Energy Efficiency LTE Site Operation

with Antenna Muting and dynamic Psi-Omni

Zeid Al-Husseiny
To my family and friends that has supported me during all my studies and this thesis. Without your continuous support I would not have made it this far.

Thank you.
Acknowledgements

This Masters thesis has been done at Ericsson Research in Linköping, Sweden, during spring semester 2014.

I wish to thank the people at LinLab, Ericsson Research in Linköping, Gunnar Bark for allowing me this opportunity and everyone else for making me feel welcome here. Thank you for all the open doors and enjoyable coffee breaks, all the chess games and exciting table hockey matches. Arriving at Linköping, a place I have never been to before, without knowing anyone I expected many hardships. But with everyone so welcome here it has been an enjoyable ride with difficult, yet exciting hurdles.

Above all, I wish to give my utmost gratitude to Pål Frenger, my supervisor. Your excellent guidance has simply been unparalleled. Thank you truly for your patience with me. Even with your full schedule, your door was always open for my continuous questions about simply everything. Thank you for continuously sharing your vast knowledge which I never saw the bottom of. The amount of learning you provided me has been an unforgettable experience that will forever be with me in my career. I also wish to profusely thank Erik Eriksson and Martin Hessler for their constant willingness to help every time. My topic examiner at Uppsala University, Mikael Sternad, thank you for your continuous support and preparing me for this study. Everyone’s incredible insight always thrived me to work harder and aim to achieve greater heights. These 20 weeks have been pure learning at the highest level and I could not have asked for a better environment. You have allowed me to develop both technically and personally, something that will forever be with me.

Linköping, June 2014
Zeid Al-Husseiny
Abstract

Energy Efficiency LTE Site Operation with Antenna Muting and dynamic Psi-Omni

Zeid Al-Husseiny

To allow access to the network at all times a base station has to continuously stay active. While being active, a base station does not usually transmit data constantly. Typically, the base stations either send out lots of data or barely anything at all, yet, the network is actively drawing power the whole time. Succeeding in lowering the power consumed when the data rate is often so low would therefore lead to great benefits, both economically and environmentally, as well as new prospects of innovation in engineering. The process of how to dynamically change from a capacity optimized mode to an energy optimized mode as well as when to do this change is studied in this thesis for LTE.

By using methods such as antenna muting and psi-omni coverage, the power consumption can decrease. These solutions however also decreases performance, and has to be activated with great care in mind not to cause any major impact on user performance. The dynamic configuration is dependent on the load of the system, changing to an energy efficient mode when traffic is low and to a capacity optimized mode when the network needs to supply high data rates.

Simulations show that most energy savings can be found in rural and urban environments. Dynamic antenna muting achieved, summarizing macro environments, 24.9% energy savings with 95.27% downlink data rates compared to the reference case of using sector mode continuously i.e MIMO. In the same environments, dynamic psi-omni coverage together with antenna muting achieved energy savings of 43.8% with 89.3% downlink data rates compared to typical sector mode. Traffic rates are based on future demands in Europe by 2015, assuming that 20% of the subscribers are downloading 900 MB/h and the other 80% subscribers, at 112.5 MB/h.
Sammanfattning


Genom att använda metoder som ”Antenna muting” och ”Psi-Omni täckning” kan strömförbrukningen minska. Dessa lösningar minskar dock även prestanda, vilket betyder att de måste aktiveras med hänsyn till att inte orsaka någon större effekt på användare i nätet. Den dynamiska konfigurationen beror på belastningen av systemet, det energieffektiva läget aktiveras när trafiken är låg och det kapacitet optimerade läge när nätet behöver leverera höga datahastigheter.

Simuleringar visar att störst energibesparingar finns i stadsmiljöer och på landsbygden. Dynamisk antennamuting uppnådde, totalt i makro miljö, 24.9% besparing i strömförbrukning med 95.27% nedlånt datahastigheter jämfört med referensfallet att kontinuerligt använda sektor läget, dvs MIMO. I samma makro miljöer, uppnådde dynamisk psi-omni täckning tillsammans med antennamuting, energibesparings på 43.8% och 89.3% nedlånt datahastigheter jämfört med dagens sektor konfigurering. Data trafik baserar sig på framtidiga krav i Europa 2015, med antagandet att 20% av abonnenterna laddar ner 900 MB/h och de övriga 80% abonnenter, 112.5 MB/h.
# Table of Contents

Abstract vii

1 Introduction 1
  1.1 Background .................................................. 2
    1.1.1 Solutions overview ..................................... 3
    1.1.2 Macro cell deployment ................................. 4
  1.2 Problem formulation ......................................... 5
  1.3 Thesis outline ................................................ 5
    1.3.1 Assumptions and limitations ............................ 6

2 Theory 7
  2.1 Base station ................................................. 7
  2.2 Cell area ..................................................... 9
  2.3 Fading ....................................................... 9
  2.4 Transmission Control Schemes ............................ 10
    2.4.1 Time Division Duplex (TDD) ........................... 10
    2.4.2 Frequency Division Duplex (FDD) ..................... 11
  2.5 Antenna ports ............................................... 11
    2.5.1 CRS signals ............................................ 12
    2.5.2 Beamforming ............................................ 12
    2.5.3 Spatial multiplexing .................................. 13
  2.6 Access methods ............................................. 14
    2.6.1 Measurements ........................................... 15

3 Energy Saving Concepts 17
  3.1 Antenna/MIMO muting ......................................... 17
  3.2 Combined Antenna Muting with Sector-to- Omni Reconfiguration 19

4 System Evaluation 23
  4.1 Cell states .................................................. 23
    4.1.1 Antenna/MIMO muting states .......................... 24
    4.1.2 Sector to dynamic psi-omni reconfiguration states ... 24
  4.2 Conditions of changing mode ............................... 24
    4.2.1 Antenna/MIMO muting .................................. 25
    4.2.2 Sector-to-Omni ......................................... 25
  4.3 System Overview ............................................. 25
    4.3.1 Deployment .............................................. 25
    4.3.2 Macro cell deployment parameters ........................ 27
5 Power Model
  5.1 Power consumption ............................................. 29
      5.1.1 Standby mode ............................................. 31
  5.2 Energy savings ................................................... 32
      5.2.1 Energy savings using antenna muting ...................... 32
      5.2.2 Energy savings using dynamic $\Psi$-omni reconfiguration .. 34
  5.3 Model ........................................................... 35
  5.4 Data Traffic ...................................................... 39

6 Simulations & Numerical Results ........................................... 41
  6.1 Forced change of mode .......................................... 41
  6.2 Numerical results ................................................. 43
      6.2.1 Rural environment ......................................... 43
      6.2.2 Suburban environment ..................................... 46
      6.2.3 Urban environment ......................................... 49
      6.2.4 Dense urban environment ................................... 52
  6.3 Energy savings and Performance degradation ...................... 54

7 Conclusions .......................................................... 57

8 Discussions
  8.1 Decision of changing mode ..................................... 59
  8.2 Detection .......................................................... 60
      8.2.1 Transition between sector and dynamic psi-omni .......... 61

9 Further Research
  9.1 Spectrum alterations ............................................. 63
  9.2 Examining different values for timing and thresholds ............ 63
  9.3 Using MIMO in psi-omni cells .................................... 64

References ............................................................... 65

Appendix ................................................................. 67
List of Figures

1.1 Base station with 3 sector cell deployment. ......................... 2
1.2 Baseline sector site circuit chart ................................. 3
1.3 Expected area coverage deployment of Europe by 2015. ........ 4
1.4 Expected deployment power consumption distribution in Europe by 2015. ..................................................... 5

2.1 Cellular deployment. .................................................. 8
2.2 Different types of cells. ............................................. 8
2.3 Inter-Site-Distance .................................................. 9
2.4 Time Division Duplex ............................................... 11
2.5 Frequency Division Duplex ....................................... 11
2.6 Beamforming ........................................................ 13
2.7 Channel matrix ..................................................... 14
2.8 Cell area and hysteresis .......................................... 16

3.1 Circuit chart comparison between baseline sector cell and muted sector cell. ...................................................... 18
3.2 Psi-omni .............................................................. 20
3.3 Psi-omni circuit chart for DL and UL ............................ 20
3.4 Omni cell ............................................................ 21
3.5 Four cells active - antenna muting and dynamic psi-omni circuit chart. .......................................................... 22

4.1 Deployment ........................................................... 26

5.1 Power consumption breakdown of a macro BS (TRX) at full load. 30
5.2 Load dependent, power consumption breakdown of macro BS components. ......................................................... 30
5.3 Power consumption breakdown of DL and UL components. .... 31
5.4 Power consumption breakdown of DL and UL components in standby. .............................................................. 32
5.5 Power model .......................................................... 36
5.6 Power model sector versus antenna muting ........................ 36
5.7 Total power per site calculation model. ............................ 38
5.8 Daily average data traffic ........................................... 40

6.1 Forced antenna muting. .............................................. 42
6.2 Forced sector-to-omni reconfiguration. ............................ 42
6.3 Power consumption per area unit in rural deployment. ........ 44
6.4 Downlink user data rates in rural deployment. .................................................. 44
6.5 5th percentile of downlink user data rates in rural environment with medium traffic density. .......................................................... 45
6.6 Average power consumption and downlink user data rates in rural environment with medium traffic density. .................................................. 45
6.7 Summarized average power consumption and average downlink user data rates in rural environment with low, medium and high traffic density. ........................................................................... 46
6.8 Power consumption per area unit in suburban environment. ................. 47
6.9 Downlink user data rates in suburban environment. ................................. 47
6.10 5th percentile of downlink user data rates in suburban environment with medium traffic density. .......................................................... 48
6.11 Average power consumption and downlink user data rates in suburban environment with medium traffic density. .................................................. 48
6.12 Summarized average power consumption and average downlink user data rates in suburban environment with low, medium and high traffic density. ........................................................................... 49
6.13 Power consumption per area unit in urban environment. ...... 50
6.14 Downlink user data rates in urban environment. ................................. 50
6.15 5th percentile of downlink user data rates in urban environment with medium traffic density. .......................................................... 51
6.16 Average power consumption and downlink user data rates in urban environment with medium traffic density. .................................................. 51
6.17 Summarized average power consumption and average downlink user data rates in urban environment with low, medium and high traffic density. ........................................................................... 52
6.18 5th percentile of downlink user data rates in dense urban deployment with medium traffic density. .......................................................... 53
6.19 Average power consumption and downlink user data rates in dense urban deployment with medium traffic density. .................................................. 53
6.20 Summarized average power consumption and average downlink user data rates in dense urban environment with low, medium and high traffic density. ........................................................................... 54
6.21 Energy savings and performance degradation summarized from implementing energy efficiency enabler antenna muting in all environments. .......................................................... 55
6.22 Energy savings and performance degradation summarized from implementing energy efficiency enabler dynamic psi-omni together with antenna muting in all environments. .................................................. 55

