Towards Green Wireless Access Networks

Main Tradeoffs, Deployment Strategies and Measurement Methodologies

SIBEL TOMBAZ

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Abstract

Wireless access networks today consume 0.5 percent of the global energy. Rapidly growing demand for capacity will further increase the energy consumption. Thus, improving energy efficiency has a great importance not only for environmental awareness but also to lower the operational cost of network operators. However, current networks which are optimized based on non-energy related objectives introduce challenges towards green wireless access networks. In this thesis we investigate the solutions at the deployment level and handle energy efficiency assessment issues in wireless access networks.

The precise characterization of the power consumption of the whole network has a crucial importance in order to obtain consistent conclusions from any proposed solution at the network level. For this purpose, we propose a novel power consumption model considering the impact of backhaul for two established technologies, i.e., fiber and microwave, which is often ignored in the literature. We show that there is a tradeoff between the power saved by using low power base stations and the excess power that has to be spent for backhauling their traffic which therefore needs to carefully be included into energy efficiency analysis. Furthermore, among the solutions that are analyzed, fiber-based backhaul solution is identified to outperform microwave regardless of the considered topology. The proposed model is then used to gain a general insight regarding the important design parameters and their possible impact on energy- and cost oriented network design. To this end, we present a high-level framework to see the main tradeoffs between energy, infrastructure cost, spectrum and show that future high-capacity systems are increasingly limited by infrastructure and energy costs where spectrum has a strong positive impact on both.

We then investigate different network deployment strategies to improve the energy efficiency where we focus on the impact of various base station types, cell size, power consumption parameters and the capacity demand. We propose a refined power consumption model where the parameters are determined in accordance with cell size. We show that network densification can only be justified when capacity expansion is anticipated and over-provisioning of the network is not plausible for greener network. The improvement through heterogeneous networks is indicated to be highly related to traffic demand where up to 30% improvement is feasible for high area throughput targets.

Furthermore, we consider the problem of energy efficiency assessment at the network level in order to allow operators to know their current status and quantify the potential energy savings of different solutions to establish future strategies. We propose elaborate metric forms that can characterize the efficiency and a methodology that indicate how to perform a reliable and accurate measurement considering the complexity of wireless networks. We show the weakness of the current metrics reporting the "effectiveness" and how these might indicate disputable improvement directions unless they are properly revised. This illustrates the need for a standardized network level energy efficiency evaluation methodology towards green wireless access.
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Part I
Chapter 1

Introduction

1.1 Background

During the last decade, mobile radio network has experienced a tremendous evaluation. Since the introduction of GSM in the 1980’s, network optimization objective was to improve network coverage in the most cost effective manner where the growth of traffic and revenue per user were predictable. For these networks, low bandwidth services such as voice and short message service (SMS) were dominating the traffic. However, the introduction of wireless packet data networks which allow mobile internet usage in the beginning of 21st century fundamentally changed the wireless access networks’ direction. In 2007, first time data traffic exceeded voice traffic which constitutes a breakthrough point for the operators. The rapid proliferation of smartphones, laptops, and tablet PCs with built-in cellular access as well as flat rate tariff accelerate the traffic growth significantly. Today, even though every second person in the world use mobile telephony, the penetration rate of smart phones is only 25-30% [1]. Therefore, forecast indicates hundredfold to thousandfold increase in mobile traffic volume before 2020 due to the increase in both data usage per user and the penetration rate of using these devices [2].

This explosive growth will require massive capacity expansion that will demand large investment in developing current wireless access networks. In simple terms, radio network capacity can be increased by improving three key elements: spectrum, technology, i.e., spectral efficiency, and topology, i.e., network architecture, as illustrated in Fig. 1.1. Operators and vendors have different solution proposals to expand the capacity which differ according to operators’ current network and regulation situation, etc. Spectrum can be seen as an "easy way" of improving the network capacity. However it is subject to regulation and thus it is slow to implement. The challenges in spectrum licence such as cost, time, etc., have produced current cellular systems based on 3G and 4G (LTE) standards which are based on squeezing as many bits per second out of a given small spectrum allocation. Nevertheless, technology seems to run into the fundamental limits with the impressive
progress in making better use of spectrum during the last decade. Therefore, how much new solutions in physical layer can bring to cope with the mobile data growth has been broadly discussed [4]. On the other hand, network densification, i.e., enabling frequency reuse in smaller cells, presents a limitless capacity solution. Thus, it is expected to be the main expansion technique for the operators. In that regard, heterogeneous networks, i.e., strategically located large number of small base stations (BSs) such as micro-, pico- and femto BSs under the macro-cellular umbrella coverage provide an opportunity to meet the increasing demand for capacity.

In this picture, any chosen capacity expansion method to cope with the growing data volumes and customer expectations will bring enormous increase both in capital expenditure (CAPEX) and operational expenditure (OPEX). On the other hand, the operator revenues from data are also growing rapidly and replacing the decline in revenues from voice and messaging. However, annually 10% -20% increase in revenue compared to doubling traffic, pose steeply reducing revenue per unit data consumed and create a "revenue gap" as shown in Fig. 1.2 [5]. Therefore, the main challenge that operators face nowadays is to find a solution to manage the traffic growth by meeting the users’ expectation of communicating anywhere, anytime with ever increasing data speeds, in a cost effective manner.

Another important consequence of the data explosion is the rapid growth in energy consumption which was basically counted as a free resource in the past. However, even today wireless access networks are alone responsible for 0.5% of the global energy consumption and this number is expected to double within next 5 years [1]. Consequently, the cost of energy constitutes almost 50% of the operational
1.2. ENERGY EFFICIENCY CHALLENGES AND LITERATURE SURVEY

Due to the aforementioned reasons, mobile network operators and their equipment suppliers from industry and academia have started to address the arising concern of excessive energy consumption with one common goal:

- **To develop appropriate techniques in order to reduce the energy consumption of wireless access networks by considering the capacity requirement and the user satisfaction.**

However, non-energy-related optimization objectives introduce some challenges towards green wireless access which can be summarized as follows:

expenditures of mobile operators in some countries [6,7]. On the other hand, carbon footprint of overall communication sector is expected to almost triple and reach to about 235 mega-tons CO2e in 10 years unless something is done. The pressure from European Union who targets 20% greenhouse gas reduction by 2020 compared to 2000 levels and increasing energy prices introduce energy efficiency as an important design criteria for wireless access networks [8].

Up to now, networks are designed for coverage and capacity where energy efficiency has not yet any importance. Energy was only concerned for mobile stations (MSs) which impose strict limits on their power consumption due to the battery constraints. Therefore, currently energy consumption of the MSs constitutes only a small fraction of the total [9]. This situation in fact creates a vast potential for improvement of the current energy efficiency levels of wireless access networks. However it needs a paradigm shift in network design objective and a holistic system approach instead of incremental improvements in electronics and signal processing.

**1.2 Energy Efficiency Challenges and Literature Survey**

Figure 1.2: Current challenge for mobile radio networks: The revenue gap [5].


- **Equipment Level Challenges:** Current hardware for radio base stations (RBSs) are generally optimized for maximum load scenarios and due to lack of scalability, these components operate at sub-optimal points most of the time. This situation leads to significant energy loss in the equipment level. Therefore, traffic load adaptive BS components such as transceivers and power amplifiers and introduction of sleep modes will significantly decrease the energy consumption [10, 11]. Furthermore, the power amplifier which is the main consumer of an RBS with poor efficiency figure needs further improvement [12, 13].

- **Node Level Challenges:** Similar problem occurs at the node level due to the fact that RBSs are designed to guarantee a certain level of service (QoS) at any time and the energy consumption adaptation accordance with traffic is inadequate. This results in lower energy efficiency figures especially at the medium and low load conditions when the network is under-utilized. In this regard, improved link level techniques to enable the adaptation of radio transmission to the dynamic traffic load are extensively investigated in the literature [14–16]. These radio resource management (RRM) solutions are reformulated to maximize the energy savings by finding the optimum balance between the demand and the resource allocation [17–19].

- **Network Level Challenges:** From a network perspective, the main challenge originates due to the known tradeoff between energy consumption and quality of service (QoS). Therefore the decision on which entity is more important, e.g., higher performance or lower energy consumption, and how much performance degradation is allowed for a certain energy saving should be investigated in order to propose energy efficient solutions at the network level. These techniques should consider the challenging task of saving energy while QoS felt by users is minimally affected. However, the large number of energy efficiency metrics in use which capture the relationship between the level of service taken from the network and energy that has been consumed, pose many challenges which can be summarized as follows: i) The conclusion regarding the impact of the solution will differ according to the chosen QoS indicator and the performance target; ii) The identification of the reason behind the variation in energy efficiency, e.g., energy consumption is reduced for a given level of service, or there are increased benefits for a given energy consumption, will be difficult. This will both complicate to compare the results from different proposed solutions and create confusion regarding the real impact on energy savings.

Considering these main challenges, energy savings at the network level are mainly investigated at the deployment and the management perspectives. In contrast to energy efficient RRM techniques which allow seconds level dynamic adjustment, network level management ensures energy savings in accordance with slow change in the traffic in both temporal and spatial domains.
Therefore, it requires BS cooperation as well as self optimization in order to provide different energy efficient network configurations based on capacity demand [20–23]. Furthermore, defining the optimum deployment strategy for a given traffic distribution in a given environment yet constitutes potential for improvement of energy efficiency which is in the scope of this thesis as illustrated in Fig. 1.3. Considering the fact that exponential increasing traffic demand will require the deployment of several orders of magnitude more base stations, using high power macro base stations will be neither energy-efficient nor very sound from a radiation perspective. In this regard, carefully adapting the deployment of micro/pico/femto BSs to the capacity requirements is believed to enable energy savings due to their low transmit power requirements [24–27]. Cell size optimization, heterogeneous network deployment, sectorization and distributed antenna systems are some of the proposed solutions in this perspective [28,29].

Above all, a proper network evaluation methodology is also essential in order to allow operators to apprehend their current status and position themselves in the global wireless industry to identify how well they are doing in energy efficiency. This issue currently draws attention from standardization bodies such as European Telecommunication Standards Institute (ETSI) and International Telecommunication Union (ITU), however it has not yet reached a consensus [30,31].

![Figure 1.3: Overview of the problem area. The shaded area identifies the scope of the thesis.](image)

**Scope of the Thesis**

In this thesis, we consider the energy saving solutions at the network deployment level and handle the energy efficiency assessment problem in wireless access networks as highlighted in Fig. 1.3. We are herein primarily interested in answering the following questions:
• What are "green" costs of lowering energy consumption? How does the relationship between energy, spectrum and infrastructure cost impacts the network design?

