KTH Royal Institute of Technology
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Energy saving using traffic adaptive base station operation (cell DTX) in heterogeneous cellular networks

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2015

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Abstract

Nowadays, mobile broadband data traffic is growing exponentially and will continue to grow for the coming years. Accordingly, the operational cost of a mobile network will increase significantly due to the fact that a large number of base stations will be deployed to support the high traffic demand. Besides, the increase of the power consumption of a mobile network has a negative impact on the environment because of increased carbon footprint. As a result, energy efficiency in cellular networks has gained a great interest in the research community. Hence, several approaches have been investigated to lower the mismatch between base station operations and temporal and spatial characteristic of the traffic demand in a network. For example, cell discontinuous transmission which deactivates some portion of the BS during the unused transmission time interval (TTI) is one of the techniques proposed to reduce power consumption in LTE networks.

This thesis work investigates potential energy savings due to the deployment of low power BSs that have cell DTX capability in a cellular mobile radio network in both urban and dense urban area deployments. A time static system level simulation has been used in a downlink communication in order to evaluate and demonstrate the energy savings. Besides, the European long term large scale traffic model has been implemented to make the system level simulation more realistic. Area power consumption is used as the main performance metric to evaluate the energy saving in the deployment options and traffic adaptive energy efficiency features considered.

Results show that, the power saving of a heterogenous network increases as a result of the enhancement of the BSs’ hardware to put itself in to sleep mode and by deploying an optimum number of low power BS at the cell border of the macro BS considering hotspots. However, the energy efficiency techniques that can be implemented to give maximum power saving highly depends on the traffic demand of the deployment area. Hence, there is no benefit of deploying small cells if the demand is low and if there is no significant traffic load to offload from the macro layer.

In this work, using the traffic model mentioned above and time static system level simulation, it is found that an optimal number of small cells per macro gives the minimum area power consumption when the BS is capable of switching off 90% of its components during idle mode in a dense urban area deployment. This deployment scenario has around 36% power saving during the peak hour and 12.5 % daily average power saving compared to a macro only network with cell DTX.
capability. On the other hand, under urban area traffic scenario, heterogeneous deployment for the same cell DTX factor does not bring any area power consumption reduction.
Acknowledgment

I would like to thank the department of communication Systems (CoS) for accepting me as a master thesis student and for providing all the laboratory facilities throughout this thesis work.

In particular, I wish to express my sincere gratitude to my supervisors Dr Cicek Cavdar and Dr Sibel Tombaz. They were excellent advisors who were keeping me on the right direction despite their extremely busy schedules. Moreover, every single meeting with them have been best opportunity for me to learn something new regrading how to conduct research and particularly about how to dig more on the exciting area of energy efficiency in wireless networks.

I would like to thank Goran Andersson, who is a teacher at KTH and a member of the 5GrEEn project, for his continuous guidance and help on how to use WiPack (a wireless simulator) to develop the system level simulator using mathematica. Furthermore, I want to show my greatest appreciation to Prof. Jens Zander for his useful comments and advice on formulating the research questions.

A special thank go to everyone at Radio Systems Laboratory (RSnLab) who provided valuable comments and suggestions on my thesis work. I wish to dedicate this report to my lovely parents and my girl friend for their understanding and support through all the the duration of my studies. Last but not least, I would like to thank EIT ICT Master school for giving me the opportunity to complete my master studies through the international master’s double-degree program in Europe.

Stockholm, Date. June 22, 2015

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List of Acronyms

3GPP  Third Generation Partnership Project
BS   BS
DTX  Discontinuous Transmission
FLP  Feasible Load Problem
ISD  Inter Site Distance
LTE  Long Term Evolution
LTE-A Long Term Evolution Advanced
MBS  Macro BS
heterogenous network  Heterogeneous network
RB   Resource Block
UMTS Universal Mobile Telecommunications System
SA   Service Area
SINR Signal to Interference-plus-Noise Ratio
TTI  Time Transmission Interval
UE   User Equipment
ICT  Information Communication Technology
WLAN Wireless Local area network
QOS  Quality of Service
Chapter 1

Introduction

Nowadays, energy consumption due to ICT products and services is growing at a surprising rate due to the radical evolution of technology. This issue has attracted great attention of researchers because of its impact on the environment and economy. As mentioned in a recent report by Green touch, ICT contributes nearly 2-2.5% of the global CO₂ emissions, which includes emissions from ICT companies as well as the power required by ICT equipments. Particularly, mobile communication as one of the ICT sectors contributes 9% of the total [5]. Furthermore, the relative share of ICT products and services in the worldwide electricity consumption increased from about 4.0% in 2007 to 4.7% in 2012 [6]. This shows that the contribution of ICT to the global electricity consumption will increase further to support the new evolving ICT products and services such as smart phones, tablets, machine to machine communication and social networks. As a result, a lot of research is needed to be conducted to develop energy efficient ICT products, particularly on the cellular mobile data communication. For instance, this thesis work investigates the potential energy saving due to the deployment of low power BSs that have cell DTX capability in a cellular mobile radio network in both urban and dense urban area deployments.

1.1 Background and Motivation

The main drivers for energy efficiency in wireless networks are: the exponential growth of mobile broadband traffic, increase in the cost of electricity bills for mobile operators and energy mismatch between network capacity and demand request on an hourly basis. The above drivers will be described in a detailed manner one by one.

Nowadays, mobile operators are concerned with reducing the operational cost of a cellular network as the mobile broadband traffic volume is increasing exponentially due to the increase in smartphone as shown in figure 1.1 [7]. For example in 2013, an average smart phone generated 29 times more traffic than a non-smart phone.
Furthermore, a recent report by infonetics indicates the number of mobile phones will exceed the global population by 2016 and the data traffic (driven largely by IP video) is growing at 40 to 100% each year \[8\]. This has forced mobile operators to rapidly expand their network capacity to satisfy the customer need by deploying many BSs beyond what they previously predict. This in turn radically increases the energy consumption which is the major component of operational expenditure of the mobile network operators.

In addition, due to the radically increasing data traffic volume recently; mobile network operators are experiencing an increase in their electricity bills for network operation as shown in figure 1.2. Besides, wireless communication revenue is not increasing over time, resulting in a big cost-revenue gap for the mobile operators \[8\]. As a result, it is important for the mobile operators to reduce their cost per bit in order to continue to exist in the market. For example, as part of decreasing the cost of operating a cellular network, energy saving mechanisms at the BS are already playing an important role following a new paradigm of operation which is “always available when needed” rather than the traditional “always on” paradigm.
Another important driver for improving energy efficiency in mobile network operations is the increased awareness of the society on how energy consumption relates with greenhouse gas emission and global warming. As mentioned above, mobile communication contributes 9% of the total power consumption from the ICT industry and if nothing is done, the ICT industry contribution to the global carbon footprint will nearly be doubled by 2020 [5]. However, today there is a strong agreement and commitment among the major global actors to limit the future temperature increase as its impacts are so detrimental to human being.

Now, ICT consumes small energy compared to other sectors, however, its usage is increasing over time, especially in developing countries, like China and India, which are deploying new ICT infrastructures for instance, mass deployment of 3G systems and afterwards 4G systems worldwide [9]. If nothing is done, mobile communication will also consume significant energy, so it is important to focus on developing energy efficient mobile networks.

In addition, a typical example that can show the power consumption and the large electricity bill that resulted from huge energy consumption of a wireless BS (BS) is explained in short as follows. As mentioned in [1], [10], and [11] the main energy consumers of a mobile radio network are data servers, BSs and backhaul routers, where more than 50% of the total network energy is consumed by the BS as shown in 1.3. Hence, out of the total energy consumed by the radio part, 50-80% is used for the Power amplifier (PA). Moreover, as mentioned above the increasing demand for a high data rate will make the contribution of the BSs to the total energy consumption of a mobile cellular network even higher. Consequently, most of the studies on energy efficiency in mobile radio networks focus on the power consumption due to BSs. In [11], it is shown that the energy bill of a mobile cellular network accounts for approximately 18% of the operational expenditure (OpEx) in the mature European
market and at least 32% in India.

Therefore, from the operators’ perspective energy efficiency has a major economic benefits in addition to the large impact on environmental sustainability and social responsibility in combating climate change. Thus, it is urgent to shift from focusing on providing capacity and spectral efficiency to the energy efficient usage when designing cellular networks. This new paradigm of developing energy efficient cellular networks that could significantly reduce the power consumption without sacrificing the quality of service and capacity is named as “Green Communication”[12].