8.1 Activation delay .......... 60
List of Tables

4.1 Macro BS general parameters. ................................. 27
4.2 Macro BS Rural simulation parameters. .................... 27
4.3 Macro BS Suburban simulation parameters. ................. 28
4.4 Macro BS Urban simulation parameters. ....................... 28

5.1 Active, Standby and Affected components when using antenna muting. ............................................. 33
5.2 Energy savings (per site) using antenna muting. ............. 33
5.3 Active, Standby and Affected components when using dynamic Psi-Omni. ................................................. 34
5.4 Energy savings (per site) using antenna muting and dynamic psi-omni. ...................................................... 35
5.5 Data traffic peaks .................................................... 39
Acronyms and Abbreviations

2G  2nd Generation
3G  3rd Generation
3GPP  3rd Generation Partnership Project
4G  4th Generation
BS  Base station
CA  Carrier Aggregation
CRS  Cell Specific Reference Signal
DL  Downlink
EARTH  Energy Aware Radio and neTwork tecHnologies
FDD  Frequency Division Duplex
FTP  File Transfer Protocol
GSM  Global System for Mobile Communications
ISD  Inter-Site-Distance
LNA  Low-Noise Amplifier
LTE  Long Term Evolution
MIMO  Multiple Input Multiple Output
PA  Power Amplifier
PBCH  Physical Block Channel
RAN  Radio Access Network
RAT  Radio Access Technology
RB  Resource Block
RE  Resource Element
RRC  Radio Resource Control
RRU  Remote Radio Unit
RSRP  Reference Signal Received Power
RX  Receive(r)
SINR  Signal-to-Interference-plus-Noise Ratio
SNR  Signal-to-Noise Ratio
TDD  Time Division Duplex
TRX  Transceiver
TX  Transmit(ter)
UE  User Equipment
UL  Uplink
UMTS  Universal Mobile Telecommunications System
VoIP  Voice over Internet Protocol
1

Introduction

You see, wire telegraph is a kind of a very, very long cat. You pull his tail in New York and his head is meowing in Los Angeles. Do you understand this? And radio operates exactly the same way: you send signals here, they receive them there. The only difference is that there is no cat.

– Albert Einstein

The enormous success of Smart Phones and Tablets has created a greater demand for higher data rates. Supported features such as video calls and streaming motion picture become more common every day, and all this puts stress on the network. The introduction of LTE (Long Term Evolution) answered the demands of higher data rates, together with improvements in coverage, capacity and shorter delays. LTE, also known as 4G, is the latest standard in wireless communication and is an evolution of the previous generations GSM (2G) and UMTS (3G), able to handle much higher data rates using MIMO and Carrier Aggregation. As of today LTE has been commercialized since four years back and will most likely be at the front of the wireless communication industry for many years to come.

Certainly, wireless communication can contribute in decreasing $CO_2$ emissions, e.g. by reducing the need to travel. With today’s technology it is possible to have satisfying video conversations while being outdoors, compared to the cellphone’s early days that is a significantly large step, when calling and social texts were the only services available. Introducing new technology that can provide more services usually requires higher performance, which most commonly comes with the trade-off in requiring more power. Today, the energy costs to run a mobile network are for some operators comparable with personnel costs [1] [2]. An important topic for operators has therefore been energy efficiency. This thesis focuses on energy efficiency in LTE, specifically Rel-8, and how to decrease power consumption in scenarios when most of the capacity is not being used.

The scope is to analyse energy efficiency features and evaluate how they would work in a complete radio access network. How would the performance change and how much can really be gained?
1.1 Background

The industry today contains several companies in the field of radiocommunications, each with their own products. For all units to connect to the same network it is essential to have a set of rules (protocols) that all units follow. The 3rd Generation Partnership Project (3GPP) is a collaboration of several organizations to obtain a common understanding between all parties involved. Together they have set the standard for **Long Term Evolution** (LTE) which is the current forefront standardization in radio communication. They are also responsible for previous releases of standardization such as 2G (GSM) and 3G (UMTS). The first complete release of LTE was established in REL-8, with further enhancements in REL-9, 10, 11 and 12. LTE introduces new features such as MIMO and Carrier Aggregation (CA) that improves characteristics such as throughput, coverage and delay.

The deployment of a cellular site may be traditionally divided into sector cells with the base station in the middle, see Fig. 1.1.

![Base station with 3 sector cell deployment.](image)

When examining the energy consumption of a cellular network, the dominating energy consumer proved to be the access network. Which in turn, considering the amount, is dominated by the power consumption of base stations. Base stations have different sizes and their energy consumption changes depending on deployment. In a macro base station, this thesis focus, the dominating energy consumer is the *power amplifiers* (PAs) [4, section 4.2]. To cover the power needed to support the deployment in Fig. 1.1, two PAs are supplied for each sector, resulting in a total of six PAs for the whole site (see Fig. 1.2). Together, they stand for more than 50 percent of the energy consumption per macro base station, where these are always active, during both small and heavy traffic loads. When a base station does not transmit any heavy data rate i.e. the traffic becomes very low, the power usage of the PAs drop to 40-50 percent of full power as there is not much to transmit [4, section 4.3]. Although for maintaining coverage, mandatory mode signals stipulated by the LTE standard still have to be transmitted continuously [8, section 6.10.1].

In the industry today, there is a general consensus that it is theoretically possible to decrease the energy consumption significantly of telecommunication equip-
Fig. 1.2: Baseline sector circuit chart for DL and UL. Each number represents a sector cell, baseband (BB) component, with the DL being transmitted to the antennas (X) and UL received from the antennas. The triangles (P) in DL transmission signifies the power amplifiers, while the upside down triangles in the UL characterize the low noise amplifiers (LNA).

ment. This is e.g. discussed in the EU-funded EARTH project [5], where many solutions that could contribute to energy efficiency are reviewed; all the way from hardware components to deployment strategies. This thesis focuses on evaluating two of those methods and implementing them in a detailed radio access network.

1.1.1 Solutions overview

Base stations typically transmit in a bursty behaviour such that; they are either transmitting lots of data, or in an idle state transmitting very small data rates. Supported features in LTE such as MIMO and Carrier Aggregation (CA) that gives the ability to provide very high data rates becomes mostly unused in cases when transmission of small data rates are only required, especially in areas where data traffic is very low most of the day. Allowing MIMO to be activated in a base station that is barely transmitting any amounts of data is not particularly energy efficient. The first approach studied focuses therefore on muting MIMO when traffic is low. This is done by using only one of the antennas in each sector, muting the rest i.e. muting MIMO. This approach is explained further in section 3.1.
The second approach is, combined with the first approach, to also use an omni-directional signal with the existing sector antennas. This arrangement would require four cells per site instead of three, where the cells are active depending on which configuration is currently instigated. Using the same sector antennas, the omni-directional cell covers the same area as the sector cells, however, since it is a separate cell it also requires a handover to reach (see section 2.6.1). This maintains the coverage with only minor data rates applied, less than antenna/MIMO muting (previous solution). This solution would however also increase energy savings even further and could be an attractive functionality e.g in rural parking lots during the night. Further details of this approach is explained in section 3.2.

Both solutions have been designed to switch dynamically dependent on the load of the system (see section 4.2). This is to maintain the user experience with minimal disturbance, yet enabling lower power consumption when only small data rates are required.

### 1.1.2 Macro cell deployment

The evolution of mobile terminals has certainly created a greater traffic growth, both due to the large increase in terminals as well as data demanding applications e.g. video streaming services. An important aspect is thus to consider future growths in terms of data traffic rates. Inter site distances of 500 m in urban areas and 1732 m in rural/suburban areas are expected to provide reasonable capacities for coming traffic growth the nearest years. The increase in traffic rates might however lead to denser deployments and more smaller cells aimed at populated areas. Studies show that deployment in Europe by the year 2015, with the inter site distances described, will have the following distribution displayed in Fig. 1.3 [5, section 2.7.1].

![Fig. 1.3: Expected area coverage deployment of Europe by 2015.](image)

By abstracting cell planning maps, one arrives at the deployment area coverage distribution shown in Fig. 1.3. The corresponding power consumption to the mentioned area environments is illustrated in Fig. 1.4. We observed previously
that the area covered by urban deployment is significantly less compared to that of rural deployment. However, since the deployment of base stations are that much denser in urban environment compared to rural and suburban areas, urban deployment reaches in terms of consumption levels almost the same energy consumption as that of rural deployment, as seen in Fig. 1.4.

![Figure 1.4: Expected deployment power consumption distribution in Europe by 2015.](image)

### 1.2 Problem formulation

This study involves a Proof of Concept and performance evaluation of dynamic antenna muting and psi-omni configuration in an LTE network. The focus has been to implement and simulate the performance of these two methods in rural, suburban and urban deployments. Traffic scenarios have been based on expected traffic densities in Europe by 2015, considering both performance degradation and energy consumption.

The evaluation is divided into two parts, investigating:

1. Dynamic configuration of antenna muting.
2. Dynamic configuration of both psi-omni coverage and antenna muting.

### 1.3 Thesis outline

Chapter 2 describes some radio communication theory to enlighten the emerging chapters, followed by chapter 3 where the investigated concepts are presented in more detail. The contents in chapter 3 discusses the benefits of each solution...
In chapter 4 the implementation of corresponding energy efficiency and capacity modes are explained. This section supports chapter 3, where the transition between the modes are clarified. The latter sections in this chapter also evaluates the conditions for transitions and expected behaviour. Together with an overview of the system such as parameters for the following simulations.

Power consumption calculations by activating each mode and the model used are found in chapter 5. The last section contains traffic densities applied in the study as well as typical traffic changes during the hours of a day.

The last four chapters describes the results and conclusions of the investigation as well as optimizations that could be utilized in continuing studies. This includes adjustments in cell selection, transitions between modes and spectrum alterations for possible enhancements.

1.3.1 Assumptions and limitations

Turning on and off certain components tends commonly to have a certain delay, especially until they reach full utilization when turning them on. In this study it is assumed that the triggering of a cell or re-configuration can occur in milliseconds, where this triggering delay also masks the activation delay of components. To ascertain this approach, components has realistically been set to standby to activate them faster. The power model used in this thesis has been relatively strict with realistic measurement. In practice, switching components on and off might also have certain effects on their lifetime but is in this case neglected.