• What are the most important parameters that affect energy efficient deployment? Does backhaul power consumption has a significant impact?

• Does the network densification with smaller cells or heterogeneous network deployment strategies improve energy efficiency in wireless access networks?

• How to define metrics to describe the characteristics of network level energy efficiency and how to accurately perform a reliable measurement?

Towards green wireless access networks, one of the most important element is the precise characterization of the power consumption of the whole network in order to obtain consistent and realistic conclusions. Usually in the literature the total network power consumption is restricted to the sum of the power consumption of all BSs where the backhaul contribution is usually neglected [26,32,33]. However, due to the fact that backhaul power consumption for small cells can reach the same amount as the power consumption of the access point itself, the contribution of mobile backhaul power consumption will be highly dependent on the deployment strategy and thus it should be carefully considered in any energy efficiency analysis [34]. In the thesis, we handle this issue and present a novel power consumption model for mobile radio networks which considers the impact of mobile backhaul for fiber and microwave based solutions. The proposed model is then used to gain a general insight regarding the important design parameters and their possible impact on overall energy efficiency before getting into details in this large and comprehensive research area. Especially, the investigation of the main tradeoffs in wireless access networks by considering the total cost as the main design constraint was missing in the literature. In the thesis, we present a detailed cost model to highlight the tradeoffs between energy, infrastructure cost and spectrum and analyze the "green" costs of lowering power consumption in mobile radio networks.

We also investigate the optimum deployment strategies to improve the energy efficiency of the network which in fact depend on many parameters, e.g., coverage and capacity requirement, type of BSs, etc. Despite its large popularity, we have identified several contradictory conclusions regarding the efficiency improvement through the deployment of small cells and indoor and outdoor heterogeneous networks [25,28,29,35,36]. In this regard, we refine the base station power consumption model such that the parameters are determined by the maximum transmit power and demonstrate how different assumptions about capacity requirement affect the energy efficiency in different levels of network densification. We then analyze the energy savings through the deployment of heterogeneous networks with various type of BSs for both uniform and non-uniform traffic scenarios.

Finally we introduce a network level energy efficiency assessment framework which informs operators regarding the "effectiveness" of their network. This issue
is still in its infant stage although a substantial interest is mostly shown by standard-
ization bodies and industry players [30,31]. In this regard, even the identification 
of appropriate metrics that can describe the characteristics of energy efficiency in 
network level creates a big challenge. We handle this issue in the thesis and discuss 
how to define the metrics and how to perform a reliable and accurate measurement 
considering the complexity of wireless networks.

1.3 Contributions of the Thesis

In this section we briefly outline the contribution of the studies presented in the 
attached papers. This thesis is a compilation of six publications: four conference 
papers and two journal articles.

Chapter 2

This chapter overviews the main tradeoffs and analyzes some of the design con-
straints for future broadband wireless access networks in terms of total cost and 
energy. The findings are presented in the following papers:

• **Paper 1.** S. Tombaz, A. Västberg and J. Zander, “Energy and Cost Effi-
cient Ultra High Capacity Wireless Access”, IEEE Wireless Communication 

• **Paper 2.** S. Tombaz, K.W. Sung and J. Zander, “Impact of Densification 
on Energy Efficiency in Wireless Access Networks”, accepted to IEEE Global 
Comm. Conf. Workshops (GLOBECOM Wkshps), 2012.

Paper 1 introduces a high-level framework to investigate the impact of "green 
costs" of different energy efficient network architectures. The paper presents a 
detailed cost model and analyzes the impact of each cost factor on the design in 
order to highlight the tradeoffs between energy, infrastructure cost and spectrum for 
wireless access networks. In Paper 1, all authors contributed in devising the problem 
formulation, modeling and writing process, whereas simulations are executed by the 
author of this thesis.

Paper 2 focuses on energy oriented design and investigates the impact of network 
densification on energy efficiency under different network capacity constraints. The 
paper introduces a refined power consumption model where the parameters are 
determined by the maximum transmit power of BSs and presents an analytical 
framework to derive the optimum transmission power which maximizes energy ef-

ciciency. In Paper 2, the modeling, simulation and writing process were performed 
by the author of this thesis, while valuable insight has been provided by Ki Won 
Sung and Jens Zander.
Chapter 3

Chapter 3 focuses on the power consumption modeling for mobile radio networks considering backhaul in order to highlight the effect of mobile backhaul on the total power consumption. Initial assessments consider two established backhaul technologies, i.e., fiber and microwave, for various topological choices and results are presented in:


Paper 3 and 4 present an enhanced power consumption model for mobile radio networks with fiber and microwave backhauling solutions respectively. Different backhaul topologies are considered and their impact are evaluated with a case study. The author of this thesis executed the numerical results of both papers and wrote paper 3, whereas paper 4 is jointly edited by Paolo Monti. All authors of paper 3 and 4 contributed to the modeling and the problem formulation and Jens Zander and Lena Wosinska provided insight for the direction of the papers.

Chapter 4

This chapter investigates energy efficiency improvement through different heterogeneous networks compared to conventional deployment. The results and conclusion of this study are included in:


Paper 5 presents an energy efficiency assessment methodology in order to make a fair comparison between different heterogeneous deployment scenarios for different traffic distributions. The tradeoff between additional power consumed and the area throughput improvement from deploying small low power base stations are also analyzed.

This paper has been coauthored with one student of the wireless networks project course. The author of this thesis proposed the problem formulation, acted as a advisor and wrote the paper. Ideas were refined with the second author who also
developed the simulation code. Professor Jens Zander provided valuable insights regarding the direction of the paper.

Chapter 5
Chapter 5 considers the network level energy efficiency assessment issue in wireless access networks in order to allow operators to monitor their energy figures and identify possible improvement directions. This investigation is presented in:


Paper 6 presents an overview of current energy efficiency metrics in use and discusses their weaknesses in representing the "effectiveness" at the network level. The paper proposes more elaborate metrics which consider several network performance indicators and introduces an evaluation methodology. A list of research topics is also provided for fostering further studies. In Paper 6, all authors contributed in devising the problem formulation and the methodology proposal. It is jointly edited by Ki Won Sung while valuable insight provided by the other coauthors.

Other Related papers
The following paper, although not included in the thesis, discuss the conflict between two important design objectives, i.e., energy efficiency and throughput for low-power wireless system which opportunistically shares radio spectrum in temporal domain.


1.4 Thesis Outline
The thesis consists of two parts. The first part, comprising Chapter 2 through Chapter 5, contains the results and discussion of the included respective papers. Concluding remarks and recommendation for future works are outlined in Chapter 6. The second part contains verbatim copies of all papers that constitute the contribution of this thesis.
Chapter 2

Fundamental Tradeoffs in Green Wireless Access

Traditional design paradigms, based on assumptions of spectrum shortage and high cost base station sites, have produced current cellular systems where energy has yet any importance. However, as the energy saving and environmental protection gain interest, energy efficiency becomes an important design criteria for wireless access networks. Therefore vendors are actively investigating solutions at the equipment level to decrease the power consumption of the BSs. However, we believe that despite the necessity of these improvements, a holistic system approach is essential in order to cope with the increase in energy consumption in wireless access networks. To this end, we should consider a clean-state approach and aim to answer how different deployment strategies affect the total cost and energy consumption of the wireless access networks.

In this chapter, we handle this question, overview the main tradeoffs and analyze some of the design constraints for future green wireless access networks. This analysis will help us to gain insight about the important design parameters and their possible impact on overall energy efficiency improvement. More specifically, we first compare the "energy" and "cost" oriented optimal deployment strategies where the energy consumption and total cost are the main design constraints in the network respectively. To this end, we consider simple scenarios where a certain capacity has to be provided in a dense, interference limited network and investigate the relationship between infrastructure, spectrum and energy cost components. We further focus on energy oriented design and investigate the relationship between energy efficiency and densification with regard to an area capacity requirement by considering impact of interference, noise, backhaul and cell size dependent idle power consumption.
CHAPTER 2. FUNDAMENTAL TRADEOFFS IN GREEN WIRELESS ACCESS

2.1 Related Literature

Research on energy efficient wireless access networks is an extensive area that enclose all the layers and architectures. There is a great interest from academia to reduce the power consumption at all levels of the network, including hardware design, network management, network deployment, and resource allocation [9,16,37]. However, a high-level framework to indicate the main tradeoffs in wireless access networks by considering the total cost was missing. This issue has only been marginally considered in [38,39] which took the deployment cost of the proposed energy efficient solutions into account. However, backhaul power consumption has been ignored and total cost has not been investigated.

On the other hand, impact of network densification problem has been handled by several works [29,35,36,40]. The tradeoff between the power saved by using low power base stations and additional baseline power consumption because of the increase in the number of BSs deployed was the main consideration. Area power consumption of different deployment scenarios for a minimum received power target at the cell edge have been evaluated in [36] considering different idle power consumption figures and it has been stated that large cell deployments are more energy efficient due to the high idling power of existing BSs. On the contrary, in [29,35,40] small-cell based mobile radio networks have been claimed to be an efficient solution to provide high data rates with low power consumption. However, neither the impact of interference level nor the dependency of power consumption parameters on cell size has been taken into account in previous studies. The increase in system throughput via deployment of short-range BSs has mostly been ignored.

Existing Power Consumption Model

The power consumption model of a base station that maps the radio frequency (RF) output power to the total power supply for each type of base station is proposed within the energy aware radio and network technologies (EARTH) energy efficiency evaluation framework [33]. This model is widely used in the literature in order to assess the energy efficiency of the wireless access networks.

In the model, total power consumption of the BS is divided into two parts: (i) The idle power consumption, i.e., the power consumed in the BS even when there is no transmission; (ii) The traffic load dependent power consumption, which is expressed as below [33]:

\[ P_{in} = N_{TRX}(aP_{tx} + b_{radio}), \quad 0 \leq P_{out} \leq P_{max} \tag{2.1} \]

where \( P_{max} \) and \( N_{TRX} \) denote the maximum transmit power and the number of transceivers respectively. On the other hand, \( a \) represents the portion of the transmit power dependent power consumption due to feeder losses and power amplifier,

\footnote{The term "idle" will be used interchangeably with "baseline" in this thesis.}
whereas $b_{\text{radio}}$ accounts for the power consumption because of the active site cooling and the signal processing which constitutes the major part of the total power consumption of the BSs. The values of the parameters are defined in [33] based on the direct measurement of the BSs in different load situations and given by the following table.

