techniques, RE optimization can increase the ratio significantly, especially during low load when a typical network wastes an enormous amount of energy.

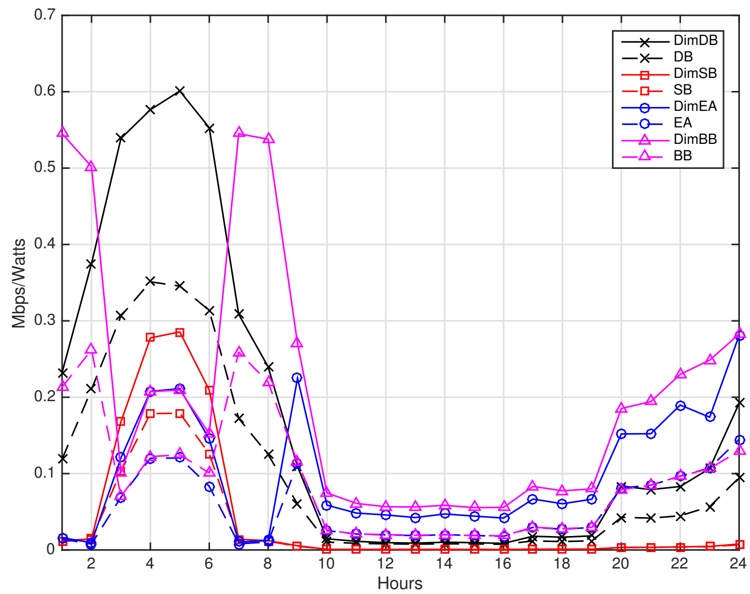

Figure 5.14: HPN user achievable data rate and HPN energy consumption ratio

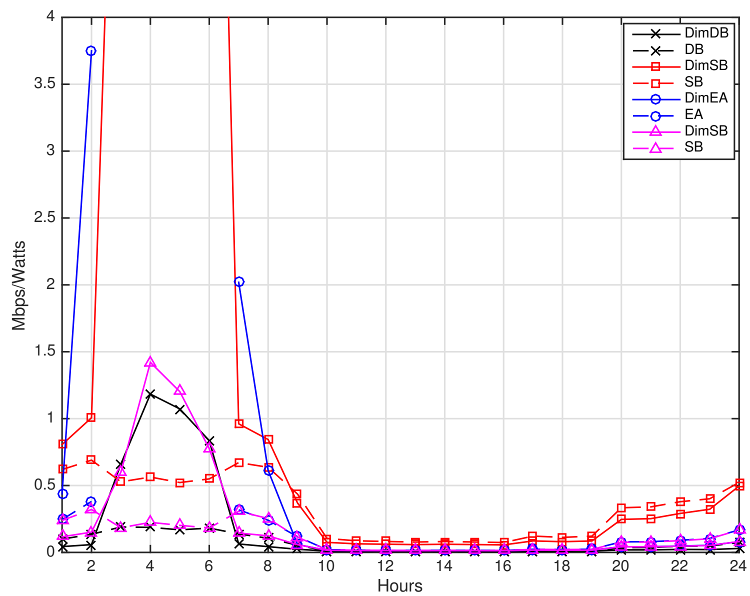

Figure 5.15: LPN user achievable data rate and LPN energy consumption ratio

In this thesis, we propose two cell selection algorithms, Bandwidth-based cell selection and Energy-aware cell selection. The methods intend to create possibilities to reduce energy consumption in the HPNs and, consequently, the network. The bandwidth-based cell selection algorithm can be considered as a greedy heuristic algorithm. The energy-aware cell selection is an advanced algorithm of the bandwidth-based that focuses on quiet hours. Here, we examine the performance of the bandwidth-based algorithm by comparing the results to an optimum from Brute-force search or exhaustive search in a small environment. Brute-force search is to consider all possibilities of UEs cell selections. The scenarios contain, nine users, one HPN and two LPNs, with the bandwidth (B) of 0.5, 1.0 and 1.5 MHz at each eNBs. We conduct 100 iterations to vary users location, service demand level and order of arrival. Figure 5.16 shows the eNBs locations and an example of UEs location. We input the results of the UEs cell selections to the RE energy reduction model to calculate the energy requirement by the selections. In each iteration, we select the result from Brute-force search that demands the lowest energy to compare with the result from our bandwidth-based cell selection. Last, we compare the customer satisfaction rate in the selected cases.

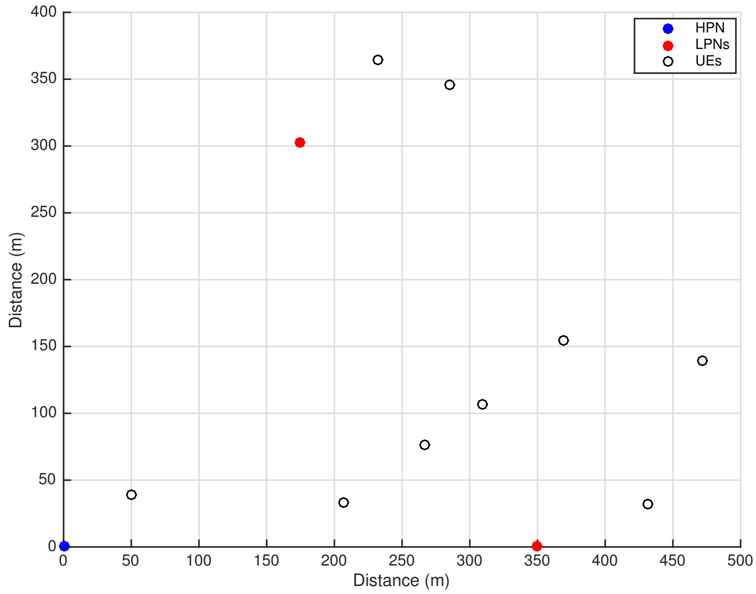

Figure 5.16: eNBs locations and user locations example

Figure 5.17 shows comparisons of energy requirement when the network utilizes BB cell selection and the optimum result of Brute-force search from the same user settings. The figure presents a group of cases that the network needs to operate at almost full capacity when it uses BB and has limited available bandwidth of 0.5 MHz. In spite of the particular cases, BB results in a comparable level of energy consumption to the optimum results from Brute-force search. The average of the energy consumption in each scenarios is shown in Table 5.5.

Even though BB requires relatively higher energy consumption than the optimum from Brute-force search, Figure 5.18 - Figure 5.20 indicate considerably higher customer satisfaction rates by BB in most of the cases. Also, Table 5.6 present the average of customer satisfaction rate from the scenarios. The rate depends greatly on the available bandwidth in the system. When the bandwidth is limited (B = 0.5 MHz), more cases result in low customer satisfaction. The satisfaction rate is as low as approximately 55% with BB. In the same setting, even though brute-force search yields lower energy requirement, the algorithm

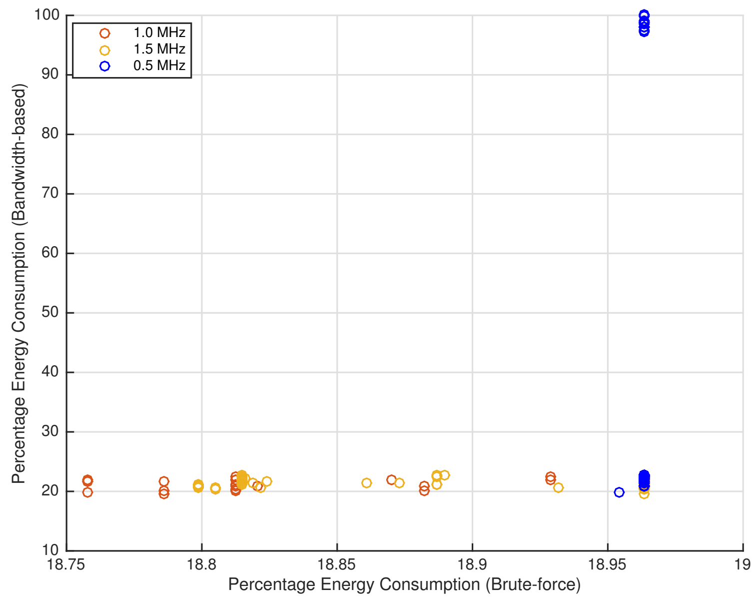

Figure 5.17: Percentage of energy consumption; Bandwidth-based vs. Brute-force

cannot satisfy any user in the network. When there is more available bandwidth, the network can satisfy more users. BB can satisfy all users in several cases when B is 1.5 MHz promoting the average customer satisfaction rate of 98.11%. On the other hand, in the low energy-consuming cases by brute-force search, the system could satisfy as low as 21% of the users and 61.56% on average. However, brute-force search can also yield 100% customer satisfaction rate when there is more available bandwidth with low energy consumption. The scenarios represent the disadvantage of BB which we address by proposing energy-aware cell selection to produce further energy reduction possibility during quiet hours.

Table 5.5: Average percentage of energy consumption with Bandwidth-based cell selection in comparison with Brute-force search

	B = 0.5 MHz	B = 1.0 MHz	B = 1.5 MHz
Bandwidth-based	31.47%	21.85%	21.68%
Brute-force	18.96%	18.93%	18.93%

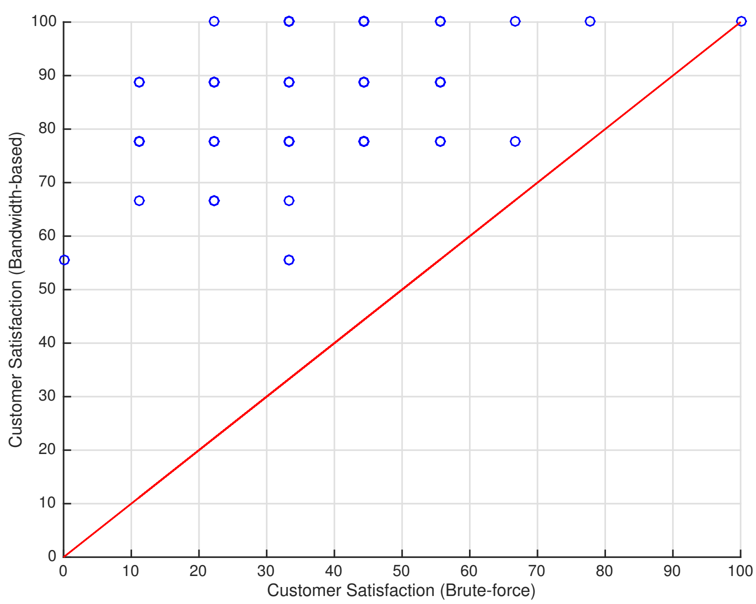

Figure 5.18: Customer satisfaction; Bandwidth-based vs. Brute-force (0.5 MHz bandwidth)

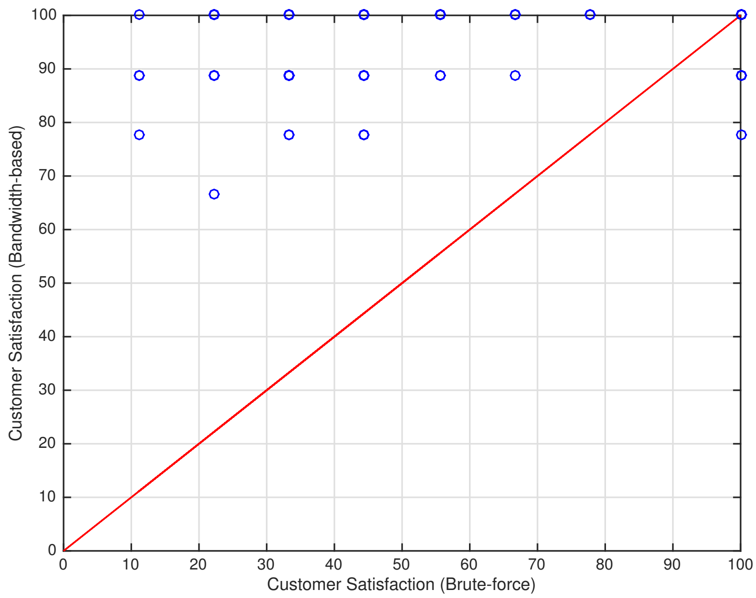

Figure 5.19: Customer satisfaction; Bandwidth-based vs. Brute-force (1.0 MHz bandwidth)

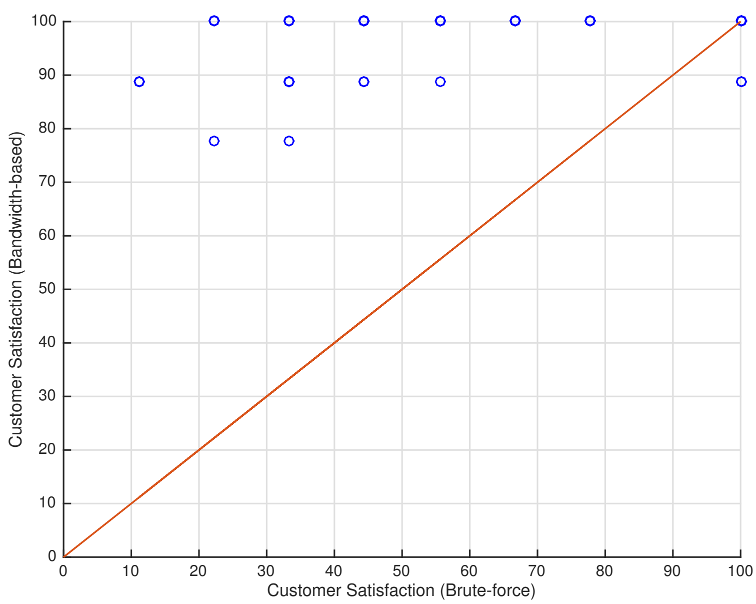

Figure 5.20: Customer satisfaction; Bandwidth-based vs. Brute-force (1.5 MHz bandwidth)

Table 5.6: Average customer satisfaction with Bandwidth-based cell selection in comparison with Brute-force search

	$B = 0.5$ MHz	$B = 1.0$ MHz	$B = 1.5$ MHz
Bandwidth-based	85.78%	95.11%	98.11%
Brute-force	37.33%	53.33%	61.56%

6.0 ENERGY OPTIMIZATION IN MINIMUM CAPEX NETWORK

In this chapter, we expand our energy optimization goal into network planning. The goal of our network planning is to plan a network with minimum CAPEX in a city-like area. The area contains various types of service area, namely, residential, highway, entertainment, business and unoccupied. Each kind of service area possesses unique traffic demand characteristic. Then we examine our energy optimization and cell selection in the network to analyze the power reduction and the customer satisfaction in the different kinds of service area and the potential for network improvement.

In Section 6.1, we discuss a network planning optimization model. Next, we present our simulations in Section 6.2. In section 6.2.1, we explain the characteristic of our simulation environment including determination of the service areas and the various traffic demand. Simulation process and results of coverage-driven and service-driven network planning are explained in Section 6.2.2. Last, we examine the proposed energy consumption optimization model in the sample city-like area in Section 6.2.3.