When considering handover algorithms, a limitation in this investigation has been that the UE must detect a cell before performing corresponding handover. Where in practice, according to [8, section 5.3.1.3], it would be possible for the base station to assign the UE to a specific cell. Dropping the UE connection is also another possibility, barring it from the serving cell [8, section 5.3.9], this compels the UE to connect to a new serving cell unlike the previous one (see section 4.1).

The TCP protocol used in the simulations serves as a limitation due to congestion and TCP slow start. Where in practice, it would be possible to adjust the parameters leading to smoother transitions and higher data rates.

In each mode, capacity optimized or energy optimized, we also use the same amount of transmissions, which leads to performance degradation shown in the numerical results, chapter 6. While in practice, it would be possible to send more transmissions when entering an energy efficiency mode and yield the same performance as the capacity optimized mode.
2

Theory

This chapter provides an explanation to some radio communication theory applied in the study to clarify expressions that will appear in the coming chapters.

2.1 Base station

The hierarchy of a telecommunication system begins with the core network. From the nodes of the core network expands the radio access network (RAN), which uses radio access technology (RAT) to provide the services requested by the user equipment (UE). A base station is what encapsulates the RAT and manages the RAN. This means that for a terminal, a UE, it will only see the base station as the provider, not the core network. To request any services a UE must also receive access to a base station, this is explained more in section 2.6.

The structure of a communication network is often modelled as a hexagonal tessellation where each hexagon corresponds to a cell in the network, resulting the name cellular network (see Fig. 2.1). Each cell is in turn managed by a single base station. In practice, there are two kinds of cells when considering deployment, they are sector cells and omni-directional cells (omnicells). The omni-directional cell is a hexagon with the base station in the middle, see Fig. 2.2a. The other type of cells, sector cells, consists of three hexagonal cells with a base station in the edge of where all cells intersect (see Fig. 2.2b). Depending on the deployment it might be more efficient to use one type of cells over the other.

A terminal connects to the base station with best reception, typically the cell where the terminal is currently positioned. In turn, the terminal is managed by that base station whenever any services are requested e.g, calls and data. When a UE finds a cell with better reception, it changes connection to that cell by performing a handover, explained in section 2.6.1. A terminal has typically better reception close to the base station as the signal is commonly stronger, further away tends to lead to weaker signals and more interference from other cells.
Fig. 2.1: Cellular deployment.

Fig. 2.2: Different types of cells.

(a) Omni-directional cell.

(b) Sector cell.
2.2 Cell area

A representation mainly used for defining the size of a deployment is the Inter-Site-Distance (ISD). This is the distance between two independent base stations of equal deployment. The representations of parameters used in this thesis regarding cell coverage is portrayed in Fig. 2.3.

![Inter-Site-Distance](image)

Fig. 2.3: Inter-Site-Distance

The areas are calculated using the ISD and cell radius

\[
\text{Area}_{\text{cell}} = R^2 \frac{3 \cdot \sqrt{3}}{2} \tag{2.1}
\]

\[
\text{Area}_{\text{site}} = \text{Area}_{\text{cell}} \cdot 3 = ISD^2 \frac{\sqrt{3}}{2} \tag{2.2}
\]

where the \( ISD = 3R \).

2.3 Fading

Radio communicated signals propagates from the transmitter to the receiver in form of radio waves. Like light waves, radio waves gets reflected and refracted by its surroundings which causes the signal to take several different paths before reaching the receiving end. In each of these traversed paths the signal gets attenuated or amplified depending on its surroundings. A large building or very long distances between transmitter and receiver can cause the signal to fluctuate, both in phase and in amplitude, significantly. In radio communication this form of deviation where the original transmitted signal suffers from its surroundings is defined as fading.
Shadow fading or shadowing is the type of fading caused due to large objects such as trees, mountains and buildings interfering with the signal. While multipath propagation, where the signal reaches the receiver using several paths, is referred to as multipath fading.

As the signal traverses numerous paths, the target also receives several copies of the signal. Each received signal have thus different phase shifts, amplitudes and delays depending on its path. When using multiple antennas, it is often desired to have high mutual fading correlation between them (see section 2.5.2). When being behind a large building, the signal might also perceive a deep fade, causing a part of the signal to distort considerably.

2.4 Transmission Control Schemes

An essential part of any radio communication system is to specify the scheme for transmission flow. Specifically for cellular systems, it is necessary to set up a two-way stream that allows both talking and listening to another terminal. The process of how two-way communication takes place over a communication channel is called duplexing. Essentially there are two different forms of duplexing, full duplexing and half duplexing. In the latter, half duplexing, the communicating parties take turns transmitting. Here, receiving (RX) and transmitting (TX) do not take place at the same time; when someone talks, the other party has to listen/wait for it to finish until it can start talking. Full duplexing however, allows simultaneous transmission and receiving. This enhances the performance which is often desired but comes with the consequence of increased resource consumption and/or further complexity. All schemes brings forth certain advantages and disadvantages, the choice of scheme depends therefore very much on the circumstances.

To attain the behaviour of full duplexing where transmissions occur simultaneously, it is necessary to separate the transmissions in some way. Enabling the receiver to receive while transmissions are still being transmitted. A widely used scheduling scheme for achieving this is frequency division duplex (FDD). Cellular communication are however not limited to full duplexing, a widely used scheduling scheme using half duplexing is time division duplex (TDD), which transitions between receiving and transmitting without perceiving any significant delay. Each has its advantage and disadvantages depending on the scenario (see below), LTE supports both TDD and FDD.

2.4.1 Time Division Duplex (TDD)

In TDD the transmission takes place over a single frequency, with a time-frame for transmitting and a time-frame for receiving. The time-frames are separated by a guard interval or guard time to allow the transmission or reception to finish. This interval is usually very short to be noticed by either party, but can overall decrease the efficiency of the system as one might have to switch several times between transmitting and receiving. The guard time is based on; the propagation delay that the transmitted signal has reached the receiving end, together with the time to switch between transmitting and receiving. So, when
distances are very long the delay will increase and may become a disturbing factor, however when the distances are short the delay becomes undetectable.

Fig. 2.4: Time Division Duplex

2.4.2 Frequency Division Duplex (FDD)

In FDD, the transmitted and received signals takes place on different frequencies, requiring multiple channels. The channels are separated by a guard band to operate such that the receiver does not get affected by the signal being transmitted. Although this technique does not use the available spectrum most efficiently, it enables transmitting and receiving to occur truly simultaneously.

Fig. 2.5: Frequency Division Duplex

2.5 Antenna ports

A base station consists of one or several antennas, where each antenna or a number of antennas in turn are mapped to an antenna port. The number of antenna ports are hence less than, or equal to, the number of antennas. In LTE
Rel-8 where multi-antenna transmission in the downlink (DL) are supported, the number of transmit antennas are based on the number of cell-specific reference signals (CRS). Thus, as an antenna port is defined by an associated CRS, to the UE each antenna port is seen as a transmit antenna. Up to four cell-specific antenna ports are supported, where each transmits a cell-specific reference signal.

Using multiple antennas in the receiver and/or in the transmitter can yield certain improvements at the expense of complexity and cost. Many antennas enhances the ability to serve more users per cell, which in turn allows vast improvements in system performance as well as system capacity. Better coverage is also gained, and most importantly, from the end user point of view and expected future growths, higher data rates is achieved. The ability to support MIMO (Multiple Input Multiple Output) is one of the great advantages of LTE, see following subsections of advantages in using multiple antennas.

2.5.1 CRS signals

Pilot signals are continuously sent in order to pick up new terminals, in LTE, four pilot signals are sent every millisecond. Each cell has its own specific pilot pattern corresponding to its cell identity, this is found in the cell specific reference signals (CRS). Except for cell search purposes, CRS are used for downlink channel estimation for coherent demodulation/detection as well as downlink channel quality estimation.

2.5.2 Beamforming

The use of multiple transmit antennas can yield enhancements both in Signal-to-Noise Ratio (SNR) and diversity. Beamforming indicates as the name might imply, directing (beaming) a signal to a specific target. Shaping the signal in such way leads to less noise, while at the same time, amplified signal strength, increasing the SNR significantly. This occurs by creating a phased array (an array of antennas) that builds up destructive and constructive interference for different phases (see Fig. 2.6). Signals at particular angles will hence become attenuated or amplified, compared to an omnidirectional antenna where the signal is uniformly spread in all directions. This method makes it possible by combining certain elements in the phased array to amplify the signal where receivers can be found and attenuate it where there are none.

Certain knowledge must however be acquired to perform beamforming, specifically the channels relative phases. For example in TDD (described in section 2.4.1), the same channels are used both for uplink and downlink, beamforming can in such case always be performed as the relative phases are already obtained.
Fig. 2.6: Constructive and destructive interference produces beamforming.

### 2.5.3 Spatial multiplexing

The theory derived above proves that multiple antennas can bring forth better SNR and/or additional diversity against fading. However, the use of both multiple transmit (TX) antennas and receiving (RX) antennas i.e. MIMO, produces a combined functionality called spatial multiplexing. By creating multiple parallel channels, one for each antenna, dividing the SNR in each channel, spatial multiplexing allows increased utilization of higher Signal-to-Noise/Interference ratio (SINR) as well as achieving extensively higher data rates.

If we assume that interference is small, Signal-to-Noise Ratio (SNR) is calculated using the signal strength and noise effect, \( S/N = SNR \). Together with the channel capacity \( C \) and bandwidth \( BW \), the normalized channel capacity is expressed by:

\[
\frac{C}{BW} = \log_2 \left( 1 + \frac{S}{N} \right). \tag{2.3}
\]

Using beamforming (explained in previous subsection 2.5.2) it is possible, under certain conditions, for the SNR to grow proportionally to the amount of antennas i.e. \( N_T \times N_R \), where \( N_T \) and \( N_R \) are the amount of transmit and receiving antennas respectively. With MIMO, using both multiple TX antennas and multiple RX antennas, it becomes possible to set up several parallel channels splitting the SNR equally among them. The amount of possible channels is determined by the least amount of antennas on either side \( N_{ch} = \min \{N_T, N_R\} \). The channel capacity for each channel is then expressed by:

\[
\frac{C}{BW} = \log_2 \left( 1 + \frac{N_R}{N_{ch}} \cdot \frac{S}{N} \right). \tag{2.4}
\]

Calculating the total amount of capacity derived from Eqn (2.4) utilizing all channels, results in:
\[
\frac{C}{BW} = N_{ch} \cdot \log_2 \left( 1 + \frac{N_R}{N_{ch}} \cdot \frac{S}{N} \right). \tag{2.5}
\]
Increasing the attained capacity significantly. Fig. 2.7 illustrates a simple case using two transmit antennas and two receiver antennas, multiple parallel channels are created and expressed in Eqn (2.6).

\[
\begin{align*}
\bar{r} &= \begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \cdot \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} = H \cdot \bar{s} + \bar{n}. \tag{2.6}
\end{align*}
\]
Assuming that the channel matrix \(H\) is invertible such that \(W = H^{-1}\), it is possible to recover the signal in presentation of:

\[
\begin{pmatrix} \hat{s}_1 \\ \hat{s}_2 \end{pmatrix} = W \cdot \bar{r} = \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + H^{-1} \cdot \bar{n}. \tag{2.7}
\]
We see from Eqn (2.7) that the signal can be perfectly recovered in the events of no noise.

