On the Design of Energy Efficient Wireless Access Networks

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Abstract

Wireless access networks today consume 0.5 percent of the global energy. Rapidly growing demand for new services and ubiquitous connectivity, will further increase the energy consumption. This situation imposes a big challenge for mobile operators not only due to soaring cost of energy, but also increasing concern for global warming and sustainable development.

This thesis focuses on the energy efficiency issue at the system level and studies how to incorporate energy-awareness into the design of future wireless access networks. The main contributions have been given in the areas of energy efficiency assessment, architectural and operational solutions, and total cost of investment analysis.

The precise evaluation of energy efficiency is the first essential step to determine optimized solutions where metrics and models constitute the two key elements. We show that maximizing energy efficiency is not always equivalent to minimizing energy consumption which is one of the main reasons behind the presented contradictory and disputable conclusions in the literature. Further we indicate that in order to avoid the debatable directions, energy efficient network design problems should be formulated with well defined coverage and capacity requirements. Moreover, we propose novel backhaul power consumption models considering various technology and architectural options relevant for urban and rural environments and show that backhaul will potentially become a bottleneck in future ultra-high capacity wireless access networks.

Second, we focus on clean-slate network deployment solutions satisfying different quality of service requirements in a more energy efficient manner. We identify that the ratio between idle- and transmit power dependent power consumption of a base station as well as the network capacity requirement are the two key parameters that affect the energy-optimum design. While results show that macro cellular systems are the most energy efficient solution for moderate average traffic density, Hetnet solutions prevail homogeneous deployment due to their ability to increase the capacity with a relatively lower energy consumption and thus enable significant energy savings in medium and high capacity demand regions. Moreover, we investigate the energy saving potential of short-term energy aware management approach, i.e., cell DTX, taking advantage of low resource utilization in the current networks arising from strict QoS requirements. With the help of developed novel quantitative method, we show that Cell DTX brings striking reduction in energy consumption and further savings are achievable if the networks are designed taking into account the fact that network deployment and operation are closely related.

Finally, we develop a general framework for investigating the main cost elements and for evaluating the viability of energy efficient solutions. We first reveal the strong positive impact of spectrum on both energy and infrastructure cost and further indicate that applying sustainable solutions might also bring total cost reduction, but the viability highly depends on unit cost values as well as the indirect cost benefits of energy efficiency.

Results obtained in this dissertation might provide guidelines for the network designers to achieve future high-capacity and sustainable wireless access networks.

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Chapter 1

Introduction

In recent years, with the explosive growth of mobile communications in terms of number of connected devices, and the demand for new services and ubiquitous connectivity, the energy consumption of wireless access networks is experiencing a significant increase. This situation impose a big challenge for mobile operators not only due to soaring cost of energy, but also increasing concern for global warming and sustainable development. Hence, it becomes urgent for mobile operators to support vastly different quality of service requirements of increasing number of users in an energy efficient manner. To support access to information anywhere, and anytime at a low energy consumption would require a paradigm shift in the network design objective.

In this thesis, we provide guidelines for the design of energy efficient wireless access networks. This is achieved through the following contributions: i) novel power consumption models and instructions on how to properly use the existing network level metrics in order to accurately evaluate the energy efficiency of a given network, ii) key dynamics and tradeoff relationships between important design parameters in order define energy efficient architectural and operational solutions, and iii) a techno-economical evaluation framework in order to identify under which circumstances energy efficient solutions also result in total cost savings.

The thesis structured as follows. A general background for the problem is introduced in Section 1.1, including the main challenges faced in the evolution towards green wireless access networks and high level research questions. Section 1.2 presents a detailed overview of prior work aiming to reduce the energy consumption at different layers. The main research problems addressed in this thesis are defined in Section 1.3 and in Section 1.4 a brief explanation of the research methodology that has been used is presented. A summary of the main contributions of this thesis is given in Section 1.5, along with references to previously published or submitted materials. Chapter 2 describes the study approach that has been followed, together with the general assumptions and models used in the evaluation. Chapter 3 contains the key results obtained and finally the thesis is concluded in Chapter 4.

1.1 Background

"After its invention, the telegram took 90 years to spread to four-fifths of developing countries; for the cell phone, the comparable diffusion was 16 years."
R. J. Samuelson, Washington Post [1].

1.1.1 Evolution of Mobile Communications

Since the introduction of GSM in the 1980's, mobile wireless services have experienced a tremendous evolution and become important components of daily life. Today, there are more than 4 billion mobile subscriptions in the world; more than half of the population. In 2008, the number of mobile subscriptions overtook the total number of fixed broadband subscriptions (only about 1.3 billion worldwide) [2,3]. The driving force behind this rapid growth is the introduction of wireless packet data networks which enabled mobile internet usage in the beginning of 21th century and fundamentally changed the direction of wireless access networks. Mobile operators experienced a major breakthrough in 2007 when for the first time the aggregate amount of data traffic exceeded voice traffic. This resulted in a paradigm shift from low bandwidth services, such as voice and short message, to bandwidth hungry data services.

Forecasts of the telecommunication market indicate a continued rise in the number of mobile subscribers and their monthly data demand—these are the fundamental drivers of traffic growth [4, 5]. According to surveys, global mobile penetration rate will reach 100 percent after 2020 [2]. Moreover, as the internet of things becomes a reality, there will be massive growth in the number of connected devices—which is expected to be around 50 billion devices by 2020; ranging from ultra-low power sensors to machines. Simultaneously, the introduction of data hungry devices such as smartphones and tablets and associated applications are expected to lead to a thousand-fold traffic increase in 2020 in comparison with 2010 result in a monthly data traffic of 200 exabytes world-wide [4, 6, 7]. A common belief is that future wireless access networks will need to cope with vastly different challenges and expectations than they do today.

1.1.2 Why Save Energy?

The growing demand for ubiquitous connectivity and new services, however, comes with an undesired consequence of increasing energy consumption. Currently, information and communications technology (ICT) is responsible for 3 percent of worldwide electricity consumption out of which wireless access network contributes approximately 10 percent at 60 billion kWh per year [2,8,9]. This consumption corresponds to typical annual electricity consumption of 20 million European households. Annual electricity consumption has risen 16-20 percent every year, corresponding to a twofold increase in every 4-5 years [10].

This situation impose a challenge for mobile operators since rising energy consumption together with energy prices directly result in an increase in their operational expenditures (OPEX). In fact, operators' cost figures show that nowadays the energy cost of running a network constitutes almost 50 percent of overall OPEX [11, 12]. It should be noted that this cost is not only due to the direct cost of electricity, but also comes from the operation of off-(electrical)grid base stations (BSs) in the network. In such cases, especially in many emerging markets, delivering fuel to the BS sites accounts for a significant share of the operator's total energy cost [11].

In addition to rising operational expenditures, there is another important consequence of increasing energy consumption: carbon-dioxide (CO_2) emissions whose devastating impact on climate change has been highlighted in many recent studies [13, 14]. The reports show that ICT, the fifth largest industry in power consumption, emits 2 percent of the world-wide CO_2 representing approximately one forth of the emissions produced by cars. Despite the fact that these numbers look rather small, they are expected to increase by nearly a factor of 3 due to upward trend in energy consumption [2, 10, 11, 13]. This issue motivates governments to take political action in order to prevent global warming. In 2008, the European Commissions (EC) decided to lower CO_2 emissions by 20 percent by 2020 [15]. This also creates another strong driving force for mobile operators.

The aforementioned figures regarding energy consumption and its consequences on OPEX and CO_2 emissions may be outdated or inaccurate due to the rapidly evolving ICT environment. However, they clearly indicate that sustainability of ICT and mobile radio networks are at risk—unless there are changes to address these issues. Therefore, in order to enable the continuation of the global success of ICT, which is the core of many achievements of today's networked society, it is essential to change the present growth trend of energy consumption.

1.1.3 Challenges for Green Wireless Access Networks

Due to the reasons described in the previous subsection, one of the biggest challenges for mobile operators is to provide 1000-fold capacity to 50 billions devices, requiring access to information anywhere and anytime to anyone and anything, in an affordable and sustainable way.

In this regard, identification of the most promising areas where the largest improvements could take place is highly important. As was noted energy consumption of the mobile terminals constitutes only a small fraction of the total [16, 17] mainly due to the fact that strict battery constraints of the terminals lead to low power consumption solutions resulting in high energy efficiency.

Current mobile radio networks have been optimized for quality of service, coverage, scalability, etc.—energy was not explicitly included as a design objective. This situation introduces some technical drawbacks impairing the realization of green wireless access. These drawbacks can be summarized as follows:

- **Equipment Level Challenges:** Current hardware for BSs 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 at the equipment level.

- **Node Level Challenges:** Similar problem occurs at the node level due to the fact that BSs are designed to guarantee a certain level quality of service (QoS) at any time and energy consumption adaptation in accordance with traffic is inadequate. Additionally, strong requirements for high system throughput and low latency set an upper bound for the average resource utilization to lower radio interference levels and wastes energy, especially under medium and low load conditions.

- **Network Level Challenges:** From a network perspective, the main challenge originates due to the known tradeoff between energy consumption and network performance. Therefore, a 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 create a challenge for the operators. Moreover, due to the fact that wireless access networks are often dimensioned for peak hour traffic, energy is wasted primarily for two reasons: 1) Mobile traffic shows significant variation in both spatial and temporal domains; and 2) Power consumption of the BSs are almost load-*independent*.

Overcoming these challenges creates a vast potential for an improvement in energy efficiency of wireless access networks. However, there is a need for a paradigm shift in network design objectives and a holistic system approach needs to be taken instead of waiting on incremental improvements in BS equipment.

1.1.4   Thesis Focus and High Level Research Questions

In this thesis, we will mainly focus on energy efficiency of the network side of mobile radio systems and seek energy saving solutions at the network level. Therefore, the main goal of this thesis is:

> *to incorporate energy-awareness into the design of future wireless access networks in order to identify **architectural** and **operational** solutions enabling the reduction of energy consumption **without** degrading users' perceived quality of service, and to analyze the **economic viability** of the proposed solutions.*

Based on this main goal more specific problems are addressed in this thesis. These specific problems are defined as sub-problems under the following high-level problems:

- HQ1: How to assess the energy efficiency of a given network?

- HQ2: How should wireless access networks be deployed and operated in an energy efficient manner?

- HQ3: What are the consequences of energy efficient solutions on total cost?

1.2 Related Work

Before we introduce the research problems and contributions of this thesis in more detail, we will give an overview of related prior work aiming to lower the energy consumption of wireless access networks. In this overview we focus mostly on work that address the network level challenges.

1.2.1 Main Projects on Energy Efficiency

Due to the soaring cost of energy and increasing concern for the environment, energy efficiency has become a hot research topic amongst network operators, their equipment suppliers, academia, and the regulatory and standardization bodies such as International Telecommunication Union (ITU), the 3rd Generation Partnership Project (3GPP), and European Telecommunication Standards Institute (ETSI). This trend has created an innovative research area called *green radio*. With financial support from governments, many green projects were initiated by several consortia of industry and academia over the last few years in order to reduce CO_2 emissions. In this respect, they aim to define a unified approach while taking components, node architectures, radio transmission techniques, and network architectures into account.

Among the main projects, Mobile VCE Green Radio [18] aims at developing green radio architectures, focusing mostly on BS design issues such as power amplifiers (PAs), sleep modes, etc. OperaNet (Optimising power efficiency in mobile radio Networks) [19] proposes a holistic approach considering a complete end-to-end system with optimized cooling systems, terminal design, energy recovery in base stations, etc. Greentouch [20] has a ambitious goal of improving the energy efficiency of ICT networks (optical, wireless, etc.) by a factor of 1000 by 2015 when compared to 2010 levels mainly by introducing a fundamentally new network architecture. On the other hand, the EARTH (Energy Aware Radio and neTwork technologies) consortium [12] presents an integrated approach and aims at minimizing the energy consumption of LTE networks with solutions at each of the level from the lowest level up to the system level.

The key solutions proposed in the research area of *green radio* is given in detail in the following subsections.

1.2.2 Key Solutions

The rapid growth in energy consumption has created a paradigm shift towards energy-efficiency-oriented design in wireless access networks [21, 22]. Therefore,
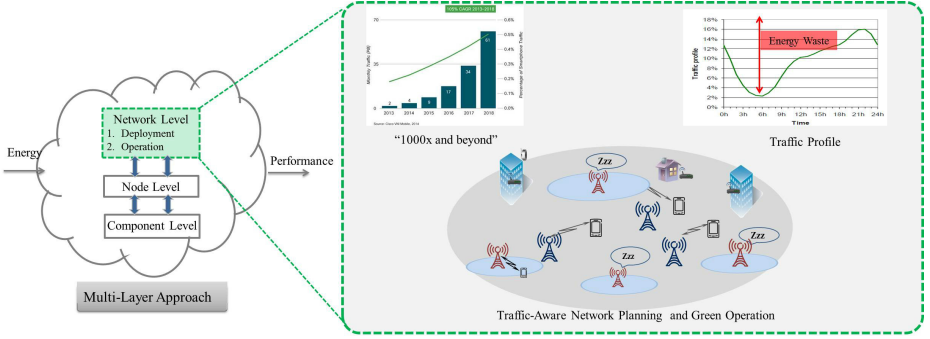
Figure 1.1: Multi-layer approach for future green wireless access networks.

various energy saving solutions have been proposed at different layers, some of these are illustrated in Figure 1.1, such as i) more efficient hardware design to lower the BS power consumption, ii) more elaborate network management strategies to match the capacity offered to the actual demand, ii) radio resource management solutions to optimize the decision of when and how to transmit, and iv) intelligent network architectures to cope with the traffic growth in a more energy efficient manner.

In the paragraphs below, we will highlight some of the promising solutions which aim to lower energy consumption of wireless access networks.