<table>
<thead>
<tr>
<th>Base Station Type</th>
<th>$P_{\text{max}}$ [W]</th>
<th>$a$</th>
<th>$b_{\text{radio}}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro</td>
<td>40</td>
<td>2.66</td>
<td>118.7</td>
</tr>
<tr>
<td>Micro</td>
<td>6.3</td>
<td>3.1</td>
<td>53</td>
</tr>
<tr>
<td>Pico</td>
<td>0.13</td>
<td>4.2</td>
<td>6.8</td>
</tr>
<tr>
<td>Femto</td>
<td>0.05</td>
<td>7.5</td>
<td>4.8</td>
</tr>
</tbody>
</table>

In the thesis, this model will be used for benchmarking purpose. The extended version of this model where we incorporate the backhaul power consumption in [41] will be used in order to indicate the fundamental tradeoffs in green wireless access.

### Cost Model

Despite the growing impact of energy cost on OPEX, it is not the only concern for the mobile operators when they decide the system design and deployment. Considering the increasing revenue gap, operators’ main goal is to minimize their total cost while satisfying the QoS requirements. Here, we propose a simple cost model by assuming that the total cost of deploying and operating a mobile radio network consists of cost for deployment, spectrum licences and energy which can be expressed as

$$C_{\text{tot}} = C_{\text{spectrum}} + C_{\text{infra}} + C_{\text{energy}}.$$  \hspace{1cm} (2.2)

We illustrate the relative effect of each cost items on the network design in Fig. 2.1 in order to indicate the evaluation of mobile radio networks. Here, point
Figure 2.1: Key design constraints in wireless access networks [42].

A represents the current macro-cellular networks where the main design constraint has been the high spectrum cost. As the demand for capacity increases and the spectrum licenses require billion of dollars, the solution has been sought at the physical layer by aiming to increase spectral efficiency, i.e., squeezing as many bits/s out of a given small spectrum allocation. In this case, infrastructure cost was the dominant factor for the network design whereas energy was considered as basically a free resource (Point B). However, projections indicate that new spectrum bands will be available in both licensed as well as secondary access spectrum ("white space"). On the other hand energy consumption and the cost of energy are expected to grow rapidly in the upcoming years which takes us to point D. Therefore we can foresee that energy and infrastructure costs will dominate the design of future wireless access networks.

In this section, we first investigate the optimum deployment by considering the energy as the only or at least dominating constraint (Point C in Fig. 2.1). Then we will incorporate other key constraints into the design in order to illustrate the main tradeoffs and analyze their impact on future green wireless access networks.

**Energy Oriented Deployment**

Improving the energy efficiency in cellular mobile radio networks has recently gained great interest in the research community. The improvements in the literature has been achieved in two main ways:

- Reducing the energy consumption of BSs which are the main consumer in the whole network. The solutions have either been found at the equipment level, e.g., more efficient power amplifiers, or at the management level, e.g., adapting the BS activation based on the traffic situation.
- Employing energy saving network deployment strategies.
In the second approach, energy savings is achieved by carefully adapting the deployment of different type of BSs in accordance with the traffic requirement. In urban areas where large traffic is generated, a dense deployment will be required whereas in rural areas only a few macro type BSs will be deployed for coverage. This well known strategy has been used in current wireless access network design in order to satisfy the certain demand with minimum deployment cost by managing the spectrum. However, as we mentioned before energy cost has been ignored in the design and thus the relationship between network density and the total energy consumption has not been well known. Here, we aim to investigate the optimum network design from energy perspective and analyze how the reduction in transmit power and the additional baseline power consumption due to densification will impact the total network power consumption.

In a downlink direction of wireless communication, the required transmit power per base station, $P_{tx}$, in order to achieve a minimum required data rate, $\bar{R}$, for a worst case scenario (user at the cell edge, i.e., distance to BS is $R_{cell}$) using Shannon’s theory can be modeled by [36,43]

$$P_{tx} = \left[2^{\frac{\bar{R}}{W}} - 1\right] \frac{N_0 W}{cG} R_{cell}^\alpha.$$  \hspace{1cm} (2.3)

Here, $N_0$ is the power spectral density of additive white gaussian noise, $W$, $c$ and $\alpha$ are the system bandwidth, the path loss coefficient and exponent respectively. We observe from (2.3) that, the required transmit power of the BS for a given data rate increases with cell range if we only take the path loss dependence into account. On the other hand, when we calculate the total transmit power of the considered wireless access network with a fixed area, $A$, i.e., $P_{tx,tot} = \frac{A}{\pi R_{cell}^2} P_{tx} = N_{BS} P_{tx}$, we determine an opposite trend where increased number of BSs in the network, $N_{BS}$, decreases the total transmit power for any $\alpha > 2$. However, as it is shown in Eq. (2.1), total power consumption of a mobile radio network is not restricted to the transmission power, and therefore transmission independent power components, e.g., backhaul, cooling, signal processing, etc., should be taken into account in order to arrive at valid conclusions [24,41]. Consequently, the total power required in order to fulfill the average total network throughput requirement, $\bar{R}_{tot}$, by using $N_{BS}$ homogeneous base stations in the service area can be expressed as follows [42]:

$$P_{tot} = N_{BS} \left\{ a \left( \frac{N_0 W}{cG} \left[ 2^{\frac{\bar{R}_{tot}}{W}} - 1 \right] \left( \frac{A}{\pi N_{BS}} \right)^{\alpha/2} \right) + b_{radio} + b_{backhaul} + y \frac{\bar{R}_{tot}}{N_{BS}} \right\} + d,$$  \hspace{1cm} (2.4)

where $b_{backhaul}$ and $y$ represent the power consumed by the backhaul transceiver and the traffic dependent portion of the backhaul power consumption respectively. On the other hand, $d$ accounts for the baseline power consumption of the backhaul which constitutes a significant portion of the total, for current solutions. The details regarding backhaul power consumption modeling for different technology options will be given in the next chapter.
This equation clearly shows the relationship between power consumption, the amount of spectrum allocated, and the infrastructure cost which is related to number of base stations. We observe that, area power consumption, \( P_{area} = \frac{P_{tot}}{A} \), has the following properties:

\[
\lim_{N_{BS} \to 0} P_{area}(N_{BS}) \to \infty,
\]
as well as

\[
\lim_{N_{BS} \to \infty} P_{area}(N_{BS}) \to \infty,
\]
This indicates that there is always a non-null and finite \( N_{BS}^* \) that minimizes the area power consumption of the network where the optimum point will vary in accordance with the system bandwidth, path loss exponent, QoS requirement and the power consumption parameters which depend on the used equipment.

Fig. 2.2 shows the variation of the area power consumption with the number of base stations and its shallow minimum. We can also see the significant positive impact of system bandwidth on the optimum number of base stations and the total power consumption. Due to the fact that small amount of spectrum will require very high spectrum efficiency, i.e. \( S = \frac{R_{tot}}{N_{BS}W} \), to achieve the required data rate, area power consumption has the rapid increase as it is shown in the left part of the figure. On the other hand, as the network densified the baseline and the backhauling power consumption constitute the key elements of the total power consumption. Therefore area power consumption gives an optimal deployment density for each spectrum allocation.

![Figure 2.2: Area power consumption vs. number of base stations for different system bandwidths (A = 20km² and \( R_{tot} = 400Mbps \)) [42].](image)
2.2. ENERGY AND COST EFFICIENT HIGH CAPACITY WIRELESS ACCESS (PAPER 1)

Cost Oriented Deployment

As discussed previously, energy is not the only design criteria despite its growing importance. Therefore, it is essential to take the "green" costs of lowering power consumption into account to indicate the real objective of the operators, i.e., to maximize their profit.

The total cost can be illustrated by using the simple model given in Eq. (2.2) as below:

\[ C_{tot} = c_0 N_{BS} + c_1 \left\{ N_{BS} \left[ a \left( \frac{N_0 W}{cG} \left[ 2 \frac{\delta_{rot}}{W} - 1 \right] \left( \frac{A}{\pi N_{BS}} \right)^{\alpha/2} \right] + b_{radio} + b_{backhaul} + y \frac{\bar{R}_{tot}}{N_{BS}} \right] + d \right\} + c_2 W, \]  

(2.5)

where, \( c_0 [\text{€}/BS] \) is the annual cost per base station which includes the annualized CAPEX and OPEX excluding the energy cost. On the other hand, \( c_1 \) is the annual energy cost ("electricity bill" [€/energy unit]) and the \( c_2 \) is the annualized spectrum cost [€/MHz]. \(^2\)

Here, we first investigate the tradeoff between the energy consumption and the infrastructure cost by assuming that spectrum cost is fixed. Fig. 2.2 indicates that we need denser networks up to some extent in order to reduce the area power consumption. However our analysis in [42] showed that when we consider the additional cost of deploying the BSs, optimum deployment based on total cost requires less number of base stations under the same QoS requirement, as expected. On the other hand, it has been also presented that increasing infrastructure cost does not change the cost-optimum point but only result in a level shift on the total network cost.

Furthermore, we assess the amount of spectrum an operator should acquire as it is illustrated in Fig. 2.3 where variations of cost items as function of the system bandwidth are shown. Here, we define the optimum number of base stations as the one minimizes the total cost of the considered wireless access network which is obtained for each spectrum allocation. Firstly we note in Fig. 2.3 that the infrastructure cost is inversely proportional to system bandwidth. It is well known deployment strategy that required network density to cope with a certain amount of demand will be lower if more spectrum is available. We also show that the spectrum cost will be the dominant factor for the network design as the more spectrum is available. It is due to fact that energy consumption drops rapidly with the bandwidth as it is illustrated in the previous section. This also induces a decrease in

\(^2\)In this paper, we made the following assumptions regarding the cost items in order to provide realistic numerical evaluations: The annual cost for a macro BS whose cell range varies between 500m to a few kilometers is €0.02 million/BS [44,45] and the annual energy cost equals to €876/kW. In order to include spectrum cost, despite the high variance in different countries, we consider the 4G spectrum auctions in Sweden where €210 million is paid for a 15-year lease of 190 MHz in the 2.6 GHz band.
2.3 Effect of Densification on Green Wireless Access Networks (Paper 2)

In this paper [46], we investigate the relationship between energy efficiency and densification with regard to an area capacity requirement. We demonstrate how different assumptions about capacity requirement and base stations types affect the energy efficiency in different levels of network densification. To this end, we refine the base station power consumption model such that the parameters are determined by the maximum transmit power and develop a simple analytical framework to derive the optimum transmit power that maximizes energy efficiency for a certain capacity target. The model and the results are summarized next.

