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Energy Efficiency Techniques & Challenges for Mobile Access Networks

Master's Thesis submitted in partial fulfillment of the degree of Master of Science in Technology

Espoo, 6th May 2011

Supervisor: Prof. Jyri Hämäläinen, Aalto University

AALTO UNIVERSITY **ABSTRACT OF THE MASTER'S THESIS**

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Energy consumption of mobile access networks has recently received increased attention in research carried out in both industry and academia. The cellular networks do not have considerable share in the overall energy consumption of the ICT (Information and Communication Technology) sector. However, reduction in energy consumption of mobile networks is of great importance from economical (cost reduction) and environmental (decreased CO2 emissions) perspective.

The Thesis work has investigated the different means to enhance the capacity of evolved mobile networks and discussed the related challenges from energy consumption perspective; this discussion is followed by a simple radio network power usage model. Based on the model examples are given where two different deployment scenarios have been compared.

Further the work focused on the WCDMA energy saving through femtocell deployment. A simple model for the energy consumption per unit area has been derived based on WCDMA downlink load equations. Based on the model, two different deployment scenarios have been compared to make the conclusion from energy consumption perspective.

In the end, the impact of femtocells to the energy efficiency of the WCDMA network has been studied under the consideration of a valuable power save feature of femtocell.

Keywords: *Mobile access networks; energy and power efficiency; scenarios; comparisons; femtocells; load equations; idle mode*

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Maliha Urooj Jada

6th May 2011

To my parents & siblings

Contents

ABBREVIATIONS

BS	Base Station
CO2	Carbon dioxide
ICT	Information & Communication Technology
PST	Public Switched Telephone
PDG	Packet Data Gateway
GGSN	Gateway GPRS Support Node
SGSN	Serving GPRS Support Node
HLR	Home Local Register
IMS	IP Multimedia Subsystem
RF	Radio Frequency
PAR	Peak to Average Power Ratio
UMTS	Universal Mobile Telecommunication System
WiMAX	Worldwide Interoperability for Microwave Access
LTE	Long Term Evolution
AM/AM	Amplitude to Amplitude Modulation
IBO	Input Back Off
OBO	Output Back Off
ET	Envelop Tracking
PA	Power Amplifier
WCDMA	Wideband Code Division Multiple Access
MIMO	Multiple Input Multiple Output
BBU	Base Band Unit
DSPs	Digital Signal Processors
FPGAs	Field Programmable Gate Arrays
ASICs	Application Specific Integrated Circuits
UE	User Equipment
SINR	Signal to Interference to Noise Ratio
hrs	hours
OPEX	Operational Expenditure
CAPEX	Capital Expenditure
QoS	Quality of Service
2G	Second Generation
3G	Third Generation
QoE	Quality of Experience
EARTH	Energy Aware Radio and Network Technologies
kwh	kilowatt hour
SUB	Subscribers
AMR-HR	Adaptive Multi Rate - Half Rate
IMT Advanced	International Mobile Telecommunications Advanced
3GPP	Third Generation Partnership Project
SISO	Single Input Single Output
AWGN	Additive White Gaussian Noise
SNR	Signal to Noise Ratio
SIMO	Single Input Multiple Output

CDF	Cumulative Distribution Function
ISD	Inter Site Distance
WRC	World Radio communication Conference
IP	Internet Protocol
HSPA	High-Speed Packet Access
HSDPA	High – Speed Downlink Packet Access

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Deployment of increasingly powerful mobile network technologies has taken place within the last decade. Although network efficiency has been growing, the higher access rates have inevitably led to increased energy consumption in base stations (BSs) and network densities have been constantly growing [1].

Recently, the mobile communication community has become aware of the large and ever-growing energy usage of mobile networks [2]. Besides industry, the awareness of the ever-increasing energy consumption has stimulated research in academia, particularly on issues addressing the BS site energy consumption [3] [4] [5] [6] [7]. Yet, the work on the reduction of energy consumption has been mostly carried out by BS manufacturers [8] since high power efficiency provides a competitive advantage.

Today one of the most discussed topics is the global warming, which is due to increment of CO_2 (Carbon dioxide) and other green house gases concentration levels in atmosphere. To decrease the CO_2 emissions the consumption of fossil fuels has to be decreased [9] [10]. Thus the research has been carried out in the ICT (Information and Communication Technology) sector to reduce the consumption of fossil fuels to make the environment clean and green.

Mobile networks do not have considerable share in the overall energy consumption of the ICT sector, which itself is responsible for 2% to 10 % of the world energy consumption. However, reduction in energy consumption of mobile networks is of great importance from economical (cost reduction) and environmental (decreased CO_2 emissions) perspective.

1.1. General Energy Saving Aspects in Mobile Networks

Two following approaches towards Energy Efficient Mobile Networks are the following:

- Find appropriate solutions to the energy efficiency challenges for already existing networks (Brownfield).

- Design future networks from energy (and cost) efficient perspective (Greenfield perspective).

For the future Telecom’s energy consumption, difficulties and uncertainties exist in estimating the potential energy savings due to the different methodologies, that is, how to define energy consumption or which elements should be considered in the energy efficiency calculation [11].

Furthermore, energy savings depends significantly on *human behavior* and *utilization of resulting financial savings,* as any energy saving is followed by cost savings. From a network operator or infrastructure owner’s business perspective, the cost saving factor in many cases is of more importance than environmental protection. *Money saved by reducing energy consumption is available for other expenditures.* If the saved cost would be invested in a proper way, the low carbon society will be created. Alternatively energy savings could be affected by rebound effect in which the improper utilization of the saved cost might give unfortunate results of potentially additional CO_2 *emissions.*

Travelling by car is one of the most effective causes of global warming. Thus substitution of the office work with remote work via broadband network connectivity has the potential to significantly reduce the carbon dioxide emissions [11]. In a similar way business travel can be substituted by videoconferencing and electronic billing instead of paper bills would also contribute in making an environment green.

1.2. Energy Consumption in Cellular Network

A typical mobile network consists of three main elements: core network, base stations, and mobile terminals as shown in Figure 1. Base stations contribute 60% to 80% of the whole network energy consumption [12]. Thus the efforts in the reduction of energy consumption focus on the BS equipment, which includes the minimization of BS energy consumption, minimization of BS density (BS density is inversely proportion to cell area) and the use of renewable energy sources.

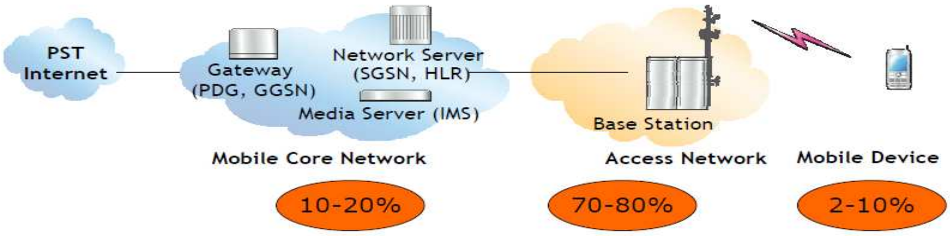


Figure 1: Energy contribution of main elements of mobile networks

1.2.1. Minimizing the BS Energy Consumption

The ways to minimize the BS energy consumption includes improvement in BS energy efficiency through better performance of BS hardware, usage of system level and software features, and usage of BS site solutions [12].

Figure 2 gives some brief idea about the energy consumption in a typical macro BS site.

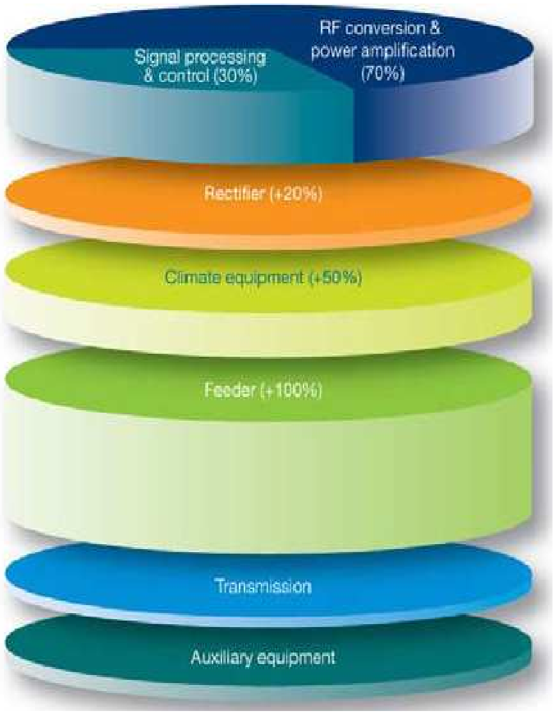


Figure 2: Energy consumption in a typical macro BS site [8]

A. *Base Station Hardware Efficiency*

For the improved performance of BS hardware; the focus should be on boosting the efficiency of power amplifier because power amplifier and its associated components can consume up to 50% of the overall power [13].

The current radio modem design paradigm requires high linearity from the radio frequency (RF) components which allows one to separate the RF design and digital signal processing design. The classic Class AB amplifier technology offers efficient operation when the RF envelope waveform is close to peak power. Unfortunately, most of the modern waveforms have high peak-to-average power ratio (PAR) forcing the power amplifier to operate most of the time in less efficient operation point. As a result efficiency around 15-25% has been measured for the waveforms used by the modern UMTS (Universal Mobile Telecommunication Systems), WiMAX (Worldwide Interoperability for Microwave Access), and LTE (Long Term Evolution) systems [13].

Figure 3 shows a typical AM/AM response (Amplitude to amplitude modulation. The output power of an RF power amplifier does not keep on increasing without limit. There exists a point when an increase in input power will not produce any significant increase in output power. This is referred to as the saturation point where output power is not proportional to input power any more. In the saturation region of an RF amplifier response, as the input increases the gain becomes compressed. This Output Power versus Input Power characteristic is referred as AM-AM distortion for a High Power Amplifier, with the associated input and output back-off regions (IBO and OBO, respectively). Output Back Off (OBO) induced by PAR means wasted power.

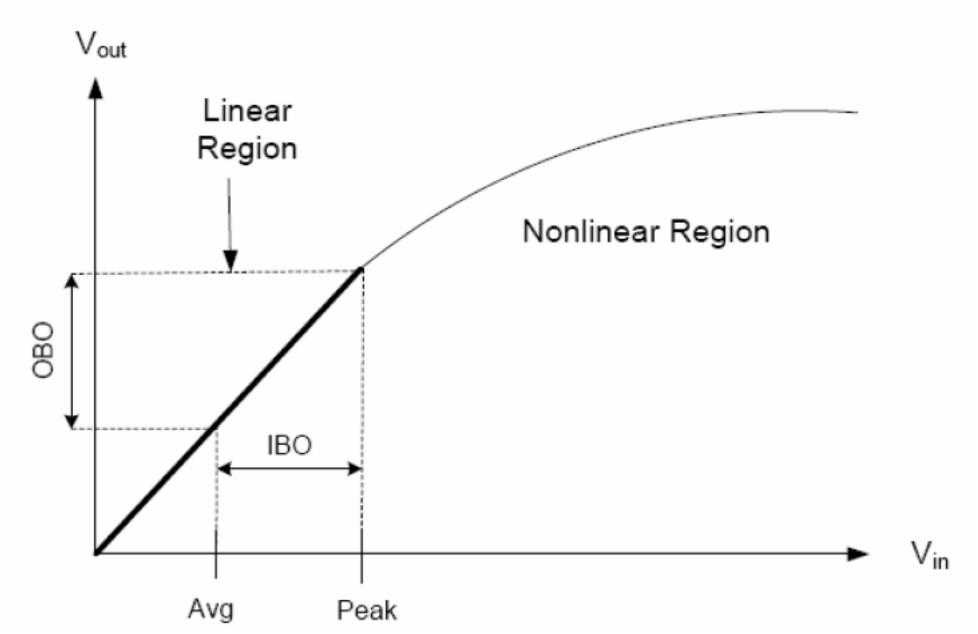


Figure 3: A Typical Power Amplifier Response

The power efficiency of a High Power Amplifier can be increased by reducing the PAR of the transmitted signal. The average and peak values should be as close together as possible in order to maximize the efficiency of the power amplifier.

It is possible, however, to achieve a significant improvement in PA efficiency using envelope tracking (ET). In ET, the voltage supplied to the final RF stage power transistor is changed dynamically, synchronized with the RF signal passing through the device, to ensure that the output device remains in its most efficient operating region close to saturation point. In one of the studies (based on the PA efficiency for BS) 50% efficiency have been reported for WCDMA (Wideband Code Division Multiple Access) waveforms for ET based PA [14]. In recent papers efficiencies close to 60% has been reported. If the energy efficiency of the power amplification can be drastically increased from the 15-25 % range to close to 60% also the energy consumption of cooling system can be significantly reduced [15][16].

Typically in multi-antenna (MIMO, Multiple Input Multiple Output) systems each antenna has its own power amplifier. If the system load is low, then energy can be saved by switching off some of the transmit antennas. For instance, UMTS supports the use of two transmit antennas. In case there are no MIMO capable terminals present in the system then the base station may switch off the second common pilot channel transmitted over the second antenna to save energy.

The energy efficiency of the base band unit (BBU) of the base station can be further improved by introducing power save modes to subunits, such as, channel cards, DSPs (Digital signal processors), FPGAs (Field programmable gate arrays), ASICS (Application –specific integrated circuits) or even clocks such that they could be switched on and off based on the base station load.

Moreover, by using the continuous Phase modulation technique, PAR can be reduced and high efficiency can be achieved in Mobile Station (or User Equipment, UE) transmitter, which contributes to the increment in power efficiency of the whole network.

B. System Level or Software Feature

The impact of different link budget and network parameters on the network energy consumption has been investigated in Chapter 2. Results indicate, for example, that if transmission power is fixed per BS but cell edge rate requirement is doubled, then a one and a half fold increase in BS density is needed. However by introducing multi-antenna sites, there will be an improvement in bandwidth and SINR (Signal to Interference to Noise Ratio) efficiency which may even fully compensate the need for increasing BS density. In a similar way, there also exist more such system level techniques to reduce energy consumption of radio network. One of them is discussed below.