1.2.2.1   Hardware Solutions

Energy efficient hardware is essential to reduce the energy consumption of base stations as this hardware's energy consumption constitutes almost 60 percent of total energy consumption of a wireless access network [21, 23]. In this regard, there is a huge potential for energy saving related to the power amplifiers as these are the main energy consumer of a BS [18]. However, due to the tradeoff between linearity and efficiency, current PAs are operating at very low efficiency levels. This not only results in significant energy waste but also increases the necessity of air conditioning due to heat. A great deal of work aims to find solutions to overcome the problems originating from static operation conditions and to increase the efficiency of the PAs [24–27]. Additionally, several cooling solutions have been introduced which significantly lower the energy consumption of BSs [18]. Furthermore, fast sleep modes solutions for BS components enable adapting to traffic load levels have been proposed and they offer promising approaches to minimize energy consumption [18, 19, 21].

1.2.2.2   Resource Allocation Solutions

Another key approach for reducing the energy consumption of a wireless access network is the use of energy-aware resource allocation schemes, including radio link

design and radio resource management techniques. The main objective of these approaches is to identify how a BS should make a decision on when and how to transmit data to multiple users within its cell considering the channel conditions of its users and the load conditions of the neighboring cells. As mentioned earlier, the main challenge occurs due to the fact that state of art resource allocation solutions (power control, beam forming, multiple-input-multiple-output (MIMO), advanced retransmission schemes, coordinated multi-point (CoMP), interference mitigation, scheduling, etc.) were proposed mainly to achieve higher peak data rates and lower latencies despite these being known to have a tradeoff relationship with energy efficiency [18, 19]. In that respect, these problems have been reformulated to minimize the energy consumption by finding the optimum balance between the demand and resources allocated [28–30]. Considering the fact that 20 percent of the BSs carry 80 percent of the traffic even during the busy hour [31], load conditions are highly important to identify energy efficiency oriented solutions.

Under low load conditions, one proposed approach aims to exploit the low bandwidth utilization in order to reduce the required transmit power to achieve a certain target capacity [32]. In contrast, another approach increases both the power and the bandwidth utilization in order to reduce the time required to serve a user in a cell. This both increases the spectral efficiency and leads to energy savings by switching off the BS transceiver equipment at the cost of increased peak transmit power due to the shorter transmission duration [9]. When the traffic load is high, different solutions have been proposed to reduce energy consumption [18, 33]. Among these proposals, exploiting MIMO techniques enabling multiuser diversity together with energy efficient resource allocation schemes have received great deal of attention in the literature. Here, the main objective is defined as minimizing the energy consumption per transmitted bit while considering channel conditions, service-dependent QoS and latency requirements, and available resources such as bandwidth, time, etc. [19]. Moreover, interference cancellation schemes and cooperative transmission solutions such as CoMP have been presented as promising energy saving solutions due to the enhancement of signal to interference plus noise ratio (SINR) [18, 33]. These enhancement techniques are used to lower the overall transmit power used which leads to significant energy saving only if the PA is able to adapt its operational point to the new output power; otherwise there is not a gain in energy efficiency.

1.2.2.3 Network Level Solutions

Considering the fact that supporting exponentially increasing traffic will require the deployment of several orders of magnitude more base stations, green design of future wireless access networks is extremely important to meet the expected traffic requirements while lowering energy consumption per BS.

Defining meaningful metrics is the first essential step in evaluating optimized solutions. However, current wireless access networks are optimized based on non-energy related objectives, such as spectral efficiency, throughput, or capacity. Un-

fortunately, these well-established metrics are not sufficient to quantify the energy
efficiency of a system. This issue has been discussed intensively in the literature
and various green metrics have been proposed [34–36]. These metrics capture the
relationship between the level of service provided by the network and the expenses
that are expended to create this benefit. These metrics are either use an efficiency
index, i.e., the ratio between performance and the consumed power/energy, or a
consumption index, i.e., the ratio between the energy/power consumed to the at-
tainable utility. Even though these metrics use the same information and thus can
easily be converted into each other, there are some substantial differences mentioned
by the EARTH consortium in [36], in which it is claimed that with an energy effi-
ciency index, it is difficult to interpret the impact on energy saving. This statement
is visualized in Figure 1.2 which illustrates that the efficiency metric shows minor
improvement when the there is 20 to 60% energy saving (quantified based on the
consumption metric), whereas this metric indicates substantial improvement when
there is a minor improvement for already efficient systems.
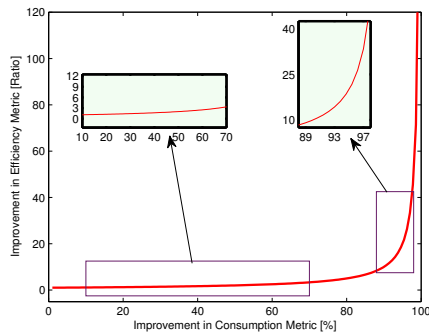
Figure 1.2: Efficiency metric versus consumption metric.

With this observation in mind, the most popular metrics used to quantify the
energy efficiency of wireless access networks are: bit/Joule, W/km^2, $W/Gpbs/km^2$,
and energy consumption ratio (ECR) in Joules/bit [18, 34, 36]. Moreover, some
relative metrics are also proposed in the literature in addition to these absolute
ones. Among these energy consumption gain (ECG) is widely used to compare a
new solution with a baseline system.

Yet another important step towards green wireless access networks is the ac-
curate characterization of the total energy consumption by a specific network for
specific operation. However, up to recently, the output power of antennas are used
as a performance measure, but this output power is insufficient to evaluate the total
power consumption considering the fact that the transmit power only constitutes
a small fraction of total, i.e., 10-15 percent depending on the BS type. Therefore,
many studies have focused on obtaining simple and accurate models to predict the
total power consumption in wireless access networks, mostly applying bottom up

approach [9, 16]. Among them, the BS power model proposed within the EARTH project constitutes a interface between the component and the network levels [9]. This model enables us to quantify the energy consumption of each component for different BS types, e.g., macro, micro, pico, and femto, the impact of each component's efficiency on the total power consumption. Moreover, the model presents a great tool to assess the energy efficiency of a network comprised of a multitude of heterogeneous elements.

The proposed metrics and power consumption models are then used to define energy-optimized solutions for the design of wireless access networks. The main objectives of these solutions can be categorized as: 1) to identify how many base stations of each kind are needed to cover a target area while satisfying the peak demand with minimum energy consumption, ii) to define how to reduce the energy wasted due to static deployment versus the very dynamic nature of traffic loads. Below, we provide a detailed literature survey of the main approaches aiming to answer these questions.

It should be noted that due to the fact that lower layers constitute a baseline for upper layer solutions, assumptions on hardware capability and resource allocation schemes greatly impact the achievable energy savings that can be achieved via energy efficient network design solutions.

Network Deployment

Network deployment strategies have always attracted considerable attention in academia. Traditionally, the design objective is to determine the number and location of the radio access sites in order to satisfy certain coverage and capacity requirements with minimum deployment cost [37]. However recently, the increased energy consumption of mobile radio networks due to the rising demand for ubiquitous information access is impacting energy cost. This resulted in a paradigm shift in the network design objective, i.e., maximizing energy efficiency rather than minimizing deployment cost.

As a result, optimal cell size in terms of energy consumption is investigated under some constraints in [38–40]. It has been shown that for short cell ranges, the necessary transmit power of the BSs significantly decreases due to the short distances between a BS and the mobile terminals as a result of advantageous path loss conditions [40]. However, unless the BSs are themselves optimized this comes with an increase in the baseline power consumption due to an increased number of BSs. This tradeoff between radio-frequency (RF) power consumption and baseline power consumption is addressed in [38] where the area power consumption of different deployment scenarios for a minimum received power target at the cell edge has been evaluated. The authors of [38] stated that large cell deployments are more energy efficient due to the high idling power of existing BSs. However, [39, 40] claimed that small-cell based mobile radio networks are an efficient solution to provide high data rates with low aggregate power consumption. The consequences of densification with universal reuse on inter-cell interference are analyzed and energy efficient

fractional frequency reuse solutions are proposed by Stolyar and Viswanathan to lower the interference and thus to improve energy efficiency [41].

For areas with high traffic demand, e.g., urban cities, heterogeneous network (HetNet) deployment strategies have been widely investigated [3,12,42–45]. In this strategy, a large number of small base stations (such as micro, pico, and femto BSs) are strategically located under the macro-cellular network's umbrella coverage in order to improve the system's capacity in hotspots. These hot spot deployment solutions are seen as one of the key solutions to improve energy efficiency while supporting localized high demand due to their ability to increase the capacity with a relatively lower energy cost due to the lower amount of power required to transmit at a given data rate over shorter propagation distances. This issue has been widely investigated in the literature for both indoor and outdoor deployments with various type of small BSs [3, 12, 43, 44] where the objective is to quantify the achievable energy savings through this deployment approach. The energy need for heterogenous networks has been assessed in [45, 46] for a uniform traffic scenario while considering different user densities. In [45], Fehske, Richter, and Fettweis have investigated the area power consumption of various deployment layouts with different numbers of micro BSs in a macro cell's umbrella coverage area; and they concluded that under full traffic load scenarios deployment of additional micro BSs is beneficial in terms of energy savings when the traffic demand is high. Moreover, the fact that deployment of many small cells within a macrocell results in the macro BS operating in low load conditions in realistic traffic conditions is handled in [43, 47]. The main objective was to analyze under which circumstances traffic offloading to small cells brings energy savings. It was concluded that despite the fact that higher densities of small BSs improve the SINR conditions due to a lower probability of receiving interference from neighboring cells, energy efficiency decreases when the resulting loads on the macro BSs exceed a certain threshold. The main reason behind this trend is that a reduction in macro BS's power consumption due to lower cell load can not compensate for an increase in aggregate baseline power consumption arising from high density of small BSs within the macrocell.

Indoor HetNet solutions have attracted great interest in order to address coverage and capacity needs in residential or enterprise environments (where 60 percent of voice and 70-90 percent of data traffic are expected to be originated) [44,48,49]. Since indoor users usually have poorer radio channel conditions with respect to outdoor users, it is believed that offloading the costly indoor users to femtocells will result in more efficient use of system resources by serving more outdoor users with the equivalent system resources thus improving the energy efficiency of the wireless access networks. Based on this main idea, energy efficiency of different femtocell deployment architectures have been analyzed in several papers [44, 47, 50–52] in which contradictory conclusions are presented. Among these papers, in [53], the tradeoff between spectrum efficiency and energy efficiency has been studied for joint macro-femto deployment where a significant reduction in energy consumption per bit of data delivered has been illustrated at the cost of a performance degradation due to co-channel interference. The large power savings via offloading data traffic

to femtocells has also been presented in [51,52,54], with regard to urban areas with high user data traffic demands. Despite its cost-effectiveness, joint macro-femto cell deployment has shown to increase the energy consumption with respect to traditional macro-only network for medium and high femtocell deployment densities when large number of users are supported per macrocell [44].

Network Operation

Currently networks are designed to guarantee a certain level of QoS during peak traffic conditions. Nevertheless, traffic loads notably vary both spatially and temporally. Blume, et al. [31] state that 80 percent of the BSs carry only 20 percent of the total traffic, whereas only 10 percent of the BSs are highly loaded. On the other hand, busy hour traffic can be up to 10 times that of an off-peak hour [9]. Therefore, the main fraction of energy is wasted due to this significant traffic variation and almost the load-independent nature of BS power consumption. Therefore, another means of network level energy saving is to enable the wireless access networks to intelligently adopt its characteristics to the dynamic load variations in order to reduce energy waste. Multi-fold ways of achieving this adaptability to the traffic to save energy are investigated in the literature over various time scales, i.e., milliseconds to hours [22,55–57]. For this purpose, the first essential step is to accurately characterize the spatial and temporal variation of mobile subscribers and their traffic demands-as has been done handled within the EARTH project [12]. As a result, both long and short term traffic models have been presented based on both data from operators and statistical approaches.

In long time-scale, the solutions are provided for a given network topology where the objective is to reduce the number of active nodes in the network (i.e., by shutting down BSs when the traffic load is low). Some of these solutions are summarized as follows. Inter-RAT energy saving solutions rely on the fact that different wireless access technologies such as GSM, UMTS, and LTE can be used to offer services in parallel in a given area. It has been shown that by dynamically selecting the best set of RATs and vertical handover schemes, the service requirements can be satisfied with minimum energy consumption [58,59]. Adaptive sectorization solutions are also shown to provide significant savings by operating BSs in omnidirectional mode instead of tri-sectorized mode during low traffic situations [59,60]. In the case of dense BS deployment with overlapping coverage, not only sectors but even BSs can be completely switched off so that the optimum number of active BSs necessary to guarantee coverage and traffic requirement will be based on complex optimization solutions [22,55,56]. Moreover, the flexibility originating from hierarchical cell structures offered in Hetnet deployments can be used for traffic adaptive BS activation solutions. In this approach, the objective is to reduce the number of small cells which were deployed to provide high data rate services during peak traffic conditions as they are under-utilized during the rest of the day [57,61,62].

Furthermore, short-term energy aware management approaches aim to dynamically match the network capacity with the actual traffic demand have recently

attracted attention. The significant energy saving potential of fast traffic adaptation techniques has been shown via a real traffic measurement. This measurement revealed that more than 80% of the base stations do not carry any traffic during millisecond time frames even during busy hour [63, 64]. The main reason behind the low utilization levels is the strong requirements of network applications on high peak data rates and low latency which limits the average resource utilization in order to reduce interference.

As a result a bandwidth adaptation approach [59, 65] is proposed based on the idea that using less frequency resources not only reduces the transmit power but also limits the number of reference symbols. Additional saving is feasible if PAs can adopt their operating point with respect to different output power levels [25, 26]. An alternative approach is presented in [59, 64] where allocation of entire resource blocks (RBs) are proposed for energy saving. This approach enables data-free transmission non-time intervals (TTIs) which are utilized by hardware that allows discontinuous transmission (DTX) on the BS side, i.e., cell DTX or micro sleep as proposed by Frenger, et al. in [64]. With the introduction of cell DTX, a cell can be put into sleep mode when there is no traffic as this significantly lowers the BSs idle power consumption. Unlike long term sleep schemes [56, 57] that aim to switch off the cells completely during low traffic periods, cell DTX leaves certain parts of the cells active to ensure that the cells can be immediately activated upon request. This enables node-level power consumption adaptation in accordance with traffic variation over a very short time scale (milliseconds) without necessitating any network level cooperation schemes and represents a great potential for energy saving [64].