Power Consumption Model

Here, we have used our extended power consumption model presented in [41] which includes backhauling power consumption to analyze the impact of densification where the total power consumption of a network is written as

Figure 2.3: Total network cost vs. bandwidth ($A = 20 km^2$ and $\bar{R}_{tot} = 400 Mbps$) [42].
\[ P_{tot} = N_{BS} \left[ aP_{tx} + b_{radio} + b_{backhaul} + \frac{(1 - \tau)P_{max}^{switch}A_{switch}}{n_{ports}C_{max}^{switch}} + \frac{\tau P_{max}^{switch}}{n_{ports}} \right]. \tag{2.6} \]

Here \( b_{backhaul} \) accounts for the power consumption of backhaul transceiver, and the uplink interface, \( P_{max}^{switch} \) is the maximum power consumed at the switch and \( A_{switch} \) is the aggregate traffic traversing the switch. On the other hand, \( \tau, C_{max}^{switch} \) and \( n_{ports} \) represent the portion of the switch power that is independent of the backhauled traffic, \( \tau \in [0, 1] \), capacity and the number of ports of the switch, respectively.

The significant effect of power consumption parameters on area power consumption has been assessed in [42] which has indicated that completely contradictory conclusions can be drawn about the cell size impact if we consider different ratios between load dependent power consumption, \( aP_{tx} \) and the idle power consumption, \( b_{radio} \). Therefore, we propose to write these parameters as a function of maximum transmit power, \( P_{max} \), of the hypothetical BSs to fairly assess the impact of network densification. We have created approximating functions that capture important patterns in the data in Table 2.1 by only considering small, low power BSs, i.e., micro, pico, femto, as below:

\[ a = \mu - \eta \log_2 (P_{max}), \tag{2.7} \]

\[ b_{radio} = \kappa P_{max} + \psi, \tag{2.8} \]

where \( \mu = 4.15, \eta = 0.5, \kappa = 7.6 \) and \( \psi = 5.1 \). It should be noted that each combination of \( a \) and \( b_{radio} \) represents a hypothetical BS customized to \( P_{max} \).

**Energy Efficiency**

Energy efficiency (\( \Psi \)) is defined as the ratio of the total number of bits that were correctly delivered in the network during the observation period (\( T \)) over the network energy consumption during the same time where the unit is bits/Joule [33]. Since the network energy consumption is the multiplication of the power consumption with time, it can also be written as the ratio of the throughput, (which is equal to network capacity, \( C_{net} \) for considered fully loaded system), over the network power consumption, \( P_{tot} \) illustrated in Eq. (2.6), which can be expressed in bps/W as below:

\[ \Psi(P_{tx}) = \frac{C_{net}}{P_{tot}}. \tag{2.9} \]

Under the assumption that the network is fully loaded regardless of the cell size, network throughput can be written as

\[ C_{net} = N_{BS}C_{cell}, \tag{2.10} \]
where \( N_{BS} = \frac{A}{\pi R^2} \) is the number of base stations and \( R \) is the cell radius.

Here, fluid model [47] is used in order to model the interference which is based on the idea of indicating the interfering base stations by an equivalent continuum of transmitters. The model assumes that mobiles and base stations are uniformly distributed in the area, thus the network has constant mobile station (MS) density and cochannel BS density. As in the previous paper, we consider worst case scenario which allows us to make an analytical analysis. Consequently, energy efficiency is given in the following expression [46]:

\[
\Psi = \frac{N_{BS} W \log_2 \left( 1 + \frac{1}{\left[ \frac{R_{area}}{R} - 1 \right]^{2-\alpha} + \frac{N_0 W}{C_{2tx} R^\alpha} } \right)}{N_{BS} \left[ a P_{tx} + b_{radio} + b_{backhaul} + \frac{(1-\tau) P_{max, switch}}{n_{ports} C_{switch}} A_{switch} + \frac{\tau P_{max, switch}}{n_{ports}} \right]}.
\]

**Problem Formulation**

In this framework, we aim to find the optimum transmit power, \( P_{tx}^{opt} \), within the range of maximum allowed RF output power of the base station, \( P_{tx}^{max} \), which maximizes the energy efficiency under the constraint that network capacity will stay constant. Note that both \( \Psi \) and \( C_{net} \) are functions of the cell range. The optimization problem can be mathematically expressed as follows:

\[
\begin{align*}
\text{Maximize} & \quad \Psi \\
\text{subject to} & \quad C_{net} = C_{target}, \\
& \quad P_{tx} \leq P_{tx}^{max}.
\end{align*}
\]

It should be noted that dense deployment of BSs results in low \( P_{tx}^{opt} \) figure. Therefore, it is possible that a transmit power higher than \( P_{tx}^{opt} \) increases \( C_{net} \) with a comparably low increase in the total power consumption, which gives an improved bps/W value. However, it is doubtful that providing more capacity than required is meaningful even if it gives higher energy efficiency. Therefore, we considered the equality constraint for the capacity target in Eq. (2.12).

**Results**

We have herein demonstrated the relationships between area network capacity, energy efficiency and cell size for fixed and variable BS power consumption parameters. We consider an area with a radius of \( R_{area} = 10 \) km covered by small base stations where the cell range varies between 50-500m. It is assumed that deployed base stations are equipped with one omni directional antenna. System and backhaul power consumption parameters are listed in Table 2.2.
2.3. EFFECT OF DENSIFICATION ON GREEN WIRELESS ACCESS NETWORKS (PAPER 2)

Table 2.2: Experimental parameters

<table>
<thead>
<tr>
<th>System and Path Loss Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency ((f))</td>
<td>2GHz</td>
</tr>
<tr>
<td>Bandwidth ((W))</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Path loss constant ((c))</td>
<td>(10^{-3})</td>
</tr>
<tr>
<td>Antenna Gain ((G))</td>
<td>2 dBi</td>
</tr>
<tr>
<td>Path Loss exponent ((\alpha))</td>
<td>4</td>
</tr>
<tr>
<td>Thermal Noise ((N_0))</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Noise figure</td>
<td>10 dB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Backhaul Power Consumption Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b_{\text{backhaul}})</td>
<td>3W</td>
</tr>
<tr>
<td>(P_{\text{max}}^{\text{switch}})</td>
<td>300W</td>
</tr>
<tr>
<td>(\tau)</td>
<td>0.8</td>
</tr>
<tr>
<td>(C_{\text{max}}^{\text{switch}})</td>
<td>10 Gb/s</td>
</tr>
<tr>
<td>(n_{\text{ports}})</td>
<td>24</td>
</tr>
</tbody>
</table>

It should be noted that for each densification level and network throughput target \(C_{\text{target}}\), transmit powers of BSs in the area are adjusted to \(P_{tx}^{\text{opt}}\) which is given as below:

\[
P_{tx}^{\text{opt}} = \frac{N_0 W R^{\alpha}/cG}{\left[\frac{1}{2\left(\frac{R^2 C_{\text{target}}}{R_{\text{area}} W}\right) - 1}\right] - \frac{2}{(\alpha - 2)} \left(1 - \left(\frac{R_{\text{area}}}{R}\right)^{2 - \alpha}\right)}.
\]  

(2.13)

Results show that the deployment of the largest feasible cell size which can satisfy the given performance requirement, \(C_{\text{target}}\), maximizes energy efficiency when we consider fixed BS power consumption parameters. It should be noted that micro type base stations are considered for this purpose with the parameters of \(a = 3.1\) and \(b_{\text{radio}} = 53\) [24,33]. On the other hand, when we use the proposed model where the parameters vary based on maximum transmit power, it has been illustrated in Fig. 2.4a that the optimum point shifts towards smaller cells. It is due to the fact that impact of load dependent power consumption \((aP_{tx})\) becomes dominant for large cell size deployment because of the increase in both optimum transmit power, \(P_{tx}^{\text{opt}}\), and the coefficient \(a\) which denotes the transmit power dependent power consumption as it is shown in Eq. (2.7). As expected, higher area capacity requirement lowers the optimum cell range and favors smaller cell size which is shown more clearly in Fig. 2.4b. Furthermore, we observe that, even though energy efficiency is maximized by the deployment of larger cell size in low capacity demand region, it quickly loses its efficiency, and even becomes infeasible to fulfill the capacity demand.
CHAPTER 2. FUNDAMENTAL TRADEOFFS IN GREEN WIRELESS ACCESS

Figure 2.4: Relationship between energy efficiency, area capacity and network densification for variable BS power consumption parameters [46].
2.4 Conclusion

In this chapter, we have overviewed the main tradeoffs and analyzed some of the design constraints for future green wireless access networks in order to gain insight about their possible impact on overall cost and energy. Even though traditional mobile radio networks have been designed based on assumptions of spectrum shortage and high cost base station sites, future capacity limited systems have shown to be more and more constrained by energy cost. We herein first determined the main characteristics of such future infrastructures to show their dependence on the various cost items and analyzed the tradeoff between energy-infrastructure cost-spectrum. Moreover, we evaluated the effect of network densification on energy efficiency by considering the impact of interference, noise and cell size dependent idle power consumption.

We conclude that, spectrum has a strong positive impact on energy consumption and infrastructure cost and thus significant reduction in total cost is achievable if more spectrum is available. This indicates the importance of dynamic spectrum access and studies on feasibility of high frequency operation. Moreover, we observe that both energy and total network cost considerably depend on the base station density and as the energy price increases, the network design is more and more constrained by energy which results in the need of relatively dense networks. Network densification is also justified by the increasing capacity demand since large cell deployment quickly loses its efficiency, and even becomes infeasible to fulfill the capacity requirement. In this perspective, careful prediction of capacity demand is a key challenge for energy efficient deployment of mobile radio networks. We foresee that idle power consumption and backhaul will be main constraints in the future network design. Therefore accurate power consumption models for different backhaul technologies and consideration of spatial and temporal heterogeneity of the traffic for network deployment and operation are essential in order to proceed towards green wireless access networks.
Chapter 3

Access Network Energy Consumption Modeling with Backhaul

In order to quantify and compare the energy efficiency improvements from different solutions and identify future network strategies, the power consumption of the entire network needs to be precisely characterized. Although mobile backhaul is a part of mobile radio network, its power consumption is mostly omitted due to the fact that for a macro type BS, the power required to backhaul its traffic constitutes only small fraction of the total BS power consumption. However, with the potential evolution towards heterogeneous network (HetNet) deployment, where a large number of small base stations is used to meet the increased need for coverage and capacity, power consumption of backhaul is expected to be one of the bottlenecks for future green wireless access networks.

In this chapter, we will assess the power consumption of mobile backhaul for two main backhaul technologies, i.e., fiber and microwave, and incorporate into the base station power models. Our objective is to show the impact of different technology and architectural options of backhaul on the total power consumption of the network. We consider three backhaul topologies for microwave solutions, i.e., ring, tree and star, and only one topology is analyzed, i.e., a dedicated point-to-point (P2P) star, for fiber solution. To this end, we handle a case study to evaluate and compare the energy efficiency of each backhaul technology.