B.1 BS switching in conventional macrocell topology

One of the main energy saving approaches is the system level feature in which underutilized cells (BS's) are switched off whenever traffic load is small as depicted in Figure 4. The network load in some areas may vary significantly due to the mixed effect of two traffic properties:

- Daily changes in user data consumption, for instance, data traffic may be small at night times.

- The user density may greatly vary: Office areas may provide heavy load on day time and very small user load during the night times, while load on residential areas increases during the afternoon as subscribers have returned from places of work, study and so on. .

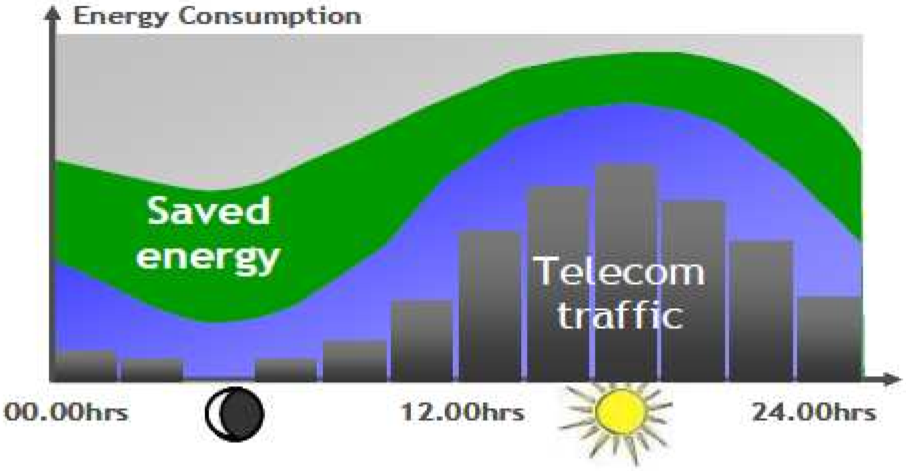


Figure 4: Energy Saving depending on traffic profile for 24 Hours

When cells are switched off, it is assumed that the radio coverage and feasible service conditions can be guaranteed by the remaining active cells (BSs), probably with some increment in the BS transmitting power. This increase in transmission power in remaining active BSs, however, can be small when compared to the savings achieved by switching off some BS sites. Moreover, in order to avoid this increment in transmission power, *wireless relays*, *cooperative communication* and *electrically tilted antennas* can be used to guarantee the radio coverage [5].

Energy saving through BS switching has been under discussion over the last few years. For instance, researchers have proposed that power saving algorithms can be centralized (when all the channel information and traffic requirements are known) or decentralized (no such information is required) [5]. Energy savings are higher in centralized approach because BS density becomes lower, while coverage guarantee is better in decentralized approach because more BS’s stay active. In this research the focus was on the relation between BS energy saving and load balancing. The purpose of load balancing is to equally distribute traffic service among BS's to achieve better coverage, whereas the aim in BS energy saving is to concentrate traffic to as few BS's as possible. Through examination it was found out that load balancing appears to be *important* BS energy saving algorithm due to its decentralized and dynamic nature.

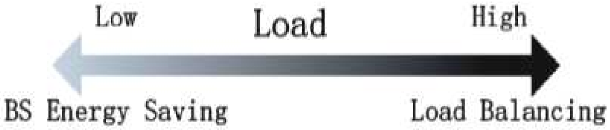


Figure 5: Relation between BS Energy Saving and Load Balancing [6]

Similar approach was applied in other researches whereby focus was on cell layout [6]. To achieve optimal energy saving it was discovered in [6] that in real networks only a small fraction of cells need to remain on during the night time. In [6] few typical cellular network configurations (Hexagonal; Crossroad; Manhattan/linear; Manhattan/squared as shown in Figures 6 and 7 respectively) had been compared assuming two different daily traffic patterns: symmetric trapezoidal traffic pattern and asymmetric traffic pattern which is derived from measurements over a real network. Comparison indicates that the best solution is not to switch off the largest possible number of cells; rather it is important to make tradeoff between the night zone period (low load) and the number of cells that are switched off. According to this work, the best performing scheme is switching off 4 cells out of 5 with crossroad configuration. Within the above mentioned network topologies, the energy savings of the order of 25-30% are possible to achieve.

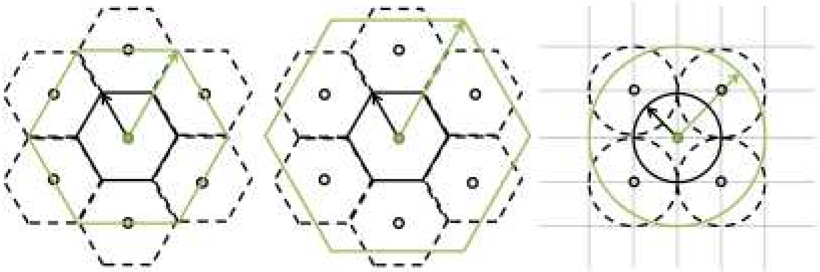


Figure 6: Hexagonal and crossroad configurations [6]

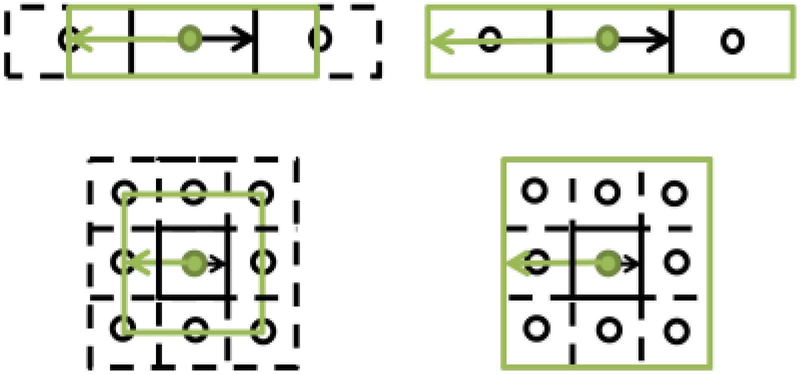


Figure 7: *Manhattan configurations: linear (top) and squared (bottom) [6]*

C. Site Solution

Energy efficiency can not only be improved in BS equipment, but also certain power solutions could be adapted on the site level to save the energy. These are referred to as site solutions. In [12] the few mentioned site solutions which have the potential for energy saving are:

- Outdoor sites
- Cooling solution for indoor sites
- RF head
- Modular BS

With outdoor sites, the cooling requirements can be lowered by raising the allowable operating temperature range for the BS site wherever possible because the upper limit set for the temperature is now high so less cooling would be sufficient to keep the temperature within limits. This leads to the reduced energy consumption by the cooling equipment and thus less CO_2 emissions observed. With indoor sites the energy could be saved by utilizing fresh air cooling systems instead of using air conditioner that consumes energy for its operation. With RF head or modular BS the RF transmitter is located close to BS antenna, this way the cable losses decreases and the network performance is improved. Alternatively, less transmit power is required to achieve the same network performance.

1.2.2. Minimizing the Base Station density

The deployment of small, low power femto BSs alongside macrocellular BSs is often believed to reduce the energy consumption of cellular network [17]. This idea is studied in Chapter 4, where analysis is based on WCDMA load equations. It has been demonstrated that when femtocells are introduced to the network, they will reduce the macro BS density. Thus reducing the energy consumed by the macrocellular side of the network. But not necessarily the total energy consumed by network due to the lack of femtocell ability in practical to switch on/off depending upon indoor traffic (discussed in Chapter 4).

1.2.3. Alternative energy resources

Mobile networks can be made much more energy efficient than they are today and networks may become even fully self-sustainable by using renewable energy resources which are using natural resources such as sunlight, wind, tides, and geothermal heat. All these resources are regenerative which makes them different from fossil fuels and thus they will not produce greenhouse gases, that is, CO_2.

Currently renewable energy resources are mostly used on sites that are at long distances from electricity grid, or on locations where electricity supply is unreliable. The importance of these renewable energy resources is increasing as the costs of expanding network into remote areas grow [12].

The most important thing to take into account while planning to operate the BS site by renewable energy resources is the site location and the energy consumption of the BS site. The availability of energy resources defines the site location and the energy consumption depends upon the load.

The most reasonable renewable energy resources for BS sites are derived from the main source of energy i-e sun and also wind.

A. Solar energy

Solar energy is free, abundant, and inexhaustible. It is the source of all forms of renewable energy supply: direct solar power and heat, hydro, bio mass, wind-power and wave power. Direct solar power systems are now the subject of intense activity in different parts of the world. Related technology could provide us with electrical resources totaling up to a thousand times our current demands.

For low and medium capacity sites, or repeaters sites, solar power can be used to provide virtually free energy, at least in terms of OPEX (Operation Expenditure). While the initial CAPEX (Capital Expenditure) per kilowatt is higher for such solutions, they can provide a positive business case compared with diesel generators within one or two years of operation.

Figure 8: Solar panels deployed at BS

For the solar power plant installment near BS, more site space is required. Moreover, the climate variations in sunshine develop the need of higher energy storage capacity in solar power plant.

On the other hand, it is expected for the future network to have a combination of alternative energy sources to meet the seasonal variation differences [8].

B. Wind Energy

As with solar power, wind power can provide virtually free energy. However wind power industry is constructing very large wind turbine and the challenge is to find a cost effective solution for BS site (Ericsson).

Figure 9: Wind Power turbine deployed at BS

The advantage of wind power is that it can maintain the BS site at low cost. On the other hand the disadvantage of it is that wind is unpredictable, so there must be some small diesel generator as backup in situations when there is low wind or no wind. Currently, the extra site space is required because of the need to install the wind turbine tower along with the BS tower [8].

2. MOBILE NETWORK EVOLUTION: ENERGY EFFICIENCY CHALLENGES

2.1. Introduction

In the last decade we have come across the rapid development of the mobile network technologies. In the establishment of new mobile networks the focus has been shifted from 2G (Second Generation) mobile network technologies to 3G (Third Generation) and now beyond 3G (e.g. LTE) networks, which are based on the latest standard and are being recently commercialized. With each new mobile network generation, new services are being introduced and achievable data rates per user are increased.

One of the main motivations behind mobile networks evolution is Internet access, so there is a need to constantly increase the user data rates in order to provide the mobile internet based services with an end-user acceptable quality of experience (QoE). The internet based services are initially being designed assuming fixed line capabilities; therefore to shift from the fixed line services to mobile services the data rates on mobile systems have to be increased. The large scale deployment of mobile Internet is ongoing in many countries to fulfill its high demand due to the rapid increment in the number of mobile data users.

Although new networks are more efficient, it is expected that increasing demands for high data rates will cause the constant increase in network densities and thus the increased energy consumption in the mobile networks. Therefore, it is of great importance for network operators to adopt energy efficient techniques while building the new networks.

To provide higher user data rates and serve a growing number of mobile data users, there is a need for higher network capacity. There exist several ways to increase the network capacity which includes; wider frequency bandwidths, enhanced radio link technologies, higher transmission powers, more dense networks and heterogeneous deployments. All of these techniques have been discussed in detail in this chapter, showing the challenges they come across from the energy efficiency perspective.

Also there exists a need for capacity enhancement features to make the networks energy efficient, that is, the capacity enhancement features must provide the reduction in network's energy consumption. This need for capacity enhancement for having energy efficient networks has been explained taking into account the power distribution in the network.

2.2. *Network Energy Efficiency*

Recently several projects in wireless communications (working as consortium of worldwide renowned companies and research institutes) have been focusing on the energy efficiency and not on just the reduction of total energy consumed by the network [10], that is, they are concerned about the reduction in energy per bit. One of the proposed units to measure efficiency is Watt per bit. And energy efficiency is considered from network perspective.

The formula proposed for the network energy efficiency is:

$$Network\ energy\ efficiency\ = \frac{Total\ Traffic\ Delivered\ to\ User}{Total\ Power\ per\ User} \tag{1}$$

- Growth in the network traffic and/or reduction in the power consumed per user will increase the network energy efficiency.
- Growth in the traffic will increase the revenue from services (Green Services which focus on energy saving and carbon emission reduction). Traffic is measured as bits per second.
- Reduction in the power consumption per user will reduce the carbon footprint and also decrease the operation cost.
- For a given application, if QoS is not met then energy efficiency is zero.
- If optical fiber is used instead of wireless, the networks will be more energy efficient but the cost possibly will increase by very large amount.

ICT is responsible for 2-10% of world's energy consumption. The research efforts are also focusing on means to use ICT in order to reduce the remaining 98% of energy consumption in the world.

2.3. *The Need of Capacity Enhancement Features*

To emphasize the need for capacity enhancement features for energy efficient networks, we start by recalling the power usage in base station.

Electronic devices consume power when being switched on and in conventional mobile networks the baseline assumption is that BSs are on all the time. Power supplies, basic operation functions and signaling between nodes (between Radio BS and Mobile BS in idle mode) consume power even when the network is not carrying any traffic [18].

The BS power usage can be divided into static and dynamic parts [18],

$$P_{BS} = (P_{BS})^{Static} + (P_{BS})^{Dynamic} \tag{2}$$

2.3.1. *Static Power*

The static power consumption contains both powers that are needed to keep BS site equipments operable as well as power that is spend on continuous basic radio access operations such as common channel transmission.

Usually power-saving features are designed *to lower this static power consumption*. There are many features today that monitor network activity and successively shut down unneeded equipment during times of low traffic without degrading quality of service. [18]

2.3.2. *Dynamic Power*

Dynamic power is a significant portion of power consumed by a network which varies in direct relationship with the amount of traffic being handled in a network at a given time.

This dynamic part of the power consumption can be made more efficient by employing capacity-enhancing features so that more traffic can be handled with a given amount of energy. In this regard most network equipment vendors have designed the range of capacity enhancement features.