1.3   Problem Statement

Based on the observations and literature review presented above, we see that the accurate evaluation of energy efficiency and the identification of architectural and operational solutions for minimum energy consumption are very important to achieve energy efficient networks. Another important aspect is the analysis of the impact of energy minimizing approaches on the total cost which has mostly been ignored in the literature.

Based on these key aspects, the specific problems addressed in this dissertation are defined in the following subsections.

1.3.1   Energy Efficiency Assessment

The initial problem faced in an evolution towards green wireless access networks is the lack of a widely-accepted methodology to evaluate the energy efficiency of a given network. Therefore, defining suitable energy efficiency metrics and characterizing the total network energy consumption are key aspects to determine optimized solutions. Although extensive studies have been conducted on these issues,

we identified different energy efficiency improvement directions in the literature. These differences are partly due to employing different sets of metrics and models.

Energy efficiency metrics are of primary importance to define green wireless access networks since these metrics directly impact optimization decisions. However, despite the fact that there are well-established QoS oriented performance indicators for wireless access networks(such as data rate, spectrum efficiency, etc.), there is no consensus on how to quantify energy efficiency at the network level. The existing proposals mostly aim to capture the relationship between the level of service provided by the network and the energy consumed in order to represent energy efficiency. This situation poses many challenges which can be summarized as: i) The conclusion regarding the impact of the solution differs according to the chosen QoS indicator and the performance target; and 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 amount of energy consumption, is very difficult. These both complicate a comparison between the results from different proposed solutions and create confusion regarding the actual energy savings.

Regarding energy consumption modelling, although accurate models for different base station types have been proposed by the EARTH consortium, the impact of mobile backhaul (MBH) has been mostly ignored in the literature due to the fact that for a macro BS, the power required to backhaul its traffic constitutes only small fraction of the total BS power consumption, i.e., less than 5 percent. However, backhaul power consumption for small cells can reach the same total amount of energy consumption as the power consumption of the BS itself, the contribution of MBH will be highly dependent on the deployment strategy. Especially with the potential evolution towards HetNet deployment, where a large number of small base stations is used to meet the increased need for coverage and capacity, power consumption of MBH might become a bottleneck for future green wireless access networks. Therefore, in order to obtain consistent and realistic results concerning the overall network power consumption, in order to define energy efficient solutions, the backhaul power consumption should be carefully considered in any energy efficiency assessment.

Therefore with regard to energy efficiency assessment, the following key problems are addressed:

- EEE1: **What** key aspects need to be considered when using different set of metrics and models to avoid choosing inappropriate methods for energy efficient network design?

- EEE2: **How much** power is needed to backhaul mobile traffic and **what** is its impact on the total power consumption of wireless access networks?

1.3.2   Energy Efficient Solutions

Concerning the second high level problem treated in this dissertation, we will seek solutions to minimize the total energy consumption in two main areas: network deployment and network operation.

Despite the fact that clean-slate deployment strategies have been widely investigated in the literature, there are surprisingly completely contradictory conclusions regarding the impact of cell size and heterogenous network deployment solutions on energy efficiency. For example, while densification and small cell deployment were suggested as promising solutions for significant energy saving in [40, 51], the opposite is claimed in [38, 44]. Therefore, it is essential to gain general insights regarding the important design parameters and their possible impact on overall energy consumption. Moreover, a methodology ensuring a fair comparison between different network architectures with various types and number of BSs is very important to assess potential energy savings. Otherwise, network over-provisioning, i.e., providing more capacity than required, might be indicated with higher energy efficiency figures with the consideration of an efficiency index.

More specifically, in order to identify energy efficient architectural solutions, we are primarily interested in this dissertation in answering the following questions:

- EES1: **What** are the fundamental tradeoffs in green wireless access networks?

- EES2: **How much** energy we can save through clean slate indoor and outdoor deployment strategies?

Regarding the energy efficient network operation solutions, several methods are proposed in the literature which aim to reduce energy waste arising from significant spatial and temporal traffic variation during a day. Most of these studies focused on long-term sleep mechanisms and aim to dynamically reduce the number of active network elements in accordance with the expected daily variation of the traffic for a given network deployment. However, the great potential for energy savings through short-term energy saving approaches has been mostly overlooked. This potential arises due to the fact that in a short enough time resolution, e.g., millisecond level, there is no user in most of the cells most of the time. However, on a longer time scale, only a few cells carry no traffic [64]. Unfortunately, long term ON/OFF schemes require a longer waiting time to switch on the BSs, which may have undesirable consequences on the network's performance since current wide area cellular standards (GSM, UMTS, and LTE) rely on continuous or periodic signalling. Therefore, in this thesis we investigate the energy saving potential of cell DTX that allows dynamic sleep mode operations of the BS. Moreover, the fact that energy saving through network operation is closely related to the initial network deployment has been mostly ignored in the literature. This originates from the fact that network design determines the relationship between the network capacity and peak traffic demands, and thus the resulting flexibility impacts the operational decisions made in accordance with traffic variation.

With regard to energy efficient solutions, the following key problems are addressed:

- EES3: **How much** energy we can save via cell DTX for a given traffic pattern?

- EES4: **Is** further energy saving achievable when cell DTX is incorporated into a clean-slate network deployment?

1.3.3 Energy-Cost Tradeoff Analysis

Due to the fact that the motivation for reducing the energy consumption of wireless access networks is driven not simply by environmental concerns, but mainly by economic forces, it is fundamental to analyze total investment cost. Indeed, introducing solutions for minimum energy consumption may impact both OPEX and capital expenditures (CAPEX). Therefore, a general framework that captures the main source of total cost (e.g., infrastructure, spectrum, energy, etc.) and describes the relationships amongst each other is highly important. Moreover, a detailed methodology is needed to assess the economic viability of any proposed solution aiming solely to lower total energy consumption.

To analyze the energy and cost tradeoff, we address the following problems:

- ECTA1: **How** does the relationship between key cost elements impact the future design of green wireless networks?

- ECTA2: **Under which** circumstances will an operator get a total cost saving from an energy efficient solution?

1.4 Research Methodologies

This section gives a brief explanation of the research approach followed in this thesis in order to answer the research questions stated in Section 1.3. Specifically, we present the research methodologies applied to the essential building blocks of the methodological framework illustrated in Figure 1.3.

To begin with, we focus on energy efficiency metrics and power consumption models in order to have an accurate indication of how energy savings can be achieved in wireless access networks. In order to identify the key mistakes that should be avoided, we followed an experimental research method for interpreting the existing metrics and make a critical analysis by using a simple network dimensioning problem. With the help of the derived closed form of the objective function, we analytically evaluate when different metrics indicate contradictory conclusions. Regarding accurate characterization of the total power consumption, we propose novel backhaul power consumption models and incorporate them into existing base station power models. In order to describe the main characteristics of the models and to illustrate the non-negligible impact of backhaul power consumption, we apply
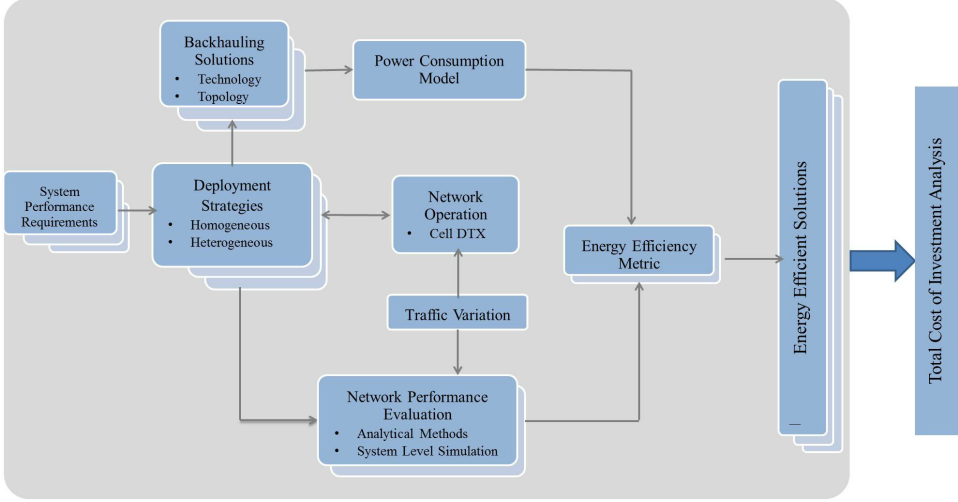
Figure 1.3: Methodological Framework.

the quantitative descriptive method by comparing the total network power consumption with and without backhaul power consumption based on the selected technology and architectural solution taking into consideration different data rate requirements, i.e., from today's requirement to 2020 levels.

Secondly, we define network level solutions to reduce the energy consumption of wireless access networks via clean-slate architectures and traffic-adaptive operational schemes. In order to define the deployment strategy with the highest energy efficiency, we select the quantitative experimental methodology to investigate the system's performance and to establish cause and effect relationships. In order to do this, we perform system level simulations that evaluate the network's performance and total power consumption for various candidate deployment solutions satisfying the system's requirements and identify the one with the minimum total energy consumption. The energy savings are quantified with respect to a defined baseline deployment strategy. We also assess the sensitivity of results relative to the system's requirements and other related model parameters to establish a reliable and repeatable quantification. In order to evaluate the energy saving through cell DTX which offers fast traffic adaptation capability to BSs in the network, system level simulations are carried out driven by expected patterns of daily traffic variation. With the help of the proposed method, we define feasible load levels for a given deployment and the traffic pattern as these enable us to quantify the daily energy consumption with and without cell DTX. We apply a reverse method to identify the deployment that maximizes the saving from cell DTX and quantify the additional achievable savings.

Moreover, we present a simple cost model to analyze the tradeoff between energy,

spectrum, and infrastructure cost and their impact on future very-high-capacity wireless access networks by applying the descriptive quantitative research method. After noticing that an energy efficient design strategy solely aimed at energy minimization can be obtained with a cost increase, we perform a detailed total cost of investment analysis to identify under what circumstances, the resulting incremental increase in capital expenditures can be compensated for the cost reduction due to energy saving. For this purpose, we select the experimental research method with a quantitative case study strategy in order to define the main relationships between variables and to make an empirical investigation to answer the research question stated in ECTA2. To this end, we perform a net present value analysis and valuate the total investments over network's expected lifetime taking discounting into account for two case studies. First we evaluate an existing deployment and quantify the the energy saving when upgrading the existing BS transceivers' to enable cell DTX. Then we define the "break-even" cost of the new hardware, i.e., when the cost of upgrading is worthwhile from an economic perspective. We also extend our analysis to greenfield deployments and quantify and compare the total cost of investment of energy-minimal and CAPEX-minimal deployments in order to define the conditions under which an operator achieves a total cost saving from a greenfield energy-optimized deployment. We also perform a sensitivity analysis with respect to unit cost parameters for both scenarios.

For the fundamental steps explained above, we mostly use system level simulations for data analysis and the deductive approach for drawing conclusions. The parameter sets utilized in the simulations are mostly based on the widely accepted 3GPP specifications. We consider the estimated data traffic patterns obtained by the EARTH consortium-it relies on data from existing networks and the mobile data forecast presented by CISCO [4]. The replicability and the reliability of the results are ensured by the detailed explanation of the simulation approaches and the detailed sensitivity analysis.

1.5 Thesis Contributions

In this section we briefly outline the contributions of this thesis as presented in the attached papers.

1.5.1 Overview of Publications

This thesis is a compilation of eleven peer-reviewed publications and submitted papers. These can be divided into three parts: i) Energy Efficiency Assessment; ii) Energy Efficient Solutions; and iii) Energy-Cost Tradeoff Analysis. An overview of these papers and their relationships are illustrated in Figure 1.4.
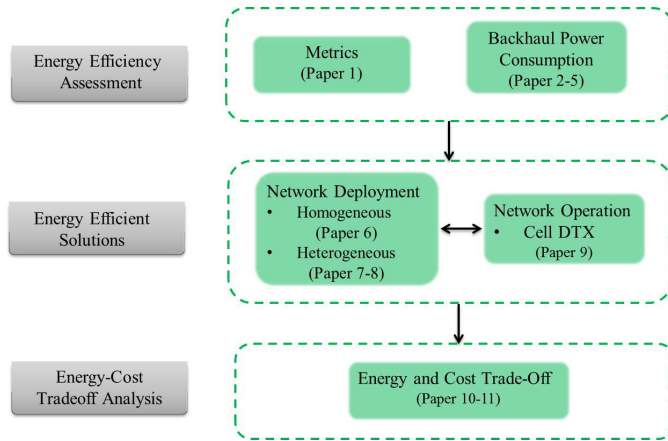
Figure 1.4: Contributions of the Thesis.

1.5.1.1   Energy Efficiency Assessment

Before starting any discussion on "green" networks, we first focus on how to measure and assess the energy efficiency of wireless access networks.

In particular, we discuss the importance of energy efficiency metrics and power consumption models on an accurate evaluation of energy efficiency by demonstrating the impact of different sets of metrics and models on the solution of a simple network dimensioning problem. Our main contribution is to identify under which circumstances widely accepted metrics and models result in contradictory and debatable directions for green wireless access networks. The findings are presented in:

- **Paper 1**: S. Tombaz, K.W. Sung and J. Zander, "On Metrics and Models for Energy Efficiency in Wireless Access Networks", submitted to IEEE Wireless Communications Letter, 2014.

In Paper 1, the modeling, simulation and writing process were performed by the author of this thesis, while valuable insight was provided by Ki Won Sung and Jens Zander.