6.1 NETWORK PLANNING OPTIMIZATION

In this section, we present our optimization model to plan a city-wide network with minimum CAPEX. Consider an area of A km^2, we define a set of test points tp when $tp \in [1, N^{TP}]$. Test points exist to guarantee network coverage while do not present any traffic demand. We also determine a set of potential HPN sites ps when $ps \in [1, N^{PS}]$ and a number of high-demand spots hp when $hp \in [1, N^{HP}]$. The potential HPN sites limit possible locations to deploy an HPN. The limitation resembles reality where several factors such as geographic terrain, accessible infrastructure, surrounding obstacles, site acquisition difficulties could restrict the freedom of deploying an HPN. We let ψ^{ps} equal to one when there is an HPN deployed at potential site ps. A high-demand spot represents a small area where users gather creating a cluster of users. Unlike HPNs, we determine that LPNs have no limitation in terms of location of installation. We assume we can install an LPN at a test point location. Θ^{tp} equals to one when there is an LPN installed at test point tp. Moreover, because we determine that HPNs need to provide full coverage of the area regardless of LPNs being active [112], each test point must be covered by at least one HPN. We let $\tau^{tp,ps}$ equal to one when test point tp is covered by HPN from potential HPN sites ps and zero otherwise. Also, we determine that a high-demand spot hp must be covered by at least an LPN. We let $\lambda^{hp,tp}$ be one when a high-demand spot hp is covered by an LPN from test point tp and zero otherwise. Furthermore, to concern about the relation between the location of LPNs and high-demand spots [65,66], we include consideration of the distance between high-demand spots and LPNs location into the objective. Also, we determine the cost of deploying a network contain cost of the eNB that includes base station equipment, radio equipment, site installation and buildout, Φ^{HPN} for an HPN and Φ^{LPN} for an LPN, the cost of backhaul between HPNs and LPNs, α, [113] and the cost of LPNs being away from high-demand spots, β. To plan a network with minimum CAPEX, we present an optimization model as follows.

$$\begin{aligned}\min \quad & \sum_{ps=1}^{N^{PS}} \Phi^{HPN}\psi^{ps} + \sum_{tp=1}^{N^{TP}} \Phi^{LPN}\Theta^{tp} + \\ & \sum_{ps=1}^{N^{PS}}\sum_{tp=1}^{N^{TP}} \alpha dist^{ps,tp}\psi^{ps}\Theta^{tp} + \sum_{hp=1}^{N^{HP}}\sum_{tp=1}^{N^{TP}} \beta dist^{hp,tp}\lambda^{hp,tp}\Theta^{tp} \end{aligned} \tag{6.1a}$$

s.t.

$$\sum_{tb=1}^{N^{TP}} \tau^{tp,ps}\psi^{ps} \geq 1 \qquad \forall ps \tag{6.1b}$$

$$\sum_{hp=1}^{N^{HP}} \lambda^{hp,tp}\Theta^{tp} \geq 1 \qquad \forall tp \tag{6.1c}$$

$$dist^{tp,ps}\tau^{tp,ps}\psi^{ps} \leq R^{HPN} \qquad \forall tp,\ \forall ps \tag{6.1d}$$

$$dist^{hp,tp}\lambda^{hp,tp}\Theta^{tp} \leq R^{LPN} \qquad \forall hp,\ \forall tp \tag{6.1e}$$

$$\psi^{ps} \in \{0,1\} \qquad \forall ps \tag{6.1f}$$

$$\Theta^{tp} \in \{0,1\} \qquad \forall tp \tag{6.1g}$$

$$\tau^{tp,ps} \in \{0,1\} \qquad \forall tp,\ \forall ps \tag{6.1h}$$

$$\lambda^{hp,tp} \in \{0,1\} \qquad \forall hp,\ \forall tp \tag{6.1i}$$

The objective (Eq. 6.1a) comprises of two parts. The former two terms are to minimize the cost of eNBs installation by minimizing the number of eNBs deployed. The latter two terms are to optimize the location of LPNs. The total cost of installing backhaul connecting the LPNs and the HPNs, α, depends on the distance between the LPNs and their connecting HPN $dist^{tp,ps}$ is the distance between potential HPN site ps to test point tp. Locating an LPN also needs to consider the distance between the LPN at test point tp and their responsible high-demand spot hp, $dist^{hp,tp}$, to provide satisfying service to clusters of users. β is a factor penalizing when the LPNs are away from high-demand spots. Because HPNs handle providing full coverage at all time, constraint at Eq. 6.1b ensures that all test point have at least one HPN covering. Eq. 6.1c guarantees that LPNs cover all the high-demand spots. Eq. 6.1d and Eq. 6.1e impose that test point tp and high-demand spots hp need to be within the service radius of the respective HPN and LPN. Eq. 6.1f - 6.1i set the binary nature of the decision variables.

Considering our purpose of planning a network in a city-wide area, the number of decision variables is tremendous. The size of the problem causes the problem to become an NP-hard problem. We choose to break the problem into two parts, coverage-driven network planning, and service-driven network planning. The first part contains the consideration of providing full coverage to the area. Meanwhile, the second part concerns the addition of demand in high-demand spots. The addition of service demand in high-demand spots represents increase of demand in particular spots that require supplementary network resource to provide satisfying service to added users. The coverage-driven optimization problem becomes as follows.

$$\min \sum_{ps=1}^{N^{PS}} \Phi^{HPN} \psi^{ps} \tag{6.2a}$$

s.t.

$$\sum_{tb=1}^{N^{TP}} \tau^{tp,ps} \psi^{ps} \geq 1 \qquad \forall ps \tag{6.2b}$$

$$dist^{tp,ps} \tau^{tp,ps} \psi^{ps} \leq R^{HPN} \qquad \forall tp, \ \forall ps \tag{6.2c}$$

$$\psi^{ps} \in \{0,1\} \qquad \forall ps \tag{6.2d}$$

$$\tau^{tp,ps} \in \{0,1\} \qquad \forall tp, \ \forall ps \tag{6.2e}$$

And, the service-driven optimization problem becomes the following.

$$\begin{aligned} \min \ & \sum_{tp=1}^{N^{TP}} \Phi^{LPN} \Theta^{tp} + \sum_{ps=1}^{N^{PS}} \sum_{tp=1}^{N^{TP}} \alpha dist^{ps,tp} \psi^{ps} \Theta^{tp} + \\ & \sum_{hp=1}^{N^{HP}} \sum_{tp=1}^{N^{TP}} \beta dist^{hp,tp} \lambda^{hp,tp} \Theta^{tp} \end{aligned} \tag{6.3a}$$

s.t.

$$\sum_{hp=1}^{N^{HP}} \lambda^{hp,tp} \Theta^{tp} \geq 1 \qquad \forall tp \tag{6.3b}$$

$$dist^{hp,tp} \lambda^{hp,tp} \Theta^{tp} \leq R^{LPN} \qquad \forall hp, \ \forall tp \tag{6.3c}$$

$$\Theta^{tp} \in \{0,1\} \qquad \forall tp \tag{6.3d}$$

$$\lambda^{hp,tp} \in \{0,1\} \qquad \forall hp, \ \forall tp \tag{6.3e}$$

6.2 SIMULATIONS

In this section, we discuss our simulations of the network planning. Firstly, we define our simulations environment and demand characteristics. Secondly, we present results of coverage-driven network planning and service-driven network planning. Lastly, we examine the energy optimization in the result network. We divide the simulations into three parts. 1) We define an area to depict a middle-sized urban city. The city requires a full coverage of cellular network and contains "general" users. Deterministically located test points ensure that the network can provide a full coverage to the area. Also, we divide the city into five types of service area. Each type of service area possesses various characteristics of traffic demand that varies by time. Consider the uniqueness of the traffic demand in each area of the city, we determine high-demand spots that symbolize coverage holes left by HPNs or generate additional traffic or "high-demand spots" users at locations. The extra traffic distinguishes the overall traffic demand between service areas. 2) We present the HPNs location that provides full coverage of the city that result from the coverage-driven network planning model. Also, we show the result of service-driven network planning model which is LPNs location. 3) We experiment energy-aware cell selection and resource-based energy optimization model in the simulated city. The results of the energy optimization are compared to those of a typical cellular network operation proposed in literatures (SINR-based cell selection and on/off LPNs). The comparisons lead to the possible benefit of our energy optimization to network expansion. In the next section (6.2.1), we explain features of the target area and its traffic demand in different types of the service area. Then, in Section 6.2.2, we present the full coverage network result from the model presented in the last section and the result of LPNs deployment to serve the extra demand. Last, in Section 6.2.3, we examine the proposed energy optimization in the simulated environment and analyze the result.

6.2.1 Service Area and Traffic Demand Definition

To simulate an area of a mid-sized urban city, we define an area of 36 km^2 or 6 $\times$ 6 km. In the city, we define five different types of service area, namely, unoccupied, residential,

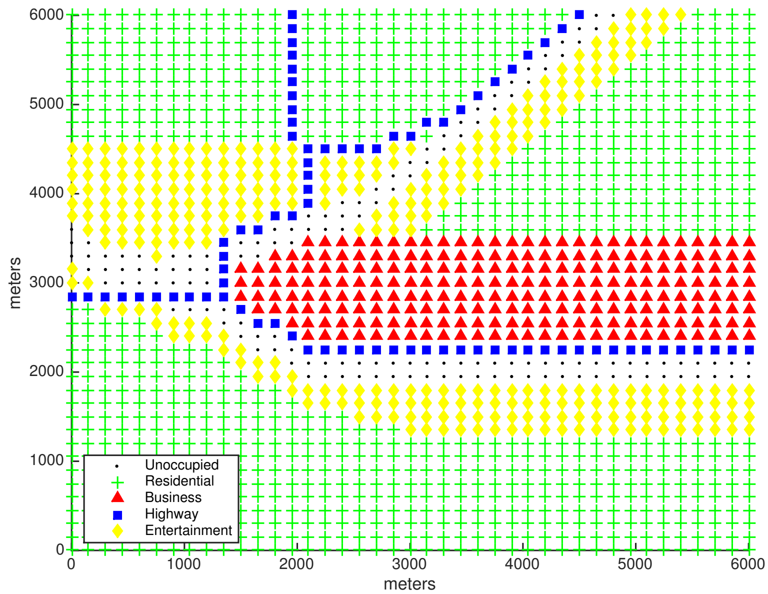

Figure 6.1: Test points in five types of service area

highway, entertainment and business. Also, to ensure the full coverage of the network, 1,681 test points ($N^{TP} = 1681$) are deterministically distributed throughout the area with 150 m of distance apart. Figure 6.1 presents the area of each type. Black '·', green '+', red '△', blue '□' and yellow '⋄', represent test points in unoccupied, residential, business, highway, entertainment area respectively. We determine that there be three possible sites for installing an HPN for every square kilometer. Thus, there is the total of 108 uniformly distributed possible sites ($N_P = 108$) in the city. The uniform distribution of the possible locations of HPNs is done by randomization of locations on two axes separately. Figure 6.2 shows the area of interest with test points colored by their respective areas and an example of a set of possible HPN locations (blue circle).

Because actual cellular network traffic is difficult to obtain, we define that there is a maximum of 200 general users per km^2 and each high-demand spot generates additional 10% of the concurrent general users. Each type of service area thus contains various numbers of high-demand spots to differentiate the unique user congestion in the areas. We adopt ratios

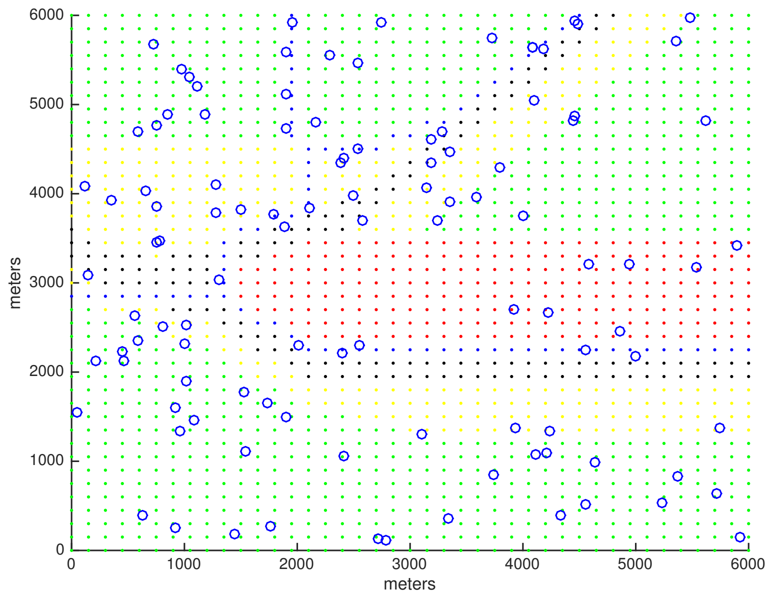

Figure 6.2: Location possible HPN sites

of user density from [36]. The ratios of user density per km^2 ranked from the busiest area to the least occupied area are 4.5 : 2 : 1.5 : 1. In this work, we determine that the business area has the most users density. Also, we assume that the residential area has the least demand due to the high availability of wireless internet access in residence. Therefore, to distinguish the traffic demand in the types of service area, we define the number of high-demand spots in each service area according to the ratio and size of each type of service area. Table 6.1 shows the detail information of the service areas. Next, to moderate the size of the optimization problem, we use the test points as possible sites of high-demand spots and LPNs location. An LPN is considered more manageable to deploy and not require a dedicated space. All test points in the area then get randomly selected to be high-demand spots according to the area-specific numbers showed in the table. Figure 6.3 shows an example of selected test points for high-demand spots in service areas. Furthermore, we normalize and proportionate average demand in [28] for a percentage of maximum traffic in service areas. The average of traffic demand in the percentage of the maximum for every service area is presented in

Figure 6.4. The average traffic demand gives input to the simulation of the number of users in every hour. The generation of the number of users and their locations remains the same as in the previous chapters. Figure 6.5 - 6.8 show an example of users location at the hour of 4, 9, 13 and 21.

Table 6.1: Information of service areas

	Business	En*	Highway	Residential	Un**
Number of test points	234	305	80	923	139
Ratio of extra users	4.5	2	1.5	1	0
Number of high-demand spots per km^2	9	4	3	2	N/A
Size of area (km^2)	5.27	6.86	1.80	20.77	1.30
Total number of high-demand spots	47	27	5	41	N/A