Rank

In order for the UE to know if spatial multiplexing is used or not, information is sent in the rank indicator. Spatial multiplexing divides the SINR, hence it can only be used when there is not too much interference. Typically, UEs close to a base station will send and receive data using spatial multiplexing i.e rank 2, and users far on the cell edge that receives interference from neighbouring cells, use rank 1 i.e no spatial multiplexing due to low SINR.

2.6 Access methods

Access methods are part of the control plane protocols. For any communication to occur, the terminal must first connect to the network. This typically takes place when the terminal, e.g. a UE, is powered up after being turned off, starting with an initial cell search. One should however emphasize that the terminal does not only search for cells when powering up, the search is always
ongoing to find and measure the reception quality of neighbouring cells. After the cell search the terminal has to receive and decode a set of information needed to communicate and operate correctly in a cell, this set of information is called the cell system information. The control plane protocols are responsible for connection setup, security and mobility. Control messages can be sent both from the core network and from the base station. The Radio Resource Control (RRC) transmits all control messages sent from the base station and handles the RAN-related procedures, such as the transmission of cell system information mentioned earlier to be able to communicate with a cell.

A terminal may enter one of two states.

- The first state, denoted as \texttt{RRC\_IDLE}, is when the terminal is simply camping (being registered to a cell). This is instigated when a terminal does not require any transmissions, and is thus neither connected to any particular cell. Being in this state the power consumption in the terminal decreases substantially as the terminal sleeps most of the time. The system however, wakes up the terminal periodically for it to receive paging messages from the network, such as system-information and incoming connection requests.

- The second state, activated when a terminal is requesting service from the network, is called \texttt{RRC\_CONNECTED}. The purpose of this second state is to transmit data from and/or to the terminal. Thus the terminal is connected to a cell and when necessary, switch cell by performing a handover (see subsection below). By being connected, a terminal is currently requesting some sort of service from the base station e.g DL reception.

\texttt{RRC\_CONNECTED} is intended for data transfer to/from base station and terminal. This state is however only accessible when both terminal and radio access network has exchanged parameters necessary for communication, concluding that an RRC (Radio Resource Control) context has been established.

A terminal constantly conducts measurements on neighbouring cells to select the cell with best reception. As stated above, cell searches are conducted continuously, however, depending on the terminal’s state, different transition procedures occurs. See below

- Cell selection - Whenever a terminal decides for the first time in which cell it should register to, it performs a cell selection.

- Reselection - Whenever a terminal in the state \texttt{RRC\_IDLE} checks for available cells, it performs a reselection.

- Handover - Whenever a terminal in the state \texttt{RRC\_CONNECTED} discovers a cell with better reception and decides to connect to that cell, it performs a handover to change cell (see below).

2.6.1 Measurements

The RSRP (Reference Signal Received Power) is defined as the linear average of received signal power of the resource elements (REs) that carry the same
cell specific reference signal across the measured frequency bandwidth. The UE conducts continuous measurements on the desired signals RSRP and the RSRQ, signal quality, and sends these measurements to the base station of the serving cell. However, before each measurement is sent, the UE performs layer 3 filtering on the RSRP and RSRQ value according to Eqn (2.8) described in [8, section 5.5.3.2]. The filtering procedure uses the current measurement, $M_n$, and the previous filtered value, $F_{n-1}$, to obtain the current filtered value $F_n$,

$$F_n = (1 - a) \cdot F_{n-1} + a \cdot M_n,$$  \hspace{1cm} (2.8)

where $a$ is a filter coefficient. Both measurements, RSRP and RSRQ, of serving cell and neighbouring cells are passed through the layer 3 filtering before transmitted to the base station.

Applying the RSRP and RSRQ, of both serving and neighbouring cells, the UE compares the received measurements and provides the base station with information of any necessary action e.g. if it should perform a handover. This decision is evaluated through comparing the measurements of serving cell with the measurements of neighbouring cells. A parameter specified by the base station, maxReportCells, denotes the amount of maximum cells a UE is allowed to include in its report. The UE evaluates both enter and leaving conditions with the measurements obtained to judge if any event is fulfilled. These conditions also includes the hysteresis of the cell to avoid ping-pong behaviour, switching back and forth between two cells (see Fig. 2.8). All events are listed in [8, section 5.5.4], Eqn (2.9) below is a simpler description of evaluations in the A3 event, neighbour becomes better than serving$^2$,

**Entering condition**: $M_n - Hys > M_s$,  \hspace{1cm} (2.9)

**Leaving condition**: $M_n + Hys < M_s$,

where $M_n$ is the measurement of neighbouring cell and $M_s$ the measurement of serving cell. Note that, for a handover to occur the enter condition would have to be fulfilled, and the leaving condition not fulfilled.

![Cell area with respective hysteresis.](image)

---

$^1$Remark: the first measurement $F_0$ is set to $M_0$.

$^2$Note that Eqn (2.9) is only an illustration of the A3 event, all conditions are listed in [8, section 5.5.4]
3

Energy Saving Concepts

This chapter evaluates the investigated solutions of this study. What are their gains and what kind of losses do they bring? Briefly, the concept is to dynamically switch from the typical capacity optimized sector mode, to another, more energy efficient solution when most of the capacity is unused e.g. during the night.

3.1 Antenna/MIMO muting

Antenna/MIMO muting is a solution discussed in EARTH [5, section 2.5.1] [7]. The conclusion reached regarding MIMO, which is mainly used for capacity and higher peak data rates, is that MIMO is not particularly energy efficient when there is no data to transmit. The principle is such that, when an increased capacity and/or high data rates are required, MIMO should be activated. However, when large capacities are not required it should be possible to turn MIMO off, and by doing so, make it possible to reduce power consumption.

MIMO, which stands for Multiple Input Multiple Output requires multiple antennas (see section 2.5.3). The idea behind antenna/MIMO muting is thus to mute some of the antennas when there is no, or very low, traffic. Discussed in [5, section 2.5.1] are various ways to accomplish this. In this study, the approach used has been to mute all antennas except for one. This is achieved by adding together the signal from all antenna ports in a sector cell, and transmit the signal through only one antenna port (see Fig. 3.1). To the UE this will appear as if the signals are fully correlated, as if all signals had the same phase shift. Using only one antenna port requires also only one power amplifier per sector, as can be seen from Fig. 3.1. With sector cells still deployed, but with less antenna elements, the coverage is considered intact. The cell manages the terminals as previously except with smaller data rates given that MIMO is now no longer supported. It is also evident from Fig. 3.1 that DL is the only affected factor, while UL remains unaffected.
The consequence of this solution is mainly that MIMO is no longer supported, meaning that the peak data rates previously attained is no longer achievable. Then again that is also the benefit, because muting allows the base station to consume less power as only one power amplifier per sector cell will be required. The calculations of how much energy savings gained by activating this energy efficiency enabler are calculated and explained in section 5.1.

In LTE-Rel 8, where multi-antenna transmissions are supported, the UE requires information on how many antenna ports are used when transmitting. This information is acquired by blindly decoding the PBCH (Physical Block Channel), described in section 2.6. Additionally, Rel-8 specifies that the amount of cell-specific antenna ports used is a static number. This results in the fact that the UE only needs to decode this number once, there is no obligation either for the UE to ever re-evaluate this number [reference]. Hence, if the antenna ports transmitting have been determined to be using for example four antenna ports, the base station will also be demanded to send four cell-specific reference signals (CRS), see section 2.5.1. This would also apply if the load had decreased and it would be sufficient to use only one antenna port, the base station would still be required to transmit using four antenna ports [9, section 6.4].

In the algorithm for antenna/MIMO muting, muting one antenna port will certainly have negative effect on the decoding of the PBCH. Since this would change the amount of antenna ports used. The robustness however considered built into the design of LTE to operate consistently on a fading radio channel, [6] shows that the system will in most cases still operate accurately.

In typical sector mode with multiple antennas, terminals may receive a beam-
forming and/or a diversity gain. These gains are introduced by one antenna transmitting the signal and another antenna shifting the phase of that signal, amplifying it in the direction of the receiver (see section 2.5.2 where this is explained in more detail). Except for MIMO, which increases capacity and peak data rates, beamforming and/or diversity gain increases the SINR [10, section 5.4]. In practice, terminals whom are close to the cell edge experiences higher interference, leading to decreased SINR (Signal-to-Interference-plus-Noise Ratio). This fact indicates that MIMO should not be used as it requires to share the SINR between the antennas (see section 2.5.3 for how MIMO works). Multiple antennas yields however as mentioned a beamforming gain specifically advantageous for terminals close to the cell edge, possible without spatial multiplexing. Meaning that not only will MIMO be lost when antenna/MIMO muting is activated, but other multiple antenna gains such as beamforming gain will also no longer be applicable, indicating that terminals will suffer from a loss in SINR. This mode will however only become active when traffic is low, the lost beamforming and diversity gain are therefore expected not to have any significant impact on performance.

The biggest benefit of this solution is that it is independent per cell. The cells with low traffic are specifically targeted, muting only the antenna elements in those sectors. This makes it possible to, instead of continuously using 6 PAs per site, with antenna muting; a site may use 3, 4, 5 or 6 PAs depending on the load on the system.

3.2 Combined Antenna Muting with Sector-to-Omni Reconfiguration

The second investigation proposes an additional cell, attaining the so called dynamic psi-omni coverage. The reason for the name psi-coverage is because of the resemblance to the greekish letter ψ; employing one radio unit and three sector antennas (see Fig. 3.2). This solution is also proposed in EARTH [5, section 3.3.2], where it considers switching between three sector cells and a psi-omni cell. The reconfiguration occurs by the use of a splitter, distributing the signal coming from one PA through the same sector antennas already set up, see Fig. 3.3. We also observe from the circuit chart in Fig. 3.3 that this procedure would only effect the DL and not the UL, and it would require the use of only one power amplifier instead of six PAs as in the typical sector/MIMO configuration.