We proposed novel power consumption models for different backhaul architectures and incorporated them into existing base station power models in order to obtain quantitative insights into specific green network designs. We then evaluate the impact of backhaul on the energy consumption of wireless access networks taking into account: i) the expected traffic growth, ii) mobile radio network deployment, e.g., homogeneous and heterogeneous; and iii) deployment areas, e.g., rural and dense urban. The models and the key results are presented in:

- **Paper 2**. S. Tombaz, P. Monti, K. Wang, A. Västberg, M. Forzati, and J. Zander, "Impact of Backhauling Power Consumption on the Deployment of Heterogeneous Mobile Networks", In Proc. of IEEE Global Communications Conference (GLOBECOM), December 2011.

- **Paper 3**. P. Monti, S. Tombaz, L. Wosinska and J. Zander, "Mobile Backhaul in Heterogeneous Network Deployments: Technology Options and Power Consumption ", In Proc. of IEEE International Conference on Transparent Optical Networks (ICTON), July 2012.

- **Paper 4**: S. Tombaz, P. Monti, F. Farias, M. Fiorani, L. Wosinska, and J. Zander, "Is Backhaul Becoming a Bottleneck for Green Wireless Access Networks?", In Proc. of IEEE International Conference on Communications (ICC), June 2014.

- **Paper 5**: M. Fiorani, S. Tombaz, P. Monti, M. Casoni, L. Wosinska, "Green Backhauling for Rural Areas", In Proc. of IEEE International Conference on Optical Network Design and Modeling (ONDM), May 2014.

The author of this thesis acted as the lead author for the Papers 2 and 4, wrote the initial paper draft, and provided the numerical results. The other co-authors of these papers were involved in editing the draft and developing the backhaul power consumption models used in these papers. Papers 3 and 5 were initially drafted by Paolo Monti and Matteo Fiorani respectively, while the author of this thesis contributed the numerical results and was actively involved in editing the papers. All co-authors contributed to the modeling and the problem formulation with Jens Zander, Lena Wosinska, and Maurizio Casoni providing insight into the direction of these papers.

1.5.1.2 Energy Efficient Solutions

Based on the developed power consumption models and identified key aspects to accurately characterize the energy efficiency of a given wireless access network, we next focused on network level **architectural** and **operational** solutions to minimize the total energy consumption.

In particular, we analyzed the different deployment scenarios that can cope with the expected traffic growth in a more energy efficient manner. Here the deployment has been done for a busy hour traffic and temporal traffic variation has not been considered. Firstly, we investigated the relationship between energy efficiency and densification with regard to an area capacity requirement for homogeneous network deployment. We demonstrated how different assumptions about capacity requirement and base stations types affect the energy efficiency in different levels of network densification. The results and conclusion of this study are included in:

- **Paper 6**. S. Tombaz, K.W. Sung and J. Zander, "Impact of Densification on Energy Efficiency in Wireless Access Networks", In Proc. of IEEE Global Communications Conference Workshops (GLOBECOM Wkshps), December, 2012.

In Paper 6, the modeling, simulation, and writing process were performed by the author of this thesis, while valuable insight was provided by Ki Won Sung and Jens Zander.

We also investigated the impact on energy efficiency of various indoor and outdoor small cell deployments under an umbrella macro-cellular coverage on energy efficiency. We quantified potential energy savings through HetNet deployment for various network performance requirements. The results and conclusion of these studies are included in:

- **Paper 7**. S. Tombaz, M. Usman and J. Zander, "Energy Efficiency Improvements Through Heterogeneous Networks in Diverse Traffic Distribution Scenarios", In Proc. of ICTS International Conference on Communications and Networking in China (CHINACOM), August, 2011.

- **Paper 8**: S. Tombaz, Z. Zheng and J. Zander, "Energy Efficiency Assessment of Wireless Access Networks Utilizing Indoor Base Stations", In Proc. of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), September, 2013.

The papers above have been coauthored with two different master's thesis students. The author of this thesis proposed the problem formulation, acted as an advisor to the master's students, and wrote the papers. The ideas in each paper were refined with the second author who also developed the simulation code. Jens Zander provided valuable insights regarding the direction of these papers. Note that the results presented in these papers and in this thesis were obtained *during* the evaluation of the simulation codes developed by these students and differs from the results presented in student's master thesis.

Additionally, we investigated operational solutions to reduce energy consumption in wireless access networks. In particular, we developed a quantitative method to analyze the daily energy saving possible using cell DTX which (enables sleep mode operation of the base station when there is no traffic). We also considered the fact that the saving is closely related to the initial deployment and thus incorporated cell DTX with the network design. The findings are presented in:

- **Paper 9**: S. Tombaz, S.-w. Han, K.W. Sung, and J. Zander, "Energy Efficient Deployment with Cell DTX", under minor revision to IEEE Communications Letter, 2014.

In Paper 9, the modeling, simulation, and writing process were performed by the author of this thesis. The other co-authors were actively involved in developing& editing the draft and provided valuable insights into the direction of the paper.

1.5.1.3 Energy-Cost Tradeoff Analysis

After noticing that an energy efficient design strategy solely aimed at energy minimization can be obtained with a cost increase, as the final part of this thesis, we performed a total cost of investment analysis in order to analyze the tradeoff between energy and cost.

In particular, we introduced a high-level framework to investigate the impact of "green costs" of different energy efficient network architectures. To this end, we first presented a detailed cost model and analyzed the impact of each cost factor on the design in order to highlight the tradeoffs between energy, infrastructure, and spectrum costs for wireless access networks. The results and conclusion of this study are included in:

- **Paper 10**. S. Tombaz, A. Västberg and J. Zander, "Energy and Cost Efficient Ultra-High-Capacity Wireless Access", IEEE Wireless Communication Magazine, vol. 18, no. 5, pp. 18- 24, October 2011.

In Paper 10, all of the authors contributed to devising the problem formulation, modeling, and writing process, while the simulations were performed by the author of this thesis.

Finally, we performed a more detailed economic analysis in order to identify whether or not the additional capital investment required for energy efficient solutions is recovered by the energy savings. For this purpose, we analyzed the total cost of investment in the case of upgrading existing BS transceivers' to enable cell DTX in a given deployment and defined the "break-even" cost of the new hardware. Furthermore, we investigated a greenfield deployment scenario and compared the total cost of investment for energy-optimized and CAPEX-optimized deployments. The findings are presented in the following paper:

- **Paper 11**. S. Tombaz, S.-w. Han, K.W. Sung, and J. Zander, "An Economic Viability Analysis on Green Solutions for Wireless Access Networks", to be submitted to IEEE Journal on Selected Areas in Communications, 2014.

In Paper 11, the modeling, simulation, and writing were performed by the author of this thesis. The other co-authors were actively involved in developing&editing the draft and provided valuable insights into the direction of the paper.

1.5.2 Other Related papers

The following papers, although not included in this thesis, contain material that is similar to or related to the contributions of this thesis:

- **R1**. S. Tombaz, K.W. Sung, and J. Zander, "Energy and Throughput Tradeoff in Temporal Spectrum Sharing ", Int. Conf. on Cognitive Radio Oriented Wireless Networks (CROWNCOM), 2012.

- **R2**. M. Olsson, P. Frenger, C. Cavdar, S. Tombaz, D. Sabella, and R. Jäntti, "5GrEEn: Towards Green 5G Mobile Networks ", Int. Conf. on Cognitive Wireless and Mobile Computing, Networking and Communications (WiMob), 2013.

- **R3**. S. Tombaz, K.W. Sung, G. Miao, and J. Zander, "Energy Efficiency in Network Level: Definition, Measurement and Prediction ", to be submitted to Energy Research, Engineering and Policy Journal, 2014.

Chapter 2

Methodology and Theoretical Models

The purpose of this chapter is to give further details about the methodology followed in this thesis to answer research questions stated in Section 1.3.

2.1 Base Station Power Consumption Model

Throughout this thesis, we use the BS power model proposed within the EARTH energy efficiency evaluation framework [66]. This widely used model constitutes a interface between the component and network levels, and enables the assessment of energy efficiency in wireless access networks.

In the model, the total power consumption of the BS is divided into two parts: (i) The idle power consumption[1], i.e., the power consumed in the BS even when there is no transmission ($P_{tx} = 0$); (ii) The traffic load dependent power consumption, which is expressed as [66]:

$$P_{in} = \begin{cases} N_{TRX} \left(\Delta_p \, P_{tx} + P_0 \right) & \text{if } 0 < P_{tx} \leq P_{max}, \\ P_0 & \text{if } P_{tx} = 0 \ \text{(without cell DTX)}, \\ \delta \, P_0 & \text{if } P_{tx} = 0 \ \text{(with cell DTX)}, \end{cases} \quad (2.1)$$

where P_{max} and N_{TRX} denote the maximum transmit power and the number of transceivers respectively. On the other hand, Δ_p represents the portion of the transmit power dependent power consumption due to feeder losses and power amplifier, whereas P_0 accounts for the power consumption because of the active site cooling and signal processing[2].

Traditional BSs consume considerable power even when there is no user in the cell, i.e, P_0. However, with cell DTX [64], a cell can be put into DTX mode during

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[1]The term "idle" will be used interchangeably with "baseline" in this thesis—it represents the power bring consumed when operating but not transmitting.

[2]Note that we use various notations for the power consumption parameters in the papers included in this thesis.

idle state which decreases the baseline power consumption to $P_s = \delta\,P_0$, where $0 \le \delta < 1$.

The parameters of the linear model in Eq. (2.1) were obtained in [66] based on direct measurements of state-of art BSs under different load situations. These parameters are shown in Table 2.1. Note that the table does not contain the information about δ since existing state-of-art BSs do not (yet) have fast sleep capabilities. Therefore, in this thesis dissertation, we will use δ as a sensitivity parameter.

Table 2.1: Power Consumption Parameters for Base Station [46, 66]

Base Station Type	P_{max} [W]	Δ_p	P_0 [W]
Macro	40	2.66	118.7
Micro	6.3	3.1	53
Pico	0.13	4.2	6.8
Femto	0.05	7.5	4.8

2.2   Energy Efficiency Metrics

The term "energy efficiency" is generally defined as the level of service provided by the network relative to the total consumed energy to create this benefit. Various metrics have been proposed in the literature to quantify the level of service at the network level. In this thesis we use two widely accepted metrics, i.e., bit/Joule and W/km^2 to measure energy efficiency[3].

Bit/Joule is a commonly used metric, particularly for the evaluation of single wireless links [29]. Its use has naturally been extended to the assessment of whole wireless access networks. This metric considers the number of bits as the network performance indicator, hence the metric can equivalently be written as:

$$\Psi = \frac{C_{net}}{\mathcal{P}_{tot}}. \tag{2.2}$$

Here, C_{net} is defined as the aggregate network capacity, whereas $\mathcal{P}_{tot}$ is the total power consumption of the network.

W/km^2 is on the other hand relates the total power consumption of the network to size of the covered area ($\mathcal{A}$) as:

$$\Omega = \frac{\mathcal{P}_{tot}}{\mathcal{A}}. \tag{2.3}$$

---

[3]Note that the metric considered is clearly indicated in each paper.

2.3   Evaluation of Energy Efficiency

In this section we briefly introduce the research approaches followed to answer the first question high level question, HQ1: *How to assess the energy efficiency of a given network?*.

2.3.1   Energy Efficiency Metrics

First, we focus on energy efficiency metrics which have a significant importance since the choice of metric directly impacts the optimization decisions. In order to identify the key mistakes that should be avoided, we consider a simple network dimensioning problem. The objective of this network dimensioning problem is to maximize the energy efficiency by optimizing the number of BSs under certain performance requirements assuming a greenfield deployment. We obtain a closed form for the objective function and analytically illustrate when different metrics indicate contradictory conclusions. The mathematical proof is supported by an quantitative example. The key results are presented in **Paper 1** and summarized in Section 3.1.

2.3.2   Evaluation of the Backhaul Power Consumption Impact

Another fundamental step towards energy efficiency assessment is an accurate characterization of the total power consumption ($\mathcal{P}_{tot}$).

In the literature, the total power consumption of a network consisting of m types of BSs is calculated as the sum of the power consumption of all BSs:

$$\mathcal{P}_{tot} = \sum_{i=1}^{m} N_i P_i, \tag{2.4}$$

where N_i and P_i denote the total number and the power consumption of i-th type of BS in the network.

In these models, backhaul power consumption is generally ignored under the assumption that the power required for backhauling constitutes a small fraction of the total power consumption. In order to assess whether or not this assumption is valid, we evaluate the impact of backhaul power consumption P_{bh} taking into account various technology and architecture options, together with different wireless deployment scenarios. Moreover, we investigate how the impact will evolve with an expected traffic growth.

The general methodology followed for assessing backhaul impact is illustrated in Figure 2.1. The first step is a *Traffic Forecast*. The output of this step is a characterization of the average area traffic demand for the considered network area and for the time period under examination. The estimate is based on long-term, large scale-traffic models, and on forecasted data for network and service usage such as: the area population density, the percentage of active users at busy hours, the
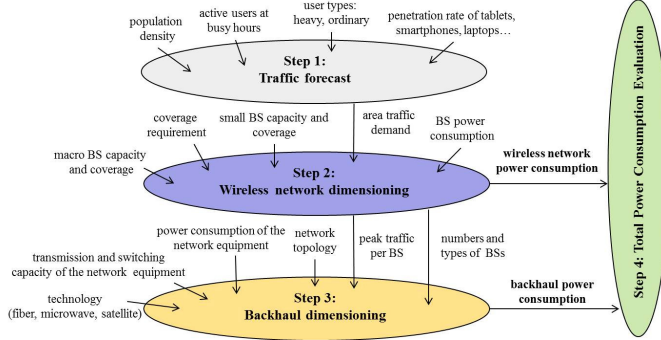
Figure 2.1: Methodology used for evaluating the total energy consumption.

specific user behavior (i.e., heavy vs. ordinary users), the penetration rate of different terminal types (i.e., laptop, tablet, and smart-phone), and the average data traffic demand of each terminal type. The second step targets *Wireless Network Dimensioning*. As an output, this phase returns the total power consumption of the wireless network segment, the number and type of BSs deployed in the area, and the peak traffic level for each BS type during the considered time. Note that while **Papers 4&5** follow the first two steps in order to identify the wireless deployments under certain service requirements, e.g., coverage and capacity, **Papers 2&3** rely on the three cost-efficient Hetnet deployments proposed by Johansson in [37]. The third step represents the *Backhaul Dimensioning* phase. This step provides the number of each of the types of the required backhaul equipment (e.g., microwave antenna, fiber switches, satellite antenna, etc.). The output of this step depends upon the output of the wireless network dimensioning phase and on the specific choice for the MBH architecture. Finally, the last step of the methodology presented in Figure 2.1 is the *Total Power Consumption Evaluation*. In this step the total power consumption of the access network is calculated as the sum of the power consumed by the wireless segment, i.e., $\mathcal{P}_{tot}^{ref}$, and the power consumption of backhaul segment MBH, i.e., P_{bh}.