*Entertainment
**Unoccupied

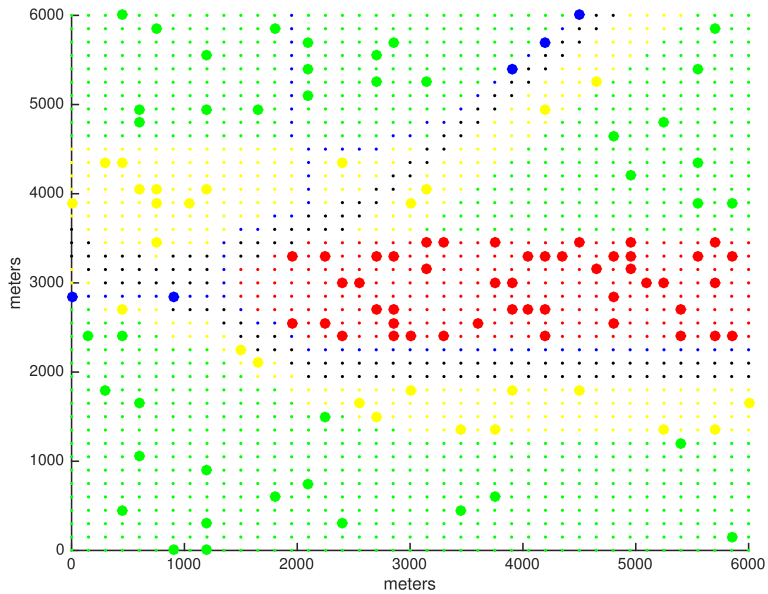

Figure 6.3: Locations of high-demand spots in service areas

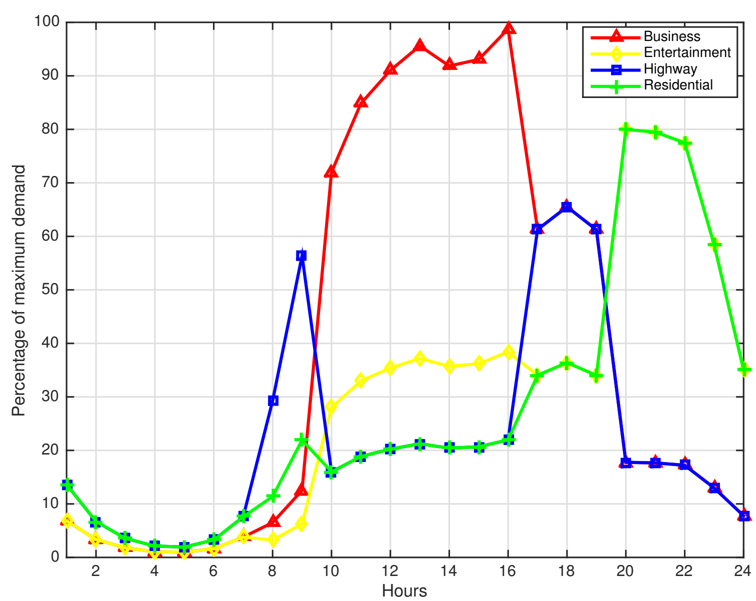

Figure 6.4: Average traffic demand in percentage of maximum by areas

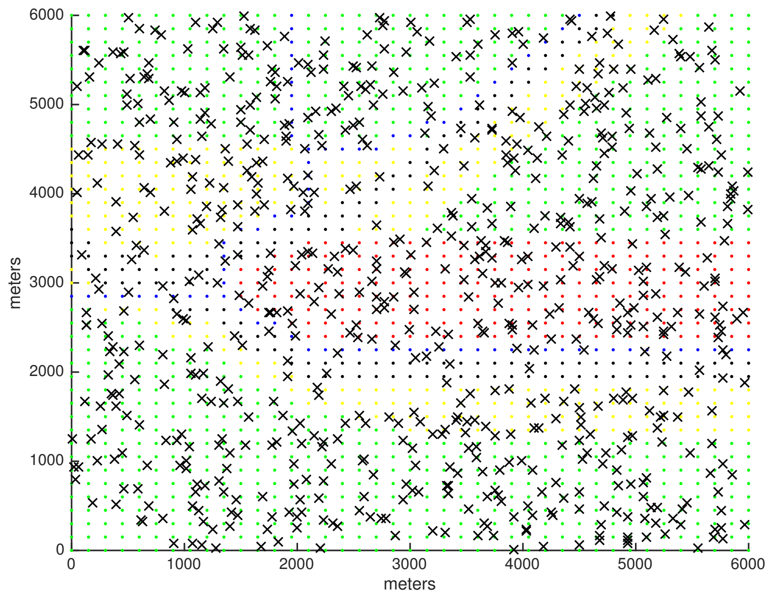

Figure 6.5: Example of users location at the hour of 4

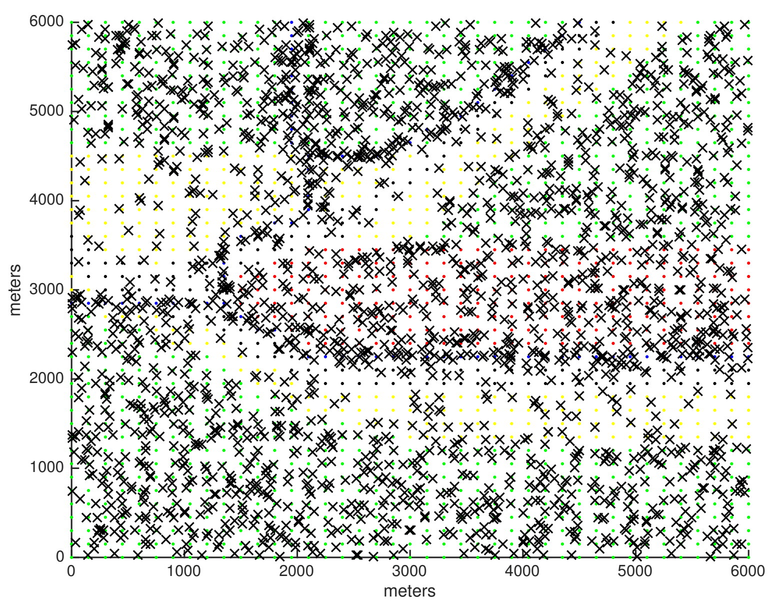

Figure 6.6: Example of users location at the hour of 9

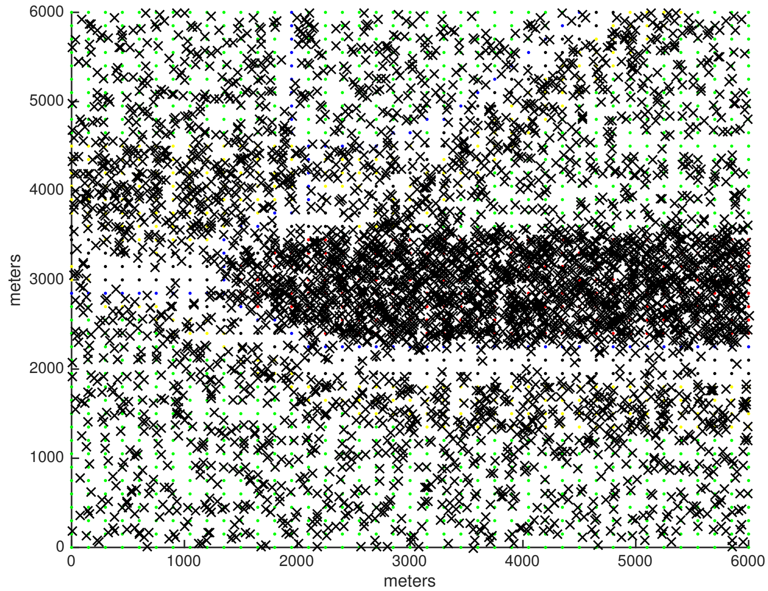

Figure 6.7: Example of users location at the hour of 13

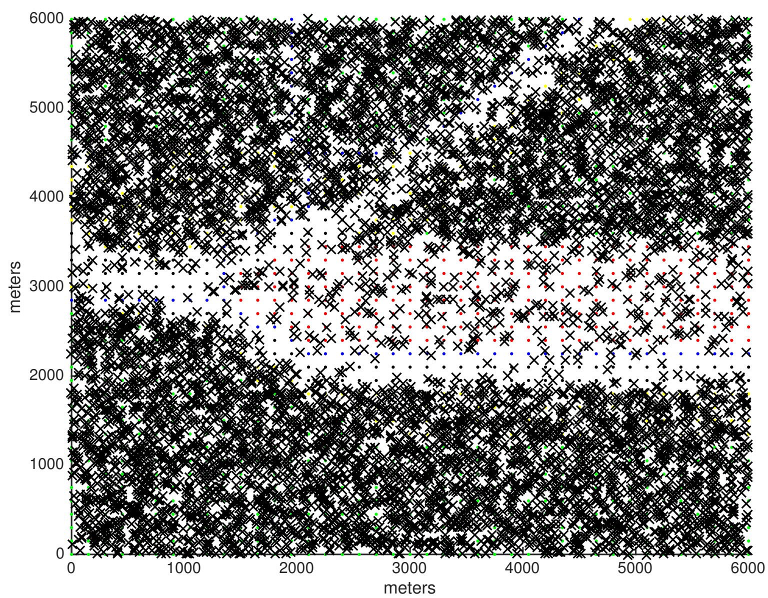

Figure 6.8: Example of users location at the hour of 21

6.2.2 Simulation Results

To create alteration, we generate ten different sets of possible HPN sites. We determine that each HPN can cover up to 1,200 meters in radius ($R_{HPN} = 1200$ m) [36, 71]. As a result of coverage-driven network planning model 6.2, from out of the ten generated sets of possible locations, nine sets yield a feasible result. In the only case that does not have a feasible result, we cannot find a possible set of HPNs that meets the constraint of HPN radius (Eq. 6.2b. Out of the nine results, we select three sets of HPNs location that require the lowest number of HPNs ($N^{HPN} = 21$) to be installed. Figure 6.9 shows one of the three results of HPNs location. The example of HPNs location in the figure shows the most possibility of being realistic when we consider types of the service area. There are two main reasons for selecting this scenario. First, there is neither possible HPN location nor selected HPN location in the unoccupied zone. Second, there are few potential locations and selected locations in the business downtown area which we consider more difficult to deploy an HPN than outside of the area. Solid circles show selected HPNs location, blank circles show possible HPN locations and dots are the location of test points. This result is comparable to the result of a similar scenario that requires full coverage in [71] in terms of the number of HPNs per area.

After we locate the HPNs, we proceed to the service-driven network planning according to model 6.3. We define the coverage of LPNs be 150 m ($R_{LPN} = 150$ m). Also, according to [65, 66], the network could provide better service and save more energy consumption when the LPNs are close to the high-demand spots. Therefore, we set $\alpha = 1$ and $\beta = 10$ to favor the LPNs being close to their high-demand spots and correspond to a scenario in [71] which produces the minimum OPEX and CAPEX. Service-driven planning model 6.3 gives a result of 120 LPNs ($N^{LPN} = 120$). Figure 6.10 presents location of LPNs with a backhaul link to their associated HPN. Moreover, based on the distribution of eNBs, when LPNs attach to an HPN creating a cluster of eNBs, the network can operate with higher energy efficiency [66]. The main HPN and the member LPNs exchange their information collected by a minute supplement protocol in eNBs [6]. We continue to consider these eNB member groups in our experiment on energy reduction in the next section. When we operate EA cell selection, the members only start their operation only when notified by the main HPN.

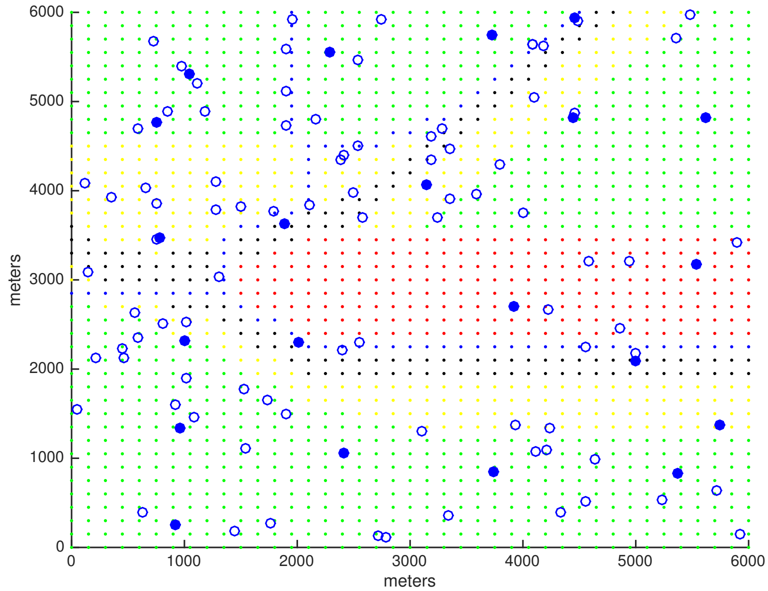

Figure 6.9: Locations of possible HPN sites and selected HPN locations

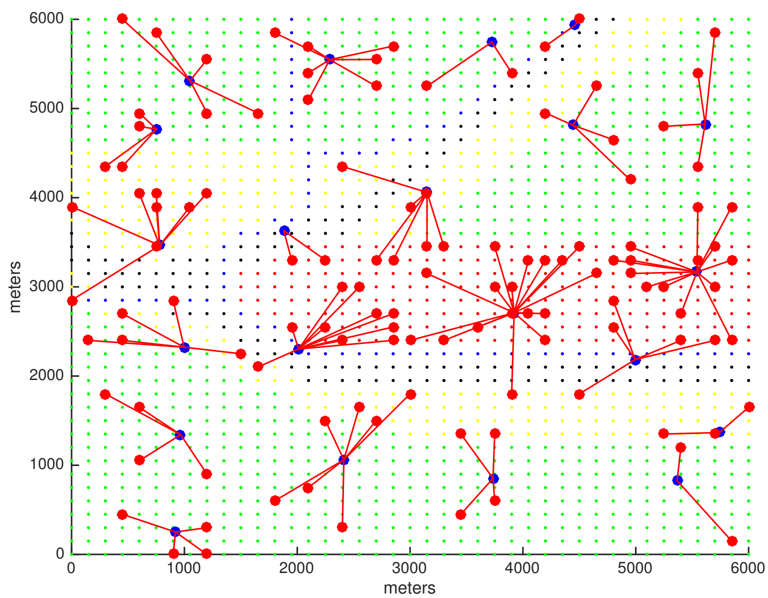

Figure 6.10: Locations of LPNs and their connection to HPNs

Considering the cost of deploying the network, we adopt a CAPEX model for HPNs and LPNs in Table 6.2 which is taken from [113]. The model normalizes all the costs in terms of HPN equipment. We determine 1 euro equal to 1.4 dollars making HPN equipments (c_{eq}) cost $28,000. As a result, deploying the network that contains 21 HPNs and 120 LPNs in the city costs $6.8 M.

Table 6.2: CAPEX information for eNBs

CAPEX	c_{EQ}	c_{RN}	c_{BT}	c_{Site}
HPN	c_{eq}	$0.25c_{eq}$	$0.25c_{eq}$	$1.5c_{eq}$
LPN	$0.5c_{eq}$	$0.25c_{eq}$	$0.25c_{eq}$	$0.5c_{eq}$

c_{EQ}: eNB equipment
c_{RN}: Radio equipment
c_{BT}: Backhaul transmission equipment
c_{Site}: Site installation and buildout

6.2.3 Energy Optimization

The experiment proceeds to examine our energy optimization models on the result city network. Table 6.3 summarizes simulation parameters used in the optimization. We conduct the simulation for 50 iterations. Traffic characteristics comply with what explained in Section 6.2.1. The locations of all eNBs are shown in Figure 6.10. The network utilizes *Energy-aware* cell selection and *Resource-based* energy optimization. Our analysis starts with a comparison of the network energy requirement when the same network utilizes the proposed mechanisms and standard techniques. Because the number of iterations is relatively low, we perform the simulations of every scenario with the same set of user data to provide a fair comparison. The user data includes the number of users, the users location, and the users service demand. After analyzing the total energy savings of the network, we investigate the energy consumption for each type of service area individually. Then, we show the impact of the optimization toward the network performance. Note that because currently there is yet a standard interference management in HetNet, we experiment the worst case scenarios with no interference mitigation in this study. The interference that a user experiences is the summation of received signals from all other tier-sharing eNBs at their maximum transmit power. Last, we review the advantage of our models over the typical mechanism and the potential network improvement.