When networks are expanded the large scale deployment of capacity enhancement solutions would be effective from economical and environmental perspective because then unnecessary addition of new sites or nodes can be avoided, that is, the BS density will not be increased much and energy consumption can be even reduced in the network.

Figure 10 provides a conceptual illustration of the way in which energy efficiency is increased through the use of a capacity enhancing feature. This figure shows the relation between energy efficiency and enhanced system capacity. *By employing capacity enhancing features into the network, more traffic can be handled with a given amount of energy or the network will reach same capacity by utilizing less power.*

The energy efficiency has been depicted here in terms of power usage per subcriber. The less power utilized for certain subscribers, the more energy efficient will be the network. In figure 10 $X_{initial}$ refers the low energy efficient state of the network and as we move from $X_{initial}$ towards X_1, X_2 and X_3, we observe the increment in the network's energy efficiency.

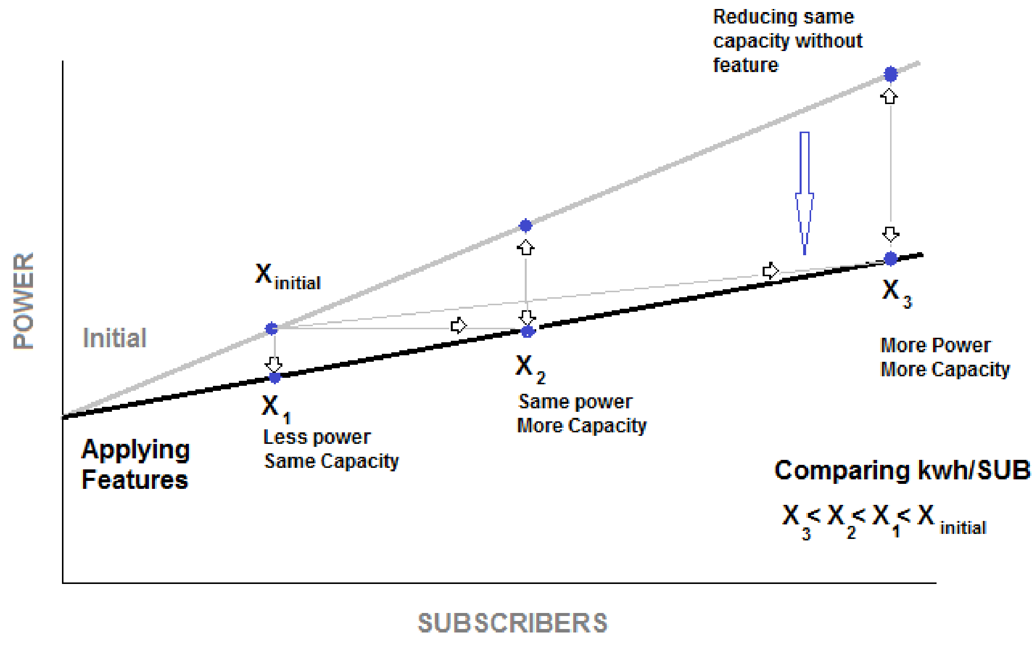


Figure 10: Enabling energy-efficient growth through capacity enhancement [18]

The base stations with dynamic power saving features have appeared only very recently and are not yet widespread in the network [19]. Capacity enhancing features that reduce dynamic part of the used power are physical layer scheduling and MIMO that both boost the resource usage efficiency. Moreover, additional examples of dynamic power reducing features are the use of AMR-HR (Adaptive Multi Rate – Half Rate) in mobile voice networks, and higher order modulation schemes for data transmission [18].

Especially for micro BS power model, the dynamic part has significant importance because for small cell the number of users (load) is statistically varying more than for large cells [19].

2.4. Capacity Enhancement: Energy Efficiency Challenges

The need for expanding system capacity grows with the number of users and with the amount of information required for a given service. But there exist challenges for such capacity enhancement solutions from an energy perspective.

In order to analyze the impact of link budget parameters on the energy consumption of the network, the formulation has been started by understanding the throughput formula (Shannon capacity formula). To make the network energy efficient the Shannon's theory can be employed in a novel manner. Shannon's theory provides guidance for discovering and developing new methodologies to maximize energy efficiency (to reduce energy per data bit) while approaching the Shannon limit of maximized network capacity [20].

The peak data rates are available only in very good channel conditions and the practical data rate is limited by the amount of interference and noise in the network. The maximum theoretical data rate with single antenna transmission in static channel can be derived using the Shannon formula. The formula gives the data rate as a function of two parameters: bandwidth and the received signal to noise ratio.

The Shannon capacity bound can't be reached in practice due to several implementation issues. To represent these loss mechanisms accurately we use a modified Shannon capacity formula which has fitting parameters W_{eff} and Γ_{eff}.

$$TP = \begin{cases} 0, & \Gamma < \Gamma_{min} \\ W \cdot W_{eff} \cdot log_2\left(1 + \frac{\Gamma}{\Gamma_{eff}}\right), & \Gamma_{min} \le \Gamma < \Gamma_{max} \\ TP_{max}, & \Gamma \ge \Gamma_{max} \end{cases} \qquad (3)$$

Here, W is the operation bandwidth, Γ is the signal to interference and noise ratio (SINR), Γ_{min} is the minimum value for SINR such that connection is blocked if $\Gamma<\Gamma_{min}$ and Γ_{max} is the SINR needed to reach the maximum throughput $TP_{\max}$. The coefficients W_{eff} and Γ_{eff} are the bandwidth and SINR efficiency factors respectively which are selected so that (3) fits with the set of applied adaptive modulation and coding curves. The values of W_{eff} and Γ_{eff} can be found by link level simulations [21] [22] [23].

2.4.1. Capacity Enhancement Features

A. Wider Bandwidth

The *channel* capacity is linearly proportional to bandwidth so the extension of operation bandwidth is the most straightforward way to increase the *system* capacity. If network element density and transmission power per unit bandwidth is kept constant then according to (3) the capacity grows linearly with additional bandwidth. At the same time required transmission power and the needed energy also increases linearly in order to keep the transmission power per unit bandwidth constant, as well if the wider bandwidth are used but cell sizes are not decreased then transmission power needs to grow accordingly.

With this approach the tradeoff remains between the system capacity and energy efficiency in the network. Although this approach has been adopted by all the latest and upcoming new mobile generations for fulfilling the increased capacity and higher data rate requirements but it does not contribute in the improvement of network's energy efficiency. The researchers have to come up with some other system-level or link-level techniques along with this approach to enhance the system capacity in an energy efficient way.

It is important to note that in (3) the bandwidth efficiency reflects the system's ability to utilize the radio spectrum and the upper limit is set by $W_{eff} = 1$.

For LTE-Advanced (LTE Release'10), it is expected that operation bandwidth will be divided to 20 MHz carriers and carrier aggregation over up to five carriers is then used to reach the data rate targets set by IMT-Advanced (International Mobile Telecommunications Advanced) (peak rate: 1 Gbps data rate in local area) [24]. Following the 3rd Generation Partnership Project (3GPP) recommendations [21] the maximum BS transmission power is 43 dBm in Wideband Code Division Multiple Access (WCDMA with 5 MHz channel), 46 dBm in Release'8 LTE (10-20 MHz channel) and thus, LTE-Advanced with carrier aggregation will lead up to five times higher transmission power than used in Release'8 LTE and up to ten times higher transmission power than used in WCDMA.

B. Enhanced radio link technologies

Network operator is interested in the improved network efficiency, that is, how the maximum number of users can be served, the maximum data rate can be provided and the BS site density can be decreased. The efficiency is considered in the link budget calculations and in the capacity simulations.

The LTE link performance is benchmarked with the theoretical Shannon limit. To guarantee consistent performance 3GPP has defined a set of radio performance requirements.

The radio link efficiency has been improved a lot by setting up the advanced radio link technologies like, multiple-input and multiple-output, or MIMO, for evolved 3G networks WCDMA, HSPA and recently LTE Release'8.

The impact of radio link efficiency is embedded into parameter pair (W_{eff}, Γ_{eff}), which are also referred to as the fitting parameters for Shannon performance curve. The higher the efficiency, the closer to one are the values of W_{eff} and $1/\Gamma_{eff}$.

LTE is highly efficient and is performing less than 1.6-2 dB from the Shannon capacity bound in case of AWGN channel. In fading channel the link performance on

SISO (Single Input Single Output) is close to Shannon limit that defines fundamental upper bound. However for SISO the best Shannon fit parameters are significantly worsened compared to AWGN (Additive White Gaussian Noise): the equivalent W_{eff} (Bandwidth Efficiency) has reduced from 0.83 to 0.56 and the Γ_{eff} (SNR efficiency) has been increased from 1.6-2dB to 2-3dB. Whereas for SIMO (Single Input Multiple Output) the Shannon fit parameters are better than SISO: W_{eff} is 0.62 and Γ_{eff} is 1.8dB. Similarly for MIMO the Shannon fit parameters gets better than SIMO: W_{eff} is 0.66 and Γ_{eff} is 1.1dB which makes it closer to Shannon bound and makes the link performance more efficient in comparison to the cases of SISO and SIMO. In MIMO antenna systems, there is more room for optimization but it is well acknowledged that along with the link performance increase, some more solutions are required for future challenges regarding capacity enhancement [7].

It can be observed that by increasing the number of antennas on the transmitter and receiver sides the Shannon fit parameters can be further improved leading to higher spectral efficiency and thus higher throughput. With higher spectral efficiencies less radio resources per information bit are needed and thus the energy could be saved accordingly. However there exist certain limitations on the increment of number of antennas due to size and cost constraints.

C. Higher Transmission Powers

In this section SINR has been analyzed in detail to describe the impact of transmission power in different system environment for increasing system capacity. The target SINR is adjusted according to the transmission power of the signal. The idea of this approach is that communication links in worse propagation conditions have to use higher transmission power to attain a given target SINR level. But for reliable communication links a small increase in transmission power is sufficient to increase the SINR value by large amount.

To start with the general form of SINR

$$\Gamma = \frac{P_{Tx,0}/L_0}{P_N + \sum_k P_{Tx,k}/L_k}, \tag{4}$$

where $P_{Tx,k}$ refers to BS transmission power in *k*th BS, L_k is the related path loss and P_N is the noise power. The reference user is assumed to be connected to BS with index 0.

If all BSs apply the same transmission power and we let the power grow without limit, then we have

$$\Gamma \xrightarrow[P_{Tx \to \infty}]{} \frac{1}{\sum_k L_o / L_k} \tag{5}$$

Thus, SINR admit an upper limit that depends on the path losses towards BSs. If the network is noise limited, that is, right side term in (5) is clearly larger than Γ_{max} then data rates can be improved through higher transmission powers. However from (3) it is obvious that due to logarithm much more power would be required to achieve the same increase in the capacity as achieved by the increase in the bandwidth. Therefore, this strategy is not as energy efficient way to increase capacity as compared to the strategy where bandwidth is extended. If system is interference limited, that is, if the right side limit term in (5) is small then large BS transmission powers will waste a lot of energy and just create more interference to the network.

D. Impact of cell edge coverage requirement

The cell edge coverage can be defined using a probabilistic throughput requirement

$$\Pr(TP < TP_{min}) = Pr_{out} \tag{6}$$

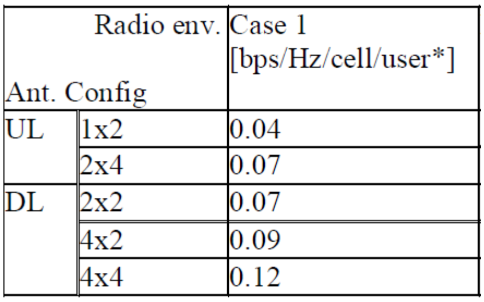
In (6) Pr_{out} is the outage probability and TP_{min} defines the minimum SINR in (3). The outage probability is an important statistical measure to access the quality of service provided by the system. It is the probability of failing to achieve a specified SINR value and thus the minimum throughput value which is sufficient for satisfactory reception.

Requirement (6) can also be given in terms of spectral efficiency if throughput is scaled by the used bandwidth

$$Pr\left(S_{eff} < S_{eff_{min}}\right) \leq Pr_{out} \quad , \tag{7}$$

The cell edge user throughput is defined as the 5% point of CDF (Cumulative Distribution Function) of the user throughput normalized with the overall cell bandwidth. For example LTE-Advanced cell edge throughput requirements have been given using this approach [25].

TABLE 1. 3GPP PERFORMANCE REQUIREMENTS ON CELL EDGE (CASE 1)



Radio env. Ant. Config		Case 1 [bps/Hz/cell/user*]
UL	1x2	0.04
	2x4	0.07
DL	2x2	0.07
	4x2	0.09
	4x4	0.12

For Case1 carrier frequency is 2GHz, ISD (Inter Site Distance) is 500 meters, bandwidth is 10MHz, path loss is 20dB, and user speed is 3 km/h.

There are two important parameters in (6) that impact on the cell power usage. First, tough coverage constraint with very low outage probability will lead to the need for a high BS transmission power or dense network. Both of these options will mean increased energy consumption in the network. Second, if operator plans to improve the service level in the whole network, then it should take into account the minimum throughput requirement of (6). Another option would be to provide more radio resources per user which is a possible strategy if network load is not too high or operator is able to introduce new spectrum resources. It is expected that all these approaches will increase the energy consumption of the network.