In general in today’s cellular network, there is an over-dimensioning situation where most of the time the supplied amount of energy is much higher than the required for proper operation of the network as shown in 1.4. This mismatch is created since up to now, BSs have been designed with the “always on” paradigm to guarantee the QOS for peak hour traffic, regardless of the energy consumed by the underutilized BSs during the low traffic hours typical at night, holidays. Furthermore, the report from EARTH[3] also shows that there is a traffic variation even in hourly basis which suggests another potential for energy saving. Not only that, but according to traffic measurements in real networks more than 80% of the BSs do not carry any traffic in millisecond level time frame even during busy hour [13], [14]. Hence, the ”Green Communication” concept can be used as a slogan to investigate potential of energy saving by adapting the cellular network system characteristics to the dynamic load variations even in millisecond level, particularly by implementing traffic adaptive power saving mechanisms on the BSs.
1.1 Background and Motivation

Moreover, in order to improve the energy consumption of a cellular mobile radio network, the following two ways can be used. First, trying to reduce the power consumption of a BS by using power-efficient hardware or network software. Second, is by using network deployment strategies, that is by deploying low BSs in to the traffic hotspots with the help of Hetnet deployment. This is supposed to decrease the total power consumption compared to the macro BS. Because, a BS near to the mobile users requires lower transmit power due to the advantage of path loss conditions [15].

The concept of Hetnet is mainly proposed in LTE-Advance framework to boost spectral efficiency of a mobile cellular network. Because, radio link performance is approaching the theoretical limits with 3G, the network densification is taken as a means of increasing the system performance[16]. Under such circumstances, the macro BSs are used for coverage purpose. On the other hand small, low power BSs, can be introduced to fill the coverage holes and in the mean time increase the network capacity by providing high data rate to the nearest users. Now, these Hetnets are proposed to increase the energy efficiency of the network. As a result, in the last few years a lot of research has been conducted to investigate the above potential energy saving due to Hetnet deployment and traffic adaptive BS on/off techniques. Furthermore, in this thesis work the energy saving of a Hetnet with the micro-sleep (cell DTX) capabilities is also investigated in different area deployments. Cell discontinuous transmission (DTX) is a new feature that enables sleep mode operations at BS side during the transmission time intervals when there is no traffic.
1 Introduction

1.2 Related Work

Future wireless networks require enabling techniques, which make use of green communication concepts, to improve the energy consumption of a network. These enabling mechanisms empower cellular network to adapt its characteristics with respect to the load variation to reduce the energy wastage without sacrificing the guaranteed quality of service. So, in order to realize the above goal of network sustainability and energy efficiency of wireless cellular networks, particularly to reduce the power consumption of BSs a lot of techniques have been proposed from different perspectives. Broadly, these energy efficiency mechanisms can be classified according to the time scale in which they operate. Hence, they can be grouped as short time scale, medium time scale and long time scale operating techniques[2].

The fast adapting mechanisms are implemented in short time scale, which is in the transmission time interval (in millisecond time interval) to reply fast enough to changes in the network due to cell load. For e.g cell DTX, is an energy saving scheme in time domain which can be achieved by deactivating hardware components (such us power amplifier) in millisecond time level in LTE when the load is low[13]. However, medium time scale techniques operate per hour-basis in order to be able to adapt the system capacity to the traffic daily variation as mentioned in [3]. Typical examples of energy saving technique with medium time scale operating range are cell zooming, switching off small cells and cell switch on/off. Furthermore, there are also other network energy saving strategies that are analyzing the recent innovative wireless technologies which can improve the energy efficiency of a cellular network in a longer time scale for example, Hetnet deployment.

In the following sections energy saving strategies operating in short time scale, medium time scale and longer time scale will be discussed in a more detailed manner.

1.2.1 Short time scale techniques/cell DTX

As mentioned above, cell DTX is one of the energy efficient techniques that operate in short time scale. However, this approach has limitations since 3GPP standard requires transmission of control signals even in the absence of downlink data traffic, but cell DTX is basically a discontinuous down link transmission where the BS will sleep in empty sub frame. However, regardless of its limitation in [13] it is shown that how energy consumption can be reduced in LTE using discontinuous transmission (DTX) concept on the BS side and in this paper fast cell DTX approach has achieved 61% of energy saving in a realistic traffic scenario. Further more, in [17] the performance of energy saving schemes in dense LTE network is evaluated by switching off capacity cells (small cells) during low-traffic hours and reducing power consumption with the help of variable network deployment and fast cell DTX.
1.2 Related Work

Moreover, in [4] the work of [17] is further extended and effect of small cell sleep mode deployment with fast cell DTX is investigated which shows around 40% energy gain compared to switching off completely as in [17]. Moreover, in [18] the maximum energy saving of the cell DTX is analyzed with a clean state network deployment. As a result, optimal BS density that consumes the lowest energy is obtained for a given QOS considering daily traffic variations.

1.2.2 Medium time scale techniques

In medium time scale operating energy saving techniques, the network capacity tries to adapt to the traffic demand according to a regular variation pattern of load during the day (typically at night) which can also be used to predict the average capacity demand within a geographical region. Typical examples of medium time scale techniques are cell switch on-offs techniques, cell zooming and cooperative cell zooming. These techniques are explained briefly as follows.

1.2.2.1 Cell switch on-off/ macrosleep

Cell switch on-off is a system level approach that shuts down some of the cells when the traffic load is low and the UEs are handed over to the remaining cells. These techniques are applied in UMTS, LTE and Hetnet in order to optimize energy utilization without sacrificing user experience. In following section the cell switch on/off algorithms proposed for UMTS cellular networks are discussed one by one. First, in [19] a dynamic network planning is widely explained that works based on the instantaneous traffic load for reducing the number of active access devices when they are underutilized (typically at night) and when some of the active devices are switched off. As a result, the radio coverage will be taken care by the remaining active devices with some increase in their transmission power. Second, in [12] both centralized and decentralized approaches of turning off BSs are proposed and tested by simulations. Hence, in case of a centralized algorithm, each BS’s traffic will be examined and a decision to be switched off or not be will be made from a central controller of the network. But, in a decentralized algorithm each BS locally estimates its traffic load and decides independently whether it is going to be switched off or not.

Apart from the switching on/off mechanisms for UMTS, in [20], [21],[22], [23] different switching on/off mechanisms are suggested for LTE and Heterogeneous network. First,[20], a switch on/off algorithm that exploits the knowledge of the distance between the user equipment and the associated BS for LTE-A was developed and the proposed idea is to switch off an eNodeB not according to its traffic load, but according to the average distance of its users. As a result, the eNode that serves distant users will be switched off first and neighboring BSs will crease their power.
so as to guarantee that service is available over the whole network with the desired quality.

However, in [21] and [22], centralized and a distributed approach of energy efficiency schemes in the HetNet scenario are formulated as optimization problems respectively. In these papers, an iterative improvement algorithm to power on-off network cells is devised and evaluated for each approach. Further more, in [23], the ability of putting small cells in to a low power sleep mode during a low traffic is proposed as a Hetnet energy saving scenario. In this paper, three different strategies of controlling the status of small cells are investigated. These are: small cell driven controlled sleep mode, core network controlled sleep mode and UE controlled sleep mode. According to the simulation, core network driven approach with the adjusted macro cell configuration is found to be the most energy efficient strategy although the other two are also energy efficient relative to the absence of sleep mode.

1.2.2.2 Cell zooming

In general, cell size is fixed in cellular networks as it is based on the estimated traffic load. However, the concept of cell zooming (both centralized and distributed algorithms) is introduced in [24] which adaptively adjusts the cell size by deactivating light loaded BSs dynamically to match the system capacity when the mobile network is working on off-peak. Besides, the active BSs will react to the changes in the network layout to pay off to the coverage losses. According to simulations the proposed algorithms reduce the energy consumption by large amount. However, due to the absence of inter cell cooperation this approaches results in coverage holes and cell edge UEs may experience higher interference. Thus, in order to avoid the coverage holes and throughputs losses, inter cell cooperation is implemented in both [25] and [26] by developing the notion of energy partition which is an association of powered–on and powered-off BS following a Self-Organizing Network manner. However, these cooperative cell zooming algorithms also have a downside, they increase system complexity and overhead although they are able to eliminate the coverage hole and cell edge UE interference problems.

1.2.3 Long time scale techniques

As a complementary way to BS cell switch on/off techniques for reducing power consumption in cellular networks, different energy efficient heterogeneous deployment strategies are proposed in the following papers [27],[15],[28] and [29]. First, in [27] the idea of lowering power consumption of a cellular mobile radio network by deploying small cell, low power BSs, is investigated from deployment perspective. In this paper, the potential improvements of area power consumption by varying the number of micro BS deployed per macro cell is evaluated per a given system performance and load. Second, in [15], a framework that can be used to evaluate and optimize
cellular network deployments is provided with respect to the average number of micro sites per macro cell as well as macro cell size. Furthermore, in [15], [28], and [27] and the potential energy saving of different network deployment strategies are evaluated taken in to account the effect of cell size, various BS types and number of additional BS at the cell boarder of a macro cell. However, its main contributions are investigating the power saving capability of pico BSs and WLAN access points placed at the cell boarder of macro cell and exploring the non uniform traffic case in a Hetnet. Moreover, in [29] a novel deployment approach is proposed from small cell site locating perspective in which a picocell is deployed at the cell edge instead of under the umbrella of the macro cell. This picocell has a directional antenna which is equivalent to a combiner of picocells associated with macro cells and result showed that this novel approach has tripled the energy efficiency of a Hetnet compared to the traditional scheme.