3.1 Related Literature

Power consumption assessment of wireless access networks has been considered in several papers [48–50] and a widely-agreed power model is proposed within EARTH project [33]. This model is commonly used in the literature to evaluate the energy efficiency of the proposed solutions, where total power consumption is calculated by
only considering the type and the number of BSs in the network [28, 32, 51]. However, due to the fact that backhaul power consumption for small cells can reach the same amount as the power consumption of the access point itself, the contribution of mobile backhaul power consumption will be highly dependent on the deployment strategy and thus it should be carefully considered in any energy efficiency analysis [34]. Backhaul power consumption has only been considered in the papers which evaluate the impact of base station cooperation techniques in order to analyze tradeoff between the performance gain and the additional power requirement due to the exchange of channel state information (CSI) across the backhaul infrastructure [52]. Despite the consideration of different backhaul technology solutions, i.e., microwave, PON, optical, these simple models are inadequate to make accurate assessment.

3.2 Mobile Backhaul Solutions

Mobile backhaul is counted as part of the mobile radio network which connects BSs to network controllers over a variety of transport media. The rapid growth in data traffic put severe demands on backhaul capacity which requires urgent changes in the backhaul architecture. Today, operators can choose from three physical mediums: optical fiber, microwave radio and copper.

![Figure 3.1: Different backhauling solutions [53].](image)

The forecast on the penetration rate of these solutions are shown in Fig 3.1 where fiber is expected to be the main choice for the backhauling applications because of its ability to handle exponentially increasing network capacity. However, its higher CAPEX and longer deployment time urge operators to find short term solutions [54]. Microwave is an appealing solution due to its quick and relatively cheap deployment potential [55]. On the other hand, there are still a great interest on DSL-technology in order to increase their capacity so that the usage of existing infrastructure will be feasible [56]. Deployment of different backhaul solutions will vary in accordance with the availability of equipment, current infrastructure, licence cost and operators business situation, etc. The importance of deployment cost and
the capacity considerations aside, the power consumption is also essential to decide the future backhauling solutions.

### 3.3 Power Consumption of Fiber-Based Backhaul (Paper 3)

We herein present a novel power consumption model for wireless access networks by considering fiber-based backhaul which is the most appealing solution due to its high capacity [41]. The impact of backhaul power consumption on different network deployments is also evaluated.

#### Backhauling Solution

Fig. 3.2 represent the considered fiber-optic point-to-point ethernet backhauling layout. For simplicity, it is assumed that backhaul solution has only one aggregation level which means that the backhaul traffic from nodes is accumulated at the switches just before the edge network. We also assume that all the backhaul links are optical fibers where each node requires an optical small-form factor pluggable (SFP) interface to transmit their traffic over the backhauling fiber.

![Carrier ethernet backhauling layout](image)

**Figure 3.2:** Carrier ethernet backhauling layout [41].

#### Power Consumption Model

The total power consumption of a network, $P^{FIB}$, which consists of $m$ type of base stations by incorporating the power consumed by the fiber-based backhaul ($P_{bh}^{FIB}$) can be expressed as
CHAPTER 3. ACCESS NETWORK ENERGY CONSUMPTION MODELING WITH BACKHAUL

\[ P^{FIB} = \sum_{i=1}^{m} N_i P_i + P_{bh}^{FIB}, \]  

(3.1)

where \( N_i \) and \( P_i \) are the total number and the power consumption of \( i \)-th type of BS (e.g., Macro base stations) respectively where \( P_i = a_i P_{tx} + b_{radio,i} + c_i \). It should be noted that, here we enhance the model in Eq. (2.1) by the inclusion of \( c_i \) which indicates the power consumed at the SFP interface.

Here, backhaul power consumption \( P_{bh}^{FIB} \) consists of the power required for backhaul the traffic from BSs to the aggregation switch(es), i.e, downlink \( (P_{dl}) \), and from switch(es) to the edge network, i.e, uplink \( (P_{ul}) \), as well as the the power consumption of the switch(es) \( (P_s) \) itself which are the main consumer of the fiber-based backhaul solution. A detailed model for \( P_{bh}^{FIB} \) can be written as below:\(^1\)

\[ P_{bh}^{FIB} = \left \lfloor \frac{1}{max_{dl}} \left( \sum_{i=1}^{m} N_i \right) \right \rfloor P_s + \left( \sum_{i=1}^{m} N_i \right) P_{dl} + N_{ul} P_{ul}. \]  

(3.2)

Here \( N_{ul} \) denotes the total number of uplink interfaces which is represented as a function of total accumulated traffic in the network \( (Ag_{tot}) \) and the maximum transmission rate of an UL interface \( (U_{max}) \), i.e., \( N_{ul} = \left \lfloor \frac{Ag_{tot}}{U_{max}} \right \rfloor \). The constant \( max_{dl} \) represents the maximum number of DL interfaces that each switch has which is used to calculate the number of required switches in order to aggregate the backhauled traffic in the given wireless access network. On the other hand, \( P_s \) consists two main contributors: (i) the baseline power consumption, i.e., the power consumed at the switch even when there is no activity; (ii) traffic load dependent power consumption which is the a function of the total aggregated traffic in the switch \( (Ag_{switch}) \). The ratio between these two entities is represented by a weighting parameter \( \alpha \in [0, 1] \) which is given by

\[ P_s = \alpha P_{max} + (1 - \alpha) \frac{Ag_{switch}}{Ag_{max}} P_{switch}^{max}, \]  

(3.3)

where \( P_{switch}^{max} \) denotes power consumption of the switch at the full load scenario whereas \( Ag_{max} \) shows the maximum amount of traffic a switch can handle.

Results

In this paper, we assess the effect of mobile backhaul on the total network power consumption. To this end, we consider a case study and compare three different network deployments with respect area power consumption which satisfy the certain coverage and capacity demands. The network layouts and related assumptions are determined based on the work presented in [44]. On the other hand, the values

\(^1\)Here, we assume that: 1) each base station in the network uses a dedicated downlink interface, 2) all switches and the DL interfaces are identical.
of the power consumption parameters are defined for the current fiber-optic based backhauling solutions\(^2\), which are given in Table 3.1, while the power consumption of the nodes are computed based on [33]\(^3\).

<table>
<thead>
<tr>
<th>Consumer</th>
<th>Power Consumption [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{max})</td>
<td>300</td>
</tr>
<tr>
<td>(P_{ul})</td>
<td>2</td>
</tr>
<tr>
<td>(P_{dl})</td>
<td>1</td>
</tr>
<tr>
<td>(c_i)</td>
<td>1</td>
</tr>
</tbody>
</table>

In Fig. 3.3, it is observed that the relative impact of the power consumption of fiber-based backhaul increases when we consider heterogeneous network deployment where small, low power BSs are deployed to cater for traffic demand the compared to traditional macro-only deployment. This effect is more significant for Macro-WLAN deployment which doubles the required area power consumption to satisfy a certain demand. This is due to the fact that backhaul power consumption for small cells can reach the same amount as the power consumption of the access point itself. However, this impact is shown to be insignificant for the dense macro deployment scenario which clarifies the reasoning behind the ignorance of backhaul power consumption.

It should be noted that, in this paper network deployment has not been optimized in order to maximize the energy savings. Therefore, we can expect that both the actual and the gap between the area power consumptions of these network deployments will be lower when the energy is chosen as the main objective.

### 3.4 Power Consumption of Microwave-Based Backhaul

(Paper 4)

In the previous section, we have shown that, contrary to what is believed in the literature, mobile backhaul has a non-negligible impact on total network power consumption especially when networks are densified with small, low-power BSs to cope with the traffic demand. Therefore, in this paper [34], we extend our the analysis for microwave based solution in order to investigate whether the conclusions vary accordance with the technology and the topology selections.

\(^2\)Please note the considered solution has the following characteristics: (i) The data rate at the DL and UL interface are 1 Gb/s and 10 Gb/s respectively; (ii) Switch power consumption is calculated for \(\alpha = 0.9\), \(max_d = 24\) and \(Ag_{max} = 24Gb/s\). We have also investigate the impact of different baseline power consumption ratio in [41].

\(^3\)In the network layout, macro type base stations have 3-sectors where each can have two carriers, whereas small, low power BSs are assumed to have single carrier and omni-directional antennas.
CHAPTER 3. ACCESS NETWORK ENERGY CONSUMPTION MODELING WITH BACKHAUL

Backhauling Solutions

Herein, we handle ring, tree and star topologies for the microwave-based backhauling which are illustrated in Fig. 3.4 and compare the results with the fiber-based backhauling solution where the power consumption model is given in the previous section. For microwave based solutions, the number of sites that each radio access node, i.e., (RAN), is connected depends on the considered topology which affects the number of required links and consequently required power for backhauling. Regardless of the selected solution, each topology has a hub node that backhauls all the traffic towards the sink node. Therefore, the number of hubs in the network varies with the total number of BS in the area as well as the size of the considered topology. For simplicity, we assume that any BS in the topology, i.e., macro, pico BS, can be a hub node.

The backhaul links for each BS are dimensioned to cater for the capacity requirements which depend on the total traffic needs to be backhauled through the considered BS in the high load scenario. This is more challenging for ring and tree topologies due to the fact that most of the BSs in the topology are connected to one or more BSs which therefore need to carefully be considered while dimensioning. It should be noted that the topologies are only compared in terms of power consumption where other differences such as resilience and latency are ignored in this paper.

Power Consumption Model

Likewise the model in Eq. (3.1), the total power consumption of a network which consists of \( m \) type of base stations with the consideration of microwave based back-
3.4. POWER CONSUMPTION OF MICROWAVE-BASED BACKHAUL (PAPER 4)

Figure 3.4: Topology solutions for microwave based backhauling (Source: Senza Fili) [57].

haul can be written as

\[
P^{MW} = \sum_{i=1}^{m} N_i P_i + P_{bh}^{MW},
\]

(3.4)

where the power consumption of \(i\)-th type of BS, \(P_i\), is computed based on the model in Eq. (2.1) and the backhaul contribution (\(P_{bh}^{MW}\)) is expressed as follows:

\[
P_{bh}^{MW} = P_{sink} + \sum_{j=1}^{N_{BS}} P_j^{MW}.
\]

(3.5)

Here, \(P_j^{MW}\) and \(N_{BS}\) denote the power consumed for microwave backhauling of base station \(j\) and the total number of BSs in the network respectively. On the other hand, \(P_{sink}\) represents the power consumption of the sink node, i.e, the node is assumed to backhaul the all network traffic towards the edge network. We herein model \(P_j^{MW}\) as a function of number of microwave antennas (\(N_{ant}^{j}\)) used at the \(j^{th}\) BS and the total aggregated traffic that related BS needs to backhaul through (\(C_j\)) which is given by
\begin{equation}
P_j^{MW} = P_{j,agg}(C_j) + P_{\text{switch}}(N_{j}^{\text{ant}}, C_j) \tag{3.6}
\end{equation}

where

\[
P_{j,agg}(C_j) = \begin{cases} P_{\text{low}} \quad \text{if } C_j \geq T_{\text{low}} \- c \\ P_{\text{high}} \quad \text{if otherwise} \end{cases} \tag{3.7}
\]

and

\[
P_{\text{switch}}(N_{j}^{\text{ant}}, C_j) = \begin{cases} 0 \quad \text{if } N_{j}^{\text{ant}} = 1 \\ P_s \left[ \frac{C_j}{C_{\text{MAX}}^{\text{switch}}} \right] \quad \text{if otherwise} \end{cases} \tag{3.8}
\]

As it is illustrated in Eq. (3.7), we assume that power consumption of microwave solution in order to backhaul the traffic \( P_{j,agg} \) is denoted as a step function by considering the fact that different type of equipment will be selected based on the capacity requirement of the BS. For simplicity we define two power regions, i.e., \( P_{\text{low}} \) and \( P_{\text{high}} \), for each BS which represent low and high traffic capacity conditions respectively.