E. Impact of carrier frequency and propagation environment

The carrier frequencies tend to increase: from 900MHz of first 2G networks the carrier frequency has been increasing to 1800MHz (2G extension bands), 2100GHz (main 3G bands), 2600MHz (LTE bands) and it will soon jump up to 3500MHz (bands granted by World Radio communication Conference WRC'07 for IMT-Advanced). At the higher carrier frequencies, the signal path loss in wireless medium is stronger which requires either transmission power or network density to be increased. Furthermore, while additional carriers and extended bandwidths lead to an easily predictable increase in energy consumption, the effect of higher carrier frequency can be predicted only when propagation modeling is accurate. Since details of sophisticated propagation models are out of the scope of this thesis we adopt a simple path loss formula

$$L = \frac{L(d) \cdot L_{SF}}{G} \tag{8}$$

In (8) *L(d)* refers to a distance dependent model such as Okumura-Hata, L_{SF} is the lognormal shadowing and *G* refers to the BS antenna gain. We have embedded the antenna gain into propagation model for simplicity. It is recalled that antenna gain depends on the angle between receiver and antenna main directions. Yet, in dimensioning, the antenna gain in main direction is applied. Since Okumura-Hata model is a so-called single slope model it admits the form

$$L(d) = \alpha \cdot d^{\beta} \tag{9}$$

where parameter α includes the impact from carrier frequency and BS antenna height while the path loss exponent β depends only on the BS antenna height. Let us consider a simple example. Assume that the system carrier frequency is increasing from 2.1GHz to 2.6GHz. Then according to Okumura-Hata model, the path loss increases round 2.4dB and thus, energy consumption in radio operations increases by factor of 1.74. If BS range in urban area is for example 1km, then path loss from higher carrier frequency can be compensated on the cell edge by increasing the BS antenna height from 25m to 38m. This might be difficult due to regulations and negative visual impact. Finally, we note that the propagation environment greatly affects the strength of the path loss so that in rural environment much larger areas can be covered than in urban environments with the same BS transmission power.

F. More dense networks and heterogeneous deployments

The larger operation bandwidth and increased power consumption as well as high macrocell site costs are driving towards smaller cells which ultimately become part of heterogeneous networks. The deployment of small, low power base stations, alongside conventional sites is often believed to greatly lower the energy consumption of cellular radio network because when communication distance is decreased, less power per bit is needed and available spectrum resources are shared between fewer users. From energy efficiency perspective some of the main challenges in small cells and heterogeneous deployments are:

1) Number of sites follows square law with respect to inverse of the range. This puts a high pressure on the energy efficiency of the small nodes. Also the network capital expenses increase rapidly unless BS/site prices are decreasing proportionally to the square of inverse of the range.

2) Backhaul availability limits the density of small cells and wireless nodes like relays will spend part of the transmission power on backhaul communication. Yet, if relays are used on the cell edge this additional power consumption may be small [26] and thus the macrocell BS transmission power gets reduced.

3) Antennas in small cells are located below the rooftop and therefore coverage areas of small cells will be fragmented. Then coverage holes become more severe and unnecessary high transmission power might be used to solve the coverage problems. This increases interference which will decrease the system power efficiency.

4) Mass deployment of femtocells may lead to a situation where numerous small access points are turned on and spending energy even when traffic is nonexistent. On the other hand, in case of home cellular, data transfer becomes highly energy efficient due to small communication distance.

5) To avoid high operational expenses and unnecessary power consumption small cells should support of plug-and-play. Thus, practically implementable self-configuration, self-optimization and self-healing algorithms should be used to keep the system efficient.

3. SIMPLE MODEL FOR POWER CONSUMPTION

3.1. Introduction

The number of mobile subscribers has increased tremendously during last decade. Along with voice communication, the data usage has also grown fast. The customers are used to high data rate performance of fixed line systems so they also expect the comparable performance from the wireless networks. Thus the operators demand high data capacity with low cost of data delivery which is the main motivation behind the development of 3GPP LTE. [23]

More specifically, the motivation of LTE Release 8 includes:

- Wireline capability evolution gives boost to evolution in wireless domain.
- Need for additional wireless capacity – to take maximum advantage of available spectrum and base station sites.
    - This will put the challenge of reducing the energy consumption while utilizing capacity enhancement features.
- Need for lower CAPEX and OPEX – Flat rate charging model.
- Competition of 3GPP technologies must meet and exceed the competition with other existing wireless technologies.
    - When it comes to the competition with other technologies, then energy efficiency become one of the key factor of competition basis.
- Low complexity - Flat IP architecture.

As environmental and economic issues have become more important, cellular network operators are paying more attention to environmental issues. Power consumption by a node (Home e Node-B, Relay node or Femto node) in such a network can have an effect on the environment. Power generation often requires environmental inputs. Thus, reduced power consumption can have an advantageous affect on the environment, as well as reduced overall costs for the network. Therefore, one of the main performance targets for LTE includes the surety that the new system could facilitate lower investment and operating costs compared to earlier systems. From this perspective the reduced energy consumption for LTE play an indirect but important role in reducing the cost and making the technology greener. Another main performance target for LTE is the optimized terminal power efficiency which still needs improvement.

Similarly the need for capacity and coverage of cellular networks is increasing as more and more people utilize cell phones and other types of wireless communicators, which in turn increase power demand on the overall network. Because of the increased power demand, the desire to reduce power consumption (that is, save power) is likewise increasing with regard to systems and nodes. It is expected to increase the energy efficiency of the system, by providing cellular service to more users utilizing the available (limited) power resources.

According to big players in the wireless communication industry, the focus regarding Green communication schemes should be mostly on the LTE as they are the most recent networks and when new sites have to be deployed, it is easier to incorporate the green communication radio solutions into LTE networks rather than for the old networks (2G and 3G).

- *Power Model*

Modeling is of great importance because it is useful in making decisions based on quantitative reasoning and it also helps in performing desired analysis. The main goal of the power consumption model is to make realistic input parameters available for the simulation of total power consumption in mobile communication networks and also to compare different network deployments.

The total power consumption of the mobile network over some time period can be expressed in the form

$$P_{Total} = N_{BS} \cdot P_{BS} + N_{UE} \cdot P_{UE} + P_{Other} \tag{10}$$

In (10) the first term in the right defines the power consumption in all BSs (N_{BS} and P_{BS} refer to number of BSs and power consumed by single BS respectively), second term defines the power usage in all User Equipments UEs (N_{UE} and P_{UE} refer to number of user equipments and power consumed by single UE respectively) and the last term contains power spent by other mobile network elements such as core network elements and radio network controllers in WCDMA/HSPA High-Speed Packet Access, for example. We ignore the second term on the right since terminal power and energy efficiency has been under extensive investigations for a long time due to strict battery constraints. Therefore, recent energy efficiency studies have been focusing on the network side where more room for notable improvements exists. Furthermore, since we concentrate on the energy efficiency of the radio access the last term in (10) is out of our scope. We also recall that BS energy efficiency is of great importance for operators since BSs form a vast majority of mobile network nodes and thus, they also have largest contribution to the energy consumption of a modern mobile network creating a significant operational cost factor [27] [28] [29].

To start with, we assume an extreme case of full traffic load in BS and express the power spent by BS in the form:

$$P_{BS} = P_{Oper} + P_{Tx,in} = P_{Oper} + \frac{P_{Tx,out}}{\eta} \tag{11}$$

In (11) the term $P_{Tx,in}$ is the power utilized that is needed to create maximum transmission power $P_{Tx,out}$ in the antenna output and η is the efficiency of the transmission chain. Term P_{Oper} contains all other power that is needed to operate BS on full load condition.

3.2. Comparison Cases

Based on the model, we have compared two hypothetical network deployment scenarios by setting different network parametric assumptions for both. Moreover, within these two scenarios we have further compared two networks to estimate how the change in network configurations will affect the energy consumption in the modified network (Network 2) w.r.t the reference network (Network 1). This analysis will make it visible which network deployment approach is more advantageous in terms of energy saving.

We note that first scenario is related to the case where operator is updating BSs in an existing deployment while second scenario considers Greenfield operator, that is, building new network.

The goal of this example for comparison scenarios is to make visible the impact of *different link budget* and *network parameters* to the network energy consumption.

We will compare power usage in two different networks (network 1 and network 2) by computing the ratio between powers that are needed in all BSs in the networks.

$$R = \frac{N_{BS,2} \cdot P_{BS,2}}{N_{BS,1} \cdot P_{BS,1}} \tag{12}$$

3.2.1. First Scenario

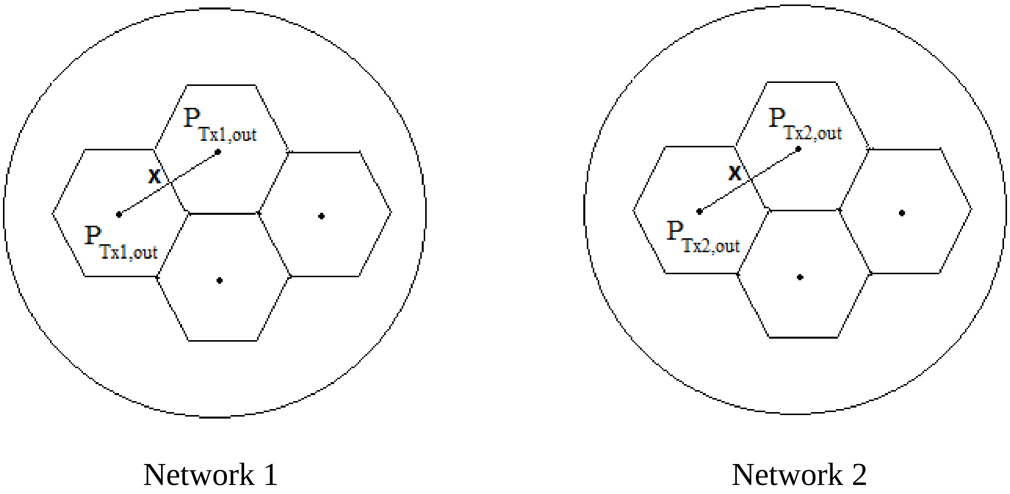


Figure 11: Pictorial representation for First Scenario Network Comparison

In the first scenario case both networks apply the same BS grid (same BS antenna height, same number of BSs, etc), that is, the inter site distance (ISD) x is fixed as shown in Figure 11, and the focus is on the difference of BS power between two networks. The BS power varies depending upon the throughput, bandwidth efficiency, outage probability, and SINR efficiency.

According to (11) and (12) the ratio R can be written in the form

$$R = \frac{P_{BS,2}}{P_{BS,1}} = \frac{1 + \left(P_{Tx1,in}/P_{Oper}\right) \cdot \left(P_{Tx2,in}/P_{Tx1,in}\right)}{1 + P_{Tx1,in}/P_{Oper}} \tag{13}$$

where we have assumed that operation powers are the same for BSs of the first and second network and difference occurs only between transmission powers. Let us further define

$$\rho = \frac{P_{Tx1,in}}{P_{Oper}}, \qquad \nu = \frac{P_{Tx2,out}}{P_{Tx1,out}} \tag{14}$$

In (14) parameter ρ refers to the ratio between transmission chain input power and power spent for all other operations in a BS of the first network. We use first network as a reference and consider impact of changes that reflect only to the required output transmission power. By ν we denote the ratio between maximum output transmission powers.

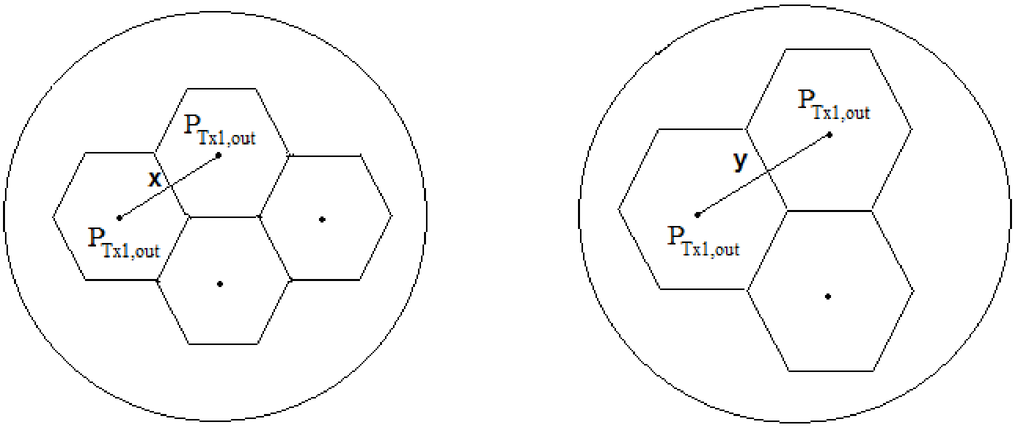
Using these notations we obtain

$$R = \frac{1+\rho \cdot (\eta_1/\eta_2) \cdot \nu}{1+\rho} \tag{15}$$

The idea in expression (15) is that we can separate factor ρ and ratio η_2/η_1, that are merely product specific, from factor ν that reflects the impact of changes in radio related parameters.

3.2.2. Second Scenario

In the second scenario the BS output transmission power is fixed, that is, the BS output power in both the compared networks remain same. However the inter site distance (ISD) is scaled which reflects to the number of BS sites. In this scenario the cell ranges varies in the second network depending upon the new values of throughput, bandwidth efficiency, outage probability, SINR efficiency which are set for second network. Thus the ISD varies from x to y as shown in Figure 12, which will bring change in the BS output power consumption and in the overall power consumption of the modified network (Network 2) with respect to reference network (Network 1) due to the change in the BS density , that is, different number of BSs.



Network 1

Network 2

Figure 12: Pictorial representation for Second Scenario Network Comparison

Here the ratio R is in the form

$$R = \frac{N_{BS,2}}{N_{BS,1}} \cdot \frac{1 + \left(P_{Tx1,in}/P_{Oper}\right) \cdot \left(P_{Tx2,in}/P_{Tx1,in}\right)}{1 + P_{Tx1,in}/P_{Oper}} \tag{16}$$

$$= \frac{N_{BS,2}}{N_{BS,1}} \cdot \frac{1 + \rho \cdot (\eta_1/\eta_2)}{1 + \rho} = \left(\frac{D_1}{D_2}\right)^2 \cdot \frac{1 + \rho \cdot (\eta_1/\eta_2)}{1 + \rho}$$

Here D_1 and D_2 refer to the ranges of the BSs and we have used the fact that number of BSs in the network is proportional to the square of inverse of the range.