Coverage is maintained as the same sector antennas are used. However, the psi-omni cell is one large "cell" covering the same area as the previous three sector cells (see Fig. 3.4). This leads to each site gaining four cells instead of the typical number three; three sector cells and one large psi-omni "cell" with the same area coverage as the three sector cells together.

Unlike however the solution proposed in EARTH [5, section 3.3.2], this approach applies the previous solution, antenna/MIMO muting, before considering dynamic psi-omni. Although this method also contain consequences, such
as worse data rates and changes of intra-cell interference, one should emphasize that in the same way power consumption increases when performance grows, power consumption also decreases in this case when performance declines (see section 5.1 for calculations regarding energy saving).

Fig. 3.2: Three sectors using only one Remote Radio Unit (RRU), typically three RRUs are needed for a three sector site.

Fig. 3.3: Psi-omni circuit chart for DL and UL.
To avoid high inter-cell interference, because of the four cells per site and with cells overlapping, either the three sector cells or the psi-omni cell is activated. When a cell is not active it will be in a dormant state, unable to receive or transmit any data and hence produce no interference. Also, a cell that is dormant is neither detectable by the UE (this is further explained in section 4.1). When it is determined that a psi-omni cell should become active, all terminals currently attached to any of the cells going dormant will perform a handover to the psi-omni cell. In turn, when it is time to switch back to sector cells, all terminals will perform a handover to an activated sector cell. Thus in the timeframe between activating and deactivating cells, at that intermediate moment, all cells in a site will be active as they need to serve as well as be visible to the UE (see Fig. 3.5).

This fact introduces a delay as the terminal is needed to perform a handover. The switch is only expected to arise when traffic is minimal, assuming that it will not have any significant noteworthy impact on the performance when switching to the psi-omni cell. However, when switching from the psi-omni cell to the sector cells, the switch ends up in the events of requesting higher data rates. Required to perform a handover in such occasions is expected drag the performance down until the handover has finished and the terminal is attached to a sector cell.

Another drawback in using this method is that, with three sector cells in a site there is typically some interference between them. However, in the case of dynamic psi-omni the same signal is sent through the whole cell. This can be seen by comparing the cell borders from before in Fig. 1.1 with Fig. 3.4. Instead of the cells causing interference between them, in a psi-omni cell the signal is on the other hand enhanced. Although this might seem advantageous at first, it also points to the fact that depending on deployment, certain locations will have varying reception. Typically it is more desirable have consistent reception rather than experiencing fluctuations at the same location, this effect is therefore considered as a drawback.

Due to the fact that this approach can only provide small data rates, it is only activated when antenna muting (section 3.1) has been activated for a long time assuming that the load will continue to stay small.
Procedure

When traffic in a cell is fairly low, antenna/MIMO muting will get activated. In turn, when all sector cells in a site have become muted for a certain amount of time, the psi-omni cell will get activated and the three sector cells will go dormant (this is explained in detail in section 4.2).

The idea is to use antenna/MIMO muting for fast transitions switching only to the psi-omni cell when traffic is at a minimum. Using this solution together with antenna/MIMO muting decreases the power consumption from 6 PAs of a typical three sector site to using 1, 3, 4, 5 or 6 PAs depending on the traffic. This would allow large savings in terms of energy consumption while still keeping the coverage intact. The major part to be studied is the change in performance when going from one mode to another since it is desired that the terminal is not heavily effected by the processes.
4

System Evaluation

This chapter is meant to explain the differences between each transitions in detail, how does the transitions occur and what are their procedures. Each proposed solution is defined here as an energy efficiency enablers. The first solution, antenna/MIMO muting, targets the power consumption of each sector cell. Whereas the second solution that includes antenna/MIMO muting together with dynamic psi-omni targets the power consumption of both sector cells individually as well as the whole site.

4.1 Cell states

The base station and its cells transition between a set of states that will be explained in this section. The transition of these states determines in turn the activation and deactivation between the solutions discussed. The reference case of typical sector cells with MIMO equipped is onwards defined as the capacity optimized mode, and the two energy efficiency enablers as energy optimized modes.

Implementing these states and transitioning between them has been one of the main areas in this thesis. As they will display how the solutions are working and how, as well as why, the transitions are occurring.

There are four states that a cell can enter; active, dormant, barred and muted. The first three states: active, dormant and barred, are qualities only available for the dynamic psi-omni mode. "Active" and "dormant" defines the current activated respectively idle cells. The barred state on the other hand is a middle state that an active cell enters in the events of turning dormant. Muted is the state that defines the energy efficiency enabler antenna/MIMO muting, by inspecting if a cell is currently "muted", one can come to the conclusion if the cell in question currently has high, or low load.
4.1.1 Antenna/MIMO muting states

Muting mode/state

When investigating the energy efficiency enabler antenna/MIMO muting, the psi-omni cell is constantly dormant, meaning that we only consider the three sector cells. These sector cells are in this case always active, and become muted only when certain conditions are fulfilled (explained in section 4.2). An active cell is defined as a cell that is currently running and reachable from all terminals. When a sector cell is muted, the state will be set to mutedOn defining that antenna/MIMO muting is activated. When a sector cell needs to run at full power without any muting, the state instead becomes mutedOff. Note that, the muted state can only be activated from sector cells, a psi-omni cell does not have any changeable muted state in this study.

4.1.2 Sector to dynamic psi-omni reconfiguration states

Active

The active state defines that a cell is currently reachable. As the opposite of dormant state, it indicates that the cell is not barred and not empty.

Dormant

The dormant state indicates that a cell is barred and empty. Note that all four cells in a site can never be dormant at the same time, there will always be at least one active cell at all time allowing connection and reachability. Strictly, either the three sector cells or the dynamic psi-omni cell will be active.

Barred

The barred state is initiated when it is time to transition between the active and dormant state. Typically the transition takes place when traffic is very low or non-existent, or when it very high. By turning the site barred it becomes unreachable, this includes new transitions as well as redirection of current users. More practically, when it is time to transition to psi-omni from (muted) sector, all sector cells will become barred while the psi-omni cell turns active. This leads to transitioning all current terminals from the sector cells as well as redirecting new incoming users. Similarly, when the load increases and the psi-omni cell is no longer able to handle the ongoing traffic, the omni cell will become barred and the sector cells will in that case become not barred i.e active.

4.2 Conditions of changing mode

This section describes the conditions and transitions between each energy efficiency solution and the typical sector, capacity optimized, mode. The concept of the energy efficient enablers, and the capacity optimized mode is such that:

○ Cells activates the capacity optimized mode when lots of data need to be sent. This configuration specializes in increasing the capacity without any concern for energy consumption.
The energy optimized modes on the other hand specializes in minimizing the energy consumption and simply maintain the same coverage, only able to handle small data rates.

The current load on the system and multiple timers are used to set the conditions for changing mode. How much resources each cell require is a reflection of the current traffic. Future behaviour is anticipated with the use of timers e.g. if the load has been either low or high for certain amount of time it is assumed that it will continue that way. Since changing mode minimizes the power consumption when shifting down, it also affects the user performance when shifting up. Timers are therefore included not only to anticipate future behaviour but also to avoid ping-pong behaviour, the continuous change back and forth between capacity and energy optimized mode. The precise conditions of load levels and timers are defined below.

4.2.1 Antenna/MIMO muting

- When a cell uses less than 20 percent resources for 30 ms continuously, all except one antenna will be muted i.e. antenna/MIMO muting will be activated.
- When resources require more than 30 percent for more than 5 ms continuously it is assumed that the system will be loaded with heavy traffic and antenna muting is deactivated, returning the cell to full power i.e MIMO.

4.2.2 Sector-to-Omni

- Dynamic psi-omni coverage is activated when all three sector cells in a site are muted for 200 ms continuously, it is assumed that traffic will continue to be low from now on, enough for the psi-omni cell to handle.
- Sector cells are activated when resources in the dynamic psi-omni cell exceeds 70 percent for 10 ms continuously. The site returns to antenna/MIMO mode while the psi-omni cell becomes barred. Although the site returns to capacity mode of sector cells, the site will still be in antenna muting mode except for the cell(s) that require resources exceeding 30 percent from previous condition.

4.3 System Overview

The parameters used for the simulations presented in section 6 will be stated here along with brief information regarding the parameters.

4.3.1 Deployment

The deployment uses 7 sites where each site consists of 3-sector cells (Fig. 4.1) and one psi-omni cell (Fig. 3.4). To present the results independent of cell size, power consumption per area unit is measured against system throughput per area unit. This simplifies the comparison between different scenarios as each base station will be treated the same, depending only on the area covered.
Fig. 4.1: 7 sites deployment with 21 cells.
### 4.3.2 Macro cell deployment parameters

Table 4.1: Macro BS general parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nr of Sites</td>
<td>7</td>
</tr>
<tr>
<td>Nr of Sector cells</td>
<td>21</td>
</tr>
<tr>
<td>Nr of Psi-Omni cells</td>
<td>7</td>
</tr>
<tr>
<td>Attenuation factor</td>
<td>37.6</td>
</tr>
<tr>
<td>Attenuation constant</td>
<td>-15.3</td>
</tr>
<tr>
<td>Shadowing correlation</td>
<td>0.5</td>
</tr>
<tr>
<td>Packet size</td>
<td>2 MB</td>
</tr>
<tr>
<td>VoIP user intensity</td>
<td>0</td>
</tr>
<tr>
<td>VoIP initial users</td>
<td>21</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>BS maximum Tx power</td>
<td>46 dBm = 40 W</td>
</tr>
<tr>
<td>Antenna (elements)</td>
<td>2</td>
</tr>
<tr>
<td>Shadow correlation distance</td>
<td>50.0</td>
</tr>
<tr>
<td>Duplex scheme</td>
<td>FDD</td>
</tr>
</tbody>
</table>

Table 4.2: Macro BS Rural simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTP user intensity</td>
<td>1, 5, 9, 13, 17, 21</td>
</tr>
<tr>
<td>FTP initial users</td>
<td>1, 5, 9, 13, 17, 21</td>
</tr>
<tr>
<td>User speed</td>
<td>33.3333 m/s = 120 km/h</td>
</tr>
<tr>
<td>Shadowing $[\sigma]$</td>
<td>8 dB</td>
</tr>
<tr>
<td>Cell radius</td>
<td>577.3333 m</td>
</tr>
<tr>
<td>ISD</td>
<td>1732 m</td>
</tr>
</tbody>
</table>
Table 4.3: Macro BS Suburban simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTP user intensity</td>
<td>1, 5, 9, 13, 17, 21</td>
</tr>
<tr>
<td>FTP initial users</td>
<td>1, 5, 9, 13, 17, 21</td>
</tr>
<tr>
<td>User speed</td>
<td>8.3333 m/s = 30 km/h</td>
</tr>
<tr>
<td>Shadowing [σ]</td>
<td>8 dB</td>
</tr>
<tr>
<td>Cell radius</td>
<td>577.3333 m</td>
</tr>
<tr>
<td>ISD</td>
<td>1732 m</td>
</tr>
</tbody>
</table>

Table 4.4: Macro BS Urban simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTP user intensity</td>
<td>1, 5, 9, 13, 17, 21</td>
</tr>
<tr>
<td>FTP initial users</td>
<td>1, 5, 9, 13, 17, 21</td>
</tr>
<tr>
<td>User speed</td>
<td>0.8333 m/s = 3 km/h</td>
</tr>
<tr>
<td>Shadowing [σ]</td>
<td>6 dB</td>
</tr>
<tr>
<td>Cell radius</td>
<td>166.6667 m</td>
</tr>
<tr>
<td>ISD</td>
<td>500 m</td>
</tr>
</tbody>
</table>
5

Power Model

This chapter aims at explaining the energy evaluation framework applied in the thesis. The objective is to describe, which components are affected in the transitions? And how much of the energy is decreased by activating each energy efficiency enabler?