1.2.4 Hybrid techniques

In this category of energy saving techniques both deployment strategies (long time scale ) and cell switch on-off approaches are coupled for maximum energy efficiency. For example in [30] the paper focuses on the impact of radio planning strategies (deployment) on the performance of sleep mode. It shows that 10% to 30% energy saving can be achieved using switch off strategies which are based on cell load or BS coverage overlap in a network which is already deployed in an energy efficient manner. Apart from this, [31] shows that the effectiveness of a deployment scheme where BSs can be switched off when the traffic is low compared with the BS deployment scheme that works based on peak traffic load. To summarize the related work, the characteristics of the energy saving techniques is shown in Table 1.2.4as follows

In spite of all the above studies on power saving strategies in cellular networks, what seems not explored much is the power saving potential when cell DTX (i.e micro sleep at the BS side) is mixed with Hetnet deployment. Particularly, investigating the idea of developing an energy efficient small cell deployment strategy in Hetnet by finding the optimum number of small cells per macro cell that minimize the area power consumption of an LTE network. In addition, the micro sleep or cell DTX capability of a cell is more practical compared to the macro sleep(hourly basis sleep), since the scheduling of UEs is done per TTI (in millisecond time frame) and the cell is not required to transmit continuously, unlike WCDMA. As a result, there is a potential for reducing power consumption in LTE when there is low or no traffic in the radio frame. Moreover, there is also a possibility of power consumption reduction using Hetnet deployment in a hotspot area.
1 Introduction

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<th>drawbacks</th>
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<td>cell DTX</td>
<td>[13], [17],[4]</td>
<td>Low loads</td>
<td>NO</td>
<td>It limits the power consumption when there is no data traffic</td>
<td>Advanced hardware is required to fast switch on the PA</td>
</tr>
<tr>
<td>Cell zooming</td>
<td>[24]</td>
<td>Low load regions</td>
<td>Not required</td>
<td>It reduces the number of active BS in a region</td>
<td>It may result in coverage holes and cell edge UEs may perceive higher interference</td>
</tr>
<tr>
<td>Cooperative cell zoom-</td>
<td>[25],[26]</td>
<td>Low/medium regions</td>
<td>Required</td>
<td>It avoids coverage holes and throughput losses</td>
<td>It increases the system complexity and overhead</td>
</tr>
<tr>
<td>Deployment</td>
<td>[27], [15],[28],</td>
<td>High load regions</td>
<td>Can be beneficial</td>
<td>It optimizes the network deployment with respect to the energy efficiency and QoS constraints</td>
<td>Back haul requirement are neglected</td>
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Table 1.1: Characteristics of energy saving techniques operating in short time scale, medium time scale and long time scale
1.3 Thesis objectives and Research questions

In this section the main thesis objectives and the research questions to be investigated are discussed briefly.

1.3.1 Thesis objectives

Based on the literature gap stated above, in this thesis we aim to

- Assess the energy saving that can be achieved by introducing cell DTX into a heterogeneous cellular networks.
- Investigate how many small cells per macro cell can lead to a minimum area power consumption.

1.3.2 Thesis Research questions

In order to achieve the thesis objectives, the following research questions have been formulated and investigated in detail

- Can mixing cell DTX with HetNet network deployment increase the energy efficiency in a cellular network?
- How many small cells with cell DTX capabilities should be deployed per macro cell for a minimum area power consumption?
- How much energy can be saved by combining cell DTX and optimum small cell deployment for a given traffic demand?

1.3.3 Thesis outline

The structure of the paper is the following: First, chapter one, introduces the required background knowledge and related works. Chapter two and three describe the system model and detailed mathematical problem formulation respectively. Chapter four deals with the simulation and analytic methodology used to solve the research question, particularly the simulation steps and related algorithms are described in this chapter. Then, the respective results with their analysis is presented in chapter five. Finally, conclusions are drawn and suggestions for further work are also provided in chapter six. Not only that, but intermediate results and supplementary graphs are placed in chapter 7 as appendix.
This chapter deals with the details of the model used for simulating Hetnet. It describes the deployment system configuration, the traffic model, the power model used to calculate the area power consumption of the different approaches used for developing energy efficient wireless networks.

2.1 Network layout

This thesis considers an LTE cellular system with Orthogonal Frequency division multiplexing as a downlink transmission technique and a reuse factor of one. The network is modeled as a grid of 19 hexagonal macro BSs and low power BSs (small cells) with radius $R(\sqrt{3})$ and $r(\frac{100}{\sqrt{3}})$ meters respectively, and inter-site distance (ISD) indicated by $D$ as $\sqrt{3} \cdot R$. Each BS is located in the middle of a cell and its antenna system is considered to be an omnidirectional antenna, which means one BS serves exactly one cell. Moreover, the small cells are also deployed at the edge of the macro cells. In this thesis work, all the experiments are done considering only in the downlink communication (transmission from a BS to UE), since the main focus is on the power consumption of the BS when trying to serve users. Moreover, the wrap-around technique is implemented for better interference calculation and to create more realistic experimental environment. Particularly, the aim of this technique was to avoid the underestimation of the interference experienced by the border cells, and this is done by replicating several times the target 19 BS network around itself as shown in the figure below.
In this thesis work, a number of assumptions were taken to simplify the complexity of the system simulation. For example:

- all the users within the cell are assumed to be fully served by the BS of that cell.
- it is assumed that every BS utilizes all its resource blocks (RBs) in each transmission time interval (TTI) in order to serve a single user. This simplification is done, because simulating a scheduler at the BS is a complicated task and it is beyond the scope of this thesis work.
- it is assumed that there are no signaling and fading in the network.
- feasible load is calculated taking into consideration the interference from other cells using iterative load calculating algorithm.
- file size is assumed to be fixed.

2.2 Traffic Model

In this thesis work, a traffic model that takes into account both the temporal and the spatial variation of data volume is used to represent the traffic generated by the users in a cellular network. The network is assumed to be deployed in an urban and dense urban deployment areas where the user density is $\rho$ [users/Km2]. According to [3]
2.3 Link level performance

dense urban area deployment (in Europe) is an area with 3000 citizen/km² on average and urban area deployment is 1000 citizen/km² on average. Moreover, the average number of active users per km² in given time interval T (here T = 1 hour), denoted \( \lambda(t) \) can be calculated as large scale traffic models as follows

\[
\lambda(t) = \rho \alpha(t) \quad \text{from [3]}
\]  

(2.1)

In equation 2.1 \( \alpha(t) \) represents the typical daily user activity profile in the service area, denoted by \( \mathbf{A} \). The reference traffic model used in this thesis is illustrated in figure 2.2 and it is taken from [3] where \( \alpha(t) \) varies from 2% in the low traffic hour up to 16% during the busy hour. In addition, the users are randomly distributed in all the 19 macro BS and small cells that represent the service area.

![Figure 2.2: Illustration of data traffic average daily profile \( \alpha(t) \) in Europe [3]](image)

2.3 Link level performance

In this section, all the inputs required to calculate the load of cell are explained in detail. Those are: the path loss model, inter cell interference model, signal to interference plus noise ratio (SINR) and instantaneous data rate of the users.

2.3.1 Path loss model

The path loss of the downlink communication of the LTE network is modeled by Okumura-Hata model for both urban and dense urban regions. This model is an extension of the COST231 model to 2 GHz and the ITU-R extension to 100 km. For
The "urban" and "metropolitan" areas the model used for calculating the path loss is expressed as follows:

\[ L_u = \begin{cases} 
69.82 + 26.16 \cdot \log_{10} f - 13.82 \cdot 10(h_b) - a(h_m) + \\
(44.9 - 6.55 \cdot \log_{10} h_b) \cdot \log_{10}(bd) & \text{for } f < 1500 \text{MHz} \\
46.3 + 33.9 \cdot \log_{10} f - 13.82 \cdot \log_{10}(h_b) - a(h_m) + \\
(44.9 - 6.55 \cdot \log_{10} h_b) \cdot \log_{10}(bd) + c & \text{for } f > 1500 \text{MHz}
\end{cases} \]

where the antenna correction \( a(h_m) \) is dependent on the city type, \( h_m \) is the mobile station height, \( h_b \) is the BS height and \( f \) is the operating frequency. As can be seen from the path loss function from WiPack, a wireless simulator developed using Mathematica in KTH, the city type for urban and metropolitan areas is large or otherwise it is a medium-small.

\[ a(h_m) = \begin{cases} 
8.29 \cdot \log_{10} 2(1.54 \cdot h_m) - 1.1"large", & 150 < f < 300 \text{MHz} \\
3.2 \cdot \log_{10} 2(11.54 \cdot h_m) - 4.97"large", & 300 < f < 2000 \text{MHz} \\
(1.1 \cdot \log f - 0.7) \cdot h_m - (1.56 \cdot \log_{10} f - 0.8) & \text{medium – small}
\end{cases} \]

The constant \( c \) clutter is

\[ c = \begin{cases} 
3"\text{metropolitan}", & 1500 \leq f \leq 2000 \text{MHz} \\
0 & \text{otherwise}
\end{cases} \]