Thus, in addition to product specific values of ρ, η_1 and η_2 we need in first scenario the output transmission power ratio v for fixed BS range and in second scenario we need the range ratio D_1/D_2 on the condition that output transmission powers are fixed.

3.3. *Computation of Transmission Power Ratio and Range Ratio*

Let us start from the coverage requirement (6). By using the formula (3) the throughput can be expressed in terms of SINR,

$$\Gamma = \Gamma_{eff} \cdot \left(2^{TP/W \cdot W_{eff}} - 1\right) \tag{17}$$

Furthermore, the inequality in (6) can be written between SINR and minimum required SINR,

$$\Gamma \leq \Gamma_{min} = \Gamma_{eff} \cdot \left(2^{TP_{min}/W \cdot W_{eff}} - 1\right) \tag{18}$$

Here SINR is given through equations (4), (7) and (9). Let us introduce interference margin I_M through SINR approximation on the cell edge:

$$\Gamma = \frac{P_{Tx,0}/(P_N \cdot L_O)}{1+\sum_k P_{Tx,k}/(P_N \cdot L_k)} \approx \frac{P_{Tx,0}}{P_N \cdot I_M \cdot L_O} \tag{19}$$

This margin is widely used in network dimensioning so that link budgets can be formed without extensive system simulations. After combining (18), (19) and (8) we get

$$L(D) \cdot L_{SF} \geq \frac{G \cdot P_{Tx,0}}{P_N \cdot I_M \cdot \Gamma_{min}} = L_{max} \tag{20}$$

In (20) D is the BS range and L_{max} refers to the maximum allowed path loss. Since shadow fading is lognormal variable we use decibel scale and write (6) in the form

$$Pr((L_{SF})_{dB} \geq (L_{max})_{dB} - \left(L(D)\right)_{dB}) \leq Pr_{out} \tag{21}$$

Furthermore, as shadow fading is Gaussian in decibel scale we can use Marqum Q-function to assume equality for a while and write

$$Q\left[\frac{(L_{max})_{dB} - (L(D))_{dB}}{\sigma_{SF}}\right] = Pr_{out} \tag{22}$$

In (22) σ_{SF} is the standard deviation for the shadow fading. Marqum Q-function is monotonic and it has unique inverse. Unfortunately this inverse does not admit closed-form expression and we can only formally write

$$(L_{max})_{dB} = (L(D))_{dB} + \sigma_{SF} \cdot Q^{-1}(Pr_{out}) \tag{23}$$

Let's recall the inequality and use again the linear scale. Then we obtain the following requirement for transmission power

$$P_{Tx,0} \geq \frac{P_N \cdot I_M}{G} \cdot \Gamma_{eff} \cdot \left(2^{\frac{TP_{min}}{W \cdot W_{eff}}} - 1\right) \cdot \alpha \cdot D^{\beta} \cdot 10^{\frac{\sigma_{SF} \cdot Q^{-1}(Pr_{out})}{10}} \tag{24}$$

In comparisons we may use minimum power that is defined by equality in (24). Thus we have

$$P_{Tx,out} = \frac{P_N \cdot I_M}{G} \cdot \Gamma_{eff} \cdot \left(2^{\frac{TP_{min}}{W \cdot W_{eff}}} - 1\right) \cdot \alpha \cdot D^{\beta} \cdot 10^{\frac{\sigma_{SF} \cdot Q^{-1}(Pr_{out})}{10}}, \tag{25}$$

$$D = \left(\frac{P_{Tx,out} \cdot G}{\alpha \cdot P_N \cdot I_M \cdot \Gamma_{eff}} \cdot \left(2^{\frac{TP_{min}}{W \cdot W_{eff}}} - 1\right)^{-1} \cdot 10^{-\frac{\sigma_{SF} \cdot Q^{-1}(Pr_{out})}{10}}\right)^{\frac{1}{\beta}}.$$

Using these formulae we can compute *v* and ratio *D₁/D₂* provided that parameters in (25) are known.

3.4. Examples

We consider a LTE related example where parameters for the reference system are selected according to [23]. Assume first comparison scenario where receiver noise power, interference margin, BS antenna gain, mean path loss parameters and shadow fading standard deviation are the same for systems that are compared. Then we have

$$\nu = \frac{\Gamma_{eff,2}}{\Gamma_{eff,1}} \cdot \frac{2^{\frac{TP_{min,2}}{W \cdot W_{eff,2}}} - 1}{2^{\frac{TP_{min,1}}{W \cdot W_{eff,1}}} - 1} \cdot 10^{\frac{\sigma_{SF}\left(Q^{-1}(Pr_{out,2}) - Q^{-1}(Pr_{out,1})\right)}{10}} \tag{26}$$

Equation (26) allows us to track the impact of antenna configuration, minimum throughput requirement and outage probability: (W_{eff}; Γ_{eff}; TP_{min}; Pr_{out}). Assume 10MHz bandwidth and 8dB standard deviation for shadow fading. Then we obtain the results of Table 2 for different parameter combinations.

TABLE 2. FIRST COMPARISON SCENARIO, EXAMPLE POWER RATIOS

Reference parameters: (0.56;2.0;0.5;0.10)	
New parameters	***Value of v***
Case 1: (0.56;2.0;1.0;0.10)	3.15 dB
Case 2: (0.56;2.0;1.0;0.05)	6.03 dB
Case 3: (0.66;1.1;1.0;0.10)	-0.20 dB
Case 4: (0.66;1.1;1.0;0.05)	2.68 dB

In Figure 13 we have the ratio *R* of (13) in decibels. It is found that if we increase the power consumed on the radio side in comparison to the power consumed on the operation side, the total power difference in compared networks increases in a different way for cases 1, 2, 3 and 4 depending on the network configurations. In cases 1 and 2, the minimum value of the throughput has been doubled with respect to the reference network. The power difference is larger in case 2 than in case 1 because the outage probability has been decreased in case 2. Curves show that impact of both cell edge rate requirement and outage probability are large. Yet, the power share between radio and other operations in BS will define the practical cost impact. If BS is using only small portion of the power for keeping BS up and running, then changes in rate requirement and outage probability will have noticeable effect to the operation costs.

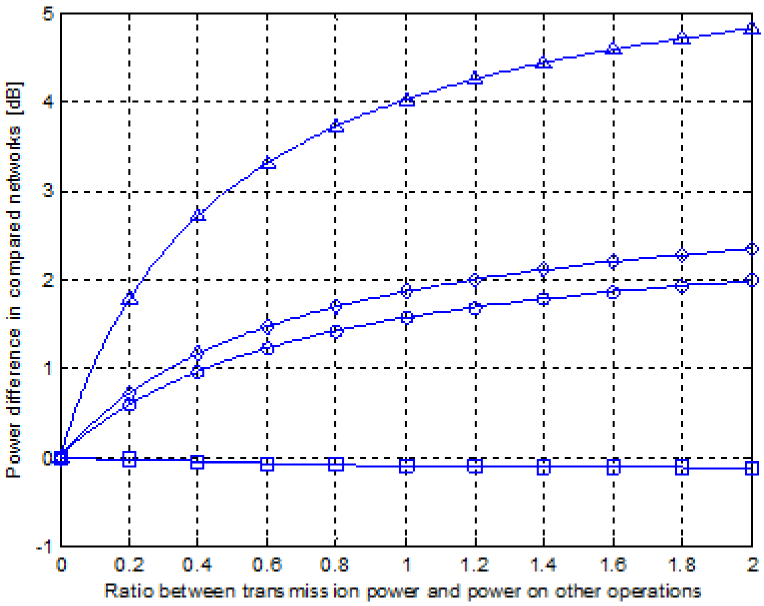


Figure 13: Difference of total power usage in networks according to (14) when example parameters are from Table 1. Notations: Case 1 ('Diamond'), Case 2 ('Triangle'), Case 3 ('Square') and Case 4('Circle').[7]

Furthermore while comparing cases 3 and 4 with cases 1 and 2 we see that the improvement in bandwidth and SINR efficiency (reflecting use of multiple antenna) will reduce the detrimental effect from increased rate and decreased outage probability requirements. In fact, in case 3 the value of v comes out to be negative showing that potential need for additional transmission power due to increased rate requirement can be compensated by introducing multi-antenna system. For first scenario case 3 is the best one in which energy can be saved in the network.

For the second comparison scenario, we take the same assumptions as that for first comparison scenario. Then we have

$$\frac{D_1}{D_2} = \left(\frac{\Gamma_{eff,2}}{\Gamma_{eff,1}} \cdot \frac{2^{\frac{TP_{min,2}}{W \cdot W_{eff,2}}} - 1}{2^{\frac{TP_{min,1}}{W \cdot W_{eff}}} - 1} \cdot 10^{\frac{\sigma_{SF}\left(Q^{-1}(Pr_{out,2}) - Q^{-1}(Pr_{out,1})\right)}{10}} \right)^{\frac{1}{\beta}} \qquad (27)$$

We also assume here that both networks have the same efficiency, that is, $\eta_1 = \eta_2$. This makes the ratio R independent of value ρ. Thus (16) admit a simple form

$$R = \left(\frac{D_1}{D_2}\right)^2 \tag{28}$$

Equation (27) allows us to track the impact of antenna configuration, minimum throughput requirement and outage probability: (W_{eff}; Γ_{eff}; TP_{min}; Pr_{out}). Assume 10MHz bandwidth, 8 dB standard deviation for shadow fading and the path loss exponent of 3.76 for LTE framework. Then we obtain the results depicted in Table 3 for different network configurations. We note that ratio *R* is now given in both linear and decibel scale since it indicates both the coverage ratio and the power ratio. From (16) we see that R also points out the ratio between numbers of base stations in compared deployments.

TABLE 3. SECOND COMPARISON SCENARIO, EXAMPLE POWER RATIOS

Reference parameters: (0.56;2.0;0.5;0.10)	
New parameters	***Value of R***
Case 1: (0.56;2.0;1.0;0.10)	1.47 (1.68dB)
Case 2: (0.56;2.0;1.0;0.05)	2.10 (3.22dB)
Case 3: (0.66;1.1;1.0;0.10)	0.97 (-0.10dB)
Case 4: (0.66;1.1;1.0;0.05)	1.39 (1.44dB)

Simulation results for second comparison reveals the fact that changes in rate and outage requirements may have crucial impact to coverage. Doubling the rate requirement on cell edge will lead to approximately one and a half fold increase in base station density and if also outage probability is halved then even two fold increase in base station density is needed. Yet, this huge cost source can be reduced by introducing multi-antenna sites. Result shows that the Greenfield operator should be very careful when setting the network parameters: requirements for cell edge may dominate in network power consumption. For second scenario also case 3 proves to be the best case which offers maximum opportunity to save network’s energy. Results show that by improving the bandwidth efficiency and SINR value, the operator can make true savings in network OPEX.

3.5. *Analysis for Comparison Scenarios*

For both scenarios Case 3 (0.66;1.1;1.0;0.10) is the only option in which energy could be saved but in negligible amount. For the first scenario the power difference depends upon the BS power distribution: P_{oper} and $P_{Tx,in}$.

The energy saving increases as P_{BS} distribution changes from 0 to 2 but it is not sufficient. During the whole day, the P_{BS} distribution might vary or may remain fixed but it could be of any value in the network. So we calculated the energy decrement percentage (for modified network 2 in comparison to reference network 1) for every value of P_{BS} distribution and on averaging it over the whole P_{BS} distribution range which varies from 0 to 2, we see the decrement in the energy consumption by 2.07% only.

However in second scenario, the power difference does not depend on the P_{BS} distribution for all the cases. But energy saving is possible only in case 3 as in scenario 1. In case 3 the energy saving remains same, independent of the P_{BS} distribution so there is a constant 2.27% of energy consumption decrement. So there is a very minute difference between the energy decrement of both scenarios for case 3.

The situation is the same for cases 1, 2 and 4 but all these cases show that the energy consumption has been increased in modified network with respect to reference network. In scenario 1 the maximum energy consumption at P_{radio}=2 P_{oper} is more in comparison to the constant energy consumption values for scenario 2.

The averages taken for the total energy consumption in modified network 2 (in comparison to reference network 1) for every distinct value of the P_{BS} distribution which varies from 0 to 2 are: Case 1 Average P_2=1.48P_1; Case 2 Average P_2=2.35P_1; and Case 4 Average P_2=1.38P_1. If we compare these average powers with the constant power consumption of scenario 2 we will observe very minute difference again as was for case 3.

Hence scenario 1 is the preferred approach for almost all the cases (that is, for all different network parameter settings).

Only in case 3, scenario 2 shows more energy saving than scenario 1 but with very minute difference, so even such network parametric setting shows that it would be preferable to adopt an approach of updating BS in an existing network deployment rather than going for building new network which has possibility of saving energy with very insufficient amount but will enough increase the cost of the network.

4. ENERGY EFFICIENCY MODEL FOR WIRELESS HETEROGENEOUS NETWORK

4.1. Introduction

In mobile communications small cells are potentially more energy efficient than usual macrocells due to the high path loss between users and macro base stations. Also heterogeneous deployments of both cell types can be used to optimize the network energy efficiency. The power consumption of each individual network element has an impact on the energy efficiency of any deployment. The network energy efficiency also depends on the required transmit power and load.

This chapter constitutes my two publications [30], [34]. It discusses the impact of femtocells to the WCDMA network energy efficiency, and the importance of femtocell feature (idle mode) from the perspective of energy saving.