5.1 Power consumption

DC power consumption breakdown for different base station types have been performed in [4, section 4.2]. Base stations comes in various forms e.g macro, micro, pico and femto, depending on type and size the power consumption breakdown varies. In this thesis the evaluation of energy efficiency are aimed at macro base stations (BSs), further calculations are beyond this point only intended for macro BSs.

Fig. 5.1 displays the altogether components of a macro BS at maximum load. The component in the BS that encapsulates both the downlink (DL) and (UL) is called a transceiver (TRX), in a BS of three sectors there are six TRXs, two for each sector. Fig. 5.1 shows as mentioned the component breakdown of the whole site, but as it incorporates both UL and DL parts it can be also be defined as the power consumption distribution in a single, or six, TRXs at maximum load\(^1\).

DL and UL uses the same components with the exception of the power amplifier (PA). Hence, the calculations in Fig. 5.1 are as mentioned both of DL and UL. The power consumption dependent on load of each component is displayed in Fig. 5.2. We observe here that the change in power consumption is in all parts, except the PA, very small. Note also that the power consumption of the other components are almost independent of the load. This concludes that the UL mostly has to run with the same output maintaining a constant service, while the DL can be considered a more varying segment. Fig 5.3 illustrates the power consumption of each component in a macro BS with 10% load, separately for DL and UL. Once again we observe that the PA is the dominating energy consumer.

\(^1\)Calculations are based on power model software developed in the EU funded EARTH project [4].
Fig. 5.1: Power consumption breakdown of a macro BS (TRX) at full load.

Fig. 5.2: Load dependent, power consumption breakdown of macro BS components.
5.1.1 Standby mode

When activating either energy efficiency enabler, the DL components in the TRX will enter standby mode i.e sleeping mode. This allows the components to decrease their power consumption almost completely, exploiting only a small part necessary to reach full utilization more quickly when required. Standby mode is equivalent to almost turning off the PA which is the goal of both investigated solutions, decreasing the power consumption of the dominating consumer (see Fig. 5.4). Diminishing the power consumption of the PA leads in turn to reducing the power consumption of several other components such as cooling, main supply and BB since they no longer require to run with the same effect. The concept however of each energy efficiency enabler is as mentioned to only affect the DL when the load is small, such that; when the capacity offered by LTE is mostly unused, DL can be decreased. Note that standby mode only affects the DL, the UL components remains therefore unchanged as they remain close to what they are with 10% load (see Fig. 5.2). It is expected however that cooling is only necessary when a TRX is active as other components will heat up depending on the load. In the events that the TRX has entered standby mode, cooling is assumed to be temporary turned off as most of the components will utilize minimum amount.

![Graph showing power consumption breakdown for DL and UL components in a macro BS at 10% load.](image)
5.2 Energy savings

By allowing some of the transceivers to enter standby mode the all-over consumption of the base station decreases. Described in this section are power consumption calculations for each applied energy efficient enabler.

5.2.1 Energy savings using antenna muting

Activating antenna muting in one, two or three sectors will aggregate different amount of energy savings. Using this approach one can put up to three out of the six transceivers (in a BS) in standby mode. Table 5.1 presents which of the components that have been affected by this change, and which of them are in active respectively standby mode. Components identified as affected are from a radio communication perspective considered overhead components, these are electrical equipment that will scale up and down depending on the load and other components power levels.

---

2Calculations of energy savings in this section have been compared between standby mode and power consumption at 10% load. A cell exploits however different amounts of power depending on load. Hence, in the events of activating capacity mode i.e sector mode, the load will most likely be higher. A small error will exist in the calculation and it is expected that there will be a small error in calculations. This transient is however assumed to be sufficiently small that it can be overlooked.
Table 5.1: Active, Standby and Affected components when using antenna muting.

<table>
<thead>
<tr>
<th>Component</th>
<th>Active</th>
<th>Standby</th>
</tr>
</thead>
<tbody>
<tr>
<td>(DL) PA</td>
<td>3/6 = 50 %</td>
<td>3/6 = 50 %</td>
</tr>
<tr>
<td>(DL) RF</td>
<td>3/6 = 50 %</td>
<td>3/6 = 50 %</td>
</tr>
<tr>
<td>(DL) BB</td>
<td>All</td>
<td>None</td>
</tr>
<tr>
<td>(DL) DC-DC</td>
<td>Affected</td>
<td>—</td>
</tr>
<tr>
<td>(DL) Main Supply</td>
<td>Affected</td>
<td>—</td>
</tr>
<tr>
<td>(DL) Cooling</td>
<td>Affected</td>
<td>—</td>
</tr>
<tr>
<td>(UL) RF</td>
<td>All</td>
<td>None</td>
</tr>
<tr>
<td>(UL) BB</td>
<td>All</td>
<td>None</td>
</tr>
<tr>
<td>(UL) DC-DC</td>
<td>Affected</td>
<td>—</td>
</tr>
<tr>
<td>(UL) Main Supply</td>
<td>Affected</td>
<td>—</td>
</tr>
<tr>
<td>(UL) Cooling</td>
<td>Affected</td>
<td>—</td>
</tr>
</tbody>
</table>

With these calculations simulations showed that by muting one sector the following power consumption were acquired

\[
\frac{1 \times TRX_{active} + 1 \times TRX_{standby,muted}}{2 \times TRX_{active}} = 0.5 + 0.41 = 0.91 = 91%. 
\]

Summarized in table 5.2 are possible energy savings with different amount of muted sectors.

Table 5.2: Energy savings (per site) using antenna muting.

<table>
<thead>
<tr>
<th>Muted sectors</th>
<th>Energy savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (reference)</td>
<td>0.0 %</td>
</tr>
<tr>
<td>1</td>
<td>9.0 %</td>
</tr>
<tr>
<td>2</td>
<td>18.0 %</td>
</tr>
<tr>
<td>3</td>
<td>27.0 %</td>
</tr>
</tbody>
</table>
5.2.2 Energy savings using dynamic $\Psi$-omni reconfiguration

Note that when switching to psi-omni coverage the change occurs from antenna muting configuration and not from typical sector (MIMO). The standby and active transceivers are in this case different compared to the earlier concept of antenna muting, where it is now possible to turn off certain components completely, not only putting them on standby. This reasoning comes from the fact that the switch back from psi-omni coverage also arrives in antenna muting and not in sector configuration, as described in section 4.2. The motive for putting components in standby was to quickly reach full power when necessary. However, since the return mode antenna muting will also have standby components, leaving the components for full blown MIMO also on standby is considered excessive, since they would have the time to power up to standby power levels when antenna muting is active.

Table 5.4 presents the active, affected and standby components when dynamic psi-omni is activated. Observe that compared to the concept of antenna muting the BB is also now affected, since the BB of only one sector cell will be utilized the other two may be on standby. Dynamic psi-omni uses only one RRU, the PA and RF uses thus 1/6 of their respective total components. This equals the components of one transceiver, maintaining 3 others on standby for when antenna muting is to become active. The reason for 3 components on standby is that during the change between dynamic psi-omni and antenna muting all four cells will be active. 2 PA and 2 RF parts can therefore be completely turned off, which can be seen from Fig 3.3 where 1 PA and 1 RF component per sector cell were previously in standby when antenna muting was active.

<table>
<thead>
<tr>
<th>Component</th>
<th>Active</th>
<th>Standby</th>
</tr>
</thead>
<tbody>
<tr>
<td>(DL) PA</td>
<td>1/6 = 16.67 %</td>
<td>3/6 = 50 %</td>
</tr>
<tr>
<td>(DL) RF</td>
<td>1/6 = 16.67 %</td>
<td>3/6 = 50 %</td>
</tr>
<tr>
<td>(DL) BB</td>
<td>1/3 = 33.33 %</td>
<td>2/3 = 66.67 %</td>
</tr>
<tr>
<td>(DL) DC-DC</td>
<td>Affected</td>
<td>—</td>
</tr>
<tr>
<td>(DL) Main Supply</td>
<td>Affected</td>
<td>—</td>
</tr>
<tr>
<td>(DL) Cooling</td>
<td>Affected</td>
<td>—</td>
</tr>
<tr>
<td>(UL) RF</td>
<td>All</td>
<td>None</td>
</tr>
<tr>
<td>(UL) BB</td>
<td>1/3 = 33.33 %</td>
<td>2/3 = 66.67 %</td>
</tr>
<tr>
<td>(UL) DC-DC</td>
<td>Affected</td>
<td>—</td>
</tr>
<tr>
<td>(UL) Main Supply</td>
<td>Affected</td>
<td>—</td>
</tr>
<tr>
<td>(UL) Cooling</td>
<td>Affected</td>
<td>—</td>
</tr>
</tbody>
</table>
Simulations using the calculations in table 5.3 resulted in the following BS power consumption when dynamic psi-omni is activated

\[
\frac{1}{6} TRX_{active} + 3TRX_{standby, \Psi-omni} = 0.375 \times 37.5\%.
\]

We acquire the results in table 5.4 by summarizing the energy savings gained when using the concept antenna muting together with dynamic psi-omni.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Energy savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector (reference)</td>
<td>0.0 %</td>
</tr>
<tr>
<td>1 Muted sector</td>
<td>9.0 %</td>
</tr>
<tr>
<td>2 Muted sectors</td>
<td>18.0 %</td>
</tr>
<tr>
<td>3 Muted sectors</td>
<td>27.0 %</td>
</tr>
<tr>
<td>(\Psi)-Omni</td>
<td>62.5 %</td>
</tr>
</tbody>
</table>

### 5.3 Model

In this investigation, as stated in section 3.2, a base station site consists of four cells; three sector cells and one additional psi-omni cell that covers the same area as the three sector cells. However, the four cells are not always active (see section 4.1), as the cells dynamically changes, the power level required will change too. This section describes the model designed that encapsulates the mentioned adjustments.