### 2.3.2 Inter cell interference model

In this thesis work, the interference model used takes into account the time variation of the interference of a given cell. This model helps us to measure a realistic data rate of users and cell loads of the macro and small cells, which are directly interconnected to the interference of a cell. Moreover, in this case the other option, which is the "worse case" interference scenario might not provide us an accurate result due to its unrealistic nature. As a consequence, the realistic modeling of these effects requires "coupled-processor queuing models as explained in [32]. In line with the interference model used in [32] and [33], the interference model used in this thesis is a time-averaged interference that considers the cell load of all the interferes to calculate the interference of a given cell. Accordingly, the interference power \( I_j \) experienced by the communication link \((i,j)\) is given by the following equation

\[ I_j = \sum_{k \neq i} \eta_k \cdot P_{kj} \]  \hspace{1cm} (2.2)

where \( P_{kj} \) is the interference power coming from BS k to the user j associated with BS i and \( \eta_k \) represents the cell load of the interfering BS \( k \neq i \) and can be interpreted as the probability of transmission of BS K while BS i is serving the user j.
2.3.3 Signal to Interference plus Noise ratio

In this thesis work the signal to interference plus noise ratio denoted by $\tau_j$, experienced by the user $j$ served by BS $i$ is represented as

$$\tau_j = \frac{P_{ij}}{I_j + N} = \frac{g_{ij} \cdot P_i}{I_j + N} = \frac{g_{ij} \cdot P_i}{\sum_{k \neq i} \eta_k \cdot P_{kj} + N}$$  \hspace{1cm} (2.3)

where $N$ represents the noise power within system bandwidth $W$.

2.3.4 Instantaneous Data rate

The instantaneous data rate of user $j$ is written according to the Shannon capacity formula as shown in the equation below.

$$r_j = W \cdot SE_j$$  \hspace{1cm} (2.4)

where $SE_j$ is the spectral efficiency as given in equation 2.5 and $W$ is the LTE network system bandwidth.

$$SE_j = \min(SE_{max}, a \cdot \log_2(1 + b \cdot \tau_j))$$  \hspace{1cm} (2.5)

In equation 2.5 above $SE_{max}$ represents the maximum spectral efficiency responsible for the maximum data rate, that can be attained using the most efficient modulation and coding schemes used by the considered LTE system. In addition, the parameters $a$ and $b$ adjust for the system bandwidth efficiency and for the SINR implementation efficiency of the system as explained in[34]. However, in the simulation it is assumed that one user will be served at a time with all the available physical radio resources, which is illustrated by using $W$ in the instantaneous data rate calculation.

2.4 Power consumption model of a Heterogeneous network

The Power consumption of a Hetnet depends on the power consumption model of the different BS types considered in the simulation. Hence, the power consumption of the macro BS and small cells(micro BS) are given in 2.6 and 2.7 respectively. The result of the summation of the two equations gives the total power consumption of the network. Moreover, in this case all the BSs have equivalent cell DTX capability, which puts the BS into sleep mode within millisecond time frame as shown in 2.3.
The macro BS model with cell DTX factor $\eta_M$ is given

$$P_M = B(t) \cdot P_A^M \cdot \eta_M + B(t) \cdot \delta_M \cdot P_I^M \cdot (1 - \eta_M) \quad (2.6)$$

and the small cell BS model with cell DTX factor $\eta_S$

$$P_S = C(t) \cdot P_A^S \cdot \eta_S + C(t) \cdot \delta_S \cdot P_I^S \cdot (1 - \eta_S) \quad (2.7)$$

[4]

- $B(t)$ = the density of the macro BSs
- $P_A^M$ = macro power consumption during active mode
- $\delta_M$ = macro cell DTX parameter
- $\eta_M$ = cell load of macro BS
- $P_I^M$ = macro power consumption during Idle mode
- $C(t)$ = the density of the small cells
- $P_A^S$ = small cell power consumption during active mode
- $\delta_S$ = small cell cell DTX parameter
- $\eta_S$ = the cell load of a small cell
- $P_I^S$ = small cell power consumption during Idle mode

![Figure 2.3: Assumed model for the eNodeB power consumption as a function of time.][4]

The above power consumption model is dependent on the load of the BS $\eta$ and the cell DTX parameter $\delta$ as explained in [17],[4]. Both traffic load $\eta$ and cell DTX
parameter $\delta$ ranges from $[0,1]$, which means that a cell with higher load consumes higher energy than a cell serving relatively a smaller number of users. However, a cell with a low $\delta$ means that most of the parts of the BS can be put into micro sleep mode and be reactivated upon request, while high $\delta$ shows only small part of the BS can be shutdown and turned on in millisecond time scale. As a result, the latter case has a lower performance in terms of energy saving, since the BSs’ idle power consumption is higher compared with the one with small cell DTX factor.
Chapter 3

Problem Formulation

As clearly stated in section 1.3, in this thesis work the main purpose is to: (a) Assess the energy saving that can be achieved by introducing cell DTX, micro sleep capability, to the BSs of a heterogeneous cellular network. (b) Investigate how many small cells per macro cell can lead to minimum area power consumption. In order to achieve the above two goals, two main tasks should be accomplished. First, calculating the area power consumption and potential energy saving of the different heterogeneous deployments taking into account all the BSs have the cell DTX capabilities. Second, we need to figure out the optimum number of small cells per macro cell that results in to a minimum area power consumption of a network.

However, as shown in equation 3.6, the power consumption model of BSs of the Hetnet and the network energy expenditure are highly dependent on cell load. This dependency brings up a very important problem, which is finding the feasible load of a cell considering the inter-cell interference. The Feasible load problem of a cell is formulated and discussed in detail in [35]. Nevertheless, a short description of feasible load problem in connection to the thesis work will be explained in the next sub section. Moreover, a mathematical formulation defining the achievable power saving of a Hetnet with cell DTX capability will also be introduced.

3.1 Feasible load problem in Hetnet

In this thesis work, cell load during an observation time T, is defined as the resource utilization of the $BS_i$, which is the ratio of the amount of time that BS remain active to serve its users to the time frame T(one hour in this work) as explained in detail in [18]. So, in the case of an LTE system, the cell load will be defined as the amount of transmission time interval(TTI) used within the time frame T. Again the above definition works well under the assumption that the BS scheduler uses full available bandwidth to serve the given user during high traffic period and transmitting in a micro sleep mode during the low traffic condition. Hence, the cell load $\eta_i$ of a cell i
during a time frame of $T$ can be written as

$$\eta_i = \frac{1}{T} \sum_{j=1}^{M} t_{i,j} + \eta_{\text{signaling}} \quad (3.1)$$

where $M$ is the total number of users served by a BS and $\eta_{\text{signaling}}$ is the time required for transmitting the signaling information with in the time frame $T$, where as $t_{ij}$ is the time needed to transmit a data demand of $\theta_j$ from the BS $i$ to the user $j$ given in the following equation

$$t_{ij} = \frac{\theta_j}{r_j} = \frac{\theta_j}{\min(SE_{\text{max}}, a.\log_2(1 + b.r_j))} \quad (3.2)$$

Note here that $\theta_j$ represents the data demand of user $j$ per hour in the cellular network. The assumption of the load dependent interference model used in section 2.3.2 has increased the complexity of finding the load of a BS in a snapshot. For example, to calculate the load of a BS $i$, it is compulsory to consider the non-linear relations existing between the load of the BS $i$ and the load of all the other interfering BSs. Mathematically, combining equations 2.2, 2.3 and 3.2 allows us to rewrite the load of BS $i$

$$\eta_i = \frac{1}{T} \sum_{j=1}^{M} t_{i,j} = \frac{1}{T} \sum_{j=1}^{M} \left\{ \frac{\theta_j}{\min(SE_{\text{max}}, W.a.\log_2(1 + b.r_j))} \right\} \forall_i \in S^{BS}[18]$$

with $\eta_i \in [0, \eta_i^{\text{Max}}]$. The above equation shows that in an interference limited system, a given cell load is a function of the cell loads of all the interfering cells i.e $\eta_i = f(\eta)$. Moreover, the feasible load problem is then stated as follows as calculating the network load vector $\eta = \eta_1, \eta_2, ... \eta_N$ that balances the network resource utilization with the demand in all the cells. In this thesis work, for all the deployment scenarios investigated there is a unique load vector calculated through an iterative algorithm [18].

### 3.2 Energy /Power saving using optimal Hetnet deployment

Given a Hetnet with $N$ macro BSs and $S$ small cells with cell DTX capability, the power and energy consumption can first be calculated at the BS level and then at the network level for a given user snapshot and user assignment. Moreover, the following assumptions are made to simplify the technique of calculating power consumption in the cellular network.

- All macro and small cell BSs transmit at a constant transmission power $P_{Mt} = P_{M\text{max}}$ and $P_{St} = P_{S\text{max}}$ respectively.
3.2 Energy /Power saving using optimal Hetnet deployment

- The power amplifiers used for all the cases switch on/off instantaneously with almost no delay.
- There is no extra power consumption with the switching on/off operation.