As a result of this methodology using power consumption models proposed in each paper, we assess the impact of backhaul by comparing the total power consumption results, i.e., $\mathcal{P}_{tot} = \sum_{i=1}^{m} N_i P_i + P_{bh}$, with the reference scenario where total power consumption of a network is limited to a consideration of the wireless segment, i.e., $\mathcal{P}_{tot}^{ref} = \sum_{i=1}^{m} N_i P_i$. The key results representing the impact of backhaul for various scenarios are presented in **Papers 2, 3, 4, and 5** and summarized in Section 3.1.

2.4 Defining Energy Efficient Solutions

In this section, we briefly introduce the methodologies used to answer the second high level question: HQ2: *How should wireless access networks be deployed and*

operated in an energy efficient manner?.

2.4.1 Defining Architectural Solutions

Firstly, we focus on simple homogeneous network deployment in order to understand the dynamics and key relationships between the energy efficiency and the important design parameters such as cell range, capacity requirement, BS type, power consumption elements, etc.

As our first step, we refine the base station power consumption model such that load dependent power consumption, $\Delta_p P_{tx}$ and the idle power consumption, P_0 are written as a function of maximum transmit power, P_{max} as

$$\Delta_p = \mu - \eta \log_2 (P_{max}), \tag{2.5}$$
$$P_0 = \kappa P_{max} + \psi, \tag{2.6}$$

Here we use nonlinear regression for fitting the BS power consumption data in Table 2.1 to the approximated functions and define the best set of parameters which gives the least squares solution: $\mu = 4.15$, $\eta = 0.5$, $\kappa = 7.6$, and $\psi = 5.1$. It should be noted that each combination of Δ_p and P_0 represents a hypothetical BS customized to P_{max}.

In this way, we reduce the impact of power consumption parameters on the conclusions as to whether or not densification is plausible for green wireless access networks. In order to assess the key dynamics, we obtain a closed form expression for energy efficiency in bit/Joule and derive the optimum transmit power that maximizes energy efficiency for a certain capacity target. It should be noted that optimization problem is formulated with well defined coverage and capacity requirements. Moreover idling and backhauling power consumption are included in order to avoid debatable conclusions. More details on the closed form derivation can be found in **Paper 6**. Key findings are presented in Section 3.2.

After defining the key relationships for homogenous network deployment, we take a step forward and investigate the potential energy savings for several candidate Hetnet architectures where different types of small cells are deployed under a macrocellular umbrella coverage. We consider traditional macrocellular network deployment as the baseline architecture. In order to fairly compare different deployment options we ensure that each strategy provides the same network performance with regards to network coverage and area throughput. By this means, we prevent network provisioning, i.e., providing more capacity than required, from being indicated with higher efficiency figures.

We use inter-site distance (ISD) as a control parameter and define the optimum ISD $D_{i,opt}$ as the value that minimizes the area power consumption and achieves the target area throughput at the same time for each strategy i. We first define the maximum ISD $\hat{D}_i$ achieving at least the target area throughput in Mbps/km^2. Note that area throughput monotonically decreases with ISD, and thus all $D_i \leq \hat{D}_i$ will satisfy the requirement. Therefore, in order to obtain the optimal ISD, we

search over the feasible ISD interval $(0, \hat{D}_i]$ to find the value that minimizes the area power consumption for each strategy i.

Here, the area power consumption of a given deployment strategy i consisting of m types of BSs is calculated considering the number of BSs N_k^i, and their power consumption P_k^i as $\Omega^i = \frac{\sum_{k=1}^{m} N_k^i P_k^i}{\mathcal{A}}$ [4]. Under the assumption that small cells do not contribute to macrocell coverage, we adjust the transmit power of the macro BS in order to ensure a certain coverage requirement given by

$$P_{tx} = \frac{P_{min}}{c} \frac{R_{max}^{\alpha}}{R^{\alpha}} \left(\frac{D}{\sqrt{3}} \right)^{\alpha} = \frac{P_{min}}{c} \frac{\mathcal{C}^{\alpha/2}}{3} D^{\alpha}. \tag{2.7}$$

where P_{min} denotes the minimum required received power at the cell edge and $\mathcal{C}$ and α are the fraction of cell area where received power is above a certain level and path loss exponent, respectively.

Therefore, area power consumption will have the following dependence on cell range: $\Omega^i(D) = \frac{\sum_{k=1}^{m} N_k^i P_k^i}{\mathcal{A}} \approx \frac{f(D^{\alpha})}{f(D^2)}$. This relationship indicates that there is always a non-null and finite ISD that minimizes the area power consumption of a given deployment, i.e., D_i^*, $\forall i$. This optimum point occurs due to the tradeoff between the reduced transmit power to ensure fixed coverage and the additional idle power consumption due to densification and varies in accordance with the system bandwidth, path loss exponent, and the number of additional small cells deployed under the macrocellular umbrella coverage. Due to the monotonicity properties, the optimum ISD $D_{i,opt}$ minimizing the area power consumption and achieving the target area throughput for each deployment strategy i is defined as $D_{i,opt} = \min(D_i^*, \hat{D}_i)$.

After ensuring that each deployment strategy provides the same performance, we calculate the energy efficiency of different heterogeneous deployment strategies based on their minimum area power consumption $\Omega^i(D_{i,opt})$ $\forall i$ representing the case where the networks are designed based upon their optimum ISDs. Finally, we quantify the energy savings via each Hetnet deployment scenario by comparing $\Omega^i(D_{i,opt})$ with the reference macrocellular network deployment $\Omega^i(D_{opt}^{ref})$.

The key results indicating the energy savings through for the Hetnet solutions using outdoor and indoor small cells are presented in **Papers 7&8** and summarized in Section 3.2.

2.4.2 Defining Operational Solutions

Based on the fact that main part of the energy is wasted due to significant spatial and temporal traffic variation during a day, we aim to answer *How the networks should be operated in an energy efficient manner?*. In this regard, we focus on short term sleep solutions, namely cell DTX which allows dynamic sleep mode operations

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[4]Note that backhaul power consumption might or might not be incorporated into the model. The details are given in each paper.

at the BS on a short time resolution, e.g., millisecond level. Therefore, we narrow our interest and consider two main research questions: i) EES3: *How much energy we can save via cell DTX for a given traffic pattern?* and ii) EES4: *Is further energy saving achievable when cell DTX is incorporated into a clean-slate network deployment?*.

In order to answer the former question, we develop a novel quantitative method to evaluate the savings from cell DTX in a given deployment and daily traffic variation. The proposed method is based on the characterization of feasible cell load levels in a given hour $t \in [1, 24]$, i.e., $\eta_k^t \; \forall k$, which balance the resource utilization and the interference-dependent resource demand in the network. Here the load represents the fraction of time-frequency resources that are scheduled for data transmission in a given cell. Based on the ability to predict cell loads with an simple and tractable method, we calculate the daily average area power consumption of the network with cell DTX ($\delta \in [0,1)$) as

$$\mathbb{E}_t[\mathcal{P}_{area}^t(R)] = \frac{1}{|t|} \sum_{t=1}^{24} \frac{\sum_{k=1}^M \Delta_p \, P_k \, \eta_k^t + (1-\delta) P_0 \eta_k^t + \delta P_0}{\mathcal{A}(R)} \tag{2.8}$$

Here M is the total number of BSs in the network, R is the cell range of each BS, and $\mathcal{A}(R)$ is the network's area. While, Δ_p, P_0, and δ are the power consumption parameters introduced in Section 2.1. Note that here $\delta = 1$ represents the case where the BS does not have the cell DTX capability; hence this case is used as a reference scenario in order to assess the energy saving via cell DTX.

In this thesis, the daily traffic pattern illustrated in Figure 2.2 is employed for system level simulations. This pattern was obtained based on operator traffic data by the EARTH project [67]. The results are presented under the assumption that this daily traffic pattern remains identical throughout a year.

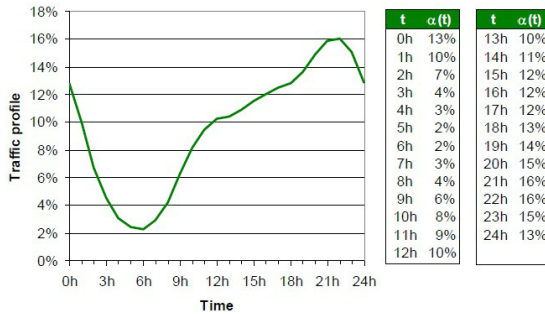| t	α(t)		t	α(t)
0h	13%		13h	10%
1h	10%		14h	11%
2h	7%		15h	12%
3h	4%		16h	12%
4h	3%		17h	12%
5h	2%		18h	13%
6h	2%		19h	14%
7h	3%		20h	15%
8h	4%		21h	16%
9h	6%		22h	16%
10h	8%		23h	15%
11h	9%		24h	13%
12h	10%			

Figure 2.2: Data traffic profile in Europe [67].

Regarding the latter question, we emphasize an often forgotten fact that network design and operation are closely related and thus independently optimized archi-

tectural and operational solutions might fail to assess the potential energy saving. This originates from the fact network design determines the relationship between the network capacity and traffic, and thus resulting the flexibility impacts the operation decisions made in accordance with traffic variation. Therefore, we incorporate cell DTX with a clean-slate deployment and obtained the optimum BS density for lowest annual energy consumption in kWh, i.e., $\min(365 \times 24 \times \mathbb{E}_t[\mathcal{P}_{area}^t(R)])$. Based on this approach, we quantify how much additional saving is achievable if networks are designed under the assumption that cells can be put into DTX mode during *idle* state.

The key results indicating energy savings through cell DTX are presented in **Paper 9** and summarized in Section 3.2.

2.5   Total Cost of Investment Model

In this section, we will present the cost models and solution approaches used to analyze the energy-cost tradeoff in wireless access networks.

2.5.1   Simple Cost Model

First, we focus on investigating the relationships amongst the main the sources of costs of wireless access networks and their impact on the future design of energy efficient networks. To this end, we propose a simple total cost of investment model as a function of spectrum leasing $C_{spectrum}$, infrastructure C_{infra}, and operation costs C_{op}:

$$C_{tot} = C_{spectrum} + C_{infra} + C_{op}. \tag{2.9}$$

With the help of this simple model, we derive a closed form expression of the total cost of investment required to fulfill a given average area network throughput requirement $\bar{R}_{tot}$ using N_{BS} base stations and W MHz bandwidth in a given service area $\mathcal{A}$. The model also presents a clear relationship between the total cost and the required total power consumption including the impact of backhaul, given by

$$C_{tot} = c_0\, N_{BS} + c_1 \bigg\{ N_{BS} \bigg[a \bigg\{ \frac{N_0 W}{cG} [2^{\frac{\bar{R}_{tot}}{W}} - 1] \bigg(\frac{\mathcal{A}}{\pi N_{BS}} \bigg)^{\alpha/2} \bigg\} +$$
$$b_{radio} + b_{backhaul} + y \frac{\bar{R}_{tot}}{N_{BS}} \bigg] + d \bigg\} + c_2 W, \quad (2.10)$$

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

The key results indicating the impact of each cost elements on the future design of high capacity design of green wireless access networks is presented in **Paper 10** and summarized in Section 3.3.

2.5.2 Economic Viability Methodology

In order to answer the question ECTA2: *Under which circumstances will an operator get a total cost saving from an energy efficient solution?*, we employ an economic viability methodology introduced in this section.

Let i denote a proposed solution to reduce the energy consumption of wireless access networks. Then, the total cost of implementing i^{th} solution can be approximated as [68]

$$C_{tot}^i = c^i \, N_{BS}^i, \quad [\text{€}] \tag{2.11}$$

where c^i is the cost per base station including capital expenditures related to installation, radio equipment, and operational expenditures such as energy, site rentals, maintenance, etc. N_{BS}^i denotes the number of base stations needed to provide the desired service level in the network. On the other hand, let C_{tot}^{ref} denote the total cost of investment of the reference system with N_{BS}^{ref} BSs each costs c^{ref}.

Then, in order to identify whether or not the additional capital investments required for a given green network strategy can be compensated by reduced energy cost, we make the following relative comparison:

$$\frac{C_{tot}^i}{C_{tot}^{ref}} = \frac{c^i \, N_{BS}^i}{c^{ref} \, N_{BS}^{ref}} \lessgtr 1 \tag{2.12}$$

According to this, an operator will get total cost benefit from the chosen energy oriented solution if the ratio $\frac{C_{tot}^i}{C_{tot}^{ref}}$ is less then one. In order to fairly compare the OPEX term consisting of the annual savings related to energy consumption with the CAPEX term consisting in mostly a one-time, high cost of upgraded BSs, the total cost analysis are performed over the network's expected lifetime.

2.5.2.1 Total Cost of Investment

In order to take the time preference in to the cost analysis, we use a common model for the total cost of an investment performed over several years, i.e., *Net Present Value (NPV)*. According to this model, the total NPV of an investment of a unit deployed at the beginning of first year and used over N years is given by

$$c = \sum_{n=1}^{N} \frac{c_n}{(1+d)^{n-1}}. \quad [\text{€}/unit] \tag{2.13}$$

where d is discount rate, c_n and N are the total costs in year n and the network lifetime respectively. Price erosion can be included into the model by letting c_n diminish over the years.