We observed in section 5.1 that the most changing and dominant energy consuming component is the power amplifier. Abstracting the performance on load dependency we arrive at a linear behaviour displayed in Fig. 5.5. This is onwards referred to as the power model, it displays the behaviour of both the PA and BS load dependent power consumption. Fig. 5.5 illustrates that the power consumption increases proportionally with the load, and that large amounts of energy are still consumed even when the load is small. Stated in the previous section was that a sector cell uses two transceivers, one PA in each transceiver. Fig. 5.6 illustrates the PAs activities in a sector cell before and after activating the energy efficiency enabler antenna muting at a specific load. The two plots above in Fig. 5.6 displays the power model of the PAs in the reference case of sector mode while the two below are the power models for the PAs when antenna muting is activated. This allows us to witness that when the energy efficiency enabler antenna muting is activated only half of the systems resources will possibly be utilized. However, we can also perceive that the energy consumption would severely decrease as the second PA in the cell is on standby. This means that it would theoretically be possible to provide close to the same services as
the reference case whenever the load is sufficiently small, yet with significantly lower energy consumption.

![Power Model](image)

**Fig. 5.5:** Power model (sector mode).

![Power Model Comparison](image)

**Fig. 5.6:** Power model comparison between power amplifiers in one cell when sector is activated (two plots above) versus antenna muting (two plots below).
Power consumption calculations changes depending on which energy efficient enabler is activated. A simple schematic is portrayed in Fig 5.7 of how the calculations are performed. Cells $0, 1, 2$ are sector cells and thus have the same available states. The psi-omni cell, cell $3$, has different possible states due to the fact that the psi-omni cell is already in muted state when it gets activated. Looking back at Fig 3.3, we observe that only one antenna port is used for each sector.

The amount of resource blocks (RB) and scheduled sub-bands determines the power model and the required power consumption. The amount of RBs comes in turn from the load on the system, the heavier the load the more RBs will be exploited. Depending on if the conditions are fulfilled an energy efficient enabler could be activated which would change the state block. In the previous section we calculated possible energy savings gained by activating each energy efficient energy enabler, scanning the state block corresponding number can be withdrawn and inserted in the factor block in Fig. 5.7. For example, if a cell is in the dormant state that cell would exert 0 power, however, if a cell is in muting state it would exert 27% less power than the reference case of sector. Accumulating finally each cell's power we attain the site's power consumption.
\[ State_{0,1,2} = \{ \text{active, muted, dormant} \} \]
\[ State_3 = \{ \text{active, dormant} \} \]

Fig. 5.7: Total power per site calculation model.
5.4 Data Traffic

Research on data traffic variations during the hours of the day in different deployments has been conducted in [4, section 3.2.2]. The daily data traffic rates are expected values of actual traffic demand in cell planning maps in Europe by 2015. Summarized in Table 5.5 are the data traffic peaks for each deployment with respective scenarios. Each scenario is proceeded by the amount of subscribers, where each subscriber is in turn categorized as either heavy or ordinary user. Heavy classified users are subscribers that consume 900 MB/hour whereas the ordinary user only consumes 112.5 MB/hour.

- Scenario 1 (Low) - 20% of the subscribers are categorized as heavy users. This is considered as a lower bound for European traffic rates by 2015.
- Scenario 2 (Medium) - 50% of the subscribers are categorized as heavy users. This is considered as an upper bound for European traffic rates by 2015.
- Scenario 3 (High) - All subscribers are categorized as heavy users. This is an extreme case even for future networks.

Table 5.5: Data traffic peaks in different deployment environments.

<table>
<thead>
<tr>
<th>Deployment environment</th>
<th>Traffic scenario 1 (Low)</th>
<th>Traffic scenario 2 (Medium)</th>
<th>Traffic scenario 3 (High)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense urban</td>
<td>83 Mbps/km²</td>
<td>155 Mbps/km²</td>
<td>276 Mbps/km²</td>
</tr>
<tr>
<td>Urban</td>
<td>28 Mbps/km²</td>
<td>52 Mbps/km²</td>
<td>92 Mbps/km²</td>
</tr>
<tr>
<td>Suburban</td>
<td>14 Mbps/km²</td>
<td>26 Mbps/km²</td>
<td>46 Mbps/km²</td>
</tr>
<tr>
<td>Rural</td>
<td>2.8 Mbps/km²</td>
<td>5.2 Mbps/km²</td>
<td>9.2 Mbps/km²</td>
</tr>
</tbody>
</table>

Note that throughput is shared between three operators. One should thus observe that the noteworthy number is a 3rd of the mentioned values in Table 5.5. Urban and dense urban has the same deployment with the difference in traffic rates, hence the word dense. It is assumed that urban scenarios has 1/3 of the traffic found in dense urban scenarios.

Fig. 5.8 displays the average data traffic during a day. As the data traffic varies from day to day points also to the fact that results gained will only be an estimate. However, with the values of expected data traffic rates and the results of today’s network system throughput, we can determine an estimated power consumption amount and average user downlink data rates in each deployment for future traffic demands. This allows us to calculate reasonable energy and cost reductions possible by the implemented studied energy efficiency enablers.
Fig. 5.8: Daily average data traffic profile in Europe.
6

Simulations & Numerical Results

An advanced dynamic system level simulator at Ericsson has been used to investigate the proposed methods for energy efficiency. The simulations in this chapter provides average downlink user data rates and power consumption per area unit in different deployments. The results in each deployment are thereafter compared to the different traffic rates calculated in section 5.4 to attain a performance evaluation and corresponding energy savings.

6.1 Forced change of mode

A forced change of mode was simulated to test the implementation of both energy efficiency enablers. By reducing the dynamic part in the algorithm, simply analysing the performance variation from the cell throughput by forcefully entering an energy efficiency mode, one could perceive if the implementation executed as presumed. Simulations in this section contained 80 users where each of them downloaded a packet size of 50 MB. After 3.0 seconds an energy efficiency enabler was activated and expected behaviour was such that, performance and power consumption should decrease. When simulation time reached 8.0 seconds the energy efficiency enabler was deactivated and performance and power consumption should return to the way they were before.

Forced antenna muting

A simulation is shown in Fig. 6.1 where the implementation of antenna muting is tested. 12 seconds simulation time with 80 users was processed in one site containing three sectors and one psi-omni cell. The psi-omni cell is in this case dormant, leaving only the sector cells activated. Each curve represents the throughput of a user downloading a packet with the size of 50 MB. Antenna muting is activated for all sectors after 3.0, and at 8.0 seconds it is deactivated again.
Forced sector to psi-omni reconfiguration

A simulation is shown in Fig. 6.2 where the implementation of sector to psi-omni reconfiguration is tested. Same as above, 12 seconds simulation time with 80 users in one site containing three sectors and one psi-omni cell was processed. Each curve represents the throughput of a user downloading a packet with the size of 50 MB. After 3.0 seconds the sectors cells are turned barred and the psi-omni cell is activated, switching all users to the psi-omni cell. After 8.0 seconds the sector cells are activated again and the psi-omni cell is turned barred, switching all users back to the sector cells.
6.2 Numerical results

This section presents the evaluated performances of the investigated solutions in macro deployments (rural, suburban, urban and dense urban) with the expected traffic densities (low, medium and high) described in section 5.4. The network capacity was sufficient to handle all expected traffic demands in mentioned scenarios, with the exception of high traffic density scenario in suburban environment.

The outline of this section describes every macro deployment as a subsection. Where in each deployment the system throughput per area unit is first presented and corresponding average user downlink data rate and power consumption per area unit. Followed by the 5th percentile and mean value at medium traffic density (scenario 2 described in 5.4). To make the achieved results easier to understand, each subsection ends with a summarize of the downlink data rates and power consumption of all traffic density scenarios. This shows how much decreased performance is introduced by each energy efficiency enabler contra the energy savings gained. The UL performance is not considered as the energy efficiency enablers are only aimed to affect the DL.

6.2.1 Rural environment

Rural environment is characterized by the large deployments with a cell radius of 577.333 m and an ISD of 1732 m. This deployment covers areas where population densities are very small compared to that of dense urban environments that has an ISD of 500 m. From table 5.5 we also observed that the peaks in system throughput in rural environment is only 3.4 percent contrast to that of dense urban. Another characterizing feature is, due to the assessment that terminals usually move through rural environment at high speeds, the user speed is valued to 120 km/h.

In Fig. 6.3 and Fig. 6.4 the power consumption and downlink data rates are displayed with the corresponding system throughput. Rural environment is estimated to require a maximum of 9.2 Mbps/km² during high traffic density scenario, pointing towards the fact that it would be possible to exert most energy savings in this environment where the load is the least. The following three figures starting with Fig. 6.5 displays the 5th percentile and mean value at medium traffic density of the reference case sector mode, antenna muting mode and dynamic psi-omni together with antenna muting.

Summarized in the last figure Fig. 6.7 are the mean value of complete energy savings and performance decrease for all three traffic density scenarios (low, medium and high).

---

1 Results of low respectively high traffic densities are summarized in the Appendix supplement at the end.
Fig. 6.3: Power consumption per area unit in rural deployment.

Fig. 6.4: Downlink user data rates in rural deployment.
Scenario: Rural with Medium traffic density

<table>
<thead>
<tr>
<th>Time [h]</th>
<th>User Data Rate [Mbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Fig. 6.5: 5\textsuperscript{th} percentile of downlink user data rates in rural environment with medium traffic density.

(a) Average power consumption per area unit.

(b) Average downlink user data rates.

Fig. 6.6: Average power consumption (a) and downlink user data rates (b) in rural environment with medium traffic density.
6.2.2 Suburban environment

Closest to rural environment is suburban environment. The same ISD as rural deployment is used with the single differences in user speed and peak traffic densities. While user speed was earlier considered to 120 km/h, in suburban areas the speed is assessed to 30 km/h. Traffic demands in suburban areas have been proved to be the hardest to achieve. This comes from the fact that the environment is very sparse yet manages fairly high traffic densities. However if we look back at Fig. 1.3, compared to rural environment, we find that suburban areas only covers 9 percent of expected deployment coverage. This points to the fact that energy efficiency in suburban areas is hard to achieve except in the few hours when traffic is very small.