Based on the above assumption and the power consumption model from equations 2.6 and 2.7, the total energy consumption of the Hetnet in a given time interval [0,T] can be expressed as follows

\[ E(S, P_{total})E_{tot} = \sum_{1}^{N} E_{Macro} + \sum_{1}^{m} E_{small} \text{ where } E_{tot} = P_{tot} \cdot T \] (3.4)

\[ P_{total} = P_{Macro}^{tot} + P_{Small}^{tot} \] (3.5)

\[ P_{tot} = (B(t) \cdot P_{M}^{M} \cdot \eta_{M} + B(t) \cdot \delta_{M} \cdot P_{I}^{M} \cdot (1 - \eta_{M})) + C(t) \cdot P_{S}^{A} \cdot \eta_{S} + C(t) \cdot \delta_{S} \cdot P_{I}^{S} \cdot (1 - \eta_{S}) \] (3.6)

As shown in the above equation the total energy consumption is dependent on both the total energy consumption of the macro BS and small cell BS. However, in this thesis work the main goal is to see the effect of adding more small cells per macro as a means of reducing power consumption of a cellular network. In this circumstance, users can also entertain a higher data rate from a nearby low power BS. As a result, the total energy consumption is mainly dependent on the number of small cells S and the main goal is finding the optimum number which lead to the minimum area power consumption in a given service area.

3.2.1 Energy/power saving of a Hetnet with cell DTX capability and small cell deployment

Since for a given observation time T the energy consumed by a Hetnet is directly proportional to network power consumption, power saving is used instead of energy saving for simplicity purpose. As a consequence, the area power consumption of a Hetnet, \( P_{A} \) can be expressed as follows

\[ P_{A} = P_{tot}/A = \frac{\sum_{i=1}^{N} P_{BS, i}}{A} \] (3.7)

\[ P_{A} = \frac{1}{A} \left\{ \sum_{i=1}^{N} P_{Macro} + \sum_{i=1}^{S} P_{Smallcell} \right\} \] (3.8)

\[ P_{A} = \frac{1}{A} \left\{ (B(t) \cdot P_{M}^{M} \cdot \eta_{M} + B(t) \cdot \delta_{M} \cdot P_{I}^{M} \cdot (1 - \eta_{M})) + C(t) \cdot P_{S}^{A} \cdot \eta_{S} + C(t) \cdot \delta_{S} \cdot P_{I}^{S} \cdot (1 - \eta_{S}) \right\} \] (3.9)
we can also define
\[ \eta_{\text{avr}} = \frac{\sum_{i=1}^{N} \eta_{M} + \sum_{j=1}^{S} \eta_{S}}{N + S} \]  
(3.10)

Note that \( \eta_{M} \) and \( \eta_{S} \) are the average cell load for the macro and small cell BSs respectively in the Hetnet for a given time duration \( T \); and these are the loads related to the maximum load that can be allowed in the system with a certain number of small cells. Moreover, the power saving that can be achieved by using the cell DTX concept in a Hetnet can be written as follows
\[ P_{S} = \frac{P_{\text{NoDTX}} - P_{\text{DTXhetnet}}}{P_{\text{NoDTX}}} \]  
(3.11)

where \( P_{\text{NoDTX}} \), is the area power consumption of a macro only cellular network with no cell DTX which can be obtained from the power model taking the cell DTX factor as 1. As a result, the power saving of a Hetnet with cell DTX compared to macro only with out cell DTX can be expressed mathematically from 2.6 and 2.7 as follows
\[ S_{1}(\delta_{M}, \eta_{M}, \delta_{s}, \eta_{s}) = \frac{P_{M} \cdot (1 - \delta_{M}) \cdot (1 - \eta_{M}) + P_{S} \cdot (1 - \delta_{S}) \cdot (1 - \eta_{s})}{P_{M} \cdot \eta_{M} + \eta_{S} \cdot \delta_{M} \cdot (1 - \eta_{M})} \]  
(3.12)

As shown from the above equations the achievable power saving of a Hetnet with cell DTX is closely dependent on the the cell DTX factor and the the average load of both the small cell and the macro cell BS. Moreover, it is also dependent on the idle power consumption \( (P_{I}^{M}) \), and \( P_{I}^{S} \) ) and active power consumption \( (P_{A}^{M}, \text{ and } P_{A}^{S}) \) of both the macro and small cells in a Hetnet. Similarly, the achievable power saving by deploying small cells that has cell DTX capability in to an already energy efficient cellular network using cell DTX can be calculated as follows.
\[ P_{S} = \frac{P_{\text{DTX}} - P_{\text{DTXhetnet}}}{P_{\text{DTX}}} \]  
(3.13)

where \( P_{\text{DTX}} \), is the area power consumption of a macro only with cell DTX which can be obtained from the power model taking the cell DTX factor as \( \delta_{M} \). Moreover, \( P_{\text{DTXSmallcell}} \) is the power consumption of the an already energy efficient cellular network after deploying \( S \) number of cell DTX capable small cells. Hence, the power saving of cellular network by deploying small cells can be expressed mathematically from 2.6 and 2.7 as follows.
\[ S_{2}(\delta_{M}, \eta_{M}, \delta_{s}, \eta_{s}, S) = \frac{S \cdot (\eta_{S}(P_{A}^{M} - P_{A}^{S} - \delta_{M} \cdot P_{I}^{M} - P_{I}^{S} \cdot \delta_{s}) + P_{I}^{S} \cdot \delta_{s})}{P_{A}^{M} \cdot \eta_{M} + \eta_{S} \cdot \delta_{M} \cdot (1 - \eta_{M})} \]  
(3.14)
Chapter 4

Methodology

The main aim of this chapter is to describe the simulation tool and the implementation procedure followed to obtain the thesis work results.

4.1 Simulation Tool

In order to investigate the power saving in a Hetnet in this thesis work, Mathematica, which is a computational software program, is used to develop the system level simulator. Furthermore, WiPack is also used as a backbone to develop the simulator for this work. The simulator is made up of several modules and scripts which implement specific algorithms and the pseudo code of the main ones will be explained briefly in the following sections.

4.2 Simulation procedure

The simulation procedure followed in this thesis work is a time static system level simulation or snapshot simulation approach where every snapshot represents the status of the Hetnet network in a simulation frame duration of $T = 1$ hour. As a consequence, all users that access the cellular network between the $n^{th}$ and the $(n + 1)^{th}$ hour were generated at the beginning of the $n^{th}$ hour along with their respective traffic demand. The above procedure was repeated for sufficient number of times for the sake of considering the randomness of the position of the users in the network. Furthermore, as mentioned earlier the energy consumption of a Hetnet with and without cell DTX was also assessed taking the same number and type of small cells per each macro cell.
As a summary, 4.1 demonstrates the general overview of the simulations of a heterogeneous cellular network in a concise manner.

4.3 Feasible load calculation

This algorithm solves the feasible load problem introduced in section 3.1 in Chapter three. It enables to find the network load vector \( \eta^* = (\eta_{M1}, \eta_{S1}, ..., \eta_{BS}) \), for a given user snapshot and a given user association scheme. As a result, the network resource utilization is in balance with the resource demand in all cells and the cell loads are within given ranges. This algorithm is an iterative approach that takes as an input the loads of the macro and small cells in worst interference scenario \( (\eta_0) \) and the accuracy parameter to stop the algorithm \( (\epsilon) \), and the output of the algorithm is a Hetnet load vector \( \eta^* \). Please note that the “worst interference scenario” is intended to be the situation in which, each user always gets interference from all the surrounding BSs when it is served by its own BS. The mains steps of the algorithm are summarized in the following pseudo-code briefly.
Algorithm 1 Feasible load of a Hetnet at time $t$ for a given inter-site distance $D$ [18]

Require: $\eta_0(t)$ is Hetnet load vector and $\epsilon = 10^{-3}$

Ensure: $\eta^*(t) = (\eta_{M1}^*(t), \eta_{S1}^*(t), \ldots, \eta_{BS}^*(t))$

1. $\eta_i^*(t) \leftarrow \eta_0(t), \forall i \in S^{BS}$
2. Compute $\eta_{new}^i(t) \forall i \in S^{BS}$ (from equation 3.3)
3. while $\max \{\eta^*(t) - \eta_{new}^i(t)\} < \epsilon$ do
4. $\eta^*(t) \leftarrow$ updateLoad ($\eta_{new}^i(t)$)
5. Compute $\eta_{new}^i(t) \forall i \in S^{BS}$ (from equation 3.3)
6. end while

Algorithm 2 Assessing daily APC saving of a Hetnet using cell DTX and small cell deployment

Require: $\lambda(t), \delta$

Ensure: $S_1$ Energy saving of a Hetnet vs macro no cell DTX
$S_2$ Energy saving of a Hetnet vs macro cell DTX

1. for $t = 1$ to $t = 24$ do
2. for $r = 1$ to $r = N_{MAX}$ do
3. Calculate $\eta_r^*(t)$ using algorithm 1
4. Calculate $\eta_r(t) = f(\eta_r^*(t))$ (3.1)
5. end for
6. Calculate $\eta(t) = mean\{\eta_r(t)\}$
7. Calculate $P_{A1}(t)$ (from equation 3.6)
8. Calculate $S_1(t)$ or $S_2(t)$ (from equation 3.12 or 3.2.1)
9. end for

The algorithm takes as an input parameters: the area traffic demand $\lambda(t)$, and the BS micro sleep parameter $\delta$. Basically, we consider a maximum number of $N_{max}$ realizations in each hour and for each realization, the algorithm calculates the network feasible load vector $\eta_r^*(t)$ and average cell load of all BSs $\eta_r(t)$. Then, the representative power consumption $P_{A1}(t)$, and energy saving of a Hetnet deployment relative to the reference macro only with cell DTX $S_2$ and the energy saving of a
Hetnet deployment relative to macro only no cell DTX $S_1(t)$ are calculated for each hour.