Table 6.4 presents the results of energy optimization in the network in three scenarios. The scenarios differ in terms of cell selection techniques and energy optimization models. In the first case, the network performs the proposed energy-aware cell selection and resource-based energy optimization (EA&RE). In the second scheme (SINR&RE), we examine the effect of resource-based energy optimization on the network that operates SINR-based cell selection. Last, we simulate the network with SINR-based cell selection and reduce the energy requirement by merely turning off eNBs that do not have any user demand (SINR). According to the table, the network performing RE together with EA cell selection can successfully reduce the energy requirement the most. The total energy consumption decreases to 73.56% of full operation consumption. RE only can also reduce the energy consumption of the network even though the system performs SB cell selection. The reduction confirms the effectiveness of the energy optimization model beyond EA cell selection. Meanwhile, the network demands the most energy when it performs only turning off eNBs. The main benefits of EA and RE are twofold. First, EA pushes more users to LPNs than SINR-based cell selections creating less energy requirement at HPNs. We can observe from the difference of energy level at HPNs and LPNs in the case of EA&RE which are 71.89% and 89.49%, respectively, compared to SINR&RE 94.06% and 56.47%. Also, EA&RE case is the only case that LPNs consume more energy in terms of percentage of full operation than HPNs. However, because HPNs consume a greater amount of energy than LPNs, the saving at HPNs influences further to the total energy consumption. The second benefit of EA and RE is RE energy optimization not only switches off eNBs but also optimizes eNBs spectrum resources and their transmit power to match the user demand. The result is there is no wasted energy in providing service to the customers. The result is evident when comparing the energy requirement in the cases of SINR&RE and SINR. In SINR, the HPNs need to operate fully(100%) while RE reduces the HPNs energy consumption to 94.06%. The saving is even larger at LPNs. LPNs consume only 56.47% of energy with RE while they consume

Table 6.3: Simulation parameters

Parameter	**Configuration**
Max. transmission power, $MaxTx$	46 dBm (HPN) [107, 108], 30 dBm (LPN) [106, 107]
Carrier frequency, f	800 MHz (HPN), 2.1 GHz (LPN)
SE energy factor, SE	27% of $MaxTx$ [73]
AC energy factor, AC	27% of $MaxTx$ [73]
Bandwidth, B	10 MHz [107, 108]
Pathloss model, L_p	L_p(HPN)= $69.55 + 26.16log(f) - 13.82 * log(hb)$
	$-a(hm) + (44.9 - 6.55log(hb))log(d)$;
	$a = 3.2(log(11.75hm))^2 - 4.97$ [103]
	L_p(LPN)= $140.7 + 36.7log_{10}(d)$ [104]
Achievable data rate, C	$C = 0.75Blog_2(1 + SINR/1.25)$ [84]
Interference, I	$\sum RSS_{eNB}$; When eNBs transmit at Maximum Tx
Noise, N	-92 dBm
Time periods, T	24 hours

Table 6.4: Energy consumption in percentage of full operation

Scenario	EA&RE	SINR&RE	SINR
Total	73.56%	90.08%	98.78%
HPNs	71.89%	94.06%	100%
LPNs	89.49%	56.47%	88.47%

EA&RE: Energy-aware cell selection and Resource-based energy reduction, SINR&RE: SINR-based cell selection and Resource-based energy reduction, SINR: SINR-based cell selection and turning on/off eNBs

88.47% when they do not optimize their resources.

Consider power consumption in each hour, Figure 6.11 shows the energy requirement in the percentage of full operation in the EA&RE case. Black ▽ indicates the total network energy consumption while blue ◃ and red ▹ indicate HPNs and LPNs power consumption. The figure shows the network consumes the most energy between 20 to 21 hour. Moreover, it is apparent that HPNs energy consumption is more influential to the network energy consumption than LPNs. Furthermore, when we consider the period of 12 to 18, we observe that almost all LPNs require operating at full capacity while HPNs can still save a certain amount of power. The saving is because, during the busiest time of the day, there are some areas that contain light user congestion. In the areas, the HPNs do not require to transmit at their maximum transmit power to satisfy few users. However, the figure cannot clearly portray the effect of our model on the network that contains the spatial variation of traffic characteristics. Therefore, we select certain eNB groups in various service areas to investigate the impact of traffic diversity on the energy requirement. The selected eNBs group to represent each service area are shown by eNBs with active connections (red lines) in Figure 6.12 to 6.15.

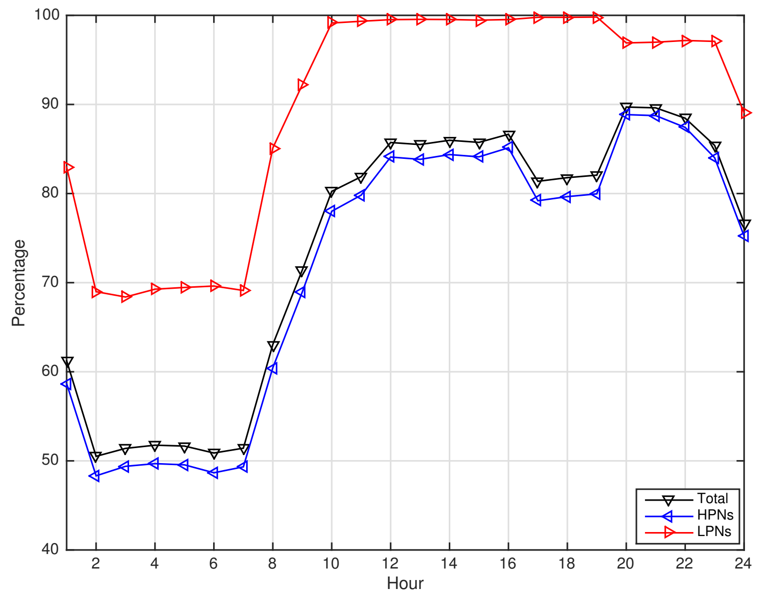

Figure 6.11: Total energy consumption in percentage of full operation

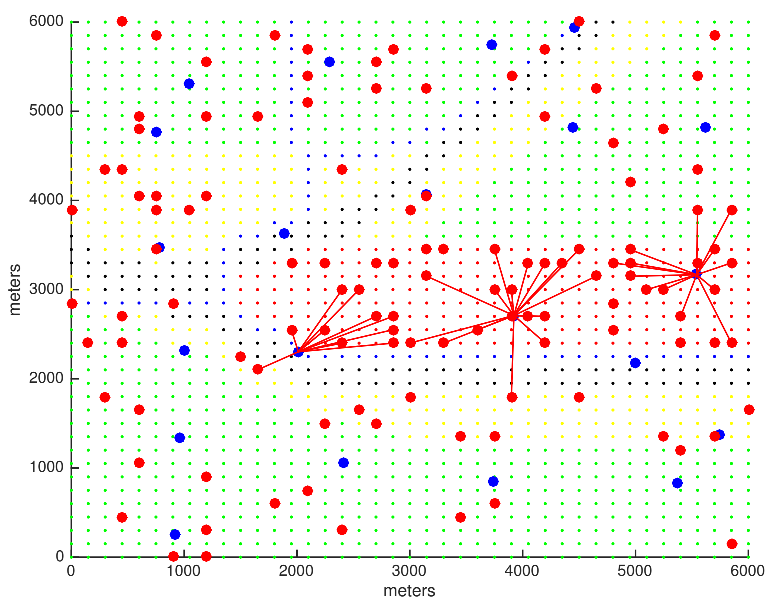

Figure 6.12: Selected eNBs for business area

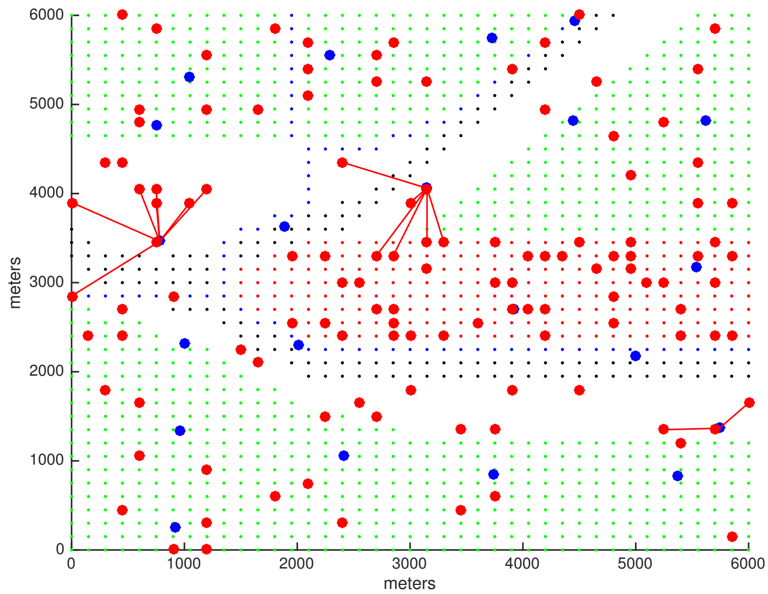

Figure 6.13: Selected eNBs for entertainment area

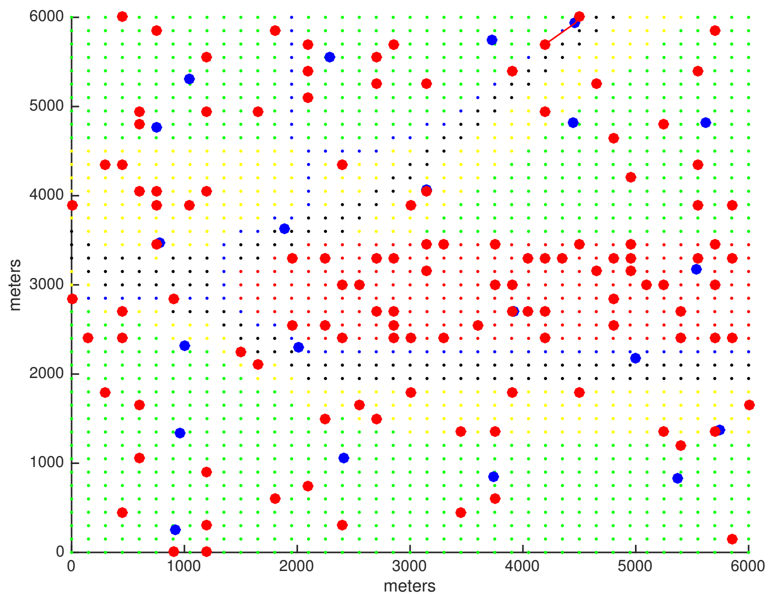

Figure 6.14: Selected eNBs for highway area

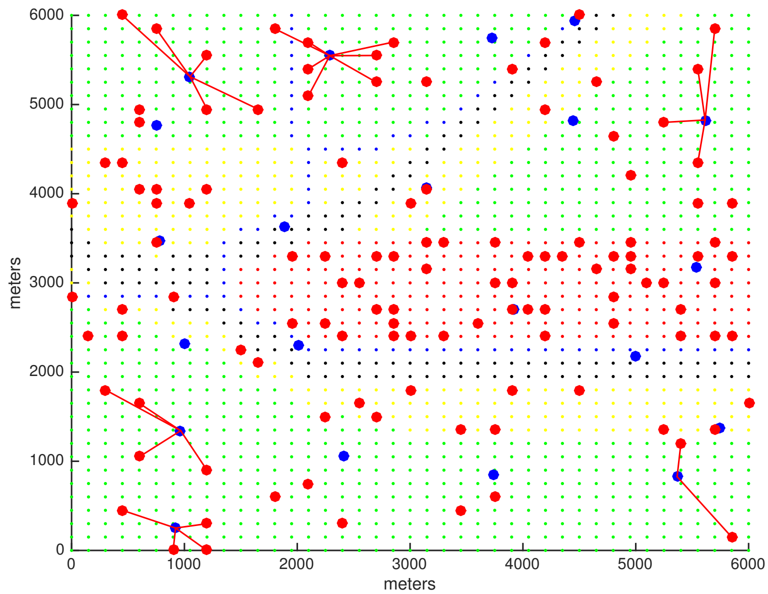

Figure 6.15: Selected eNBs for residential area

The results of energy requirement in business, entertainment, highway and residential areas are presented in Figure 6.16 to Figure 6.19, respectively. As shown in Figure 6.16, LPNs require operating at a higher capacity than HPNs. Because the business area contains a high number of clustered high-demand spots and LPNs, LPNs can cover a wide area and provide sufficient service to users. HPNs consequently receive opportunities to reduce their energy consumption especially during the night which contributes to a large power saving.

Figure 6.17 shows the result of energy optimization in entertainment area. The advantage of EA is evident in this area. Between the hour of 2-8, the service demand in this area is considerably low. Mostly, the very low traffic demand requires only HPNs to provide the service. Therefore, we can see that LPNs, on average, require significantly low power. The energy consumption in entertainment eNB groups does not exactly follow the traffic demand trend in the area. The alternation exists because one of the selected eNB groups contains many LPNs located in the business area, but the LPNs connect to an HPN in the entertainment area. The traffic in the business area that has a substantially higher level of demand alters the result.

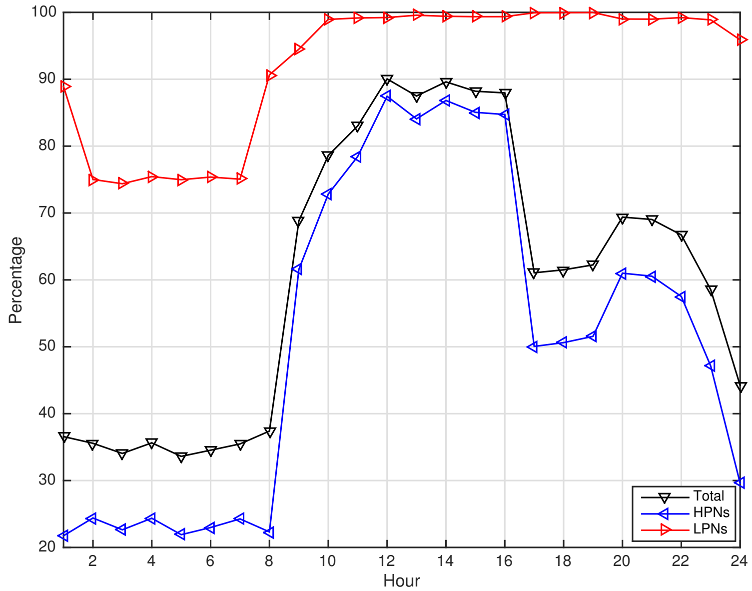

Figure 6.16: Energy consumption in percentage of full operation in business area

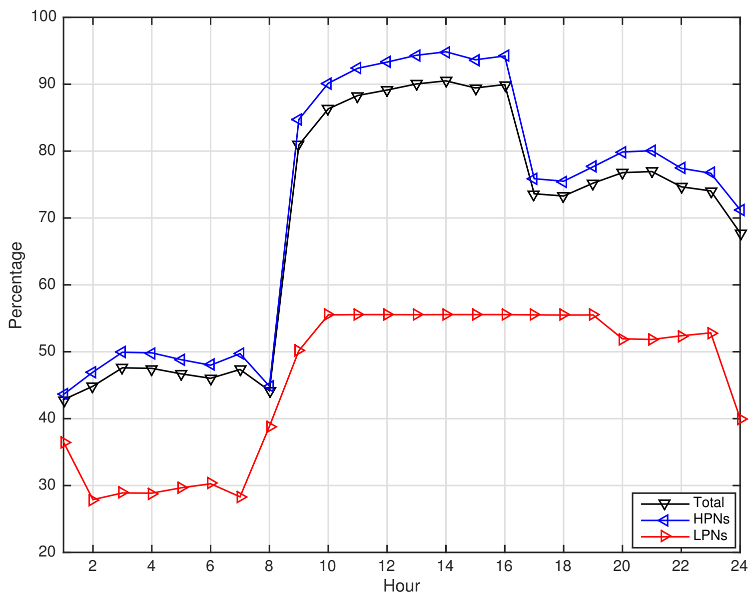

Figure 6.17: Energy consumption in percentage of full operation in entertainment area

Next, we present the result of energy optimization in highway area in Figure 6.18. Because the nature of the narrow area and the location of the group members, the result is affected considerably by nearby service area traffic demand. The neighboring service areas that are entertainment and residential area perceive extremely high traffic at night. At the hour of 9, both of the neighboring areas receive relatively lower demand than the highway area itself. At the time, the focused eNBs switch to operate LPNs at a high capacity while the HPN reduces its energy consumption to almost the minimum just to cover the area and provide lower level service. On the other hand, when the neighboring areas require great service at night, the HPN consumes significantly high energy. Due to the location of the LPNs that are close to the HPN, HPN is required providing services to users that are far away.

The last type of service area is the residential area that spreads out in the largest area in the city. The energy consumption in the area is presented in Figure 6.19. Due to the sparsity of high-demand spots, HPNs require operating at the almost full capacity to provide service to users during peak time at night. Our assumption on traffic demand in this area could be conflicting to a practical case in which accessibility to the internet in residence is high. In the case, the users demand should not consist of great high-leveled service demand. Thus, the necessity for energy at HPNs to provide high-speed service in a wide area that causes high energy consumption should be significantly lower.