Under the assumption that i) unit capital expenditures c^{capex} occurred at the beginning of the deployment, ii) all operational costs of a BS, excluding energy cost, i.e., c^o, are constant during N years, the total cost of investment of deploying N_{BS} BSs can be expressed in detail as below:

$$C_{tot} = N_{BS} \left(c^{capex} + c^o \times \frac{(1+d)^N - 1}{d(1+d)^N} \right) + \sum_{n=1}^{N} \frac{e_n \times E_n(N_{BS})}{(1+d)^{n-1}}. \quad [\text{€}] \quad (2.14)$$

where E_n and e_n denote the average annual energy consumption and unit energy cost in year n respectively.

With the help of the proposed economic viability method and the total cost of investment model, we quantify and compare the total cost of investment of two specific solutions applicable to an existing or a greenfield deployment scenarios. The key results obtained are presented in **Paper 11** and summarized in Section 3.3.

Chapter 3

Key Results

In this chapter, we present the key results obtained in this thesis, in the following subsections: i) Energy Efficiency Assessment; ii) Energy Efficient Solutions; and iii) Energy-Cost Tradeoff Analysis.

3.1 Energy Efficiency Assessment

Despite the great interest in energy efficiency in mobile radio networks, how energy efficiency should be measured is, however, still disputed in the literature. In this section, we discuss the role of metrics in order to obtain an indication of how to achieve green wireless access networks and propose novel power consumption models for mobile backhaul which is often ignored in the literature.

3.1.1 Energy Efficiency Metrics

The initial problem when evaluating green wireless access networks is to define suitable energy efficiency metrics in order to provide quantified information and make a fair evaluation of any proposed solutions at the network level. However, existing QoS oriented metrics such as data rate, spectrum efficiency, or transmit power, are inadequate to represent the "greenness" of the network. In this respect, various EE metrics have been proposed among which bit/Joule and W/km^2 are the most common metrics in the literature. Based on our extensive literature survey, we observe that the misuse of these widely accepted efficiency metrics results in contradictory and debatable directions for green wireless access networks.

   With the help of the methodology intoduced in Section 2.3, we analytically proved that *bit/Joule and W/km^2 lead to contradictory conclusions when the optimization process is not subject to a predefined network capacity requirement.* This key observation partly explains the main reason behind the opposite claims as to whether or not densification and femtocell deployment are promising solutions to reduce energy consumption in wireless access networks.

The densification problem has been evaluated in a quantitative example and the key findings are illustrated in Figure 3.1. This figure depicts the variation of the bit/Joule and W/km^2 metrics as function of number of BSs when the capacity requirement is **not** considered. It is observed that bit/Joule is monotonically increasing with network densification. In contrast, the W/km^2 metric indicates that reduced transmit power cannot compensate for the additional power consumption of the backhaul and BSs in the idle state. Therefore, W/km^2 increases with number of BSs after reaching the optimum point.
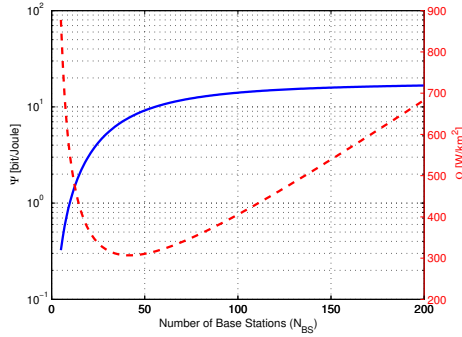

Figure 3.1: Bit per energy (solid line), area power consumption (dashed line) vs. number of base stations.

The main findings suggests that maximizing the energy efficiency is not always equivalent to minimizing the energy consumption. Therefore, in order to avoid the debatable evaluations, energy efficient network design problems should be formulated with well defined coverage and capacity requirements. More details can be found in **Paper 1**.

3.1.2 Power Consumption Modelling with Backhaul

Another fundamental step for evaluating energy efficiency is the precise characterization of the total power consumption in wireless access networks. In the literature this is generally restricted to the sum of the power consumption of all the BSs. However, the choice of specific deployment affects the exact implementation of the MBH network, and consequently the power consumption of the MBH network and thus this energy consumption should be carefully considered when making an energy efficiency assessment.

For this purpose, we present novel power consumption models for various backhaul technologies and incorporate them into existing base station power models. The combined models are used to show the impact of different technology and architectural options on the total power consumption of the network, taking into consideration different data rate requirements ranging from today's requirements

to the expected 2020 requirements. The main findings will be summarized in the following subsections.

3.1.2.1   Impact of Mobile Backhauling Solutions

In this subsection we present the results considering a few different backhaul architectures suitable for urban and rural areas. The modelling details and additional results can be found in **Papers 2, 3, 4, and 5**.

Urban Areas

As explained in Chapter 2, an initial step for assessing the impact of backhaul power consumption on the total is to define the wireless network deployment strategy. For the urban areas, we consider two different deployment strategies which provide the same coverage and network capacity. 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 indoor and/or outdoor small BSs are deployed to cater for the localized traffic demand under the macro-cellular umbrella coverage.

Note that for the results presented in this section, we consider a heterogeneous network deployment with indoor small cells (i.e., femto BSs) which have attracted great interest in order to address coverage and capacity needs in residential and enterprise environments [48]. For this scenario, the selected backhaul architectures that can cope with the expected traffic demand up to 2020 are presented in Figure 3.2. Here, the first architecture is based on a hybrid solution (i.e., combining fiber and copper-based technologies (Fiber to the Node (FTTN) using Very-high-speed Digital Subscriber Line version 2 (VDSL2)), the second relies on microwave only, and finally the third architecture employs Fiber to the Building (FTTB) and microwave technology.

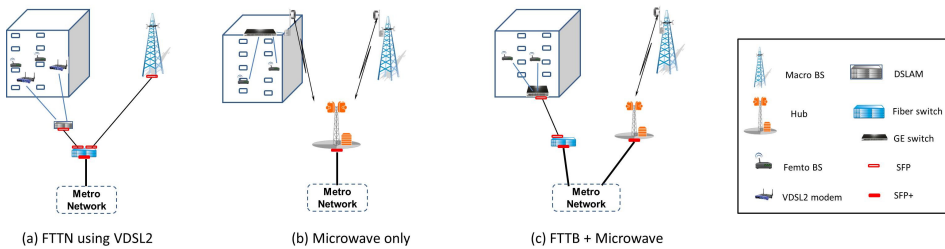(a) FTTN using VDSL2   (b) Microwave only   (c) FTTB + Microwave

Figure 3.2: Possible MBH architectures for urban areas.

Figure 3.3a depicts a comparison between the power consumption of each presented backhaul architectures as a function of the femto BS penetration rate, i.e., the fraction of apartments assumed to be equipped with femto BS. It is shown that among the considered backhaul solutions, FTTB + Microwave, which relies
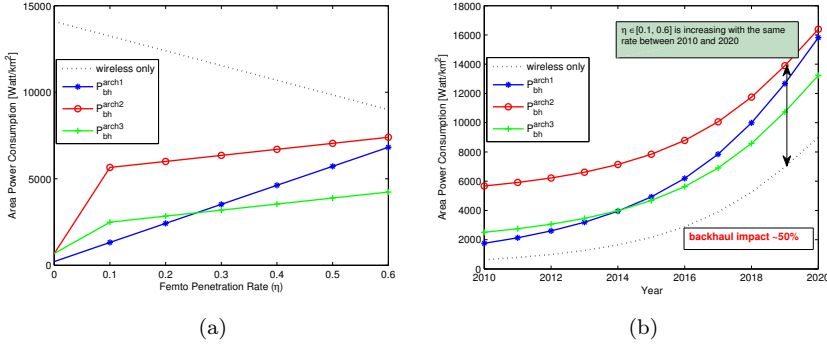
Figure 3.3: a) Area power consumption vs. femto BS penetration rate for the traffic demand in 2020, b) Area power consumption change over the years for macro+femto deployment scenario.

on FTTB to backhaul the indoor traffic, is the most energy efficient. On the other hand, the backhaul solution based on microwave only seems to be the least energy efficient due to the high energy consumption values of the microwave antennas that needs to be deployed at each macro BS and at each building that has at least one femto BSs.

Finally, the impact of backhaul on the total power consumption between 2010 and 2020 is illustrated in Figure 3.3b, for heterogeneous wireless network deployment scenarios. Note that in this specific experiment it was assumed that per-year-increase in the area traffic demand and the femto BS penetration rate is constant, i.e., 68% and 20%, respectively. The results show that even though offloading traffic to indoor femto BSs results in significant energy savings for the wireless part (Figure 3.3a), this benefits come with a drastic increase in the backhaul power consumption, i.e., the backhaul can constitute up to 50% of the total power consumption. The figure also shows the clear trade-off between the power saved by using low power base stations in the wireless segment and the additional power that has to be spent to backhaul their traffic.

Rural Areas

Providing wireless broadband access to rural and remote areas is becoming a big challenge for wireless operators, mostly because of the limited return on investment from providing and maintaining the service. Therefore, cost-effective and low energy-consuming mobile backhaul is highly important for rural areas. In this regard, we extend our focus to rural areas and evaluate the backhaul power consumption for different wireless deployments and candidate backhaul architectures.

For the wireless segment, two homogeneous deployment strategies are considered: i) macro BS and ii) small BS deployment. For the MBH segment, two wireless
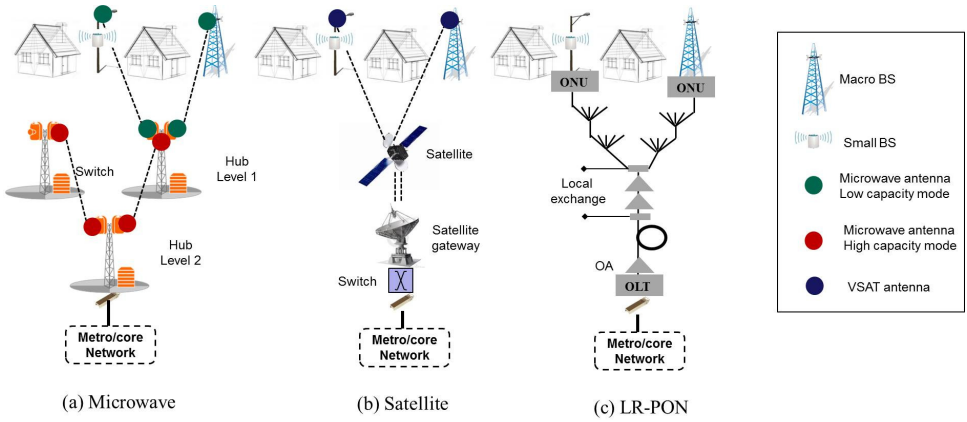
Figure 3.4: Possible MBH architectures for rural areas.

solutions, i.e., microwave and satellite, and an optical solution based on long reach passive optical networks (LR-PON) are considered as illustrated in Figure 3.4. All these options are compared in terms of their ability to satisfy the coverage, capacity, and QoS requirements of a number of rural users in the time span from 2010 until 2021.

Figure 3.5 presents the total power consumption of the access network, including both the wireless and backhaul segment for the considered architectures. To better evaluate the impact of the microwave MBH we also plotted the power consumption of the wireless access segment only (dotted lines). It is observed that, the impact of the MBH is significant in case of satellite based solutions where the backhaul is responsible for up to the 46% of the total power consumption of the access network. However, in the case of macro BS deployment and/or LR-PON-based MBH is employed, the backhaul impact is limited to several percent. It should be noted that despite the higher backhaul impact, small cell deployment still gives lower total power consumption compared to macro-cellular deployment for a high capacity demand region.

The results from urban and rural areas demonstrate that backhaul will be responsible for a remarkable share of energy consumption in future ultra-high capacity wireless access networks. Furthermore, it is shown that fiber-based backhauling solutions excels among the technologies 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 in the easy-to-deploy and comparatively cheap microwave and copper based solutions. The results also highlight the importance of designing energy efficient backhauling solutions.
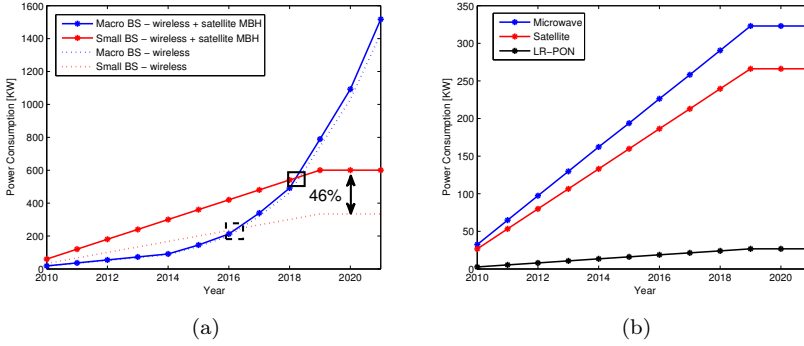
Figure 3.5: Total power consumption (wireless segment + MBH) of a wireless access network in a rural area; a) Satellite backhaul. b) Comparison of backhaul technologies.

3.2   Energy Efficient Solutions

Based on the key conclusions drawn as to how to correctly evaluate the energy efficiency of wireless access networks, in this section we focus on identifying architectural and operational solutions at a system level in order to reduce the energy consumption.

3.2.1   Energy Efficient Network Deployment

Considering the fact that exponentially increasing traffic demand will require the deployment of several orders of magnitude more base stations, energy-oriented clean slate deployment strategies have a tremendous potential to meet the requirements with lower energy consumption. In this respect, we investigate various homogeneous and heterogenous network deployment strategies in order to answer HQ2: *How should wireless access networks be deployed in an energy efficient manner?*.

3.2.1.1   Homogeneous Network Deployment

First, we focus on a simple homogeneous network deployment in order to understand the dynamics and key relationships between the energy efficiency and the important design parameters such as cell range, capacity requirement, BS type, power consumption elements, etc.