### 4.4.1 Energy/power saving in Hetnet using cell DTX for urban/dense urban area using simple analytical method

In this thesis work, in addition to the simulation methodology, a simple analytic methodology with some assumptions was also adopted to calculate the energy saving of a Hetnet particularly for the scenario when the number of small cells per macro cell was more than one. This was done mainly to simplify the complexity of the implementation of the work.

$$\eta_{M_{i+1}}^* = \eta_{M_1}^* - i \cdot \eta_{S_1}^*$$ (4.1)

where

- $\eta_{M_1}^*$ is the load of the macro BS when 1 small cell is deployed,
- $\eta_{M_i}^*$ is the load of the macro BS when $i$ small cells are deployed where $i$ ranges [1,10]
- $\eta_{S_1}^*$ is the load of small cells calculated from the simulation

Moreover, the input values for the analytic method were carefully taken from the Hetnet simulation of one small cell per macro cell. As a result, all the small cells per macro cell were assumed to have the same load as the load of the small cell from the simulation and the power consumption calculations were done accordingly for both urban and dense urban area deployment. Moreover, each of the small cells off load the macro cell by equal amount that lead to the case where the macro cell will be serving no user after deploying enough amount of small cells.

### 4.5 Simulation parameters

During the simulations, there are two types of parameters, dynamic and static parameters. For instance, to mention some of the dynamic parameters, the number of active users in the network $M$ and the area traffic demand $\alpha(t)$. Both of the above parameters change hourly depending on the simulation scenarios. Nevertheless, there are parameters which are always kept constant for all the simulations time and they are summarized in the following table 4.1. The parameters provided in table 4.1 and used for path loss calculations are set according to the specification in 3GPP.
### 4.5 Simulation parameters

<table>
<thead>
<tr>
<th>Parameters/description</th>
<th>Value</th>
</tr>
</thead>
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<td></td>
</tr>
<tr>
<td>Number of sites in service area</td>
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<td>Inter-Site Distance of macro</td>
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<td>radius of small cell</td>
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<td>Wrap-around technique</td>
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<td>Noise spectral density</td>
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<td><strong>Channel</strong></td>
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</tr>
<tr>
<td>BS height</td>
<td>30 m</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td></td>
</tr>
<tr>
<td>Simulation frame</td>
<td>1 hour</td>
</tr>
<tr>
<td>Accuracy parameter (Epsilon), ( \epsilon )</td>
<td>( 10^{-3} )</td>
</tr>
<tr>
<td>Number of Monte Carlo simulations, ( N_{\text{max}} )</td>
<td>100</td>
</tr>
<tr>
<td>Cell DTX factor, ( \delta )</td>
<td>([0.1] = 0.1, 0.3 \text{ and } 0.5 )</td>
</tr>
</tbody>
</table>

*Table 4.1: Simulation parameters.*
4.6 Performance metrics

In this thesis work similar to the previous research, area power consumption is taken as a performance measurement parameter used to assess the energy consumption of the different Hetnet deployment scenarios. Furthermore, the area power consumption saving is also formulated as the performance metric of a given Hetnet deployment. It indicates the percentage of energy saving relative to a reference. The reference used in this simulation work are macro only BSs in which all its BSs do not have the cell DTX capability and the second reference is when all the macro BSs possess the micro-sleep capability.

4.6.1 Area power consumption

Area power consumption denoted by $P_A$ is defined by the ratio of the total network power consumption to the total service area $A$. Hence, it is measured in watt per square kilometer $W/Km^2$ and mathematically it can be expressed as the equation below.

$$P_A = \frac{P_{Tot}}{A} = \sum_{i=1}^{N} \frac{P_{BS_i}}{A} \quad (4.2)$$

Moreover, the area power consumption saving $P_{Si}$ of a given Hetnet deployment relative to a reference can be expressed mathematically as follows

$$P_{Si} = \frac{P_{S_{ref}} - P_{Si}}{P_{S_{ref}}} \quad (4.3)$$
Chapter 5

Simulation Results and Discussion

This chapter presents simulation results of the implementations explained on chapter four. First, the average load of the macro and small cells for the different Hetnet deployment scenarios was investigated briefly. Moreover, the simulation results related to the potential power saving in a Hetnet using cell DTX and small cell deployment (micro cells) are also demonstrated for both urban and dense urban area deployments.

5.1 Cell DTX and small cell deployment results

In this section, the effect of using the cell DTX feature on reducing power consumption in Hetnet cellular networks is described in an elaborated way. In addition, the power saving that can be achieved via a Hetnet (micro BSs) deployment will be investigated by varying the cell DTX factor.

In this thesis work, a reference cellular mobile network, which is a macro BS only cellular network with and without cell DTX is used to estimate the power saving that can be achieved using the cell DTX and small cell deployment techniques. The power consumption calculation of the reference cellular network has taken into consideration the different traffic demands specifically urban and dense urban area deployments as explained in [3].

5.1.1 Cell load of reference macro only cellular network

In this subsection, the average load and the daily power consumption of the reference macro only cellular network will be discussed concisely. This reference takes into account both the urban and dense urban traffic demands, although in this thesis work only homogeneous users were considered in order to simplify the traffic distribution.
As mentioned above, figure 5.1 shows that the daily average BS load of the reference cellular network. This reference cellular network consists of 19 macro BS which have average cell load that follows to the daily traffic profile in Europe. Besides, the daily average cell load $\eta_i$ varies from 2% up to 33% for urban area deployment and for the dense urban deployment it ranges from 8% up to 93% as it can be clearly seen in figure 5.1. This shows that, the amount of resource blocks allocated by BS (enodb) is proportional to the number of users which are active in that cell at that particular time. Moreover, the conventional way of designing a mobile data network is based on the peak hour to keep the quality of service. As a result, in a cellular network which have been designed to support the peak hour demand, there will be a number of unused resource blocks during the off traffic period. Under this circumstance, the network shows a great potential for power saving by putting the BSs in to micro sleep mode named as cell DTX for the duration of time that the BS is not serving users.

![Average cell load of the reference cellular network, calculated using algorithm one feasible load approach, for urban and dense urban area deployment](image)

**Figure 5.1:** The daily average cell load of the reference cellular network, calculated using algorithm one feasible load approach, for urban and dense urban area deployment

### 5.1.2 Daily Area power consumption of macro only cellular network with and without cell DTX

Similar to the feasible cell load, the daily average area power consumption for urban and dense area deployments have been calculated taking the same scenarios and simulation parameter values. In general, the area power consumption in both cases has the same pattern as the feasible cell load shown above. Moreover, as can be seen from figure 5.2 the area power consumption increases from 1150 $\text{W km}^{-2}$ in low load hour to 1200 $\text{Kw km}^{-2}$ in peak hour for urban area deployment when there is no cell DTX. Similarly, in the case of dense urban area deployment the area power consumption increases from 1200 $\text{W km}^{-2}$ and 1450 $\text{Kw km}^{-2}$ for the low traffic hour and peak area power consumption.
5.2 Daily total area power consumption of LTE network using cell DTX and Hetnet deployment

Moreover, for the case where cell DTX is not applied the above figure shows that the power consumption of a network is independent of the load of the cell at the specified hour mainly when the cellular network is designed according to the peak hour load. In other words, the power consumption of a cell when serving few users has no big difference compared to the case when the cell is serving with its full capacity. As a consequence, this leads to a significant energy wastage especially during the low traffic hour due to the idle power consumption of the BSs.

However, in order to eliminate the above energy wastage, micro sleep capability can be introduced by all the BSs types. After using cell DTX to the macro only BSs, as it can be seen in figure 5.2 it is possible to save around 40% of the power consumption when cell DTX factor is set 0.5 similar to what is found in [17] and [18]. In general case, the more we deactivate parts of the BS the more power that could be saved during the low traffic period.

However, in this thesis work, the main focus is on analyzing the effect of mixing micro sleep capability and small cell deployment on the power consumption of a cellular network.

5.2 Daily total area power consumption of LTE network using cell DTX and Hetnet deployment

In the following section, the daily total area power consumption of a Hetnet is discussed in a brief way compared to the macro only BSs with and without cell DTX. In order to clarify the calculation of power consumption of a Hetnet, the power consumption of a macro layer and the small layer are also plotted separately for both deployment areas, urban and dense urban. Furthermore, the load of the macro and small cell layer in a Hetnet deployment is further illustrated graphically in the
appendix as the power model used is mainly dependent on the load of a BS in the network.