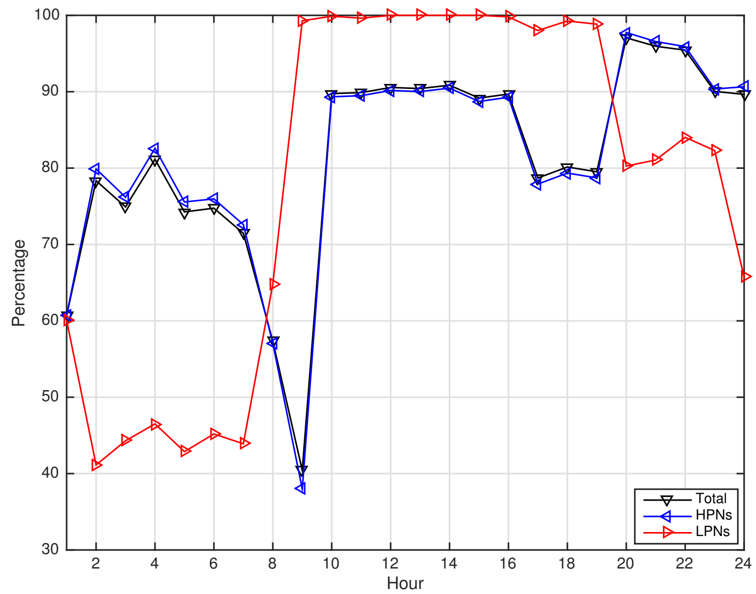

Figure 6.18: Energy consumption in percentage of full operation in highway area

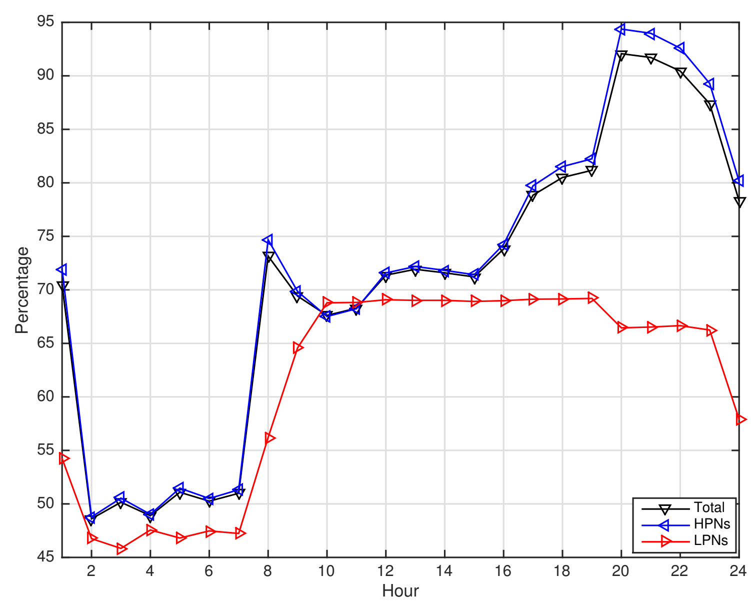

Figure 6.19: Energy consumption in percentage of full operation in residential area

Furthermore, we consider the quality of service the network provides to the customers. Figure 6.20 and Figure 6.21 present the user satisfaction rate and user satisfaction rate to power consumption ratio. The figures display the quality of service prior (dash lines) and after (solid lines) the energy reduction procedure. Blue '○' represents EA&RE case while pink '△' and red '□' display SINR&RE and SINR schemes, respectively. In Figure 6.20, we observe that the customer satisfaction rate in EA&RE case is lower than the other cases during quiet early morning hours. However, the rate is higher during the rest of the day when the traffic is significantly greater. Our worst scenario approach of calculating the interference affects this result tremendously. When there are a low number of users in the network, the system tries to optimize its energy consumption by reducing transmit power and spectrum resources assigned to users. The users that suffer from decreased quality of service are those who stand far away from the selected eNBs and experience extremely high interference from neighboring eNBs. We believe that a network with an interference management method could solve this issue and increase this satisfaction rate. Also, this low satisfaction rate of the users could be caused by a disadvantage of EA cell selection. The cell selection seeks minimum energy consumption in HPNs. Therefore, once the traffic demand reaches the determined ratio, the HPNs decide to switch on LPNs and hand over users to the LPNs. In certain circumstances, a great portion of users become congested in the LPNs and suffer from limited resources. The trade-off between the potentially additional energy requirement at HPNs to satisfy more users and declined LPN user satisfaction rate could be topic for future study. On the other hand, a benefit of RE is obvious when the traffic in the network is high. The capability of strategic resource management improves the user satisfaction. Compare the cases of SINR&RE and SINR, RE model and resource management can maintain the greater number of users satisfy. Moreover, another factor that affects the percentage of satisfied customers is the portion of users congested in particular areas. In other words, during the hour of 12 to 16, the majority of users in the network congested in the business area creating low satisfaction rate due to insufficient resources in the area. During the hour of 16 to 20, most of the users are in either highway or entertainment areas. Also, during the hour of 20 to 24, a great number of users are in the residential area. Due to the residential area spans over the largest area, the number of users in the area corresponds to the highest

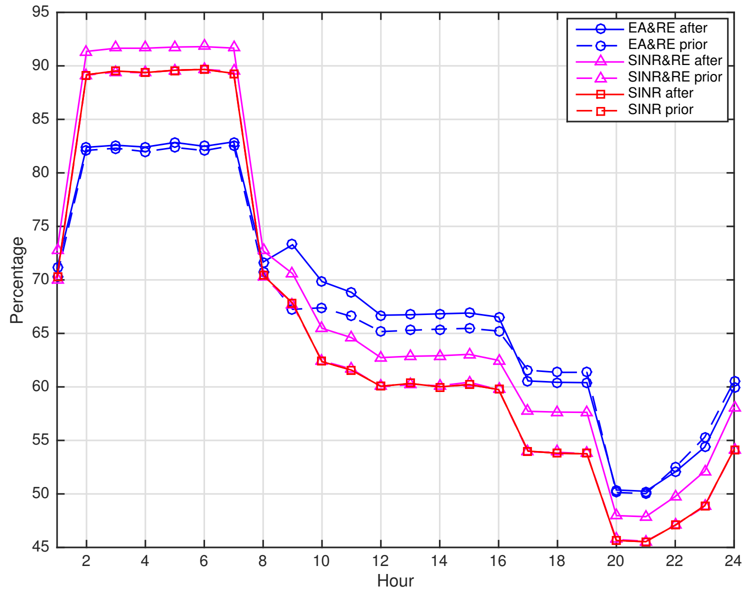

Figure 6.20: User satisfaction prior and after energy reduction

percentage of the total users and contributes greatly to the total network satisfaction rate.

Overall, the network could obviously advance and satisfy more users during peak times with more available resources. Consider the effectiveness of RE energy optimization model, Figure 6.21 displays a major improvement. In EA&RE scenario, the model can maintain the level of customer satisfaction with considerable lower energy, especially during quiet periods. The ratio decreases when the traffic increases. The lower ratio is caused by both lower satisfaction rate due to the insufficient resources and more energy required to serve the users with the insufficient resources.

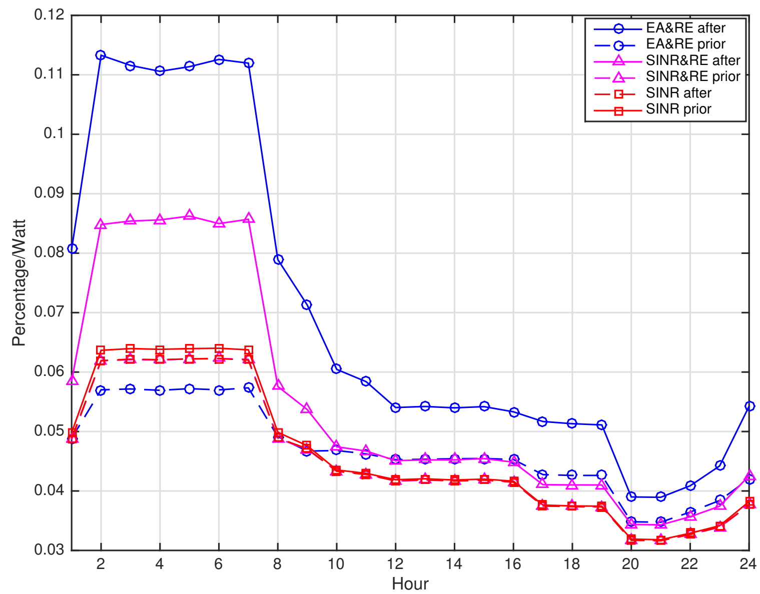

Figure 6.21: User satisfaction per energy consumption ratio

Moreover, we consider the customer satisfaction in the different types of service area. Red '△', green '+', blue '□' and yellow '⋄', represent customer satisfaction rate in business, residential, highway and entertainment area. Solid line and dash line show the rate after and prior performing EA energy reduction. Overall, when we consider the customer satisfaction by service area, we can see that customer satisfaction rate is the lowest in the business area at all hours. Insufficient resource is most concerning in the business area. Similarly, the lack of resource is also troublesome in other areas during the busy hours especially at $t = 20$. On the other hand, the customer satisfaction rate is relatively high the low load hours in highway and entertainment areas.

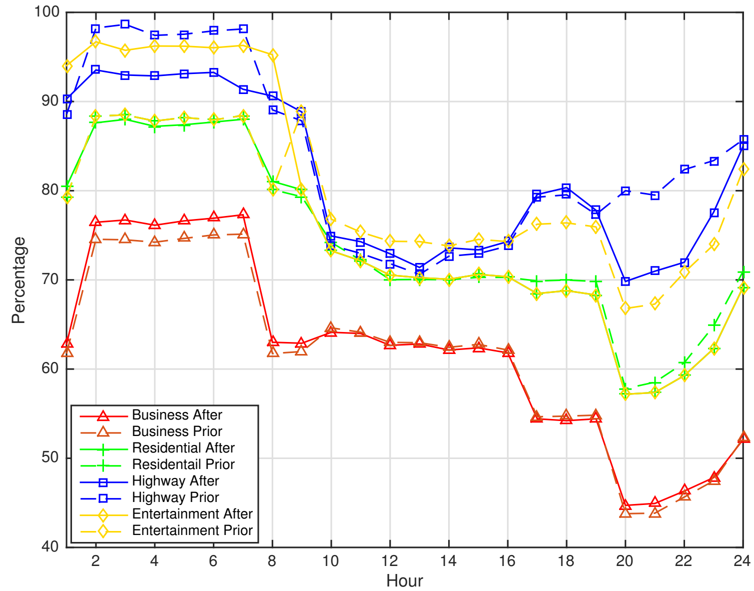

Figure 6.22: User satisfaction prior and after energy reduction by types of service area

Considering the cost of network operation, we determine the cost of energy is \$0.49 per kWh [71]. Assuming that the network has lifetime of ten years (365 days a year), the OPEX cost of the network in the three scenarios (EA&RE, SINR&RE, SINR) is \$45.59M, \$55.68M and \$61.05M over ten years. Since the cost of full operation is \$61.81M, the proposed cell selection technique and energy optimization model can save \$16.22M in ten years. From the simulations, an LPN cost of operation is \$48,790 per ten years and cost of installation is \$42,000. Consequently, the saved CAPEX cost can transform to 205 supplemental LPNs in the city. The addition increases the number of eNBs in the city to 346 eNBs. The additional LPNs can be strategically deployed near the HPNs to offload more users from the current installed HPNs and far enough from the existing LPNs to moderate the interference. Also, a further study can reveal areas with weak SINR for UEs. The additional LPNs can provide supplemental service and improve the quality of service to the UEs in the areas. However, the strategy to locate LPNs in different scenarios and constraints is a widely studied topic [17, 25–27, 71] and is not a purpose of this research. Considering the busiest

Table 6.5: Energy consumption in percentage of full operation with different traffic means

Scenario	- 10%	Current	+ 10%
Total	70.14%	73.56%	76.43%
HPNs	67.89%	71.89%	75.38%
LPNs	89.12%	89.49%	89.77%

period in the city that is at the hour of 20, the average numbers of users per km^2 are 68, 50, 47 and 192 in business, entertainment, highway and residential, respectively. With the numbers of users per area and the number of eNBs, each eNBs serve 13.8 users on average. We compare the ratio of users per eNBs in the city to the results in Section 5.2. The results show that the potential network can increase the user satisfaction rate to around 90%. The calculation could be more accurate if we consider the ratio of users per eNB separately in each type of the area. However, in the city, we cannot specify a type of service area to all the eNBs because there are several LPNs that connect to an HPN in a different service area type. Thus, we need to estimate the result from an average in the city-wide area.

Here, we investigate variation of the assumed mean traffic demand. We examine when the traffic demand estimation in the simulated network varies by ten percent; 10% lower and 10% higher than the current assumption. The network continues to utilize our proposed EA cell selection and RE energy reduction. From Table 6.5, the difference of the traffic mean creates impact on the network energy requirement. 10% fluctuation of traffic average generates approximately 3% variation of total network energy requirement. Most of the energy consumption change appears at the HPNs. The change of traffic average requires roughly 4% change of energy consumption at the HPNs. On the other hand, the varied mean traffic demand does not require significantly altered energy at LPNs. Due to our cell selection that draws the majority of users to the LPNs to reduce energy consumption at HPNs, LPNs generally operate at almost full capacity. The HPNs, therefore, require to increase their amount of service for the additional demand and to consume more power when there are 10% increase of the traffic demand average.

Regarding the customer satisfaction rate, we present Figure 6.23. From the figure, the variation of mean traffic alters the customer satisfaction in three perspectives. First, quiet hour period of the network last longer. During the quiet hours, the network can satisfy approximately the same percentage of users during quiet hours. However, because there are fewer users when the traffic average is 10% lower, the system also satisfies users at a high percentage at the hour of $t = 8$. Second, the customer satisfaction rate is considerably lower during the normal hours when the average traffic is 10% higher. The lack of available resource starts to make an impact at some areas earlier than the current traffic assumption. On the contrary, during the busy hours or between $t = 20$ to $t = 22$, the customer satisfaction rate is relatively higher when there is 10% lower traffic on average.