Numerical results show that deployment of smaller cells significantly reduces the BS's transmit power and thus increases the impact of idling and backhauling power consumption which constitutes more than 60% of the total power consumption. Therefore, reduced transmit power alone can not compensate for the additional

required idle power consumption, leading to lower energy efficiency. However, we observe that even though energy efficiency is maximized by the deployment of the largest feasible cell size in a low capacity demand region, this approach quickly loses its efficiency, and even becomes infeasible to fulfill the requirements for capacity as demand increases. For this reason we use the proposed model where the power consumption parameters vary based on coverage adaptive transmit power, and we observe that the optimum cell ranges shifts towards smaller cells. This arises from the fact that impact of load dependent power consumption becomes dominant for large cell size deployment and generates an optimum cell size for each area capacity target. In both cases, we come to the conclusion that careful prediction of capacity demand is the key challenge for energy efficient deployment of wireless networks. More details can be found in **Paper 6**.

3.2.1.2 Heterogeneous Network Deployment

After defining the key relationships for homogenous network deployment, we investigate the potential energy savings through various heterogeneous network deployment strategies. More specifically, we analyze the impact of various BS types and the number of additional BSs deployed under a macrocellular umbrella coverage on energy efficiency. The results are compared with traditional macrocellular network deployment in order to quantify the energy savings. Note that energy efficiency is represented by W/km^2 in these analyses as we found that this was a more useful metric as described in section 3.1.1.

The network layouts considered are shown in Figure 3.6. Here the central reference cell is surrounded by two tiers of interference in a hexagonal grid of 19 cells. In Figure 3.6a, we illustrate an outdoor small cell deployment with micro and pico BSs. In this scenario, we assume that macro BSs with omni-directional antennas are deployed in the middle of each cell and one or more small BSs are positioned
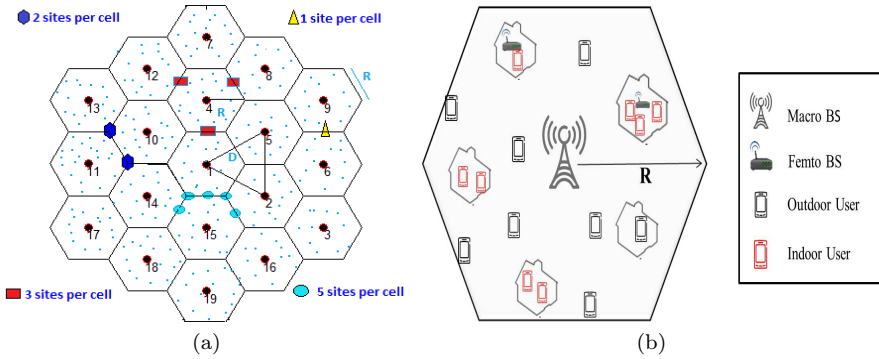

Figure 3.6: Network layouts with a) outdoor small cell deployment, b) indoor small cell deployment.

at the cell edge with a defined range and transmit power. On the other hand, Figure 3.6b represents a co-channel deployment of indoor BSs with macrocells in a hierarchical cell structure. Here, we assume that N_H single floor houses are placed at random locations within the macro coverage area where a fraction of the houses, i.e., $\rho_p \in [0,1]$, are equipped with indoor BSs. $I_p \in [0,1]$ is used to denote the the fraction of indoor users. In both scenarios, we assume that small cells do not contribute to macrocell coverage. Moreover, the users in the small cells' coverage are biased to connect to these BSs.

Based on the methodology introduced in Section 2.4, we calculate and compare the minimal area power consumption of the considered Hetnet deployment strategies with the baseline macrocellular network deployment. The results show that the optimum inter site distance obtained for each Hetnet strategy is far from that obtained for a pure macrocellular deployment. This is mainly due to the fact that each additional small cell deployment reduces the need for macrocellular densification to achieve the given area throughput target. The results obtained for outdoor small cell deployment are illustrated in Figure 3.7. We observe that conventional macro only deployment is the most energy efficient only when the traffic demand is very low[2]. 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 in accordance with the traffic density of the network. For this scenario we observed that up to 30% energy savings is achievable through outdoor small cell deployment for an area spectral efficiency target of $S{=}1$ bit/s/Hz/km^2. The detailed explanation can be found in **Paper 7**.

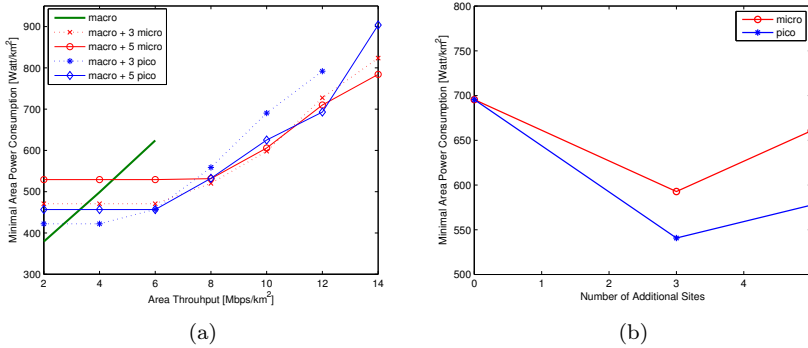Figure 3.7: a) Minimal area power consumption as a function of target area throughput for uniformly distributed traffic. b) Minimal area power consumption as a function of number of base stations at cell edge for $S{=}1$ bit/s/Hz/km^2.

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[2]Note that the intersite distance ranges from 1000 m to 4000 meters in this analysis. Therefore, the calculated area throughput range is relatively low.

Moreover, in the case of indoor small cell deployment, simulation results show that co-channel deployment of femto BSs under macro coverage significantly increases the area spectral efficiency due to the increased spectral reuse, the elimination of wall penetration loss at the cost of minor mutual interference between macro and femtocells. This effectively reduces the need for densification of the macro-cellular network resulting in lower area power consumption as illustrated in Figure 3.8a. However, we observe in Figure 3.8b that when the network is constrained by coverage, i.e., low area traffic demand region, the deployment of additional femto BSs creates capacity overprovisioning and thus increases the area power consumption. However, rapidly growing demand for capacity reverses the situation and favors femto BS deployment. We observe that in medium and high capacity demand region, up to 75% power saving is feasible as more traffic is generated indoors. More details can be found in **Paper 8**.
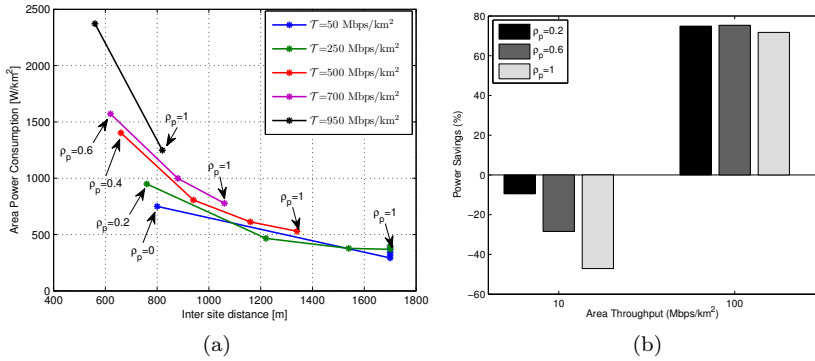

Figure 3.8: a) Relationship between area power consumption, inter site distance and femto penetration rate for $I_p = 0.7$. b) Area power consumption as a function of indoor user ratio for low and high area throughput targets.

The results from our energy efficiency analysis reveal that heterogeneous network deployments increase the area power consumption since the decrease in the transmit power is alone not enough to compensate for the high idle power consumption. However, Hetnet solutions prevail homogeneous deployment due to their superior throughput due to shorter distance between the user and the serving BS. Therefore, it has been concluded that energy efficiency improvements through HetNets are highly related to the capacity demand where significant energy savings is feasible by data offloading via small cell deployments for high area throughput targets.

3.2.2 Energy Efficient Network Operation

The main results obtained in Section 3.2.1 reveal that exponentially increasing data traffic will require network densification with small cells. Thus, in the case

of defining the network architecture with an energy-oriented objective, significant savings can be achieved with heterogeneous network deployments.

An unavoidable consequence of small cell deployment with overlay macro cells is that on average many cells will use only a fraction of their capacity and thus cause excessive energy waste even during the busy hour. This issue is particularly crucial due to the significant traffic variation during the day.

In this thesis, we focus on the short-term energy saving using cell DTX to enable dynamic sleep mode operations at BS. First we develop a novel quantitative method to evaluate the savings from cell DTX in a given deployment with a fixed daily traffic variation. Furthermore, we focus on the relationship between network design and operation in order to analyze the maximal energy saving via cell DTX.

The results in Figure 3.9 show that employing cell DTX during the planning phase of a network significantly changes the deployment for energy efficient wireless access networks especially when the cell DTX performance is good, i.e., $\delta < 0.3$. This change indicates a shift from the deployment of less-dense medium-loaded cells to dense lightly-loaded cells. These results reveal that cell DTX itself brings striking energy savings even when the network was not planned considering cell DTX. However, designing the network under the assumption that cells can be put into DTX mode during *idle* state results in additional saving by deploying slightly faster than the actual increase in capacity requirements. We conclude that if the objective is to obtain the maximum energy savings, networks have to be designed taking into account the fact that network deployment and operation are closely related. The detail explanation can be found in **Paper 9**.
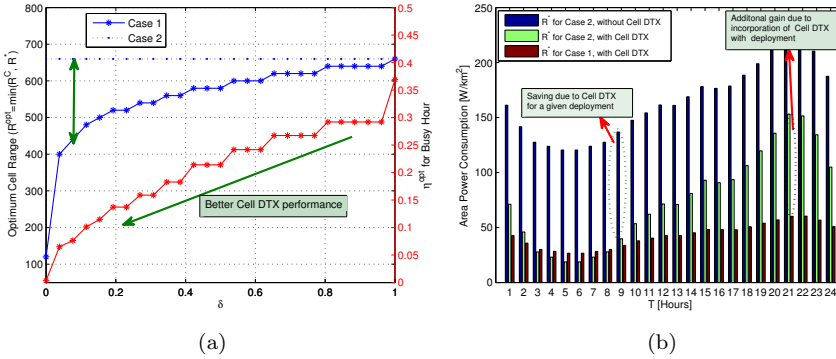

Figure 3.9: a) Impact of Cell DTX performance on optimum cell ranges and busy hour cell load levels for r_{min}=8 Mbps. b) Daily area power consumption variation with cell DTX for $\delta = 0.1$.

3.3   Analysis on Energy-Cost Tradeoff

Up to now, we assume that the main objective in wireless access network design is to obtain the most energy efficient solutions and ignore the fact that introducing these solutions may have an impact on capital expenditures. Hence, it is crucially important to assess the total cost of investment for any proposed solution solely aiming to lower total energy consumption. To this end, we first introduce a high-level framework to analyze impact of different cost elements, on the total cost. Furthermore, we assess the the economic viability of two energy efficient solutions applicable to legacy or greenfield deployment scenarios. Therefore, we investigate the circumstances where the additional capital investment required for the considered solutions is compensated by the reduced energy cost.

3.3.1   Fundamental Guidelines for Cost Efficient Network Design

In order to investigate the relationships amongst main sources of costs in wireless access networks, we proposed in Section 2.5.1 a simple model that describes total cost of deploying and operating a network incorporating infrastructure, energy, and spectrum costs.

Figure 3.10a illustrates the relative effect of each cost items on the network design and indicates the evaluation of mobile radio networks. Here, point A represents the current macro-cellular networks where the main design constraint has been high spectrum cost. As the demand for capacity increases and the spectrum licenses require billion of dollars, a solution has been sought at the physical layer by increasing spectral efficiency, i.e., squeezing as many bits/s out of a given small spectrum allocation. In this case, the infrastructure cost was the dominant factor for the network design, while 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"). Moreover, energy consumption and the cost of energy are expected to grow rapidly in the upcoming years which takes us to point D. Therefore, we predict that energy and infrastructure costs will dominate the design of future wireless access networks.

With this general overview in mind, we present a quantitative analysis in order to compare the optimum network deployment strategies when energy consumption or total cost are considered as the main design objectives. Results show that system bandwidth has a strong positive impact on energy consumption and infrastructure cost and thus a significant reduction in total cost is achievable if more spectrum is available. For this reason dynamic spectrum access or operation at higher frequencies can be the best solution (in terms of reducing energy consumption and total system cost). Moreover, results from our analysis reveal that with the expected increase in unit energy cost, future capacity limited systems are more and more constrained by energy cost. Additional details can be found in **Paper 10**.
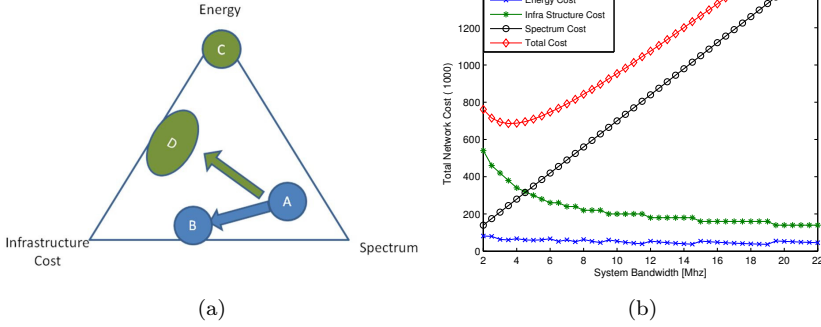
Figure 3.10: a) Key design constraints in wireless access networks. b) Total network cost vs. bandwidth ($A = 20km^2$ and $\bar{R}_{tot} = 400Mbps$).

3.3.2   An Economic Viability Analysis of Green Solutions

In this section we present a methodology for quantifying and comparing the total cost of investment of a given energy efficient solution with a basic reference system in order to identify whether or not an operator will get total cost benefit from the chosen solution. The methodology is then used for two specific solutions applicable to an existing or a greenfield deployment scenarios.