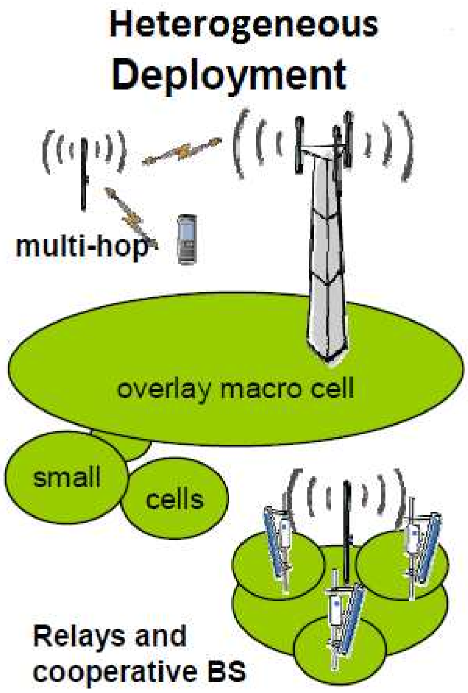


Figure 14: Heterogeneous deployment for Energy Efficient Green Networks

4.2. Impact of Femtocells to the WCDMA Network Energy Efficiency

To see the impact of load (network traffic) on the network's energy consumption, we have considered the Wideband Code Division Multiple Access (WCDMA) system because it is easy to take advantage of the downlink load equations of WCDMA for developing the model of energy consumption. Moreover, all the link level parameters can be easily tracked from deduced formulae (analytical model).

To that end, we derive power model for heterogeneous network consisting of WCDMA macrocells and femtocells deployed in a common service areas. The power model is used to investigate the impact of load sharing between femtocells and macrocells on the overall energy consumption.

Specifically, we have focused on analyzing the potential of energy saving in WCDMA networks through small, low power femto BS deployment alongside macrocellular BSs. In WCDMA networks, offloading from macrocells to femtocells results in decreased macrocell loads which in turn can be utilized through cell breathing so that inter-site distance (ISD) between active macrocells is increasing and the overall energy consumption by macrocellular system decreases. However, the reduced energy consumption by macrocellular infrastructure will be offset by the increasing energy consumption of the dense femtocell deployment.

For this study we have considered the following two network deployment scenarios:

a. First scenario is based on the case where operator is upgrading cell sites in an existing deployment.

b. Second scenario considers either Greenfield deployments of new cell sites or to adopt the approach of switching Macro BSs off whenever traffic load in macrocell is small due to the offloading to femtocell.

4.3. Modeling and Comparison Scenarios

We first recall WCDMA downlink load equations [31], [32]. Then we introduce modeling for performance comparisons and show how load equations can be utilized in this context.

4.3.1. Load Equations and Dimensioning

The cell range and ISD are defined using the layout of Figure 15. Thus, the area covered by a three-sector site is given by $A_{Site}= 9/4 \cdot R^2 = ISD^2$. In the following we simplify the load equations by assuming that dimensioning is done based on a certain service. Then we can start from a simplified form of the well known WCDMA downlink mean load equation [31] [32].

$$\lambda = \lambda_o + N_{users} \cdot \frac{(E_b/N_o)\cdot R_d \cdot v}{BW} \cdot \left(1 - \bar{\alpha} + \bar{\imath}\right), \tag{29}$$

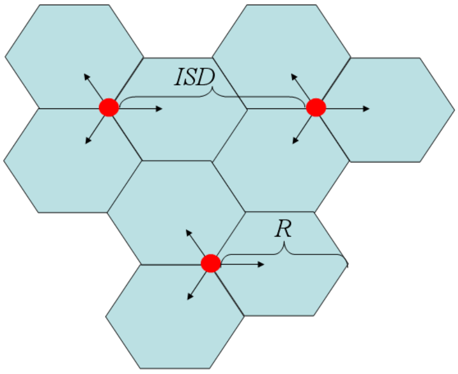


Figure 15: Macrocell layout: Cell range and ISD

In formula (29) parameter λ_0 refers to the minimum load due to control signaling, N_{user} is the number of users in the cell, E_b/N_0 is the energy per user bit divided by the noise spectral density, R_d is the user bit rate, v is the connection activity factor, BW is the system chip rate, α is the spreading code orthogonality factor and i is the other to own cell interference factor. We note that we have considered the mean load that is depending on the expected α and i over the whole cell.

Moreover, for the mean output power in BS transmission we have:

$$P_{Tx,out} = \frac{n_{RF} \cdot \bar{L} \cdot N_{users} \cdot (E_b/N_o) \cdot R_d \cdot v}{1-\lambda}, \tag{30}$$

where n_{RF} is the noise spectral density of the receiver front end. We note that part of the transmission power is used for control overhead.

After combining (29) and (30) we can express the mean signal loss as follows:

$$\bar{L} = P_{Tx,out} \cdot \frac{1-\lambda_o-N_{users}\cdot\frac{(E_b/N_o)}{BW}\cdot R_d\cdot\nu\cdot(1-\bar{\alpha}+\bar{l})}{n_{RF}\cdot N_{users}\cdot(E_b/N_o)\cdot R_d\cdot\nu}, \tag{31}$$

We note that mean signal loss is usually 6 dB less than maximum signal loss in the cell edge [31], so that in dimensioning we need to take into account the corresponding value in (31). Furthermore, the mean signal loss should include impact of distance dependent path loss, shadow fading loss and interference margin. If single slope model $a\cdot R^b$ for distance dependent path loss is used, then we can express the macrocell range as follows:

$$R = \left\{\frac{P_{Tx,out}\cdot\left(1-\lambda_o-N_{users}\cdot\frac{(E_b/N_o)}{BW}\cdot R_d\cdot\nu\cdot(1+\bar{\alpha}+\bar{l})\right)}{a\cdot dL\cdot n_{RF}\cdot N_{users}\cdot(E_b/N_o)\cdot R_d\cdot\nu}\right\}^{\frac{1}{b}}, \tag{32}$$

Here dL contains the impact of signal loss averaging as well as shadow fading and indoor penetration margins.

In simplest form of network dimensioning a target load for a certain service is first selected. Then number of supported users can be calculated from (29) and corresponding macrocell range from (32). Other information besides service rate and load in (29) and (32) can be obtained from link budget.

4.3.2. General Energy Usage Model

We start from a simple model that was previously applied in [4], [7] to describe the macrocell base station power sharing between load independent and load dependent operations:

$$P_{cell} = P_{Oper} + \lambda \cdot P_{Tx} \tag{33}$$

Here term P_{Tx} is the power that is needed to create required transmission power in the antenna output and λ is the cell load that may vary between 0.1 and 0.9 depending on the users load and radio interface configuration. Term P_{Oper} contains all load independent power that is needed to operate the BS.

The equation (33) defines the cell power while sites are usually composed by three or more sectors that each form a logical cell. Therefore, the power consumed in site is of the form

$$P_{site} = N_{cell} \cdot \left(P_{Oper} + \lambda \cdot P_{Tx}\right) \tag{34}$$

where N_{Cell} refer to the number of cells in the site. Then the site energy consumption over a certain time period T is of the form

$$E_{Site} = N_{cell} \cdot \left(P_{Oper} + \lambda \cdot P_{Tx}\right) \cdot T \tag{35}$$

Although network adaptation to temporal variations of the load is an important topic we ignore it in this paper since our focus is in the impact of femtocells. Impact of temporal load variations has been investigated in e.g. [3].

The energy usage over time T in a macrocell network is given by

$$E_{Ntw} = N_{Site} \cdot E_{Site} + N_{UE} \cdot E_{UE} + E_{Other} \tag{36}$$

In (36) the first term in the right defines the energy consumption in all macrocell BSs (N_{site} and E_{site} refer to number of BS sites and energy consumed by single BS site respectively), second term defines the energy usage in all UEs (N_{UE} and E_{UE} refer to number of user equipments and energy consumed by single UE respectively) and last term contains energy consumed by other mobile network elements such as core network elements and radio network controllers in WCDMA.

According to the justification made in previous chapter we ignore the second and the last term in (36).

When femtocells are employed in the network, the energy utilized by the network is given by

$$E_{Ntw} = N_{Site} \cdot N_{cell} \cdot (E_{cell} + N_F \cdot P_F \cdot T) \qquad (37)$$

where N_F is the number of femtocells in each macrocell and P_F is the femto BS mean power usage over time T. In order to simplify the analysis we do not share femto BS power between load dependent and independent parts since it is assumed that impact of load to the femto BS power usage is relatively small.

In order to make calculations more concrete we adopt from [4] the UMTS macrocell base station specific values

$$P_{Oper} = 137W, \qquad P_{Tx} = 57W$$

which will be then used in comparisons. It should be noted that these values do not include the energy consumption used by other elements at the base station site, mainly: antenna feeder cables, backhaul, cooling, and backup. Within three sector site the maximum energy consumption over 24 hours is round 14kWh.

For femto BS input power we use two values, 2W and 5W. The former value is optimistic but achievable in future, while latter value is already reality in commercial femtocell products [33].

4.3.3. Comparison Scenarios

Based on our derived power model, we have compared the two network deployment scenarios by setting different network parametric assumptions for both, in order to make it visible that which network deployment approach is more advantageous in terms of energy saving. Moreover, within these two scenarios we have further compared two hypothetical networks to estimate how the change in network configurations will affect the energy consumption in the modified network (Network 2) in relation to the reference network (Network 1).

As a performance measure we will use the daily energy consumption per square kilometer in the network, expressed as follows:

$$(E/A)_{Ntw} = \frac{N_{Site}^{New} \cdot N_{cell} \cdot \left(P_{Oper} + \lambda^{New} \cdot P_{Tx}\right)}{N_{Site} \cdot A_{Site}} \cdot 24h \qquad (38)$$

$$+ \frac{N_{cell} \cdot N_F \cdot P_F}{A_{Site}} \cdot 24h$$

Thus, dimension for the performance is the kWh/km^2. In the above equation, number of sites in new deployment $(N_{site})^{new}$ and corresponding load λ^{New} refer to the new parametric values of the modified network with respect to the old parametric values of the reference network. We also note that the number of femto BSs is given per macrocell in reference deployment. Either of these changes is expected to take place in one of the two compared networks depending upon the scenario.

- **First scenario:** We assume that Macrocell Inter Site Distance (ISD) is fixed, the number of macrocells is the same for both networks but load is decreasing with additional femtocells and we have

$$(E/A)_{Ntw} = \frac{N_{cell} \cdot \left(P_{Oper} + \lambda^{New} \cdot P_{Tx} + N_F \cdot P_F\right)}{A_{Site}} \cdot 24h \qquad (39)$$

Thus, addition of femtocells is only visible in macrocell load factor.

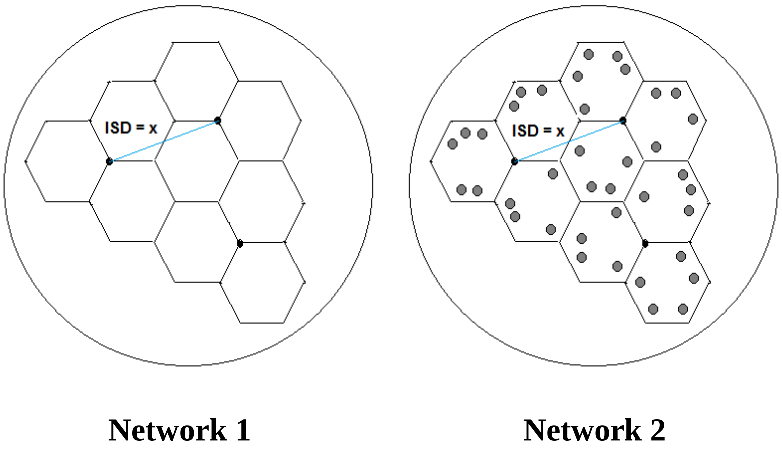


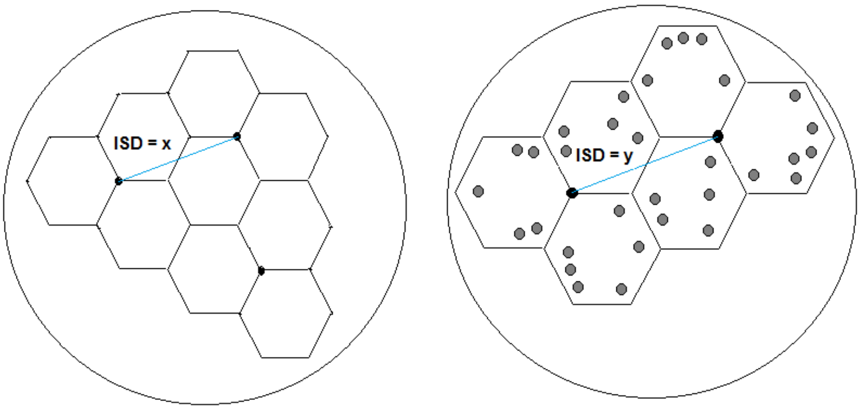
Figure 16: Network Layout; comparison in first scenario

- **Second scenario:** Assume that the macrocell ISD is not fixed but instead, we fix the target load in macrocells. Since part of the traffic is offloaded to femtocells , then the required number of macrocell BSs is decreasing due to cell breathing and we have

$$(E/A)_{Ntw} = \frac{N_{Site}^{New} \cdot N_{cell} \cdot \left(P_{Oper} + \lambda \cdot P_{Tx}\right)}{N_{Site} \cdot A_{Site}} \cdot 24h \qquad (40)$$

$$+ \frac{N_{cell} \cdot N_F \cdot P_F}{A_{Site}} \cdot 24h$$

This reduction in macrocell BS reduces energy consumption.



Network1 **Network 2**

Figure 17: Network Layout; comparison in second scenario

For comparisons we first carry out dimensioning of the network without femtocells using (29) and (32). When cell range *R* is known we can calculate site area and daily energy consumption per square kilometer from the formula

$$(E/A)_{Ntw} = \frac{N_{cell} \cdot \left(P_{Oper} + \lambda \cdot P_{Tx}\right)}{A_{Site}} \cdot 24h \qquad (41)$$

When N_F femtocells are added to the system they take a certain portion of the users, say (R_{femto}·100) % of users (R_{femto} is the ratio between femtocell and macrocell connections). Then either load in macrocells (first scenario) or ISD (second scenario) is decreasing. The latter phenomena reflects directly on the number of macrocell sites.