5.2.1 Daily total area power consumption of a Hetnet compared to macro only with no cell DTX

In the following section, the total area power consumption of a Hetnet (Macro-micro LTE), in which both types of the BSs have the cell DTX capability, is compared to the macro only BSs that do not have micro-sleep capability. Hence, in order to investigate the power consumption situation in a Hetnet, the macro layer and small layer parts are explained as follows.

5.2.1.1 Power consumption of a macro layer in a Hetnet deployment

The power consumption of a macro layer in a Hetnet has the same pattern in both urban and dense urban. As can be clearly shown from figure 7.2 and 7.1 in the appendix, the load of the macro cell is decreasing as we put more small cells and reached zero after putting more small cells. This shows that the small cells were offloading the macro cells. As a result, the macro layer power consumption was decreasing accordingly. However, after all the users are served by the small cells, the macro BS power consumption is becoming fixed, which is the idle power consumption of the macro cell layer. The above pattern of the macro layer power consumption can be seen in figure 5.3.

![Figure 5.3: The daily Total power consumption of a Macrolayer of Hetnet (different traffic profile) with cell DTX factor 0.1,0.3,0.5](image)

5.2.1.2 Daily power consumption of the small cell layer in a Hetnet deployment

The power consumption of the small cell layer is increasing as we put more small cells per macro cell for both urban and dense urban area deployment. This is quite obvious that, the more small BSs we deploy the more we off load the macro BS.
5.2 Daily total area power consumption of LTE network using cell DTX and Hetnet deployment

Hence, we see in figure 7.3 and 7.4 the total load of the small cells with in a macro cell is increasing proportionally. Further more, after fully offloading the macro BS, the power consumption of the small cells will be increased due to the idle power consumption part, although the small cells are not serving any users as can be clearly seen on 5.4. So, from the above observation deploying small cells under the macro coverage will not always lead to an energy efficient cellular network, unless the optimum number is found.

![Figure 5.4: Total power consumption of small cell layer for different traffic profile with cell DTX factor 0.1,0.3,0.5](image)

5.2.1.3 Total power consumption of a Hetnet with reference to macro only with cell DTX

The power consumption of a Hetnet has decreased when we put up to three small cells per macro with cell DTX capability. Particularly, for dense urban deployment, we get minimum area power consumption when we deploy three small cells for the cell DTX factor of 0.1 and we get two small cells when the cell DTX factor used is 0.3. This implies that small cells can reduce the power consumption provided that there is traffic that can be offloaded from the macro cells. Moreover, the small cell deployment can also lower the average load of the macro cell as can be seen from figure 5.5 and 5.6.
As shown in figures 5.3 and 5.4 generally, the daily power consumption has reduced significantly when the cell DTX is used in the BS. In addition, the figure demonstrates that the energy consumption of a dense urban area deployment is higher compared to the urban area deployment when we deploy a small cell with any cell DTX factor. Moreover, even if when we do not implement the cell DTX capability in the BS, the power consumption of a low traffic area in our case urban area deployment is slightly lower than dense urban area deployment. This shows that, there is a direct relationship between the load of a cell and its power consumption. As can be seen in the 5.7 the effect of deploying a cell DTX capable small cells (micro BSs) in to an already energy efficient macro BSs due to micro sleep technique will be analyzed in a brief way. This analysis of power saving is done for both the deployment areas, that is urban and dense urban area deployments.
The main observation from figure 5.7, it is possible to save more power by deploying small cells on a dense urban area deployment when more parts of the BS are deactivated. The typical example of the thesis work where it is possible to save maximum power due to small cell deployment is, when the cell DTX used is set to 0.1 and three micro BSs or when cell DTX is 0.3 and one small cell is deployed in a dense urban area deployment. In the first case, this circumstance it is possible to save 36% during the peak hour and 3% in the latter case. However, in this thesis work it is not possible to save power by small cell deployment during the urban area deployment, since the small cells do not have much power to offload from the macro BS.

Moreover, the above results align with the mathematical formula given in eq 3.14 which shows the more the small cell can offload the macro BS the more power that can be saved due to small cell deployment. Therefore, especially in the dense urban area deployment, the more micro sleep capable small power BS are deployed, the more power that can be saved until the macro BS is fully offloaded by the small cells. However, there is an optimum number of small cells per macro BS that can give the minimum area power consumption. In this thesis work, the optimum number of small cell hotspot is found to be three (three micro BSs cells), when 90% parts of the BS are deactivated and it is one small (micro cell) when 70% parts of the BS are deactivated.

5.3 Power saving of a Hetnet using cell DTX and optimum micro cell deployment

As discussed previously in order to estimate the area power consumption saving of a Hetnet a cell DTX factor of 0.5, 0.3 and 0.1 was used regardless of the hardware limitations. In this section, we compare the power saving of a Hetnet dense urban and Hetnet urban area deployment taking the macro only BSs with and with out
### Table 5.1: Power saving for both urban and dense urban area deployment

<table>
<thead>
<tr>
<th>Deployment area</th>
<th>cell DTX factor</th>
<th>Average Daily power saving</th>
<th>Reference cellular network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>0.5</td>
<td>17%</td>
<td>Macro only no cell DTX</td>
</tr>
<tr>
<td>Urban</td>
<td>0.3</td>
<td>43.5%</td>
<td>Macro only no cell DTX</td>
</tr>
<tr>
<td>Urban</td>
<td>0.1</td>
<td>69.9%</td>
<td>Macro only no cell DTX</td>
</tr>
<tr>
<td>Dense urban</td>
<td>0.5</td>
<td>5%</td>
<td>Macro only no cell DTX</td>
</tr>
<tr>
<td>Dense urban</td>
<td>0.3</td>
<td>18.6%</td>
<td>Macro only no cell DTX</td>
</tr>
<tr>
<td>Dense urban</td>
<td>0.1</td>
<td>50.3%</td>
<td>Macro only no cell DTX</td>
</tr>
<tr>
<td>Dense urban</td>
<td>0.1</td>
<td>12.5%</td>
<td>Macro only with cell DTX</td>
</tr>
</tbody>
</table>

As far as the power saving is concerned, in general in both of the traffic profiles the power saving is higher during the low traffic periods of a day and dropping faster during the peak traffic hours. Furthermore, as it can be clearly seen from figure 5.3 average power saving of an urban area deployment is around 69%, 43.5%, 17% when the cell DTX used is 0.1, 0.3 and 0.5 respectively where as the average power saving of dense urban area deployment is 50.3%, 18.6% and 5% respectively. These results demonstrate that as the power saving in a Hetnet becomes higher, the traffic demand in a given service area is lowered or in other words, this cell DTX strategy enable us to save a considerable amount of energy when the BSs of the Hetnet are underutilized because of low traffic load.
5.4 Sensitivity analysis of power saving in a Hetnet

On the other hand, when the power consumption of an already energy efficient macro BS due to cell DTX is compared to a small cell deployment in a dense urban area deployment, there is still a potential for power saving. However, as shown in figure 5.9 the power saving is higher mainly during the peak hour, as the small cells offload the macro BS by a greater amount on that specific period of the day.

![Figure 5.9: The percentage daily area power consumption of a Hetnet vs Macro only with cell DTX](image)

5.4 Sensitivity analysis of power saving in a Hetnet

In this section the sensitivity analysis of the power saving in a mobile cellular network is done with respect to both cell DTX and small cell deployment.

5.4.1 Sensity analysis compared to macro only with no cell DTX

The power saving of a Hetnet can be expressed as a function of the average load $\eta_{avr}$ and the cell DTX factor $\delta_{avr}$ of both of the BS types, macro and small cells as shown in the equation below. Hence, the power saving represented using $S1$ is expressed as a function of the load of both the BSs ($\eta_M$, $\eta_s$) and cell DTX factor associated with each of them ($\delta_M$, $\delta_s$).

$$S1(\delta_M, \eta_M, \delta_s, \eta_s) = \frac{P^M \cdot (1 - \delta_M) \cdot (1 - \eta_M) + P^S \cdot (1 - \delta_s) \cdot (1 - \eta_s)}{P^M_A \cdot \eta_M + P^M_I \cdot (1 - \eta_M)}$$ (5.1)

In order to analyze the effects of $\delta_M$ and $\delta_s$ on the total power saving of a Hetnet,
the first partial derivative is calculated as follows

$$\frac{\partial S_1}{\partial \delta_M} = \frac{-(1 - \eta_M) \cdot P^M_I}{P^M_A \cdot \eta_M + P^M_I \cdot (1 - \eta_M)}$$

(5.2)

$$\frac{\partial S_1}{\partial \delta_S} = \frac{-(1 - \eta_S) \cdot P^S_I}{P^M_A \cdot \eta_M + P^M_I \cdot (1 - \eta_M)}$$

(5.3)

$$\frac{\partial S_1}{\partial \eta_M} = \frac{-(1 - \delta_M) \cdot P^M_I \cdot (P^M_A - P^M_I) \cdot \eta_M + (P^S_A - P^S_I \cdot \eta_S) + P^M_I + P^S_I + P^M_A - P^M_I \cdot H}{G_2}$$

(5.4)

$$\frac{\partial S_1}{\partial \eta_S} = \frac{-(1 - \delta_S) \cdot P^S_I \cdot (P^M_A - P^M_I) \cdot \eta_M + (P^S_A - P^S_I \cdot \eta_S) + P^M_I + P^S_I + (P^S_A - P^S_I \cdot H}{G_2}$$

(5.5)

where

$$H = P^M_I \cdot (1 - \delta_M) \cdot (1 - \eta_M)$$

$$G = P^M_A \cdot \eta_M + P^M_I \cdot (1 - \eta_M)$$

Since the cell load and the cell DTX factor of both the macro and a small cell are lower than 1, it means that equations 5.2, 5.3, 5.4, and 5.5 will have a negative sign for all values of $\eta_M$, $\eta_S$, $\delta_S$ and $\delta_M$. Hence, the following conclusions can be drawn.