On the other hand, Eq. (3.8) shows power consumed at the switch \( P_s \) which is required at any BS only when it needs to backhaul the traffic of other BSs besides its own. The number of switches for each BS is computed based on the total traffic \( C_j \) and the maximum capacity of a switch \( C_{\text{MAX}}^{\text{switch}} \). It is assumed that all the used switches in the network are identical. In order to calculate the power consumption of the sink node, same assumptions are considered where the details can be found in [34].

\section*{Results}

Here, we consider two different deployment strategies which provide the same coverage and the network capacity in order to compare various backhauling solutions. The first is the traditional deployment where the required capacity is achieved by macro-only densification whereas the second strategy represents a heterogeneous deployment where pico type BSs are deployed to cater for the traffic demand under the macro-cellular umbrella coverage. It should be noted that considered case study is based on the work presented in [44]. The assumptions regarding the BS characteristics and power consumption parameters are the same as in the previous section. On the other hand, power consumption parameters for microwave based backhaul are defined based on [58] where \( P_{\text{low}} = 37W \), \( P_{\text{high}} = 92.5W \), \( P_s = 53W \), \( T_{\text{low}} = 500Mbps \), and \( C_{\text{MAX}}^{\text{switch}} = 36Gbps \).

Fig. 3.5 shows the comparison of microwave- and fiber-based backhaul solutions in terms of area power consumption for different area throughput requirements, for the heterogeneous network deployment scenario. Here we consider two cases regarding the size of the microwave topologies, i.e., small and large, in order to indicate the impact of relative performance difference between fiber and microwave
3.4. POWER CONSUMPTION OF MICROWAVE-BASED BACKHAUL (PAPER 4)

![Power Consumption Diagram](image)

(a) Small size microwave topology

![Power Consumption Diagram](image)

(b) Large size microwave topology

Figure 3.5: Area power consumption for different mobile backhauling solutions: microwave vs. fiber for Macro + Pico deployment [34].

Based solutions. It has been shown that star-like fiber solutions where each BS in the network has a dedicated P2P connection to the switches outperforms microwave
based solution in terms of area power consumption regardless of the considered topology. However, other design parameters such as the required deployment cost should also be considered which is beyond the scope of this paper.

Furthermore, among the three architectures for microwave, ring based topology is found to be the least energy efficient despite its high resilience to link failures. The reason behind is twofold. Firstly, all the backhaul links in the ring architecture operate at the high capacity region since each of them needs to carry all the traffic in the topology towards the sink node. Secondly, due to the same reason, each BS is required to be equipped with switch(es), regardless of the type. These increase the power required for backhauling when ring structure is deployed. On the other hand, star topology has the lowest power consumption, however it is inefficient since it needs longer line-of-sight links. This indicates that there is a tradeoff between the energy efficiency and resiliency which should be considered to define future backhaul solutions.

Lastly, we illustrate the impact of the considered solutions on the total area power consumption of the network in Fig. 3.6. It confirms the intuition that effect of backhaul power consumption is getting more influential as the small low power BSs are deployed to cope with the traffic. Figure proves that the conclusion is valid for all the considered technologies and the architectures.

Figure 3.6: Power consumption comparison of different backhauling solutions [34].
3.5 Conclusion

In this chapter, we have proposed novel power consumption models for wireless access networks considering backhaul in order to highlight the remarkable impact of mobile backhauling on the total power consumption. In particular, we made an initial assessment of two established backhaul technologies, for various topological choices. The models consider both static and traffic dependent part of the backhaul consumption, where the current solutions present very inefficient portfolio due to their high baseline power consumption. We then have compared the efficiency of each backhaul solution for different heterogeneous network deployment scenarios and evaluated the impact on the total power consumption.

We conclude that relative effect of mobile backhaul increases when heterogeneous networks are considered to cater for an increased need for coverage and capacity. This shows the tradeoff between the power saved by using small low power BSs and the baseline power that has to be spent to backhaul their traffic. Furthermore, it has been shown that fiber-based backhaul excels among the solutions considered due to its relatively low impact in terms of additional baseline power consumption. However, the high deployment cost and low availability of fiber especially in rural areas increases the interest on the easy-to-deploy and comparatively cheap microwave solutions where ring topology has been found to be the most costly in terms of power, despite of its resilience on link failures.

This indicates that power consumption of backhaul will be one of the most important design criteria during the evaluation process of mobile backhaul in order to cope with the increasing capacity demand. Therefore it needs to carefully be included into any energy efficiency analysis in order to accurately identify future network strategies towards green wireless access networks.
Chapter 4

Energy Efficiency Improvements Through Heterogeneous Networks

The rapid growth in power consumption has created a paradigm shift towards energy-efficiency-oriented design in wireless access networks. Therefore, various energy saving solutions have been proposed in different aspects, e.g., more efficient hardware design to impact the BS consumption directly, more elaborate network management strategies to adapt the traffic variation, radio resource management solutions to optimize the transmission and intelligent network architecture to cope with the traffic growth in a more energy efficient manner.

Previously we have analyzed the impact of cell size in a simple scenario where the traffic and the deployment are assumed to be homogeneous in order to understand the dynamics and key relationships for green wireless access networks. Herein, we will take a step forward and investigate the potential energy savings through heterogeneous network deployment strategies for both uniform and non-uniform traffic distribution scenarios. More specifically, we will analyze the impact of types and number of additional BSs as well as cell size on network energy efficiency. To this end, we will consider different heterogeneous network deployment scenarios in order to identify the most energy efficient design for variant network performance requirements.

4.1 Related Literature

Due to the fact that technology run into the fundamental limits with the impressive progress in making better use of spectrum during the last decade, network densification, i.e., enabling the frequency reuse in smaller cells, is expected to be the main capacity expansion technique where heterogeneous networks attract much attention\cite{44,59,59}. In this strategy, strategically located large number of small base stations (BSs) such as micro-, pico- and femto BSs under the macro-cellular umbrella coverage improve the system capacity in hotspots. These networks are also
CHAPTER 4. ENERGY EFFICIENCY IMPROVEMENTS THROUGH HETEROGENEOUS NETWORKS

seen as one of the key solutions to improve energy efficiency due to their ability to increase the capacity with a relatively lower energy cost compared to homogeneous macro deployment.

This concept has been considered in several papers for both indoor and outdoor deployments with various type of small BSs [24–26, 28, 32]. The energy need of heterogenous networks has been assessed in [24, 28, 32] for uniform traffic scenario considering different user densities. The power consumption models have been modified in order to represent the traffic load variation impact and it has been concluded in [32] that deployment of additional micro BSs is beneficial in terms of energy savings. On the other hand, indoor HetNet solutions have been investigated in [25, 26] which have presented contradictory conclusions regarding to the impact of co-channel deployment of femto- and macro-cells on the energy efficiency of wireless access networks.

4.2 Energy Efficiency Improvements Through Heterogeneous Networks (Paper 5)

In this paper [60], we investigate the energy efficiency of different heterogeneous network deployment strategies for different capacity requirement for both uniform and non-uniform traffic distribution scenarios, based on the inspiring work [32].

The considered network layout is shown in Fig. 4.1 which consists of 19 sites. Here the central cell is surrounded by two tiers of interferers. We assume that macro type BSs with omni-directional antennas are deployed in the middle of each cell and one or more small low power BSs such as micro, pico and WLAN are positioned at the cell edge with defined range and transmit power. We also investigate a dense macro scenario where the BSs deployed both at the cell center and the cell edge are macro type BSs. It is assumed that for all deployment scenarios, BSs at the cell edge do not contribute to macro cell coverage.

Energy Efficiency Assessment Methodology

In this paper, in order to fairly compare different deployments, we set requirements for network performance, i.e., coverage and area throughput. By this means, we prevent the network provisioning, i.e., providing more capacity than required, from being used in order to have higher efficiency figures. To this purpose, intersite distance has been identified as a control parameter to ensure that each strategy provides the same network performance by adjusting the transmission power of the macro BSs at the cell center.

1It should be noted that for the non-uniform traffic scenario, we define ten different hotspots where each has different user density and size and their location is assumed to be vary during the day. Half of the users are considered to locate in the hotspot areas.

2This methodology is proposed in [24] and energy efficiency improvement through micro sites together with macro BSs has been investigated. In our paper, we further analyze the impact of more various type of small-low power BSs in heterogeneous network deployment and more
4.2. ENERGY EFFICIENCY IMPROVEMENTS THROUGH HETEROGENEOUS NETWORKS (PAPER 5)

As aforementioned, we assume that the additional BSs deployed at the cell edge have fixed cell range and transmit power, whereas transmit powers of macro BSs at the cell center are calculated as a function of minimum required received power at the cell edge, $P_{\text{min}}$, intersite distance (ISD), $D$, and coverage requirement, $C$, i.e., the fraction of cell area where received power is above a certain level, as below [24]:

$$P_{\text{tx}} = P_{\text{min}} \frac{R_{\text{max}}}{R^\alpha} \left( \frac{D}{\sqrt{3}} \right)^\alpha = P_{\text{min}} \frac{C^{\alpha/2}}{3} D^\alpha. \quad (4.1)$$

We have analyzed how ISD affects the area power consumption of the network for each deployment strategy, and shown that there is always a finite $D_i^*$ that minimizes the area power consumption as we initially proved in Chapter 2\(^3\). On the other hand, it is illustrated that the optimum ISD is shifted towards larger ISDs when additional BSs are deployed and HetNet deployments increase the area power consumption as well as area network throughput compared to homogeneous deployment. Under these circumstances, we define an optimum ISD, $D_{i,\text{opt}}$, as one that minimizes the area power consumption under the given coverage and capacity constraints for each deployment strategy, $i$, as $D_{i,\text{opt}} = \min(D_i^*, \hat{D}_i)$. Here $\hat{D}_i$ represents the maximum ISD that can be selected to fulfill the capacity requirement. We then compare the energy efficiency of different heterogeneous deployments based on their minimum area power consumption, i.e., networks are designed based upon the optimum ISDs, for different capacity requirements. We have used the same methodology for both traffic distributions. However, unlike uniform traffic scenario, area power consumption and optimum inter site distance are determined importantly consider non-uniform traffic scenario.