4.4. Numerical Examples

We consider a WCDMA related example where parameters are given in Table 4.

TABLE 4. WCDMA NETWORK PARAMETERS

Reference parameters	
Parameter	***Value***
Operating frequency	2000MHz
BS antenna height	30m
MS antenna height	1.5m
Propagation model	Okumura-Hata (urban area)
Indoor penetration loss	10dB
BS antenna gain (incl. losses)	16dBi
User data rate	64kbps, 128kbps, 256kbps
E_b/N_0	5dB
Macro BS transmission power	20W
Femto BS input power	5W, 2W
Control overhead	15%
System chip rate	3.84Mcps
Shadow fading margin	7dB
Mean α	0.80
Mean i	0.65
Activity factor v	1.00
Minimum load	0.10

In Figure 18 we have cell ranges as a function of number of users when user data rates are 256kbps, 128kbps and 64kbps. If dimensioning is done e.g. based on 64kbps user rate and assuming load 0.8, then cell range is round 600m.

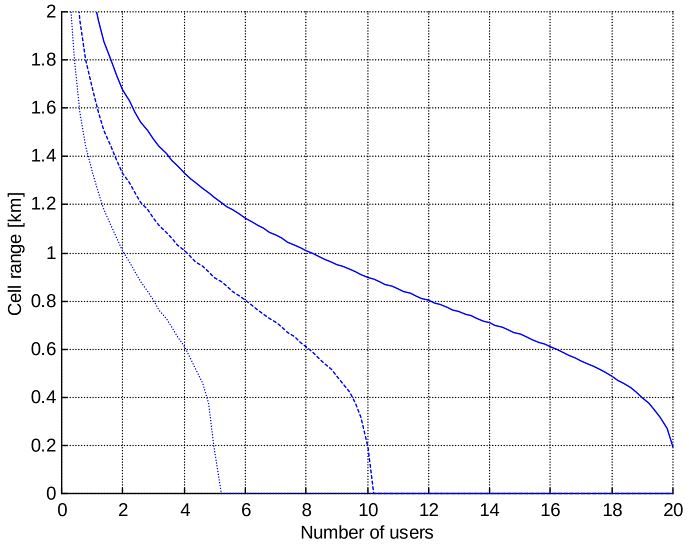


Figure 18: Cell range as a function of number of users when user data rates are 256kbps (dotted curve), 128kbps (dashed curve) and 64kbps (solid curve).

4.4.1. Numerical comparisons

Consider 64 kbps service and assume that initial system load is 0.9. We can then solve number of users from (29) and cell range from (32). Furthermore, if femtocells offload data of $R_{femto} \cdot N_{users} = N_F$ macrocell users, then we can calculate new load λ^{New} from (29) and daily energy consumption per square kilometer from (39). The algorithm for calculating the energy consumed, considering both scenarios can be more easily understood through the flow chart in Figure 19.

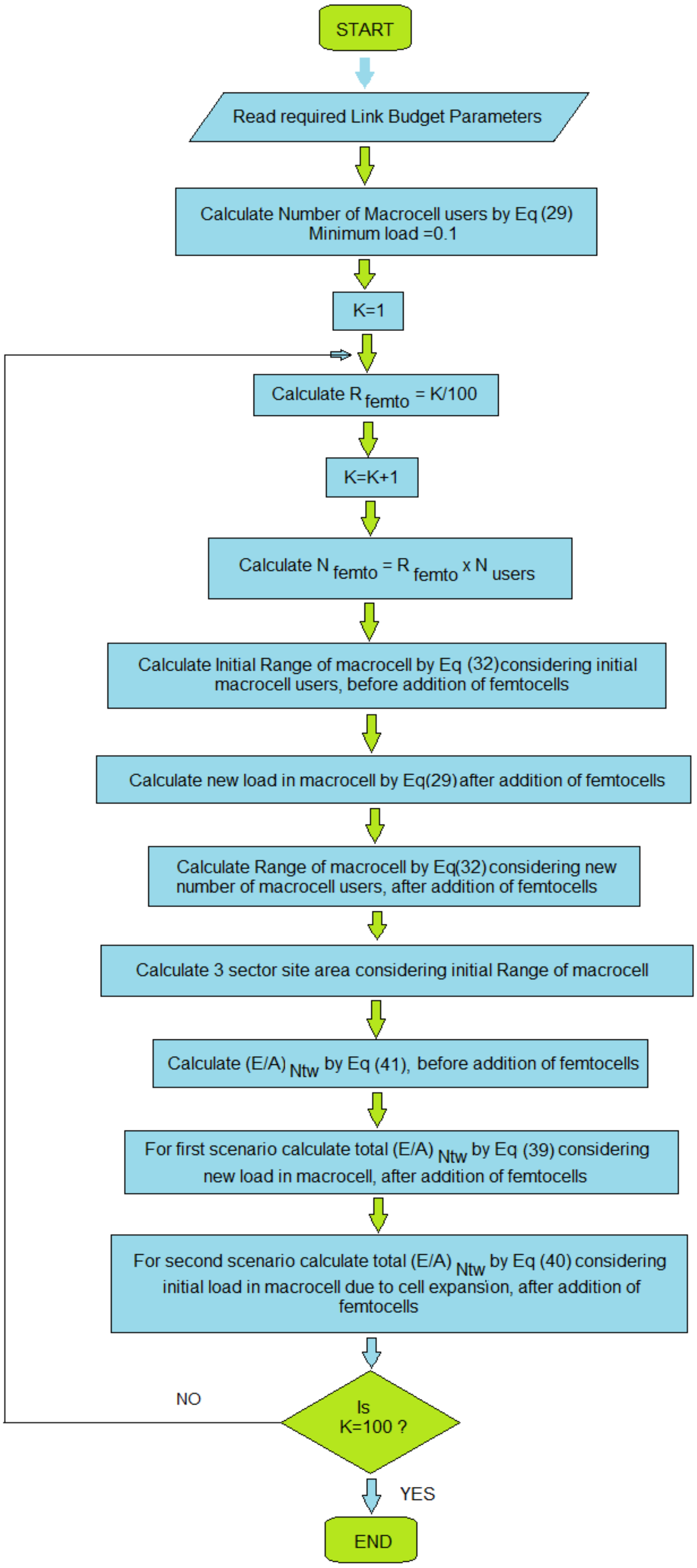


Figure 19: Flow chart for the energy consumption algorithm

Resulting numerical values are given in Table 5.

TABLE 5. DAILY ENERGY CONSUMPTION IN THE NETWORK, FIRST SCENARIO

$100\%\cdot R_{femto}$	0%	25%	50%	75%
$(E/A)_M$ [kWh/km^2]	24.35	22.88	21.40	19.93
$(E/A)_{Total}$ [kWh/km^2], P_F = 5W	24.35	25.77	27.18	28.59
$(E/A)_{Total}$ [kWh/km^2], P_F = 2W	24.35	24.03	23.71	23.39

From second row of Table 5 we find that energy consumption per square kilometer is clearly decreasing in macrocells when ratio of femto connections is increasing. If femto BS input power is 5W, then the total energy consumption in the network is growing since the load decay in macrocell load cannot compensate the additional consumption due to femtocells. On the other hand, if femto BS input power is only 2W, then the total energy consumption is slightly decreasing with additional femtocells. Finally, we note that:

- In above calculations it was assumed that femto BSs are turned on only when there is traffic. If a number of femtocells are also active when traffic is nonexistent, then network energy consumption increases accordingly.

- From network operating costs perspective the values on the second row of Table 5 are important since they contribute directly to the energy bill paid by the operator.

Results regarding to the second scenario has been plotted in Figure 20. It is found that energy consumption by macrocells is rapidly decreasing since lower load allows less dense macrocell grid. The decrease in macro BS density is limited by the non-femtocell users and in practice it is not possible to shutdown all the existing macrocell sites due to coverage reasons. Yet, if network is to be built from scratch then second scenario would be beneficial from energy efficiency perspective.

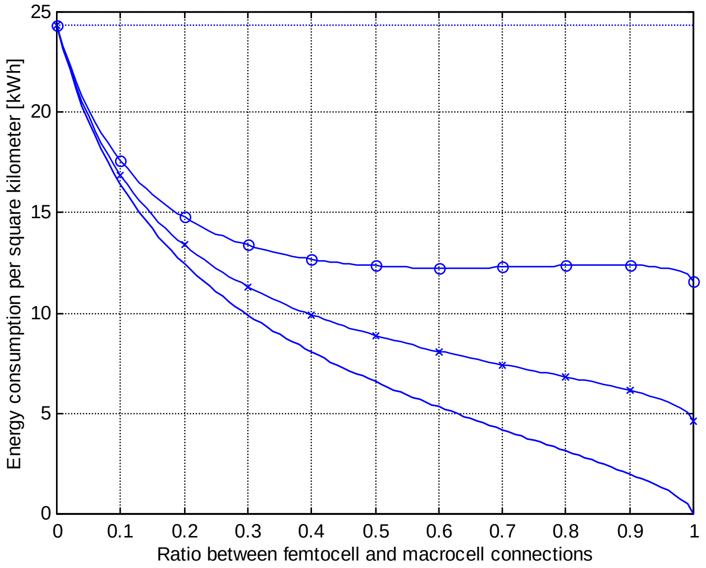


Figure 20: Daily energy consumption per square kilometer in the network when assuming second scenario. No ticks: Energy consumption by macrocells only. Total energy consumption when 5W femto BS power (o), and 2W femto BS power (x).

From Figure 20 we see that in case of 50% femtocell (2W) penetration, around 63% of energy would be saved and it keeps on increasing as the femtocell penetration increases. Whereas in case of 50% femtocell penetration (5W), the maximum energy saving would be around 49% and it will not further increase with the increase in femtocell penetration. Practically decrease in macro BS density is limited by the non-femtocell users. In order to fully exploit this gain, a Greenfield network should be built. However, part of the energy savings can be achieved also in existing networks if macrocell BSs can be switched off during low load periods.

4.5. Femtocell idle mode and network energy efficiency

We discuss the importance of designing a special feature in femtocells which supports *idle mode* to achieve significant amount of energy savings in network. If femto BSs are activated all the time then Femto BS energy consumption easily overtakes the achieved savings on the macrocell side. So femto BS should not remain activated if indoor traffic is non-existent, rather should enter sleep mode. For this femto BS should have the traffic sensing ability.

4.5.1. Effect of femtocell idle mode on overall network energy saving

When N_F femtocells are added to the system they take a certain portion of the users, say (R_{femto}·100) % of users as previuosly discussed, where R_{femto} is the ratio between femtocell and macrocell connections. Then either load in macrocells (first scenario) or number of macrocell sites (second scenario) is decreasing, thus reducing the energy consumption of the network. When both comparison scenarios are analyzed in case of the femtocells deployment that do not possess idle mode feature, we assume that there exist fixed amount of active $\mathrm{N_F}$ in the network already. And they keep on getting utilized along the $\mathrm{R_{femto}}$ scale (when macrocell users are moved to femtocells) while the underutilized ones will remain active.

We have an assumption that each femto BS will serve a single user. Initially we assume number of active femtocells equivalent to number of users in the macrocell. Then onwards vary the value of active femtocells to see the impact on the total energy saving in the network. We have another two options to take the value of $\mathrm{N_F}$, either smaller than $\mathrm{N_{users}}$ or greater than $\mathrm{N_{users}}$. Here we have not considered $\mathrm{N_F}$ to be less than $\mathrm{N_{users}}$ because this would mean that some indoor users will not be capable of being served by femto BS as per our assumption of one to one ratio between $\mathrm{N_F}$ and $\mathrm{N_{users}}$.

Resulting numerical values for 1st comparison scenario are given in Table 6 and Table 7

TABLE 6. DAILY ENERGY CONSUMPTION IN THE NETWORK WHEN DEPLOYED FEMTOCELL POSSESS IDLE MODE FEATURE, FIRST SCENARIO

100% X $\mathrm{R_{femto}}$	**0%**	**25%**	**50%**	**75%**
$\mathrm{(E/A)_M}$ [kWh/km^2]	**24.35**	**22.88**	**21.40**	**19.93**
$\mathrm{(E/A)_{Total}}$ [kWh/km^2], P_F = 5W	**24.35**	**25.77**	**27.18**	**28.59**
$\mathrm{(E/A)_{Total}}$ [kWh/km^2], P_F = 2W	**24.35**	**24.03**	**23.71**	**23.39**

TABLE 7. DAILY ENERGY CONSUMPTION IN THE NETWORK WHEN DEPLOYED FEMTOCELL DO NOT POSSESS IDLE MODE FEATURE, FIRST SCENARIO

100% X R_{femto}	**0%**	**25%**	**50%**	**75%**
$(E/A)_M$ [kWh/km^2]	**24.35**	**22.88**	**21.40**	**19.93**
$(E/A)_{Total}$ [kWh/km^2], P_F = 5W	**35.90**	**34.42**	**32.95**	**31.47**
$(E/A)_{Total}$ [kWh/km^2], P_F = 2W	**28.97**	**27.49**	**26.02**	**24.55**

From second row of Table 6 and 7 we find that energy consumption per square kilometer is clearly decreasing in macrocells when ratio of femto connections is increasing. For femto BS possessing idle mode feature with input power 5W, the total energy consumption in the network is growing since the load decay on the macrocell side cannot compensate for the additional energy consumption due to femtocells. Whereas the opposite is true for 5W femto BS that do not possess idle mode feature. Even then femtocell possessing idle mode feature are better because the energy consumption is approximately 10 kWh/km2 less in comparison to the situation when femtocell without idle mode feature are deployed in the network. On the other hand, if femto BS input power is only 2W, then the total energy consumption is slightly decreasing with additional femtocells for both types (with and without idle mode feature).