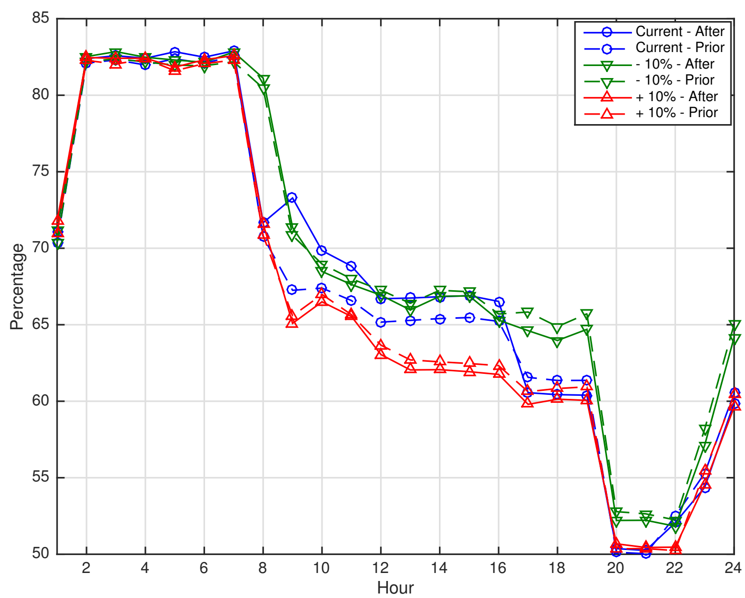

Figure 6.23: User satisfaction prior and after energy reduction with different traffic means

7.0 CONCLUSION

Energy consumption in a cellular network has become a critical concern, especially in the access network. Studies have shown great possibilities to reduce power requirement in network operation. Researchers have been proposing methodologies to minimize energy consumption and increase energy efficiency in cellular networks. Nevertheless, the main focus of the proposed work has been on finding an optimum process to switch off transmission equipment. This thesis contains three major parts. First, we propose two cell selection techniques to produce more opportunities for energy reduction in eNBs, namely, *Bandwidth-based(BB)* cell selection and *Energy-aware(EA)* cell selection. Both techniques produce significantly higher offloading rate to the system compared to a widely considered SINR-based cell selection. Also, the techniques considerably raise the user achievable data rate to most users and possess greatly higher customer satisfaction. Furthermore, the approaches noticeably create additional possibilities for energy reduction. From our simulations, with the determined network topology, our approaches yield the best network performance and the highest opportunities to reduce energy consumption in HPNs when there are 18 LPNs per an HPN. Second, we develop two energy reduction models. *Step-dimming(SD)* energy reduction successfully reduce energy requirement at HPNs by minimizing transmit power according to the current traffic load. *Resource-based(RE)* energy optimization produces power saving at all eNBs by optimizing spectrum resources and transmit power dedicated to users based on user service demand levels. The two energy models show great potential in saving power in network operation while maintaining required quality of service and customer satisfaction. Even though the models can reduce the power requirement in the network regardless of the cell selection, they perform significantly better with our two proposed cell selection approaches. Last, we examine our proposed model in a minimum CAPEX city-like network with time and spatial traffic variation. We conclude that with our energy optimization model, an operator could deploy a minimum CAPEX network in a city and satisfy almost all customers. The analysis of average traffic variation shows that our proposed models are effective with different levels of mean traffic demand. Also, the considered variation of average traffic (10%) does not alter the energy requirement greatly. Thanks to our energy minimization model, the network energy consumption is already at its minimum. On the other hand, the limited available resource can affect the customer satisfaction rate considerably.

This work extends the possibility of energy reduction in cellular access network operation. In addition to turning off the equipment or the entire base stations, we present a new way of reducing energy by optimizing spectrum resources and transmit power. Not only does the optimization take into account the number of users but also various levels of service demand from the users. We take the consideration of relatively high data rates as service levels that start to appear in many urban markets. Moreover, we further believe that energy optimization can be improved by a proper traffic load management. The traffic management can create higher feasibility for energy reduction at eNBs when the load management considers users potential energy requirement during cell selection. Additional considerations to SINR the users receive could present many more possibilities in both improved service quality and energy efficiency. Also, a recent survey [6] lists a negative impact of reducing energy by switching off equipment as one of missing concerns in literature. Our application of customer satisfaction rate instead of sole data rate reveals the first evaluation that exposes the adversity of cutting down energy consumption. Further, the same survey also notes another inaccuracy in simulation studies. The studies assume either stable or uniform traffic trend in the environment. In our last chapter, we present a city-like area where there are five distinct traffic characteristics that vary in both time and location. We can analyze the benefit and the disadvantage of models regarding different demand trend.

Nevertheless, doing research carries issues. The most challenging deficiency is the shortage of actual traffic and network information, especially energy requirement and cost of equipment. Measured traffic demand, operation information, and network specifications are very commercially sensitive. Acquiring the specific information is very difficult for external research bodies. The purpose of doing simulations is to resemble actual scenarios as accurate as possible. Scenarios with differences in, for example, traffic characteristics, service levels and area locations could contain contrasting assumptions and yield diverse results. Assumptions that appear in this thesis is constructed based on available data in publicly accessible studies. Therefore, we cannot affirm that applications of our proposed algorithms will always produce the same results in other scenarios with different assumptions and constraints. We believe the same uncertainty also applies to any theoretical research. In this thesis, we compare our numerical results to other simulation studies with similar parameters and assumptions. We found that within a scope of considerations in the similar scenarios in other studies, our results are valid. Nevertheless, the lack of measured data in research studies is a critical issue that needs to be addressed to provide certitude to an actual network.

Moreover, optimization models in a large area contain a high number of decision variables. Accurately simulating a relatively large area network requires tremendous computational resources. Assumptions and simplifications need to be made to downsize the problems to be able to perform on a stand-alone computer. Furthermore, literature on the similar matter as this thesis assumes no limitation of communication between eNBs over control plane. Additional algorithm for load management or energy reduction produces greater traffic on the control plane. As the process gets more sophisticated, the increased traffic on the control plane could become more concerning. More specifically to this work, because we aim mainly to generate a city-like area where there is always service demand, the simulation does not exploit the greatest benefit of EA. EA is suitable where the traffic is considerably low for the majority of the time. Also, peak traffic creates a significantly higher traffic and remains for a shorter period. The examples where the EA can be most beneficial are conference centers, sport or entertainment venues and rest stops on the highway. A suitable decisive condition of when to switch on the LPNs is dependent on the feature of the locations and is still an interesting study topic. Furthermore, in this work, we assume the worst case scenarios in terms of signal interference. Currently, there are several interference mitigation approaches proposed. There has been none standardized. With an interference management, especially during low load time, both network performance and energy consumption can be improved. With the lower interference, user RSS is higher yielding higher achievable data rate and transmit power required to satisfy user service demand level is lower.

Overall, to relieve and overcome the challenges, future improvement exists. Following is a list of possible research to advance our work.

- Improved EA: Currently, the system that operates EA switches to BB when the demand exceeds the limit that an HPN can provide sufficient spectrum resource and quality of RSS to meet the users service demand. The approach works efficiently when the demand increases sharply from lower than the limit to considerably higher than the limit. When the demand is slightly higher than the limit, the system turns on LPNs to offload users from the HPN. The load in each eNBs becomes light, especially in the HPN. In our work, results show a small advantage of offloading to LPNs. The users satisfaction rate increases because users in each eNBs can access greater resources from eNBs. However, instead of waking up many LPNs to balance the load, the system could require a fewer LPNs. The fewer LPNs can serve only the excessive users leaving the HPN operate at full resource at the lowest transmit power. This approach could increase energy efficiency at the HPN during the particular incident.
- Combined EA&RE: In our work, the system performs EA cell selection and RE energy optimization separately. EA connects users to eNBs regarding their expected energy requirement. Then, RE optimizes the eNBs resource and transmit power according to connected users. A process that combines EA and RE into one procedure could reduce the time and resource required to simulate the experiment. Also, a combined EA&RE could yield a higher energy efficient model that solves the problem mentioned earlier in improved EA.
- Interference managed RE: Because there is no universal standard for interference management, we decide to simulate the highest interference possible. Current interference mitigation approaches proposed in literature [50, 52, 54, 114, 115] are considerably advanced. An interference mitigation technique could provide spectrum resource management that limits the interference and, as a result, improve the network performance.
- MIMO energy optimization: Our energy optimization model considers a single-input single-output (SISO) system. LTE technology exploits the multiple-input multiple-output (MIMO) technology greatly. With multiple antennas, the system can already reach great energy saving without any energy reduction mechanism [4, 116]. However,

with the rapidly increasing user demand, it will not be long until the advanced system consumes an alarming amount of power. Fundamentally, one can apply our RE model in MIMO environment with modification regarding spectrum resource determination.

- User equipment energy consumption: Because we neglect the energy consumption of user equipment in our studied models, our proposed techniques, especially cell selection algorithms, could produce adversary consequences to user equipment. A study of requirements from user equipment in order to comply with a network effort of energy reduction is recommended to validate practicality of an energy reduction model.

This dissertation explores a new way to perceive energy reduction in access LTE network. The energy can be saved by managing the load among eNBs regarding potential energy requirement by the users and by optimizing spectrum resource and transmit power for users according to their service demand. With the expectation of lower network operation cost, an operator can deploy a larger network and satisfy more users. The user demand for higher data rate and ubiquitousness of service will continue increasing rapidly and tremendously requiring an even larger network. Cellular network industry will continue to be one of the most energy-consuming industries. Energy consumption will continue to be one of the most critical concerns both financially and environmentally. This dissertation presents a promising possibility to overcome challenges for a "greener" telecommunication network.

APPENDIX

BASELINE CUSTOMER SATISFACTION CALCULATION

In this work, we assume that the supplementary deployment of LPNs is inevitable. The addition is due to the recent rapid increase of traffic demand in cellular network. Therefore, we assume that users are satisfied when they receive higher or the same level of data rate as before the expansion of the network. To find the level of expectation of users, we perform a simulation in an extreme scenario to find the expected data rate when the network had only one traditional base station. *Customer satisfaction* rate is the percentage of satisfied user in the network and is used as an evaluation metric throughout this work (Section 4.3, 5.1.1, 5.2.1 and 6.2). This simulation result also serves as a reference and a constraint in Step-dimming energy reduction (Section 5.1).

The simulation is set on a sample service area with radius of 500 meters. The service is provided by one base station operating on 800 MHz carrier frequency with a bandwidth of 10 MHz. We vary the transmit power of the base station from 30 dBm to 46 dBm. There is no interference but noise is set at -92 dBm. We collect the average of user achievable data rate when there are 10 to 250 users in the cell. The users location is uniformly distributed the same way as in Section 4.3. Achievable data rate is calculated based on Okumura-Hata urban model [103] which is $L_p = 69.55 + 26.16log(f) - 13.82 * log(hb) - a(hm) + (44.9 - 6.55log(hb))log(d)$. The factor a is $3.2(log(11.75hm))^2 - 4.97$. Pathloss calculation follows LTE-specific modified Shannon's formula [84] which is $C = 0.75Blog_2(1 + SNR/1.25)$. B is the available bandwidth which equals to 10 MHz and SNR is the RSS of the UEs. We conduct the simulation for 10,000 iterations. Figure A1 presents the result of the simulation.

In most parts of this research, we assume that an HPN is deployed to serve 200 users. When the base station operates at full capacity and transmits at the maximum power of 46 dBm, the average achievable data rate in the result is 695.4 kbps. Therefore, we define that the user achievable data rate must be higher or equal to 695.4 kbps to be satisfactory to users.

Figure A1: Baseline average user data rate (Mbps)

Transmit power(dBm)

Number of users	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
10	8.6164	8.9517	9.2814	9.6159	9.9342	10.2539	10.5661	10.9323	11.2408	11.5822	11.9009	12.2281	12.5695	12.9102	13.2560	13.5376	13.8857
15	5.7496	5.9581	6.1710	6.4022	6.6306	6.8278	7.0413	7.2915	7.4947	7.7010	7.9513	8.1714	8.3764	8.5918	8.8280	9.0475	9.2779
20	4.3056	4.4675	4.6272	4.8018	4.9666	5.1271	5.2908	5.4687	5.6348	5.7928	5.9590	6.1190	6.2906	6.4452	6.6299	6.7876	6.9419
25	3.4461	3.5726	3.7094	3.8381	3.9762	4.1065	4.2388	4.3671	4.4960	4.6362	4.7639	4.8985	5.0304	5.1685	5.2958	5.4293	5.5589
30	2.8645	2.9813	3.0913	3.1966	3.3088	3.4231	3.5315	3.6391	3.7490	3.8622	3.9751	4.0812	4.1928	4.3042	4.4144	4.5283	4.6376
35	2.4636	2.5542	2.6509	2.7430	2.8368	2.9298	3.0293	3.1236	3.2152	3.3103	3.4031	3.4954	3.5939	3.6883	3.7806	3.8787	3.9708
40	2.1543	2.2331	2.3175	2.4020	2.4826	2.5665	2.6459	2.7274	2.8125	2.8941	2.9792	3.0622	3.1431	3.2303	3.3102	3.3894	3.4740
45	1.9147	1.9863	2.0628	2.1327	2.2045	2.2800	2.3543	2.4285	2.5007	2.5684	2.6512	2.7225	2.7952	2.8673	2.9427	3.0128	3.0912
50	1.7235	1.7891	1.8559	1.9204	1.9848	2.0497	2.1165	2.1800	2.2495	2.3141	2.3810	2.4497	2.5171	2.5819	2.6474	2.7156	2.7836
55	1.5680	1.6256	1.6842	1.7460	1.8038	1.8646	1.9258	1.9845	2.0454	2.1047	2.1669	2.2278	2.2871	2.3471	2.4071	2.4679	2.5275
60	1.4349	1.4905	1.5439	1.5994	1.6568	1.7115	1.7637	1.8209	1.8758	1.9305	1.9834	2.0393	2.0952	2.1526	2.2072	2.2630	2.3183
65	1.3239	1.3754	1.4256	1.4757	1.5280	1.5782	1.6293	1.6783	1.7307	1.7813	1.8337	1.8855	1.9351	1.9851	2.0370	2.0883	2.1400
70	1.2316	1.2771	1.3241	1.3705	1.4172	1.4651	1.5128	1.5608	1.6070	1.6559	1.7023	1.7494	1.7973	1.8440	1.8923	1.9388	1.9874
75	1.1481	1.1919	1.2354	1.2788	1.3241	1.3681	1.4119	1.4556	1.4993	1.5438	1.5888	1.6332	1.6770	1.7192	1.7660	1.8089	1.8548
80	1.0768	1.1163	1.1588	1.2008	1.2404	1.2816	1.3237	1.3641	1.4061	1.4480	1.4890	1.5309	1.5722	1.6138	1.6544	1.6978	1.7373
85	1.0137	1.0524	1.0906	1.1287	1.1686	1.2073	1.2453	1.2855	1.3238	1.3632	1.4008	1.4406	1.4804	1.5189	1.5579	1.5963	1.6351
90	0.9580	0.9939	1.0304	1.0663	1.1035	1.1394	1.1769	1.2127	1.2495	1.2853	1.3233	1.3603	1.3970	1.4334	1.4724	1.5081	1.5453
95	0.9067	0.9419	0.9758	1.0103	1.0454	1.0797	1.1139	1.1491	1.1844	1.2189	1.2540	1.2893	1.3239	1.3589	1.3944	1.4285	1.4641
100	0.8609	0.8948	0.9266	0.9602	0.9942	1.0257	1.0595	1.0913	1.1247	1.1577	1.1906	1.2238	1.2575	1.2915	1.3244	1.3571	1.3903
105	0.8200	0.8519	0.8823	0.9149	0.9459	0.9775	1.0088	1.0400	1.0712	1.1040	1.1343	1.1666	1.1978	1.2300	1.2601	1.2927	1.3241
110	0.7836	0.8129	0.8427	0.8720	0.9025	0.9325	0.9620	0.9915	1.0228	1.0524	1.0833	1.1128	1.1438	1.1741	1.2042	1.2346	1.2643
115	0.7487	0.7774	0.8064	0.8348	0.8636	0.8918	0.9207	0.9499	0.9781	1.0069	1.0361	1.0647	1.0939	1.1222	1.1518	1.1805	1.2094
120	0.7175	0.7453	0.7724	0.7997	0.8268	0.8554	0.8828	0.9095	0.9378	0.9652	0.9928	1.0206	1.0478	1.0757	1.1039	1.1305	1.1592
125	0.6886	0.7151	0.7415	0.7678	0.7947	0.8202	0.8466	0.8732	0.9001	0.9276	0.9532	0.9795	1.0058	1.0326	1.0599	1.0853	1.1126
130	0.6636	0.6876	0.7135	0.7383	0.7634	0.7887	0.8149	0.8402	0.8657	0.8908	0.9164	0.9418	0.9672	0.9931	1.0188	1.0443	1.0698
135	0.6383	0.6630	0.6866	0.7108	0.7353	0.7599	0.7843	0.8090	0.8337	0.8581	0.8827	0.9068	0.9313	0.9564	0.9810	1.0057	1.0298
140	0.6150	0.6381	0.6625	0.6858	0.7089	0.7326	0.7568	0.7799	0.8035	0.8272	0.8509	0.8746	0.8985	0.9223	0.9459	0.9696	0.9929
145	0.5942	0.6167	0.6393	0.6624	0.6848	0.7077	0.7305	0.7533	0.7756	0.7990	0.8216	0.8448	0.8672	0.8905	0.9134	0.9357	0.9591
150	0.5739	0.5959	0.6185	0.6399	0.6619	0.6841	0.7060	0.7283	0.7502	0.7723	0.7944	0.8162	0.8390	0.8606	0.8827	0.9046	0.9273
155	0.5560	0.5773	0.5984	0.6196	0.6411	0.6620	0.6833	0.7046	0.7256	0.7469	0.7687	0.7898	0.8112	0.8328	0.8540	0.8756	0.8968
160	0.5382	0.5587	0.5793	0.6005	0.6208	0.6408	0.6624	0.6824	0.7033	0.7239	0.7445	0.7651	0.7860	0.8068	0.8277	0.8485	0.8688
165	0.5221	0.5418	0.5615	0.5818	0.6017	0.6216	0.6416	0.6618	0.6820	0.7020	0.7220	0.7421	0.7621	0.7821	0.8020	0.8224	0.8426
170	0.5068	0.5262	0.5455	0.5643	0.5843	0.6033	0.6228	0.6423	0.6619	0.6813	0.7011	0.7201	0.7398	0.7593	0.7788	0.7984	0.8179
175	0.4923	0.5112	0.5299	0.5483	0.5671	0.5862	0.6049	0.6240	0.6429	0.6614	0.6806	0.7000	0.7189	0.7378	0.7566	0.7759	0.7943
180	0.4786	0.4969	0.5152	0.5332	0.5517	0.5696	0.5883	0.6068	0.6250	0.6435	0.6618	0.6806	0.6988	0.7174	0.7352	0.7541	0.7723
185	0.4657	0.4833	0.5009	0.5191	0.5368	0.5545	0.5729	0.5901	0.6083	0.6258	0.6439	0.6621	0.6796	0.6980	0.7157	0.7339	0.7513
190	0.4534	0.4704	0.4879	0.5057	0.5223	0.5403	0.5573	0.5744	0.5923	0.6097	0.6271	0.6446	0.6622	0.6794	0.6969	0.7146	0.7318
195	0.4419	0.4583	0.4752	0.4925	0.5089	0.5262	0.5430	0.5597	0.5771	0.5943	0.6110	0.6280	0.6446	0.6626	0.6794	0.6958	0.7134
200	0.4309	0.4471	0.4633	0.4799	0.4963	0.5131	0.5291	0.5459	0.5625	0.5791	0.5956	0.6121	0.6288	0.6455	0.6618	0.6786	0.6954
205	0.4202	0.4361	0.4519	0.4681	0.4842	0.5002	0.5166	0.5329	0.5489	0.5651	0.5810	0.5974	0.6136	0.6295	0.6457	0.6620	0.6785
210	0.4103	0.4258	0.4415	0.4571	0.4728	0.4885	0.5040	0.5197	0.5356	0.5515	0.5672	0.5834	0.5989	0.6147	0.6303	0.6465	0.6623
215	0.4007	0.4158	0.4310	0.4464	0.4616	0.4773	0.4925	0.5079	0.5234	0.5387	0.5541	0.5696	0.5849	0.6004	0.6157	0.6314	0.6467
220	0.3917	0.4065	0.4210	0.4362	0.4514	0.4664	0.4814	0.4962	0.5117	0.5263	0.5417	0.5564	0.5717	0.5868	0.6019	0.6167	0.6320
225	0.3829	0.3974	0.4121	0.4267	0.4415	0.4560	0.4706	0.4854	0.4999	0.5148	0.5294	0.5444	0.5591	0.5735	0.5888	0.6030	0.6180
230	0.3746	0.3886	0.4032	0.4172	0.4319	0.4460	0.4601	0.4747	0.4891	0.5037	0.5178	0.5327	0.5465	0.5613	0.5757	0.5901	0.6048
235	0.3666	0.3805	0.3943	0.4083	0.4224	0.4366	0.4506	0.4645	0.4789	0.4930	0.5070	0.5212	0.5353	0.5494	0.5636	0.5777	0.5917
240	0.3591	0.3726	0.3863	0.4000	0.4138	0.4273	0.4412	0.4549	0.4688	0.4823	0.4966	0.5103	0.5241	0.5379	0.5520	0.5654	0.5795
245	0.3518	0.3646	0.3784	0.3919	0.4052	0.4186	0.4322	0.4459	0.4589	0.4727	0.4861	0.4998	0.5132	0.5270	0.5406	0.5540	0.5675
250	0.3446	0.3576	0.3707	0.3840	0.3970	0.4106	0.4234	0.4368	0.4497	0.4633	0.4766	0.4899	0.5030	0.5163	0.5295	0.5427	0.5562