\(^3\)Notice that unlike our previous model, here transmit power is calculated by only considering the coverage requirement.

Figure 4.1: Network layouts [60].
by averaging the values that are calculated for each hotspot realization for the non-uniform traffic distribution.

Results

The results presented in this section are for a scenario where macro BSs are positioned at the cell center and intersite distance is varied from 1000m to 4000m. The total power consumption of the network has been calculated based on the model in [24] by considering the different type of BSs. We assume that mobile users connect to the BS that provides the highest signal strength. The detailed simulation parameters can be found in [60].

Fig. 4.2a shows the minimal area power consumption as a function of area throughput target for the uniform traffic scenario. We observe that conventional deployment is the most efficient only when the traffic demand is very low, i.e., up to 2 Mbps/km². However, as the area throughput requirement increases, significant gains are achieved with the deployment of additional small base stations where the most efficient deployment varies accordance with the traffic density of the network. On the other hand, it has been shown that minimal area power consumption for each deployment is constant during a capacity demand interval. It is due to the fact that in this region, coverage is the limiting factor for the network deployment, and therefore optimum ISD is the one that minimizes the total power consumption, i.e., $D_{i, opt} = \min(D_i^*, \hat{D}_i) = D_i^*$. However, network is more and more constrained by the network capacity with the data traffic growth and thus optimum intersite distance is determined by the area throughput requirement of the network, i.e., $D_{i, opt} = \min(D_i^*, \hat{D}_i) = \hat{D}_i$.

In Fig. 4.2b, we define the area spectral efficiency target as 1 bit/s/Hz/km² and compare the minimum area power consumption of different deployment strategies. We have observed that for the given capacity target, heterogeneous network deployments always give higher energy efficiency compared to traditional macro only deployment where up to 30% energy savings is achievable.

As aforementioned, we have considered the same fixed network layout for the non-uniform traffic scenario and investigated the minimal area power consumption of different deployments where the users are assumed to be distributed inhomogeneously as illustrated in Fig. 4.1b. The results have indicated similar conclusion as the uniform traffic scenario and the deployment of WLAN nodes at the cell edge resulted in the highest energy efficiency until it could no longer satisfy the demand. We are aware that, the lack of reliable traffic map and improper placement of the additional small base stations, i.e., at the cell edge instead of the center of the hotspots, are the main drawbacks of the proposed analysis for inhomogeneous traffic. More precise conclusions regarding the energy savings with heterogeneous deployment can be obtained with the consideration of optimized network planning.

Notice that, backhaul power consumption has not been considered in this paper.
4.2. ENERGY EFFICIENCY IMPROVEMENTS THROUGH HETEROGENEOUS NETWORKS (PAPER 5)

Figure 4.2: Impact of heterogeneous network deployments on network power consumption for uniform traffic scenario [60].

(a) Minimal area power consumption as a function of target area throughput for uniformly distributed traffic.

(b) Minimal area power consumption as a function of number of base stations at cell edge for uniformly distributed traffic for $S = 1\text{bit/s/Hz/km}^2$. 

![Graph showing area throughput vs. minimal area power consumption for different network configurations.](image-url)
for a given realistic traffic map where the type and number of BSs are defined in order to maximize the energy savings. This will be investigated as a future work.

4.3 Conclusion

In this chapter, we have investigated the energy efficiency improvements through HetNet deployment strategies compared to conventional homogeneous deployment for uniform and nonuniform traffic scenarios. We have analyzed the impact of the type and number of additional BSs as well as cell size on energy efficiency. To this end, we have ensured that each deployment strategy provides the same network performance, i.e., coverage and area throughput. Energy efficiency has been represented with minimal area power consumption needed to fulfill the requirement which is calculated based on the optimized ISD for each deployment.

Simulation results have demonstrated that heterogeneous network deployments increase the area power consumption since the decrease in the transmit power is not enough to compensate the high idle power consumption. On the other hand, they prevail homogeneous deployment due to their superior throughput. Therefore, it has been concluded that energy efficiency improvements through HetNets are highly related to traffic demand. For both traffic distribution scenarios, we have identified the area throughput regions where the homogeneous macro deployment gives the lowest area power consumption. Furthermore, it has been observed that, conventional macro deployment loses its efficiency and even becomes infeasible to satisfy the increased traffic demand, whereas different HetNet deployments represent large energy savings for high area throughput targets.

Discussion and Validity of Results

It should be noted that, user fairness has not been taken into account in this chapter, since average area throughput has been chosen as the performance indicator instead of user demand. This situation might result in the degradation of some macrocell users’ performance as tradeoff for improving the average network capacity. This is due to the fact that deployment of additional small base stations only increases the throughput in a small area and causes interference to the macro users who stay close to the cell border. We may expect that the unfairness between users will be even higher when we consider non-uniform traffic with regular deployment since only a small fraction of the users will experience the high capacity. Despite all, the results can be interpreted as an indication of the large energy saving possibilities with the deployment of heterogeneous networks, especially when we consider the expected traffic growth.
Chapter 5

Energy Efficiency Evaluation at the Network Level

In this chapter, we handle network level energy efficiency (NLEE) assessment issues in wireless access networks. The necessity of more energy-aware solutions in different parts of the network aside, reporting the defined "effectiveness" is also essential for any operator to fulfill the following objectives: (1) to know its current status by comparisons with other networks; (2) to identify bottlenecks of the current network that has to be improved; (3) to quantify the potential energy savings of different solutions to establish future strategies. This challenging task requires a widely-agreed energy efficiency definition, a simple, intuitive and transparent metric for keeping the scores and a well-established measurement methodology in order to quantify NLEE. Even though, there are widely-agreed metrics in the literature and standardized methodologies to assess the energy efficiency in component and equipment levels, it is more challenging to define a comprehensive metric at the network level because of their heterogeneous nature which makes it difficult to choose a common performance indicator [15, 37, 61]. On the other hand, NLEE assessment methodology is still in its infant stage although a substantial interest is shown by standardization bodies and industry players [30, 31, 62].

We here present an overview of NLEE assessment and provide important research challenges to be addressed. Firstly, we give a high-level description about a framework of NLEE assessment and key elements that constitute the framework. Then, we discuss how to define metrics and how to perform a reliable and accurate measurement considering the complexity of wireless networks.

5.1 Energy Efficiency at Network Level: Definition, Measurement and Prediction (Paper 6)

In this paper [63], we introduce a NLEE assessment framework which mainly consists of an energy efficiency measurement block and an energy efficiency prediction
CHAPTER 5. ENERGY EFFICIENCY EVALUATION AT THE NETWORK LEVEL

Figure 5.1: Graphical representation of network level measurement [63].

block illustrated in Fig. 5.1. The measurement block enables operators to apprehend their current status. By means of a comparison between their own measured metric and the results of the others, the operators would be able to position themselves in the global wireless industry, i.e., how well they are doing in energy efficiency. This part will be the main focus of this section. On the other hand, the prediction block focuses on the energy efficiency of hypothetical and future networks, and thus serves as a tool for developing network deployment and operation strategies.

The key elements of the framework can be summarized as follows:

- **Metrics of NLEE:** It is important to define metrics that can describe the characteristics of NLEE. These metrics must capture the complexity of wireless networks and provide an intuitive understanding and must be easily measured by network operators.

- **Measurement methodology:** Once the energy efficiency metrics are defined, the next step is to perform a reliable measurement. Overcoming the complexity of wireless networks is also a challenging task for developing a measurement methodology. It is desirable to establish a standard methodology that has a global applicability in order to allow the operators to benchmark their energy efficiency with their competitors.

- **Prediction model:** It is necessary to understand the reasoning behind the obtained NLEE data and predict changes in efficiency figures from different solutions with the help of a prediction model which is beyond the scope of this paper.

**Defining NLEE Metrics**

The concept of energy efficiency becomes meaningful only when it can be measured. Thus, we first need to identify a proper, widely-agreed energy efficiency definition and propose simple, intuitive, easily obtainable, vendor-neutral, transparent metrics
in order to quantify energy efficiency at network level which is generally written in the following expression:

\[ NLEE = \frac{\text{Performance}}{\text{Energy Consumption}}. \]  \hspace{1cm} (5.1)

The metric is capturing the relationship between the level of service taken from the network and the expenses that has been used to create this benefit, i.e., energy, where the higher values represent more efficient networks. It is well known that network benefit can be represented with different forms such as, data rate, drop call rate, latency, packet error rate etc., and each of them varies with time (e.g., busy hour vs. night time), location (e.g., urban vs. rural), and service type (e.g., voice vs. data) due to networks’ heterogeneous behavior. Therefore, it is very difficult to indicate the network performance with only one measure. Another drawback of this metric is that higher performance directly increases the metric value without questioning its necessity for the end user. The main weaknesses of the current metrics in use arise from the lack of consideration of these challenges where the details can be found in [63].

Here we introduce an utility based approach where the network performance is represented by more than one indicator and include service dependent QoS requirements to take user satisfaction into account so as to award a better-performing network. We propose that NLEE metric should be in the form of:

\[ NLEE = \frac{U(\text{Performance})}{\text{Energy Consumption}} \]  \hspace{1cm} (5.2)

subject to \( \text{Performance} \geq \beta \).

Here, \( U(\cdot) \) indicates the utility function of chosen performance indicators, whereas \( \beta \) is the performance constraint in order to assure certain level of performance. The main challenge is the characterization of \( \beta \), where a natural choice at first can be seen to define a fixed constraint for all networks in order to enable "fair" comparison. However users' intuition about network performance and satisfaction from the same service are different in different countries. Therefore, operator-oriented constraint, \( \beta_{\text{op}} \), is more favorable which in return will complicate the global use of the metric. In this regard, we suggest the usage of the same performance constraint worldwide to ensure the global applicability.