Utilizing equation (40), results regarding second comparison scenario has been plotted in Figure 21 from energy saving perspective for both types of femto BSs (with and without idle mode feature) having input power of 2W and 5W. Plotted curves show that total energy saving is more when deployed femto BS possess idle mode feature in comparison to the situation when they do not have such feature.

In Figure 21 different symbols are used to diferentiate the variuos plots depicting total energy saving in different conditions. For the case with $N_F = N_{users}$ we have used:

- Circle for the condition when femto BSs with 2W input power possess idle mode feature,
- Triangle (Up) when femto BSs with 2W input power do not possess idle mode feature,
- Asterisk (*) when femto BSs with 5W input power possess idle mode feature,
- Traingle (Down) when femto BSs with 5W input power do not possess idle mode feature.

Similarly in case of $N_F=2.3 \times N_{users}$ we have used; Square when femto BSs with 2W input power do not possess the idle mode feature. Simple line corresponds to the reference scenario.

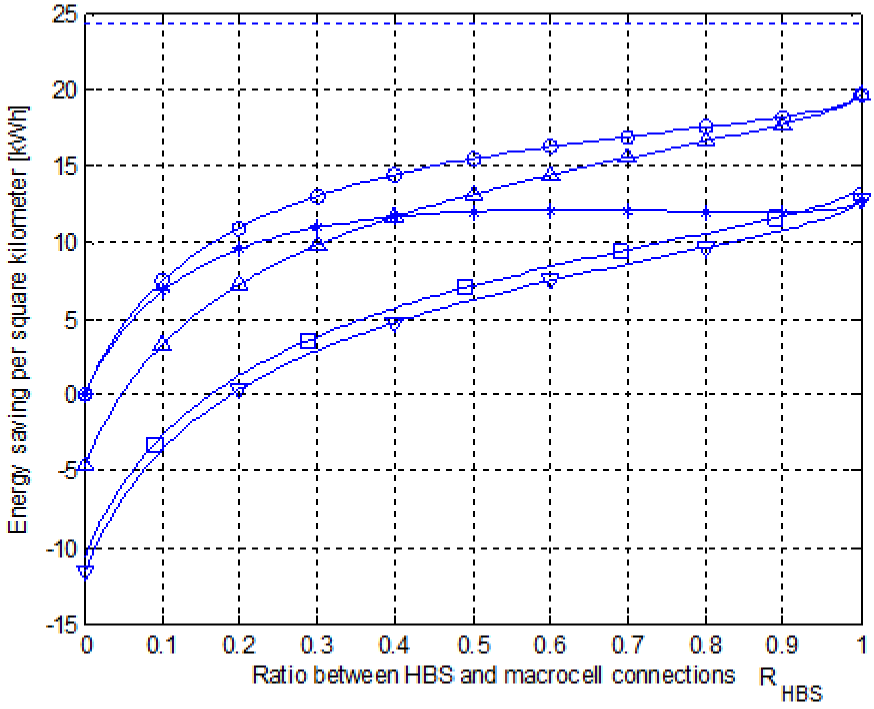


Figure 21: Daily energy saving per km^2 in the network for second comparison scenario

We observe from plots of both input powers of femto BS; when more load out of full load gets shifted from macrocell to femto BS, approximately same amount of energy can be saved from both types of femto BS deployment (with and without idle mode feature). This figure explains that femto BSs without idle mode feature would be more unfavourable when not much load of the macrocell is shifted to femto BS (low R_{femto}), that is, during situation when there is not much indoor traffic existing in the network.

With input power of 2W, when femto BSs that do not possess idle mode feature are deployed in the network, there will be extra energy consumed (no energy saving) by the network until R_{femto} reaches 0.05 since femto BS energy consumption is easily overtaking the achieved savings on the macrocell side. Whereas in case of the 5W femto BS, extra energy is consumed by the network until R_{femto} reaches 0.2, and this extra energy will be more than the extra energy consumed in case of 2W femto BS.

Therefore in case of 2W input power, the deployment of femto BSs that do not possess idle mode feature could be acceptable if femto BSs possessing this feature are unavailable. However in case of 5W input power, this femto BS feature is necessarily required.

Moreover, we vary the number of active femto BSs (2W) in the network as for example $N_F = 2.3 \times N_{users}$, then the energy saving is reduced.

It is concluded through analysis that the number of femtocells should be limited from an energy perspective and upper bound is then the number of users in the macrocell, that is, N_F *(Upper bound)*= N_{users} , for both types of femto BSs (with and without the idle mode feature). Thus the maximum gain in energy saving will be achieved when $N_F = N_{users}$.

For N_F to be greater than N_{users} we have already observed there will be more energy consumption because of the more femto BS deployment than what is required. Considering the one to one ratio assumption, only $N_F=N_{users}$ option remain where we can save maximum energy.

Even from another perspective; we can see from the plot the maximum energy saving become possible when femto BS (that are being utilized) becomes equivalent to N_{users} (at $R_{femto}=1$) that is all the macro load has been shifted to femto BS.

4.5.2. Energy Savings from the perspective of Green Field Network Deployment (In Practice)

Femtocell deployment can reduce the BS density, so it seems that building the new network site from scratch with lesser number of BS would reduce the total energy consumption of the network. But for such Greenfield network build there might exist certain periods in a day when the expected indoor traffic is not sufficient as was expected and we also have the idea of sleep mode when there are underutilized femtocells in the network in order to save energy. So in that case the service will degrade for outdoor users and there will be some coverage holes in the network because the lesser amount of macro BSs would not be able to meet the high capacity requirement (of outdoor traffic).

The penetration rate of femto BSs is equivalent to the percentage of the network's indoor traffic because as per assumption one femto BS serves the single user that has been offloaded from macro to femto BS.

In case of the Femto BS (5W) with idle mode feature, after 50 % of Femto BSs penetrations into the macro BSs network the energy saving becomes almost constant , that is, 12.03 kWh even if we keep on increasing the penetration rate uptil 100%. From Figure 22 we see that macro BS remains underutilized because of the offloading of macro BS traffic to Femto BS and therefore should be shutdown. The result shows that with the increase of Femto BS penetration, we have to shutdown as many macro BSs if we want to save sufficient energy (which we achieved for 50% femto BS penetration). Because with the increase of femto BS usage the energy consumed by femto BS will get increase so in order to compensate this energy consumption, numerous (in large amount) macro BS has to be shutdown.

Hence the maximum energy can be saved with atleast 50% of Femto BS penetration in the macro network. But if for certain network the indoor traffic is more than 50 %, then no matter how much we have been offloading the macro BS (which turn them to shutdown state) we would be saving the same maximum energy which we can achieve for 50% femto BS penetration.

On the other hand with femto BS which do not possess idle mode feature we would save less energy as compared to the ones with idle mode feature. Although the energy saving keep on increasing throughout the femto penetration from 20% to 100 % but the macro BSs have to be shutdown with the same rate as in the case of femto BS with idle mode feature.

When there is 100% of femto BS penetration , that is, the whole network traffic is originates from indoor UE, then this shows that all the existing macro BSs can be shutdown but practically this is not possible because femto BS are connected to core network via macro BS. Here some kind of a tradeoff has to be made to keep one (or few) macro BSs On and at the same time save the energy by shutting down few macro BSs depending upon the network macro load.

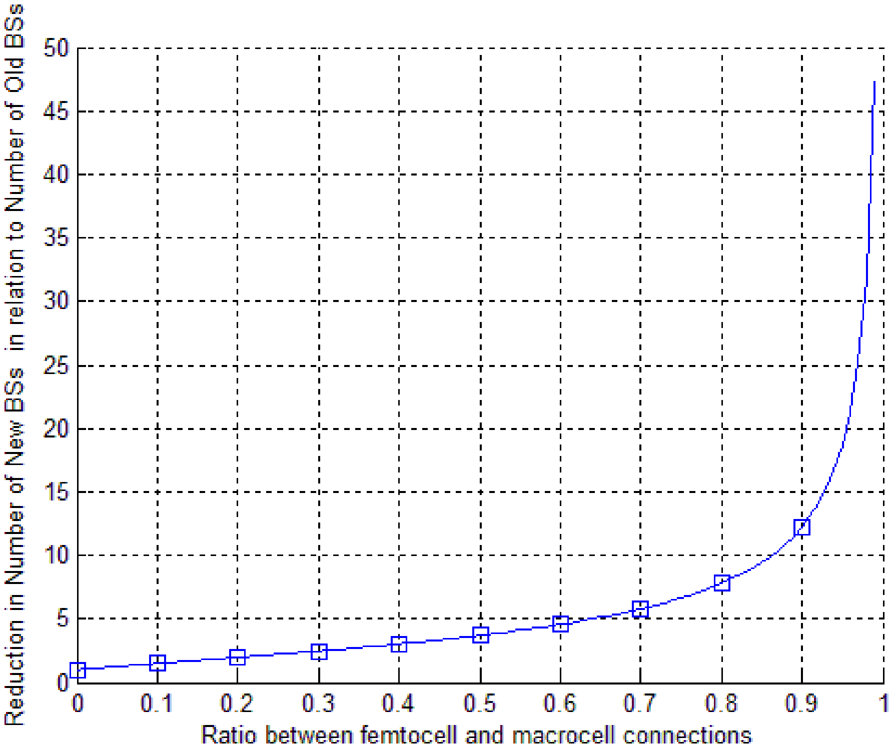


Figure 22: Reduction in Number of New BSs in comparison to Number of Old BSs

Reduction in number of BSs for new sites in relation with the penetration rate of femtocells has been shown in Figure 22 and the numerical values has been shown in

Table 8, the table also shows the respective energy saved for both types of femtocells. Let’s suppose if we assume the approach of building new macro BS site network by reducing the number of BSs to half the amount of old network’s number of BSs, considering the requirement of femtocells with 21% penetration because of the 21% expected indoor traffic existence, then 9.76kWh energy per unit area could be saved. In this situation if indoor traffic decreases to 10% for such newly build Site network, there will be coverage holes due to the missing one third number of BSs (as for 10% of indoor traffic there is a need of 3/2 times less number of BSs than the old network’s BSs). Hence to save the energy and to avoid the service degradation problem it is good to shut down the underutilized macro BSs when there exist indoor traffic in the network instead of deploying the new sites with lesser BSs.

TABLE 8. TOTAL ENERGY SAVINGS WHEN FEMTOCELLS WITH AND WITHOUT IDLE MODE FEATURE HAVE BEEN USED, AND THE REDUCTION IN NUMBER OF NEW BS SITES W.R.T TO OLD BS SITES.

Penetration rate of femtocells	0%	21%	40%	52%	77%	100%
Reduction in the number of new BS site w.r.t the old BS site network	1 time	2 times	3 times	4 times	7 times	∞ times
Total Energy Saving when femtocells with idle mode feature are used	0 kWh	9.76 kWh	11.67 kWh	12.03 kWh	12.09 kWh	12.80 kWh
Total Energy Saving when femtocells without idle mode feature are used	-11.5 kWh	0.639 kWh	4.74 kWh	6.48 kWh	9.35 kWh	12.80 kWh

On the other hand it is not convenient to use the dynamic power ON/OFF switching technique to save energy in the operation of the macrocellular BS. It will be more feasible to implement this technique when it is known in advance which periods of day there is high probability of shutting down the BSs based on predetermined traffic information. This requires the daily traffic patterns (both indoor and outdoor traffic information) of the network with high accuracy.

5. CONCLUSIONS AND FUTURE WORK

This thesis work investigated the energy consumption of mobile access networks which has recently received increased attention in research carried out in both industry and academia. This thesis also contributes to the mainstream discussion on the importance of reduction in energy consumption to achieve economic and environmental benefits. Particularly it has addressed the possible ways to minimize the energy consumption on the BS sites.

In the thesis, some factors in evolution of mobile networks were discussed from energy and power consumption perspective. Based on the discussion a simple methodology was proposed in order to model the power consumption on network of base stations. To make visible the impact of different link budget and network parameters two scenarios have introduced. Finally, to elaborate these scenarios, two simple examples were presented.

The thesis work also investigated the potential energy savings when deploying femtocells along with macro base stations in WCDMA network. To find the energy consumption per unit area, WCDMA downlink load equations were used. It was determined how the load sharing between femtocells and macrocells will contribute to the overall energy consumption of the network.

To elaborate introduced scenarios, two simple examples were presented. In first scenario the macrocell inter site distance is fixed and different femto base station penetration ratios are assumed. Analytical results show that total energy consumption in network per unit area was increasing when employing femto base stations that operate with a 5W input power. On the other hand, energy consumption was found to decrease slightly when employing femto base stations that operate with a 2W input power.

In second considered scenario the macrocell inter site distance was not fixed and the addition of femtocells to the macrocellular system decreased the macrocell base station density due to the cell breathing phenomenon. In this case there was a significant amount of energy saving. Achieved gain can be fully exploited in green field deployments but part of the energy saving potential can be utilized also in existing networks through macrocell breathing: decreased macrocell load due to femtocells results in larger macrocell coverage and in dense macrocell deployments part of the base stations can be switched off.

Finally, the thesis focused on the importance of idle mode feature for femto BS. The number of active femto base stations has significant impact on the network energy efficiency. If femto BSs are on all the time then femto base station energy consumption easily overtake the achieved savings on the macrocell side. Therefore it is essential to design efficient sleep mode procedures for femto base stations.

The analytical results concluded that in order to save the energy and avoid the service degradation problem; it is recommended to shutdown the underutilized BSs instead of deploying the new networks with less BSs (green field networks). This switching ON/OFF of the BSs should be done based on the already available daily traffic patterns.

For this reason the future work includes; taking into account the impact of daily traffic variations for the shown studies and for that purpose a new performance metrics will be needed. Furthermore, the future study includes; designing the methodology (utilizing Shannon equations) for the energy consumption of HSDPA (High Speed Downlink Packet Access) and LTE (Long Term Evolution); modeling the power usage of a heterogeneous network element such as Relays. This study was based on uncoordinated femtocellular BSs. For further studies; to see that how the coordinated and planned femtocellular BSs would affect the energy efficiency of the network.

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