- The energy saving of a Hetnet $S_1(\delta, \eta_M, \delta_s, \eta_s)$ is a decreasing function for a given $\delta_M$ and $\delta_s$. Consequently, for a set a of BSs with the same load, the more we put the BSs in to micro-sleep mode the higher the energy saving that can be attained.

- The energy saving of a Hetnet $S_1(\delta_M, \eta_M, \delta_s, \eta_s)$ is a decreasing function with respect to $\eta_M$ and $\eta_s$, therefore for a set of BS with the same cell DTX factor the higher the traffic load of a BS, the lower will be the energy saving that can be achieved.

5.4.2 Sensitivity analysis compared to macro only with cell DTX

In this sub section the effect of small cell deployment on power saving is described briefly. Hence, the following conclusions can be drawn based on the mathematical
The energy saving of a Hetnet due to small cell deployment $S_2(M, M, S), \eta_M, \delta_s, \eta_s, S)$, is an increasing function with respect to the traffic load of deployment area. Accordingly, the higher the load of the small cells, the higher energy saving that can be achieved in a target area.

Moreover, the higher the number of small cells deployed per macro BS until it reached the optimum number, the higher the power saving. However, after the threshold for minimum area power consumption, the energy consumption starts to increase as we deploy more small cells.
Chapter 6

Conclusion

In general, energy efficiency mechanisms in cellular mobile radio network can be implemented either during network deployment or network operation. Moreover, it is also possible to put network operation energy saving techniques in to an already energy efficient network by deployment to maximize energy saving in a cellular network or vice versa. As a particular example, in this thesis work, the effect of mixing small cell deployment with BSs’ operation cell DTX is investigated for different deployment areas. In general, adapting the BSs operation using cell DTX techniques to the traffic variation in a network will reduce the amount of energy wasted due to mismatch between traffic demand and BS power consumption in an LTE network. In addition deploying low power BSs at the edge of the macro cells could also decrease the area power consumption of a network significantly.

This thesis work investigates if there is a potential for energy saving by mixing cell DTX BS operation with small cell deployment. It also tries to find the optimum number of small cells that can be deployed per macro cell for a minimum area power consumption and the energy saving associated with this Hetnet deployment scenario. As a result of the analysis done in this thesis work, mixing both cell DTX and small cell deployment leads to power saving in both peak hour and off-peak hour. Since, we can save high power using cell DTX particularly when more BS components can be put in a micro sleep mode in low traffic hour and on the contrary more power saving can be achieved using small cell deployment during the peak traffic hour. So, it is more energy efficient to deploy micro sleep capable smalls in a hotspot to gain from both techniques.

6.1 Summary

In this thesis work in order to answer the above research questions mentions in chapter one, a time static system level simulation were used along with load dependent BS
power consumption. Besides, the interference model used is also load dependent which makes the load calculations of a cell complex. As a result, the iterative feasible load calculation was implemented. Moreover, in this study the following assumptions were also taken into account to simplify the simulation of the LTE network. These are: the effect of signaling and the power loss when switching on/off the components of the BS is ignored when calculating the power consumption.

In addition, the system model is a 19 hexagonal cells with omnidirectional macro BS at the center with lower power BSs are deployed at the edge of the macro BS. Besides, during the simulation process, only downlink communication of reuse factor of one is taken into account due to the main focus to the BS power consumption when serving users. Further more, COST231hata was used as an out door path loss model for both urban and dense urban area deployments and the European long term large scale traffic model has been implemented to make the system level simulation more realistic. After doing the system simulation, it is found that it is possible to save a significant amount energy in a dense urban area deployment when mixing small cell deployment with cell DTX BS operation based on the simulation models and parameters used in this work.

6.2 Finding

The main findings of the study, which answer the research questions are grouped into two. These are the power saving results of a Hetnet when the reference considered was a macro only with no cell DTX (mainly results related to cell DTX) and the other one is power saving in a Hetnet when the reference used is macro only with cell DTX, which illustrates the energy efficiency due to small cell deployment under the coverage of a macro BS.

6.2.1 Power saving with respect to cell DTX

- In the specific system level simulation scenarios where all BSs (macro and small cell) in the network have the cell DTX capabilities, it is possible to have a significant amount of power saving compared to macro only with no cell DTX. For instance, there is an average of 50.3% potential power saving for dense urban and 69.9% for urban area deployment when cell DTX mode puts 90% of its hardware in to sleep mode i.e when cell DTX factor used is 0.1. However, when the cell DTX mode puts 70% of BS hardware in to sleep mode (cell DTX factor of 0.3), the average power saving is reduced to 43.5% for urban area deployment and 19% for the dense urban deployments.
However, from the sensitivity analysis compared to macro only with no cell DTX, it is shown that the power saving that can be achieved in a Hetnet is highly dependent on the BS cell DTX capability and load status of the network that can be represented by the average cell load in the network. Accordingly, the following conclusions can be drawn.

- The area power consumption saving in a Hetnet linearly increases as the hardware deactivating capability of the BS is enhanced. That means more components of the BS can be put into micro-sleep mode without affecting the quality of service expected. As a result, for a Hetnet power consumption scenario of the same traffic demand, the more components of the BS can be put in the micro-sleep mode, the more energy saving that can be achieved.

- Similarly, the area power consumption saving of a Hetnet utilizing the cell DTX capability is also a convex decreasing function of the average network load. In other words, this can be interpreted for any cell DTX capable BS, the lower the average load of its cell, the higher the potential energy saving that can be achieved compared to macro only with no cell DTX capability.

### 6.2.2 Power saving findings with respect to small cell deployment with cell DTX capabilities

In this thesis work, it is shown that it is possible to save power even when the reference used is macro only with cell DTX. In the typical example in dense urban there is around 36% in the peak hour when the cell DTX factor used is 0.1 and 3% when cell DTX used is 0.3. However, in this thesis work it is not possible to save power by deploying small cells in the urban area deployment of any cell DTX factor. In general, the findings can be summarized as follows: The energy saving of a Hetnet due to small cell deployment, is an increasing function with respect to the traffic load of deployment area. Accordingly, the higher the load of the small cells the higher energy saving that can be achieved in a target area. Moreover, the higher the number of small cells deployed per macro BS until it reached the optimum number, the higher the power saving. However, after the threshold for minimum area power consumption, the energy consumption starts to increase as we deploy more small cells.

The above two observations can help us to conclude that cell DTX BS operation mechanisms and small cell deployment are promising tools for saving significant amount of energy in a Hetnet deployment scenarios. Moreover the effect of mixing both cell DTX and small cell deployment leads to power saving in both peak hour and off-peak hour. Since, we can save high power using cell DTX
particularly when more BS components can be put in a micro sleep mode in low traffic hour and on the contrary more power saving can be achieved using small cell deployment during the peak traffic hour. So, it is more energy efficient to deploy micro sleep capable smalls in a hotspot to gain from both techniques.

6.3 Limitations and Future Work

Even though, the system model considered in this thesis work is fairly good. However, there are still some improvements that can be made to have more realistic system model. For e.g, the current traffic model assumes all the users have the same traffic demand although the deployment of the users is not uniform. However, considering heterogeneous users will make the traffic model more practical. Furthermore, this work can be further enhanced using different parameter setting during the time static simulation of a Hetnet cellular network. For example, studying the effect of using different values for ISD of the macro and the small cell. However, to further improve the results found, a dynamic system level simulation can also be used to see the variation of the system parameters in a short duration of time. Lastly, in this thesis work, a fixed transmission power of an antenna is used for the analysis; however a variable transmission power of the BS with respect to the traffic variation can be used for further analysis.
Bibliography


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Declaration

I hereby certify that I have written this thesis independently and have only used the specified sources and resources indicated in the bibliography.

Stockholm, February 2015

My Name
This appendix provides a set of commented figures in order to support the main results presented and discussed in Chapter five.

**Figure 7.1:** Load of each macro cell in a hetnet dense urban versus number of small cells.
Figure 7.2: Load of each macro cell in a hetnet urban versus number of small cells

Figure 7.3: Total load of small cells in a hetnet denseurban area deployment
Figure 7.4: Total load of small cells in a hetnet urban area deployment