BIBLIOGRAPHY

[1] Cisco Visual Networking Index, "Global mobile data traffic forecast update, 2014–2019 http://www. cisco. com/en," February 2015.

[2] S. K. Korotky, "Semi-empirical description and projections of internet traffic trends using a hyperbolic compound annual growth rate," *Bell Labs Technical Journal*, vol. 18, no. 3, pp. 5–21, 2013.

[3] C. Han, T. Harrold, S. Armour, I. Krikidis, S. Videv, P. M. Grant, H. Haas, J. S. Thompson, I. Ku, C.-X. Wang, *et al.*, "Green radio: radio techniques to enable energy-efficient wireless networks," *Communications Magazine, IEEE*, vol. 49, no. 6, pp. 46–54, 2011.

[4] M. Deruyck, W. Vereecken, E. Tanghe, W. Joseph, M. Pickavet, L. Martens, and P. Demeester, "Comparison of power consumption of mobile WiMAX, HSPA and LTE access networks," in *Telecommunications Internet and Media Techno Economics (CTTE), 2010 9th Conference on*, pp. 1–7, IEEE, 2010.

[5] G. Auer, L. Hévizi, M. A. Imran, J. Malmodin, P. Fazekas, G. Biczók, H. Holtkamp, D. Zeller, O. Blume, R. Tafazolli, *et al.*, "Enablers for energy efficient wireless networks," in *Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd*, pp. 1–5, IEEE, 2010.

[6] J. Wu, Y. Zhang, M. Zukerman, and E. Yung, "Energy-efficient base stations sleep mode techniques in green cellular networks: A survey,"

[7] J. Gong, S. Zhou, Z. Niu, and P. Yang, "Traffic-aware base station sleeping in dense cellular networks," in *Quality of Service (IWQoS), 2010 18th International Workshop on*, pp. 1–2, IEEE, 2010.

[8] K. Samdanis, D. Kutscher, and M. Brunner, "Self-organized energy efficient cellular networks," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2010 IEEE 21st International Symposium on*, pp. 1665–1670, IEEE, 2010.

[9] K. Samdanis, T. Taleb, D. Kutscher, and M. Brunner, "Self organized network management functions for energy efficient cellular urban infrastructures," *Mobile Networks and Applications*, pp. 1–13, 2011. 10.1007/s11036-011-0293-7.

[10] R. Litjens and L. Jorguseski, "Potential of energy-oriented network optimisation: Switching off over-capacity in off-peak hours," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2010 IEEE 21st International Symposium on*, pp. 1660–1664, IEEE, 2010.

[11] Z. Niu, Y. Wu, J. Gong, and Z. Yang, "Cell zooming for cost-efficient green cellular networks," *Communications Magazine, IEEE*, vol. 48, no. 11, pp. 74–79, 2010.

[12] L. Chiaraviglio, D. Ciullo, M. Meo, and M. Marsan, "Energy-efficient management of UMTS access networks," in *Teletraffic Congress, 2009. ITC 21 2009. 21st International*, pp. 1–8, IEEE, 2009.

[13] M. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, "Optimal energy savings in cellular access networks," *Proceedings of GreenComm*, 2009.

[14] K. Son, H. Kim, Y. Yi, and B. Krishnamachari, "Base station operation and user association mechanisms for energy-delay tradeoffs in green cellular networks," *Selected Areas in Communications, IEEE Journal on*, vol. 29, no. 8, pp. 1525–1536, 2011.

[15] X. Wang, P. Krishnamurthy, and D. Tipper, "Cell sleeping for energy efficiency in cellular networks: Is it viable?," in *Wireless Communications and Networking Conference (WCNC), 2012 IEEE*, pp. 2509–2514, 2012.

[16] B. Badic, T. O'Farrrell, P. Loskot, and J. He, "Energy Efficient Radio Access Architectures for Green Radio: Large versus Small Cell Size Deployment," in *Vehicular Technology Conference Fall (VTC 2009-Fall), 2009 IEEE 70th*, pp. 1–5, IEEE, 2010.

[17] F. Richter, A. Fehske, and G. Fettweis, "Energy Efficiency Aspects of Base Station Deployment Strategies for Cellular Networks," in *Vehicular Technology Conference Fall (VTC 2009-Fall), 2009 IEEE 70th*, pp. 1–5, IEEE, 2010.

[18] H. Leem, S. Baek, and D. Sung, "The Effects of Cell Size on Energy Saving, System Capacity, and Per-Energy Capacity," in *Wireless Communications and Networking Conference (WCNC), 2010 IEEE*, pp. 1–6, IEEE, 2010.

[19] M. Arashahi, X. J. Li, and P. H. Chong, "Energy consumption in TDD-CDMA multi-hop cellular networks," in *Information, Communications and Signal Processing, 2009. ICICS 2009. 7th International Conference on*, pp. 1–5, IEEE, 2009.

[20] Y. S. Soh, T. Quek, M. Kountouris, and H. Shin, "Energy efficient heterogeneous cellular networks," *Selected Areas in Communications, IEEE Journal on*, vol. 31, no. 5, pp. 840–850, 2013.

[21] W. Guo and T. O'Farrell, "Dynamic cell expansion with self-organizing cooperation," *Selected Areas in Communications, IEEE Journal on*, vol. 31, no. 5, pp. 851–860, 2013.

[22] H. Yue, M. Pan, Y. Fang, and S. Glisic, "Spectrum and energy efficient relay station placement in cognitive radio networks," *Selected Areas in Communications, IEEE Journal on*, vol. 31, no. 5, pp. 883–893, 2013.

[23] A. A. Abdulkafi, T. S. Kiong, D. Chieng, A. Ting, and J. Koh, "Energy efficiency improvements in heterogeneous network through traffic load balancing and sleep mode mechanisms," *Wireless Personal Communications*, pp. 1–14, 2013.

[24] I. Ashraf, F. Boccardi, and L. Ho, "Sleep mode techniques for small cell deployments," *Communications Magazine, IEEE*, vol. 49, no. 8, pp. 72–79, 2011.

[25] P. Bhat, S. Nagata, L. Campoy, I. Berberana, T. Derham, G. Liu, X. Shen, P. Zong, and J. Yang, "Lte-advanced: an operator perspective," *Communications Magazine, IEEE*, vol. 50, pp. 104–114, February 2012.

[26] I. Siomina and D. Yuan, "Optimization approaches for planning small cell locations in load-coupled heterogeneous lte networks," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2013 IEEE 24th International Symposium on*, pp. 2904–2908, Sept 2013.

[27] D. Komnakos, A. Rouskas, and R. Trigka, "Mobile networks planning for minimum power consumption," in *Wireless Days (WD), 2013 IFIP*, pp. 1–6, Nov 2013.

[28] D. Tipper, A. Rezgui, P. Krishnamurthy, and P. Pacharintanakul, "Dimming Cellular Networks," *Cell*, vol. 80, p. 100, 2010.

[29] J. M. Peter Hjorth, Nina Lövehagen and K. Westergren, "Reducing CO_2 emissions from mobile communications – bts power savings and tower tube," Tech. Rep. 1, Ericson Review, 2008.

[30] L. Saker and S. Elayoubi, "Sleep mode implementation issues in green base stations," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2010 IEEE 21st International Symposium on*, pp. 1683–1688, IEEE, 2010.

[31] G. Micallef, P. Mogensen, and H.-O. Scheck, "Cell size breathing and possibilities to introduce cell sleep mode," in *Wireless Conference (EW), 2010 European*, pp. 111–115, IEEE, 2010.

[32] J. Lorincz, A. Capone, and D. Begusic, "Optimized network management for energy savings of wireless access networks," *Computer Networks*, 2010.

[33] Z. Pan and S. Shimamoto, "Cell sizing based energy optimization in joint macro-femto deployments via sleep activation," in *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, pp. 4765–4770, 2013.

[34] P. Dini, M. Miozzo, N. Bui, and N. Baldo, "A model to analyze the energy savings of base station sleep mode in lte hetnets," in *Green Computing and Communications*

(GreenCom), 2013 IEEE and Internet of Things (iThings/CPSCom), IEEE International Conference on and IEEE Cyber, Physical and Social Computing, pp. 1375–1380, IEEE, 2013.

[35] S. Cai, L. Xiao, H. Yang, J. Wang, and S. Zhou, "A cross-layer optimization of the joint macro-and picocell deployment with sleep mode for green communications," in *Wireless and Optical Communication Conference (WOCC), 2013 22nd*, pp. 225–230, IEEE, 2013.

[36] O. Blume, A. Ambrosy, M. Wilhelm, and U. Barth, "Energy efficiency of lte networks under traffic loads of 2020," in *Wireless Communication Systems (ISWCS 2013), Proceedings of the Tenth International Symposium on*, pp. 1–5, 2013.

[37] I.-H. Hou and C. S. Chen, "An energy-aware protocol for self-organizing heterogeneous lte systems," *Selected Areas in Communications, IEEE Journal on*, vol. 31, no. 5, pp. 937–946, 2013.

[38] A. Singh and R. Mahapatra, "Energy efficient analysis of heterogeneous wireless network," in *Advance Computing Conference (IACC), 2013 IEEE 3rd International*, pp. 531–535, 2013.

[39] J. Rao and A. Fapojuwo, "Energy efficiency of outage constrained two-tier heterogeneous cellular networks," in *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, pp. 146–151, 2013.

[40] S. Cho and W. Choi, "Energy-efficient repulsive cell activation for heterogeneous cellular networks," *Selected Areas in Communications, IEEE Journal on*, vol. 31, no. 5, pp. 870–882, 2013.

[41] A. Spagnuolo, A. Petraglia, C. Vetromile, R. Formosi, and C. Lubritto, "Monitoring and optimization of energy consumption of base transceiver stations," *Energy*, vol. 81, pp. 286–293, 2015.

[42] K. M. S. Huq, S. Mumtaz, M. Alam, J. Rodriguez, and R. L. Aguiar, "Frequency allocation for hetnet comp: Energy efficiency analysis," in *Wireless Communication Systems (ISWCS 2013), Proceedings of the Tenth International Symposium on*, pp. 1–5, 2013.

[43] J. Louhi, "Energy efficiency of modern cellular base stations," in *Telecommunications Energy Conference, 2007. INTELEC 2007. 29th International*, pp. 475–476, IEEE, 2008.

[44] G. Fettweis and E. Zimmermann, "Ict energy consumption-trends and challenges," in *Proceedings of the 11th International Symposium on Wireless Personal Multimedia Communications*, vol. 2, p. 6, 2008.

[45] D. Tsilimantos, J.-M. Gorce, and E. Altman, "Stochastic analysis of energy savings with sleep mode in OFDMA wireless networks," in *INFOCOM, 2013 Proceedings IEEE*, pp. 1097–1105, IEEE, 2013.

[46] Y. Qi, M. Imran, and R. Tafazolli, "On the energy aware deployment strategy in cellular systems," in *Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops), 2010 IEEE 21st International Symposium on*, pp. 363–367, IEEE, 2010.

[47] Y. Hou and D. Laurenson, "Energy efficiency of high qos heterogeneous wireless communication network," in *Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd*, pp. 1–5, 2010.

[48] C. Chang, W. Liao, and D. Shiu, "On the coverage preservation problem in green cellular networks," in *Global Communications Conference (GLOBECOM), 2012 IEEE*, pp. 3496–3501, 2012.