First, we consider an existing network deployment scenario. Here it is assumed that the network operator decides to upgrade their existing BS transceivers' to enable cell DTX in order to reduce their energy consumption. However, this comes at the expense of increased capital expenditures. In the second scenario, we consider a greenfield operator that builds a network from scratch. We assume that the initial idea is to conduct a deployment for minimum energy consumption which requires higher capital investments compared to traditional CAPEX-minimum deployment. In both scenarios, we analyze the circumstances under which resulted energy cost saving via the solutions considered can compensate for the incremental increase in the capital expenditures by considering the traditional CAPEX-minimum solutions as the reference scenario. More specifically, in the former case, we analyze the break-even cost of the new hardware Δc, defined as the point where the energy cost saving with hardware upgrade equals the required capital expenditures. In the latter, we identify the minimum the energy cost so that energy-oriented design will result in lower net present value during network lifetime. In the analysis we use other unit cost values as evaluation parameters.

We first quantify the savings achieved by the considered energy efficient solutions. The results show that cell DTX provides significant energy savings by efficiently utilizing the idle times of the BS for a given deployment. In the case of greenfield deployment, we observe that by deploying slightly faster than the actual
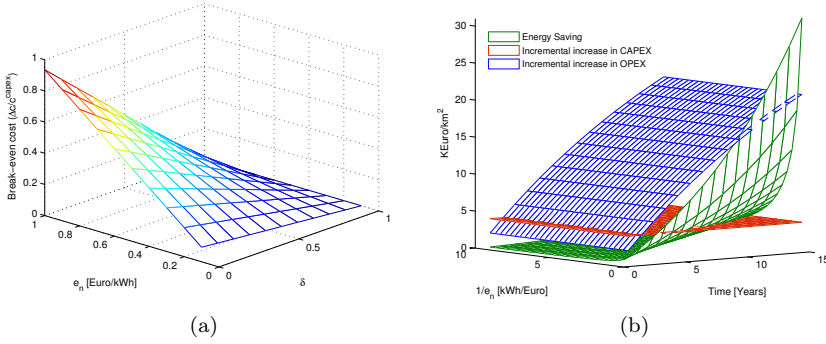
Figure 3.11: Economical viability analysis for (a) Existing Deployment (b) Greenfield Deployment.

traffic capacity requirement warrants considering that the capacity will be needed soon in the future, we can save energy along the way.

With the help of these technical results, we employ a total cost of investment analysis using the models introduced in Section 2.5.2 and illustrate the results in Figure 3.11. These results reveal that the break even upgrading cost is a increasing function of the unit energy cost. Thus, upgrading the existing BS transceivers' is *increasingly cost effective* as the unit energy cost increases. Considering todays' cost values, we can conclude that resulted energy cost saving via hardware upgrade enabling cell DTX can compensate the incremental increase in CAPEX when the price Δc is below the break even cost of 8% and 42% (of a BS cost) for the countries in low (e_n=0.1 €/kWh) and high (e_n=0.5 €/kWh) electricity price zones respectively. Moreover, the results for greenfield deployment show that the energy-oriented design, indicating denser deployment of lightly loaded cells, might compensate the additional capital investments during network lifetime only if energy is expensive and/or BSs are low cost. However, an annual increase in OPEX negatively impacts the conclusions. This means that over-dimensioning might not be motivated considering today's cost values unless the operator gets additional cost benefits from energy saving solutions. A detail explanation is given in **Paper 11**.

Chapter 4

Conclusions and Future Work

Mobile communication networks consume 0.5 percent of the global energy today. Rapidly growing demand for capacity will further increase their energy consumption. Thus, improving energy efficiency has a great importance not only for environmental reasons, but also to lower the operational cost of network operators. Therefore, the main goal of this thesis was to incorporate energy-awareness into the design of future wireless access networks and to identify architectural and operational solutions enabling energy saving without degrading users' perceived quality of service. Based on this main goal, we identified the following high-level research questions:

1. HQ1: How to assess the energy efficiency of a given network?

2. HQ2: How should wireless access networks be deployed and operated in an energy efficient manner?

3. HQ3: What are the consequences of energy efficient solutions on total cost?

In this chapter, we first provide the conclusions related to the specific problems stated in thesis according to the given high-level problems. Then, we indicate the remaining open problems and highlight the possible directions for future work.

4.1 Concluding Remarks

4.1.1 Energy Efficiency Assessment

Two key aspects of accurate energy efficiency evaluation have been taken into consideration in this thesis namely, energy efficiency metrics and power consumption models. Regarding the metrics, we demonstrated the impact of misusing two widely accepted network level energy efficiency metrics on the conclusion by using a simple network dimensioning problem. Our findings indicated that maximizing energy efficiency is not always equivalent to minimizing energy consumption which is one

of the main reasons behind the contradictory and disputable conclusions in the literature. We have shown that in order to avoid debatable evaluations, energy efficient network design problems should be formulated with well defined coverage and capacity requirements. With respect to power consumption modelling, although accurate models for different base station types have been proposed, the impact of mobile backhaul has been mostly ignored in the literature under the assumption that the power required for backhauling constitutes a small fraction of the total. In order to assess whether or not this assumption is valid, we proposed novel backhaul power consumption models considering various technology and architectural options relevant for urban and rural environments. Based on the proposed models, we assessed the impact of backhaul power consumption on various different wireless deployment scenarios and illustrated its variation over the years based on expected traffic growth. Our results indicated that backhaul can be responsible up to 50 percent of the total power consumption and thus it will potentially become a bottleneck in future ultra-high capacity wireless access networks. Therefore, in order to achieve truly green network architectures, backhaul power consumption has to be included in the energy efficiency analysis especially for heterogeneous network deployment scenarios. The results also highlighted the importance of designing energy efficient backhauling solutions.

4.1.2   Energy Efficient Solutions

Using the insights gained about accurate energy efficiency evaluation, we tackled problems related to architectural and operational aspects for energy efficient design.

To begin with, we focused on energy-oriented clean slate deployment strategies which can meet the requirements with lower energy consumption. Considering the fact that there are various contradictory results in the literature despite the intensive investigation conducted, we first analyzed the impact of several important design parameters on energy efficiency in order to gain insight regarding the main tradeoffs. In this respect, by using a homogeneous network deployment scenario and full buffer traffic model, we analyzed the key dependence of area power consumption on base stations characteristics, system bandwidth, transmit power, cell size and power consumption parameters. We also analyzed the impact of network performance requirements such as coverage, area throughput on the key relationships. We have analytically shown that area power consumption has an optimum for each set of service requirements and the optimum varies in accordance with many design parameters where spectrum is one of them. Further, we have identified that the ratio between idle- and transmit power dependent power consumption of a base station as well as the network capacity requirement are the two key parameters that affect the energy-optimum design. In this respect, we have seen that any method that decreases the transmit power, e.g., higher bandwidth utilization, or impact the power amplifier efficiency in a positive manner, increases the impact of idle power consumption and thus the results are in favor of deployment of larger cell sizes. On the other hand higher area capacity requirements shift the optimum

point towards smaller cells. Consequently, careful prediction of capacity demand has been identified as a key challenge for the energy efficient deployment of wireless networks.

Based on the understandings established, we assessed the area power consumption of several candidate heterogeneous network deployment architectures featuring varying type and number of indoor and outdoor small BSs under the macro-cellular umbrella coverage. For the considered architectures, busy hour traffic conditions are handled under both uniform and/or non-uniform spatial traffic distribution scenarios, whereas temporal variation is ignored. In this thesis, we considered two main offloading benefits of Hetnet deployments: i) The deployment of small cells in a macrocell area reduces the number of users that need to be served by the macro-cellular network and thus lower the need of macro densification. ii) The resulted less-dense macro layer is utilized through coverage adaptive transmit power adjustment technique. Based on these considerations, we presented a methodology ensuring that each strategy provides the same system performance with regards to network coverage and area throughput in order to fairly quantify and compare the area power consumption of various architectures with different number of BSs. Our results indicate that, under employed scenarios and power consumption models, 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 due to higher number of small BSs. Therefore, in low capacity demand region, conventional macro only deployment is shown to be the most energy efficient deployment scenario. However, the results reveal that Hetnet architectures prevail over homogeneous deployment due to their superior throughput arising from shorter distances between the user and the serving BS and thus enable significant energy savings in medium and high capacity demand regions where the absolute numbers are highly related to the considered scenario.

Considering the fact that there is a significant traffic variation during a day and average resource utilization of a BS is very low even at the busy hour due to the strict QoS requirements, hence main part of the energy is wasted regardless of whether or not the networks are designed for minimum energy consumption. Therefore, we investigated a short-term energy aware management approach, namely cell DTX, enabling BSs to dynamically adapt their power consumption to the temporal traffic variation in milisecond level. With the help of the developed novel quantitative method, we evaluated the energy savings with cell DTX in a given deployment and daily traffic variation. Our results showed that fast traffic adaptation capability of cell DTX brings considerable reduction in energy consumption only if the network under study is operating under low load conditions. Furthermore, we investigated whether or not further saving is feasible when one considers the often forgotten fact that network design and operation are closely related. We revealed that when cell DTX is incorporated with clean-slate network deployment, dense network deployment with lightly loaded cells tends to be preferred. This arises from the fact that this new deployment paradigm takes into consideration that baseline power consumption is load adaptive and thus transmit power dependent power consumption

is non-negligible in the total. We have seen that the resulting flexibility impacts the operation decisions made accordance with traffic variation which brings additional savings.

4.1.3   Total Cost of Investment Analysis

The results on energy efficient network design revealed that if the objective is that of obtaining the minimum energy solution, the optimum design mostly requires denser deployment which, as a consequence, increases the installation cost. Considering the fact that the motivation for reducing the energy consumption of wireless access networks is driven not only by environmental concerns, but mainly by economic reasons, we made a total cost of investment analysis in order to indicate the main tradeoff between energy and cost, as well as to identify under which circumstances an operator get a total cost saving from an energy efficient solution.

To begin with, we presented a high-level framework to investigate the relationships amongst main sources of costs on the design of wireless access networks. Our results revealed that additional spectrum is not only beneficial for reducing the total energy consumption, but also for reducing total infrastructure cost. Therefore, as the unit energy and spectrum cost increase, total cost optimum design moves closer to the energy asymptote where idle power consumption becomes a significant factor. Beside the presented tradeoffs between main cost items, we also proposed a more detailed methodology as means to estimate the economic viability of any proposed solution solely aiming to lower the energy consumption. The methodology is then used to quantify and compare the total cost of investment of two specific solutions applicable to an existing or a greenfield deployment scenarios. Our analysis demonstrated the break-even cost of the considered energy efficient solution, i.e., the point where the resulted energy cost saving equals to required capital expenditures. We have seen that the additional investment for the hardware upgrade for an existing network, or for the energy-optimized greenfield deployment can be compensated by the reduced energy cost. However in many cases the upper bound for the new hardware or the lower bound for the unit energy cost and CAPEX might be rather low or high respectively. This means that the viability of the solutions must be carefully assessed on a case by case basis.

4.2   Discussion and Future Work

In this thesis, we defined the specific research problems based on the three high level questions. Despite the fact that several contributions have been presented in this comprehensive research area, there are issues still remain to be addressed which will be summarized in this section.

To begin with, we have seen that backhaul solutions are becoming an important contributor to the energy bill of network operators, especially for emerging heterogeneous network deployment solutions. This implies that backhaul power consumption should be included in the energy efficiency analysis in wireless access networks

and a holistic approach should be applied to energy optimization to achieve a truly green integrated network architecture. However, this requires an integration of independent efforts enabling energy efficient wireless and wired networking solutions in order to identify a new converged green and commercially-viable solution.

Regarding the clean-slate energy-oriented deployment solutions, in this dissertation we mostly focused on the analysis of main relationships between key design parameters and their impact on total power consumption. Moreover, how to make fair comparison between different architectures and how to utilize hierarchical deployment with small cells to minimize energy consumption have been investigated by using candidate deployment solutions. Despite the fact that the presented results bring important insight to the problem, they fail to present the achievable energy savings. This is primarily because the savings have been identified based on a static set of assumptions on hardware capability and radio resource management techniques. Second, the approaches only considered two offloading benefits of small cell deployment and ignored the fact that enabling efficient resource allocations by offloading the users with poor radio channel conditions might bring additional savings. More importantly, the savings have been quantified based on deterministic or random small cell deployment assumptions and mostly under uniform traffic distribution scenario. This is indeed neither optimum not realistic considering real-world network conditions. Therefore, future work might investigate a holistic and optimized approach and define the objective as to identify energy efficient configurations for hierarchical cell structures considering realistic non-uniform spatial distribution of traffic, candidate base station types, and locations. We believe that the analysis should be performed considering the accurate characterization of resource utilization for each candidate topology in order to accurately identify the SINR distribution and the daily energy consumption. Moreover, as we mentioned earlier, the initial network deployment decision should take into account all applicable energy aware management mechanisms in order to comprehend achievable energy savings through heterogeneous deployments. Therefore, the capability of the hardware, i.e., whether or not dynamic sleep mode operations are applicable, and the long-term traffic adaptive BS activation solutions should be incorporated into the energy efficient design problem.

With respect to energy efficient network operational solutions, in this dissertation we have presented the potentially great energy saving of cell DTX, however we did not analyze any long-term sleep solutions. Therefore, it would be interesting to examine the energy saving through an integrated energy efficient operation scheme which considers both short- and long-term energy aware management approaches which has not been investigated in the literature. It should be noted that while cell DTX aims to finalize the transmission as quick as possible in order to enter the micro sleep mode and maximize the energy saving, long-term ON/OFF schemes aim to lower the number of active BSs in the area and distribute the load to neighbor cells. Therefore, short- and long-term sleep solutions have contradictory objectives, i.e., load balancing and load concentration respectively. It is therefore important to investigate this tradeoff and to evaluate the energy savings from integrated so-

lutions.

Finally, regarding total cost of investment analysis, a possible future work might employ an economic viability analysis for energy efficient Hetnet solutions. As our initial results indicated, the energy saving from Hetnet deployments come with an expense due to the increased number of BSs compared to macrocellular network deployment solutions. Therefore, it would be interesting to analyze the circumstances under which the resulting energy cost saving via the proposed solutions compensate for the incremental increase in capital expenditures.

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