We propose to use "number of subscribers" as the performance indicator which is more stable compared to number of bits and appropriate for common use in different load conditions. However, it is very open to manipulation unless it is properly defined. Despite its wide acceptance, the number of sim cards is insufficient to indicate network performance since it does not give any information about user activity. On the other hand, the number of active users in the network, i.e., the set of users that transmit or receive data during a defined period of time, would also fail to indicate in a fair manner due to lack of "satisfaction" information. Therefore, we
suggest to use number of satisfied users (whose QoS are above a defined threshold) in the network which is more suitable for long term comparisons and also ensures fairness. Consequently, the number of satisfied users will be a function of different QoS thresholds that are defined for each service type. In this case, the NLEE metric will be written as follows:

\[
NLEE = \frac{\text{card}(U_{QoS_1} \cup U_{QoS_2} \cup \ldots \cup U_{QoS_m})}{\text{Energy Consumption}},
\]

where, \( U_{QoS_i} \) is the set of the users with a given minimum QoS requirement for the \( i^{th} \) service type. An example of network performance requirements for different applications is given in [64] which can be used to calculate the proposed NLEE metric.

**Measurement Methodology**

The next step towards evaluation of energy efficiency at the network level is to define a widely-agreed measurement methodology that has a global applicability in order to allow the operators to benchmark their energy efficiency with their competitors via the chosen NLEE metric.

In this regard, both network energy consumption and network performance should carefully be assessed to get accurate indication of NLEE. To this end, we propose network segmentation and direct measuring at both terminal and network side instead of tackling the network as a "black box" and trusting high level data supplied by operators.

**Measuring Energy Consumption**

The simplest way of gathering information about energy consumption of the network can be seen to check operators’ energy bills. However, this high level data not only will require estimation to indicate the contribution of mobile radio network part and thus involves an estimation error, but also will fail to give insight regarding the variation of the energy consumption with the traffic. Therefore we believe that, despite its relative complexity, a field measurement is necessary to a certain extent.

To this end, we suggest to modularize the network and to choose representative sub-networks by considering their heterogeneity nature. In order to balance accuracy and simplicity, we recommend to select the sub-networks based on the population density, i.e., urban vs. rural (capacity limited/coverage limited) where all the characteristics such as, inter-site distance, number and type of BSs, backhaul solutions, network management features, etc., are assumed to be known. We then recommend to choose representative BSs with different types (e.g., macro, micro vs. pico), power sources (e.g., grid vs diesel) and measure the energy consumption for a decided duration (e.g., days vs. weeks) to keep track of consumption variation
with traffic load. The last step will require extrapolation of the gathered data to get the overall network energy consumption.

Measuring Network Performance

Due to the fact that, we have chosen number of satisfied users as the performance indicator which in fact involves several service dependent QoS requirements, the methodology will require measurement at the terminal side. Therefore, we propose to use some test users who locate at the chosen representative subparts of the network and require different services or applications. Distribution of the service requirements among the test users is suggested to be operator specific and based on their current service division. After defining what kind of services the users will demand at different part of the network, the number of satisfied users will be determined based on whether QoS requirements of the individual users are fulfilled or not according to a given service-dependent threshold. Here, regardless of the differences between networks, we propose to use same the QoS constraints to indicate the user satisfaction from the same type of services. We are aware that user profiles, so their intuition about network performance and satisfaction from the same service are different in different countries. However we believe this is essential in order to guarantee the global use. The last step requires prediction based on networks current service distribution in order to extrapolate the numbers to the network level.

Research Challenges

There are many challenges and open questions waiting to be clarified in order to make the proposed methodology applicable to accurately assess the NLEE with the suggested metric. In this part, we will touch upon some of them and express our point of view so as to initiate further discussions and to find a common agreement which will lead us towards green wireless access networks.

- Metric Oriented Challenges: The main difficulty in defining the NLEE metric in Eq. (5.3) arises from the complexity of "user satisfaction" identification. Beside the impossibility of defining one "global" constraint that will map the user satisfaction with a defined QoS threshold for all different services in the network, it is even more challenging to identify one that will be valid for all networks worldwide. In order to cope with the former problem, we propose to differentiate the satisfaction based on requested services from the network and define related widely-agreed QoS constraints, e.g., bit rate for data traffic, drop call rate for voice, etc. On the other hand, we suggest the usage of the same performance constraints worldwide to ensure the global applicability of the proposed NLEE metric and the measurement methodology despite the fact that the users’ perception of satisfaction differs by location. Furthermore, the question of: "Is it necessary to analyze the "green" cost of suggested EE
improvement solutions, e.g., deployment cost, backhaul requirement, network complexity, etc. and reflect it in the metric?” opens another direction for further discussion.

- **Methodology Oriented Challenges:** Here, the main challenge originates due to the necessity of well-defined selection criteria of the sub-networks, the representative BSs as well as the test users for the accurate measurement. Considering the fact that networks are unique, even the definition of urban vs. rural areas might be problematic. Furthermore, the time and the duration of the active measurement accordance with traffic load as well as the type of user equipment should also be clearly described in order to prevent operators from choosing relatively efficient part of their network. Regarding the selection of test users and the service distribution among them which will impact the NLEE metric considerably and thus create misleading results unless it has not properly defined, we suggest to use operator-specific service delivery divisions as a decision basis.

- **Modeling Oriented Challenges:** While a relative comparison of current energy efficiency figures between operators is one of the important purposes of NLEE assessment, it is equally important for the operators to identify the strategies for improving the energy efficiency from both short-term and long-term perspectives. Therefore we believe that on top of these, there is a need for a prediction model which represents the relationship between the NLEE metric and the key design parameters such as, coverage, traffic density, amount of spectrum, RAT portfolio, topology, etc., of the network. This will help the operators to predict the changes in efficiency figures from different solutions, and guide them towards more energy efficient networks which therefore needs further research.

### 5.2 Conclusion

In this chapter, we have handled network level energy efficiency assessment issue in wireless access networks. We have introduced high level definitions of energy efficiency and discussed the main weaknesses of the current metrics in order to evaluate NLEE. We then have proposed a more elaborate metric which considers several performance indicators in one and incorporate QoS requirement forms. A measurement methodology has been introduced to calculate the suggested NLEE metric which is based on network segmentation, direct measuring in both network and terminal side, and prediction. We conclude that network modularization and frequent observation are the only ways in order to understand the reasoning behind the obtained NLEE metric and propose solutions for the improvement. However, it comes with the increased complexity and challenges to be resolved which have also been summarized to initiate the further discussions.
Chapter 6

Conclusions

This chapter highlights the important contributions discussed in the thesis and the possible directions of future work.

6.1 Concluding Remarks

Wireless access networks today alone responsible for 0.5 percent of the global energy consumption. The rapid proliferation of smartphones, laptops, and tablet PCs with built-in cellular access that is rapidly driving the demand for increased capacity will further increase the energy consumption. Thus, improving energy efficiency has a great importance not only for environmental awareness but also to lower the operational cost of network operators. However, current networks which are optimized based on non-energy related objectives introduce challenges towards green wireless access networks. In this thesis, we investigated the solutions at the network deployment level where impacts of cell size, BS types and HetNet deployments on energy efficiency have been analyzed. A high level energy efficiency assessment issue is also considered to enable operators to monitor their energy figures.

In chapter 2, we presented a high-level framework to see the main tradeoffs between energy-infrastructure cost-spectrum and analyzed how these impact energy and cost oriented network design. We have shown that high-capacity systems are increasingly limited by infrastructure and energy costs where spectrum has a strong positive impact on both. As the energy and spectrum cost increase, cost optimum deployment moves closer to the energy asymptote where idle power consumption becomes the significant factor. We have identified that the ratio between idle- and transmit power dependent power consumption of the base station as well as the network capacity requirement are the two key parameters that affects the energy efficient architectures. In this regard, network densification has been deeply investigated with the refined power consumption model where the parameters are determined in accordance with densification level. It has been shown that network densification can only be justified when capacity expansion is anticipated and
over-provisioning is not plausible for greener network even though it might indicate improvement due to the selection of inappropriate metrics. Therefore careful prediction of the capacity demand has shown to be the key challenge for energy efficient deployment of wireless access networks. In chapter 3, we focused on the characterization of the power consumption of the whole network in order to obtain consistent and realistic conclusions. We have proposed a novel power consumption model for wireless access networks which considers the impact of mobile backhaul for fiber and microwave based solutions. We have found that there is a tradeoff between the power saved by using low power base stations and the additional power that has to be spent for backhauling. This indicated that backhaul will be responsible for remarkable share of energy consumption in future systems considering the fact that exponential growth in demand for capacity will require the deployment of several orders of magnitude more base stations. Furthermore, among the solutions that have been analyzed, fiber-based backhaul solution is shown to outperform microwave regardless of the considered topology. In chapter 4, we investigated the energy efficiency improvement through different heterogeneous deployment strategies compared to conventional deployment where the focus has been on the impacts of the type and the number of additional base stations and the cell size. We have shown that HetNet deployment both increases the energy consumption and the network throughput. Therefore the improvement is highly related to traffic demand, where up to 30% improvement is feasible for high area throughput targets. Finally in chapter 5, we handled network level energy efficiency assessment issues in wireless access networks in order to allow operators to know their current status by comparisons with other networks and identify the possible improvement directions. We have introduced the key elements of NLEE, suggested elaborate metric forms and proposed a methodology to define how to accurately quantify the energy efficiency at the network level. We have concluded that identification of appropriate metrics is crucial to prevent the indication of disputable improvement directions due to inaccurate results. A widely-accepted methodology is also indicated to have considerable influence on the design of next generation wireless systems. The proposed solutions and the indicated challenges is believed to have a significant impact on current standardization discussions.

6.2 Future Directions

We here outline the possible directions for future work. As aforementioned, energy saving potential at the network level arise from the deployment and the management of wireless access networks. From deployment perspective, network densification has been investigated in order to understand the tradeoff between the power saved due to advantageous propagation conditions and the additional baseline power consumption because of the increase in the number of BSs deployed. However, additional energy saving opportunity due to fact that densification will lower the activity levels of the BSs, has not been explored. On the other hand,
energy efficient heterogeneous deployments where the micro and pico BSs serving hotspots and femto BSs offload the traffic indoors will also be further investigated. User mobility, interference coordination and spectrum allocation will constitute the main considerations. From network management perspective, we will aim to find a unified approach to allow seamless transition between different layouts with the help of dynamic configuration of the network according to the temporal and spatial variation of the traffic to maximize the energy saving.

Regarding network level energy efficiency assessment, in the thesis we only have focused on the measurement block which enables operators to accurately apprehend their current status and position themselves in the global wireless industry. However, in order to complete the framework and to allow operators to identify the strategies for improving the energy efficiency from both short-term and long-term perspectives, we will focus on developing a prediction model.
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