[49] B. Oliver, H. Eckhardt, S. Klein, E. Kuehn, and W. M. Wajda, "Energy savings in mobile networks based on adaptation to traffic statistics," *Bell Lab. Tech. J.*, vol. 15, pp. 77–94, September 2010.

[50] Y. Peng and F. Qin, "Exploring HetNet in LTE-advanced system: Interference mitigation and performance improvement in macro-pico scenario," in *Communications Workshops (ICC), 2011 IEEE International Conference on*, pp. 1–5, 2011.

[51] J. Oh and Y. Han, "Cell selection for range expansion with almost blank subframe in heterogeneous networks," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2012 IEEE 23rd International Symposium on*, pp. 653–657, 2012.

[52] I. Guvenc, "Capacity and fairness analysis of heterogeneous networks with range expansion and interference coordination," *Communications Letters, IEEE*, vol. 15, no. 10, pp. 1084–1087, 2011.

[53] I. Guvenc, M.-R. Jeong, I. Demirdogen, B. Kecicioglu, and F. Watanabe, "Range Expansion and Inter-Cell Interference Coordination (ICIC) for Picocell Networks," in *Vehicular Technology Conference (VTC Fall), 2011 IEEE*, pp. 1–6, 2011.

[54] Y. Wang and K. Pedersen, "Performance analysis of enhanced inter-cell interference coordination in lte-advanced heterogeneous networks," in *Vehicular Technology Conference (VTC Spring), 2012 IEEE 75th*, pp. 1–5, 2012.

[55] C. Huang and C. Liao, "An interference management scheme for heterogeneous network with cell range extension," in *Network Operations and Management Symposium (APNOMS), 2011 13th Asia-Pacific*, pp. 1–5, 2011.

[56] T. Nakamura, S. Nagata, A. Benjebbour, Y. Kishiyama, T. Hai, S. Xiaodong, Y. Ning, and L. Nan, "Trends in small cell enhancements in lte advanced," *Communications Magazine, IEEE*, vol. 51, no. 2, pp. 98–105, 2013.

[57] A. Zakrzewska, D. López-Pérez, S. Kucera, and H. Claussen, "Dual connectivity in lte hetnets with split control-and user-plane," in *Globecom Workshops (GC Wkshps), 2013 IEEE*, pp. 391–396, IEEE, 2013.

[58] S. Morosi, E. Del Re, and P. Piunti, "Traffic based energy saving strategies for green cellular networks," in *European Wireless, 2012. EW. 18th European Wireless Conference*, pp. 1–6, VDE, 2012.

[59] "http://reboot.fcc.gov/reform/systems/spectrum-dashboard," July 2015.

[60] P. Goldstein, "It's over: FCC's AWS-3 spectrum auction ends at record $44.9b in bids," January 2015.

[61] FierceWireless, "Spectrum news," July 2015.

[62] W. Ni and I. Collings, "A new adaptive small-cell architecture," *Selected Areas in Communications, IEEE Journal on*, vol. 31, no. 5, pp. 829–839, 2013.

[63] Y. Chen, O. Blume, A. Gati, A. Capone, C.-E. Wu, U. Barth, T. Marzetta, H. Zhang, and S. Xu, "Energy saving: Scaling network energy efficiency faster than traffic growth," in *Wireless Communications and Networking Conference Workshops (WCNCW), 2013 IEEE*, pp. 12–17, 2013.

[64] E. Oh and B. Krishnamachari, "Energy savings through dynamic base station switching in cellular wireless access networks," in *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, pp. 1–5, IEEE, 2010.

[65] M. W. Arshad, A. Vastberg, and T. Edler, "Energy efficiency gains through traffic offloading and traffic expansion in joint macro pico deployment," in *Wireless Communications and Networking Conference (WCNC), 2012 IEEE*, pp. 2203–2208, IEEE, 2012.

[66] W. Li, W. Zheng, Y. Xie, and X. Wen, "Clustering based power saving algorithm for self-organized sleep mode in femtocell networks," in *Wireless Personal Multimedia Communications (WPMC), 2012 15th International Symposium on*, pp. 379–383, IEEE, 2012.

[67] K. Dufková, M. Bjelica, B. Moon, L. Kencl, and J.-Y. Le Boudec, "Energy savings for cellular network with evaluation of impact on data traffic performance," in *Wireless Conference (EW), 2010 European*, pp. 916–923, IEEE, 2010.

[68] J. Lorincz, A. Capone, and M. Bogarelli, "Energy savings in wireless access networks through optimized network management," in *Wireless Pervasive Computing (ISWPC), 2010 5th IEEE International Symposium on*, pp. 449–454, IEEE, 2010.

[69] T. A. Le and M. R. Nakhai, "Possible power-saving gains by dividing a cell into tiers of smaller cells," *Electronics letters*, vol. 46, no. 16, pp. 1163–1165, 2010.

[70] G. Koutitas, A. Karousos, and L. Tassiulas, "Deployment strategies and energy efficiency of cellular networks," *Wireless Communications, IEEE Transactions on*, vol. 11, no. 7, pp. 2552–2563, 2012.

[71] S. Boiardi, A. Capone, and B. Sansó, "Radio planning of energy-aware cellular networks," *Computer Networks*, vol. 57, no. 13, pp. 2564–2577, 2013.

[72] G. Auer, V. Giannini, C. Desset, I. Godor, P. Skillermark, M. Olsson, M. A. Imran, D. Sabella, M. J. Gonzalez, O. Blume, *et al.*, "How much energy is needed to run a wireless network?," *Wireless Communications, IEEE*, vol. 18, no. 5, pp. 40–49, 2011.

[73] Z. Hasan, H. Boostanimehr, and V. Bhargava, "Green cellular networks: A survey, some research issues and challenges," *Communications Surveys Tutorials, IEEE*, vol. 13, no. 4, pp. 524–540, 2011.

[74] GSMA Association, "The mobile economy 2015," 2015.

[75] K. Son, E. Oh, and B. Krishnamachari, "Energy-aware hierarchical cell configuration: from deployment to operation," in *Computer Communications Workshops (INFOCOM WKSHPS), 2011 IEEE Conference on*, pp. 289–294, IEEE, 2011.

[76] ETSI, "Technical Specification Group Services and System Aspects; Policy and charging control architecture (3GPP TS 23.203 version 13.1.0 Release 13)," *ETSI TS*, September 2014.

[77] ETSI, "Technical Specification Group Services and System Aspects; Improved video support for Packet Switched Streaming (PSS) and Multimedia Broadcast/Multicast Service (MBMS) Services (3GPP TR 26.903 version 12.0.0 Release 12)," *ETSI TS*, September 2014.

[78] K. Järvinen, I. Bouazizi, L. Laaksonen, P. Ojala, and A. Rämö, "Media coding for the next generation mobile system LTE," *Computer Communications*, vol. 33, no. 16, pp. 1916–1927, 2010.

[79] G. Araniti, J. Cosmas, A. Iera, A. Loiacono, A. Molinaro, and A. Orsino, "Power consumption model using green policies in heterogeneous networks," in *Broadband Multimedia Systems and Broadcasting (BMSB), 2014 IEEE International Symposium on*, pp. 1–5, IEEE, 2014.

[80] X. Li, Q. Fang, and L. Shi, "A effective SINR link to system mapping method for CQI feedback in TD-LTE system," in *Computing, Control and Industrial Engineering (CCIE), 2011 IEEE 2nd International Conference on*, vol. 2, pp. 208–211, IEEE, 2011.

[81] C. Turyagyenda, K. Al-Begain, and N. Albeiruti, "A novel sleep mode operation for energy efficient lte cellular networks: A sum product algorithm implementation," in *Next Generation Mobile Apps, Services and Technologies (NGMAST), 2013 Seventh International Conference on*, pp. 159–164, IEEE, 2013.

[82] Evolved Universal Terrestrial Radio Access, “3GPP TS 36.213 V8. 8.0,” tech. rep., 3GPP, 2009.

[83] M. Jcolom, *taranetz, Vienna LTE Simulators System Level Simulator Documentation*, 2010.

[84] P. Mogensen, W. Na, I. Kovacs, F. Frederiksen, A. Pokhariyal, K. Pedersen, T. Kolding, K. Hugl, and M. Kuusela, “LTE Capacity Compared to the Shannon Bound,” in *Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th*, pp. 1234–1238, April 2007.

[85] “Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation,” tech. rep., 3GPP, September 2014.

[86] A. Ambrosy, M. Wilhelm, W. Wajda, and O. Blume, “Dynamic bandwidth management for energy savings in wireless base stations,” in *Global Communications Conference (GLOBECOM), 2012 IEEE*, pp. 3502–3507, IEEE, 2012.

[87] A. Ambrosy, O. Blume, D. Ferling, P. Jueschke, M. Wilhelm, and X. Yu, “Energy savings in lte macro base stations,” in *Wireless and Mobile Networking Conference (WMNC), 2014 7th IFIP*, pp. 1–8, IEEE, 2014.

[88] “Evolved Universal Terrestrial Radio Access: Base Station BS Radio Transmission and Reception (Release 10),” Tech. Rep. 36.104, 3GPP, 2011.

[89] T. Chen, Y. Yang, H. Zhang, H. Kim, and K. Horneman, “Network energy saving technologies for green wireless access networks,” *Wireless Communications, IEEE*, vol. 18, pp. 30–38, October 2011.

[90] F. Capozzi, G. Piro, L. A. Grieco, G. Boggia, and P. Camarda, “Downlink packet scheduling in LTE cellular networks: Key design issues and a survey,” *Communications Surveys & Tutorials, IEEE*, vol. 15, no. 2, pp. 678–700, 2013.

[91] “Deliverable most suitable efficiency metrics and utility functions,” Tech. Rep. D2.4, Network technologies consortium EARTH, December 2011.

[92] D. Luo, B. Li, and D. Yang, “Performance evaluation with range expansion for heterogeneous networks,” in *Vehicular Technology Conference (VTC Fall), 2011 IEEE*, pp. 1–5, 2011.

[93] A. Daeinabi, K. Sandrasegaran, and X. Zhu, “Performance evaluation of cell selection techniques for picocells in lte-advanced networks,” in *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2013 10th International Conference on*, pp. 1–6, IEEE, 2013.

[94] P. Tian, H. Tian, J. Zhu, L. Chen, and X. She, “An adaptive bias configuration strategy for Range Extension in LTE-Advanced Heterogeneous Networks,” in *Communication*

Technology and Application (ICCTA 2011), IET International Conference on, pp. 336–340, 2011.

[95] J.-H. Yun and K. G. Shin, "ARCHoN: Adaptive range control of hotzone cells in heterogeneous cellular networks," in *SECON*, pp. 641–649, IEEE, 2012.

[96] M. Shirakabe, A. Morimoto, and N. Miki, "Performance evaluation of inter-cell interference coordination and cell range expansion in heterogeneous networks for lte-advanced downlink," in *Wireless Communication Systems (ISWCS), 2011 8th International Symposium on*, pp. 844–848, 2011.

[97] L. Zou, "3GPP specification: 3GPP TS 32.521: Telecommunication management; Self-Organizing Networks (SON) Policy Network Resource Model (NRM) Integration Reference Point (IRP); Requirements," tech. rep., 3GPP, 2012.

[98] Nokia-Siemens Networks, "Self-Organizing Network (SON):Introducing the Nokia Siemens SON Suite - an efficient, future-platform for SON."

[99] M. F. Hossain, K. S. Munasinghe, and A. Jamalipour, "Toward self-organizing sectorization of LTE eNBs for energy efficient network operation under QoS constraints," in *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, pp. 1279–1284, IEEE, 2013.

[100] T. Yuan, Z. Fei, N. Li, N. Wang, C. Xing, and J. Liu, "A QoE-based cell range expansion scheme in heterogeneous cellular networks," *Science China Information Sciences*, vol. 58, pp. 1–11, August 2015.

[101] D. Willkomm, S. Machiraju, J. Bolot, and A. Wolisz, "Primary users in cellular networks: A large-scale measurement study," in *New frontiers in dynamic spectrum access networks, 2008. DySPAN 2008. 3rd IEEE symposium on*, pp. 1–11, IEEE, 2008.

[102] S. Morosi, P. Piunti, and E. Del Re, "Improving cellular network energy efficiency by joint management of sleep mode and transmission power," in *Digital Communications-Green ICT (TIWDC), 2013 24th Tyrrhenian International Workshop on*, pp. 1–6, IEEE, 2013.

[103] M. Hata, "Empirical formula for propagation loss in land mobile radio services," *Vehicular Technology, IEEE Transactions on*, vol. 29, no. 3, pp. 317–325, 1980.

[104] "Evolved Universal Terrestrial Radio Access: Further advancements for E-UTRA physical layer aspects," Tech. Rep. 36.814, 3GPP, 2010.

[105] L. Falconetti, P. Frenger, H. Kallin, and T. Rimhagen, "Energy efficiency in heterogeneous networks," in *Online Conference on Green Communications (GreenCom), 2012 IEEE*, pp. 98–103, IEEE, 2012.

[106] Y. Wang and C. Chuang, "Efficient eNB deployment strategy for heterogeneous cells in 4G LTE systems," *Computer Networks*, vol. 79, pp. 297–312, 2015.

[107] I. Siomina and D. Yuan, “On Constrained Cell Load Coupling with Applications in LTE Networks,” 2014.

[108] S. Wang, C. Feng, C. Guo, and G. Wang, “Energy-aware network planning for non-contiguous frequency bands based cellular networks,” in *Communications Workshops (ICC), 2013 IEEE International Conference on*, pp. 554–559, IEEE, 2013.

[109] C. Desset, B. Debaillie, V. Giannini, A. Fehske, G. Auer, H. Holtkamp, W. Wajda, D. Sabella, F. Richter, M. Gonzalez, H. Klessig, I. Godor, M. Olsson, M. Imran, A. Ambrosy, and O. Blume, “Flexible power modeling of lte base stations,” in *Wireless Communications and Networking Conference (WCNC), 2012 IEEE*, pp. 2858–2862, April 2012.

[110] Y. Chen, S. Zhang, S. Xu, and G. Y. Li, “Fundamental trade-offs on green wireless networks,” *Communications Magazine, IEEE*, vol. 49, no. 6, pp. 30–37, 2011.

[111] P. Frenger, P. Moberg, J. Malmodin, Y. Jading, and I. Gódor, “Reducing energy consumption in LTE with cell DTX,” in *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*, pp. 1–5, IEEE, 2011.

[112] K. Huang and V. K. Lau, “Enabling wireless power transfer in cellular networks: architecture, modeling and deployment,” *Wireless Communications, IEEE Transactions on*, vol. 13, no. 2, pp. 902–912, 2014.

[113] Y. Chen, S. Zhang, and S. Xu, “Characterizing energy efficiency and deployment efficiency relations for green architecture design,” in *Communications Workshops (ICC), 2010 IEEE International Conference on*, pp. 1–5, May 2010.

[114] D. Lopez-Perez, I. Guvenc, G. De la Roche, M. Kountouris, T. Quek, and J. Zhang, “Enhanced intercell interference coordination challenges in heterogeneous networks,” *Wireless Communications, IEEE*, vol. 18, no. 3, pp. 22–30, 2011.

[115] A. Ghosh, N. Mangalvedhe, R. Ratasuk, B. Mondal, M. Cudak, E. Visotsky, T. Thomas, J. Andrews, P. Xia, H.-S. Jo, H. Dhillon, and T. Novlan, “Heterogeneous cellular networks: From theory to practice,” *Communications Magazine, IEEE*, vol. 50, no. 6, pp. 54–64, 2012.

[116] A. L. Swindlehurst, E. Ayanoglu, P. Heydari, and F. Capolino, “Millimeter-wave massive mimo: the next wireless revolution,” *IEEE Communications Magazine*, vol. 52, no. 9, pp. 56–62, 2014.