The first two figures Fig. 6.8 and Fig. 6.9 illustrates the system throughput per area unit corresponding to the power consumption and user performance. Afterwards the results in medium traffic density of the 5th percentile and mean value are displayed, commencing with Fig. 6.10\textsuperscript{2}. Summarized in Fig. 6.12 are time averaged energy savings and downlink user data rates in low, medium and high traffic density scenarios.

\textsuperscript{2}The results of low and high traffic densities are presented in the Appendix at the end.

Fig. 6.7: Summarized average power consumption (a) and average downlink user data rates (b) in rural environment with low, medium and high traffic density. Each energy efficiency enabler has been studied separately.
Fig. 6.8: Power consumption per area unit in suburban environment.

Fig. 6.9: Downlink user data rates in suburban environment.
Fig. 6.10: 5\textsuperscript{th} percentile of downlink user data rates in suburban environment with medium traffic density.

Fig. 6.11: Average power consumption (a) and downlink user data rates (b) in suburban environment with medium traffic density.
Fig. 6.12: Summarized average power consumption (a) and average downlink user data rates (b) in suburban environment with low, medium and high traffic density. Each energy efficiency enabler has been studied separately.

### 6.2.3 Urban environment

Arriving at urban environment we see a much higher system throughput per area unit due to denser deployment. The ISD considered in urban deployment is 500 m with user speed at 3 km/h. Power consumption per area unit is also higher due to the denser deployment, since more base stations has to be deployed. That is why, if we once again look back at Fig. 1.3 and Fig. 1.4, we see that urban deployment only covers 5% area but is responsible for 31% of total power consumption. Traffic rates are also much higher in urban deployment than in rural and suburban, however due to the denser deployments it is still expected to find potential for energy savings while still manage acceptable downlink user data rates.

Starting with Fig. 6.15 and the following two figures, the $5^{th}$ percentile and mean value with medium traffic density are displayed. Fig. 6.17a and Fig. 6.17b summarizes time averaged energy savings and downlink data rates for all traffic scenarios (low, medium and high).

---

3 The results of low and high traffic densities are presented in the Appendix at the end.
Fig. 6.13: Power consumption per area unit in urban environment.

Fig. 6.14: Downlink user data rates in urban environment.
Fig. 6.15: $5^{th}$ percentile of downlink user data rates in urban environment with medium traffic density.

(a) Average power consumption per area unit.

(b) Average downlink user data rates.

Fig. 6.16: Average power consumption (a) and downlink user data rates (b) in urban environment with medium traffic density.
Dense urban environment

Dense urban and Urban environment differs in the single prospect of traffic density, whereas the ISD, deployment and user speed are essentially the same. Traffic densities of dense urban are considered, as mentioned in section 5.4, three times the traffic rates of urban environment. The figures representing system throughput in dense urban environment is thus the same as in the previous subsection of urban environment, Fig. 6.13 and Fig. 6.14.

The characterizing fact about dense urban environment is the high user population leading to a significantly higher degree in traffic rates. Compared to rural environment where system throughput was estimated to peak 9.2 Mbps/km$^2$, dense urban is estimated to need a system throughput of 276 Mbps/km$^2$ for the same condition of high traffic densities. Shared between three operators the system throughput per operator is approximated to 3.1 Mbps/km$^2$ and 92 Mbps/km$^2$ in rural and dense urban environment respectively. It is therefore expected that due to the higher traffic rates that the adaptive configuration of switching between energy efficiency and capacity optimized mode will occur more often, leading to less energy savings and a drop in performance.

The 5$^{th}$ percentile and mean value are illustrated with medium traffic densities in the following three figures starting with Fig. 6.18$^4$. Summarized last in Fig. 6.20a and Fig. 6.20b are time averaged energy savings and downlink data rates for all traffic scenarios (low, medium and high described in section 5.4).

$^4$The 5$^{th}$ percentile and mean value for low and high traffic densities are presented in the Appendix at the end.
Scenario: Dense Urban with Medium traffic density

Fig. 6.18: $5^{th}$ percentile of downlink user data rates in dense urban deployment with medium traffic density.

Fig. 6.19: Average power consumption (a) and downlink user data rates (b) in dense urban deployment with medium traffic density.
6.3 Energy savings and Performance degradation

Summarized in Fig. 6.21 and Fig. 6.22 are total energy savings and performance degradation for both energy efficiency enablers. The outcome is obtained by combining the results from previous section together with the area coverage in each environment described in section 1.1.2. Results are compared with sector/MIMO while applying the EARTH reference scenario cases (section 5.4).

Note that the simulations performed in this chapter are aimed at worst case scenario, where the terminal only download one packet and disappear. Meaning that there is only one packet transmitted, and that packet suffers the delay of changing to a capacity optimized mode. In practice, degradation would only affect the first packet whereas the rest would occur in capacity optimized mode, hence experience no degradation.
Fig. 6.21: Energy savings and performance degradation summarized from implementing energy efficiency enabler antenna muting in all environments.

Fig. 6.22: Energy savings and performance degradation summarized from implementing energy efficiency enabler dynamic psi-omni together with antenna muting in all environments.
Conclusions

Going back to the problem formulation, we stated that this investigation would concern a proof of concept regarding two energy efficiency enablers that could contribute to the power consumption in cellular networks. The study included implementation and simulation of these concepts as well as evaluating their performance, both in downlink data rates and energy consumption. With the results chapter behind us, following conclusions can be made.

The investigation has shown that traffic is optimally served by sector cells i.e MIMO. Whether it is under small or heavy load, sector cells provides the highest downlink user throughput. As anticipated, even with adaptive configuration, energy optimized modes are unable to reach the same performance in throughput as the capacity optimized mode. Under small loads however, the ability do dynamically change to an energy optimized mode has proven to achieve satisfying downlink data rates in terminals while still reduce the network’s power consumption significantly. Most energy savings were found in rural and urban environments, with least energy savings in suburban environment.

In terms of energy efficiency, both studied approaches have achieved considerable decrease in power consumption compared to the reference case of only using sector cells. However, the performance is also affected in characteristics of degradation. From previous chapter we can conclude that in the case of using psi-omni coverage, impact on user downlink throughput becomes notable due to handovers. Although this approach results in slightly more energy savings compared to that of using only antenna muting as energy efficiency enabler, the cutback in performance is also proven to be larger. We can conclude from analysing the 5th percentile that in the case of dynamic psi-omni, some terminals suffers severe drawback in performance compared to the case of only using antenna muting. The bottleneck seems thus to be the process of handovers in using psi-omni coverage. Yet, the achieved downlink data rates are sufficient to deliver satisfying data rates, capable of handling most applications today.

We can conclude from previous chapter that even with a dynamic configuration of switching between modes, a negative impact on some users is unavoidable. This can be derived from the average and 5th percentile. While there are some terminals that suffers severely when using dynamic psi-omni, in the antenna
muting case all terminals appears to continue to operate with marginal drawback in performance. This is most likely due to the fact that the terminal influenced the most in the case of antenna muting is the user that triggers the switch, because that user will perceive the longest delay. Users that arrive after the switch has occurred will feel less, or no effect at all, due to the dynamic part. However, in the case of using psi-omni coverage, the terminal that perceives the worst impact is the user that is already transitioning. Meaning that the terminal triggering the switch to change mode will merely have to perform a handover. While in the case of where a terminal is in the middle of a handover to a cell, worst case would be if that cell was no longer active, forcing the terminal to perform yet another handover to finally reach an active cell. Therefore as a summary,

- Dynamic antenna muting is an energy efficiency enabler capable of reducing power consumption a fair amount while still provide downlink data rates as if MIMO was used continuously.

- The use of dynamic antenna muting together with psi-omni coverage decreases the power consumption even further compared to the case above, but also with slightly larger drawbacks in downlink data rates, most likely due to handovers.

Considering performance, applying only antenna muting as an energy efficiency enabler is thus believed to be the better option in all cases. Although, taking into account energy savings, depending on environment, dynamic psi-omni is also considered as a suitable option. Especially in camping areas or islands where energy efficiency is deemed more important, psi-omni coverage would serve as a more appropriate solution. This way, the performance is maintained while still capturing the essence of energy efficiency. One should also emphasize that simulations in this study were performed aimed at worst scenario where terminals downloaded one packet and disappeared, which is commonly unlikely. Had terminals instead requested continuous packets, the capacity would eventually most likely increase.

The final conclusion is that both concepts have certain potential. User downlink data rates demonstrated in the circumstances of antenna muting to be considerably closer to reference case. Yet, in environments were energy efficiency has greater demand, dynamic psi-omni coverage together with antenna muting is measured to be the better option. The conclusion is therefore to deploy both solutions, but for separate environments. With better tuning and optimization techniques it is also believed that dynamic psi-omni could become an even better solution. The optimal case would be to self power a base station with a self sustaining energy source such as solar panels, while still provide the same capacity optimized performance.

Briefly, energy efficient solutions are necessary to attain a future carbon lean economy. This investigation of two energy efficient enablers has confirmed them both feasible and successful, able create a sustainable environment for future generations. I still believe however that there is potential to be discovered, and suggests that further research is carefully conducted before commercial deployment.
8

Discussions

8.1 Decision of changing mode

The change between a capacity optimized mode and an energy optimized mode has in this investigation been determined by the amount of resource blocks (RBs) required. The amount of RBs in turn defines the load, i.e. requiring many resource blocks continuously equals a high load, similarly few RBs results in a small load. The concept has been to switch to a capacity mode when the load is high, and to an energy optimized mode when the load is small.

An approach based on considering the load is however in fact a method that lacks consistency. Because any conclusion on future behaviour cannot be provided from the load, it simply indicates the current viewpoint. A better approach of how to consider future behaviour would be to examine the packets in the buffer instead of current load. This would allow the network to know in fact if traffic will increase or decrease. However, to apply this is in the simulator used is slightly more complicated, considering although that this would avoid many of the encountered problems it would most likely be worth to try. The process in this experiment is as mentioned by the amount of how long the load has been either small or high, and from there assume that it will continue to be that way, avoiding any ping-pong behaviour. Although it is a reasonable statement, fact remains that this does not provide any specifics of future behaviour. For example, if a delay introduced an extra 0.5 seconds, a UE that would normally download a packet in:

- 1 second, would in these circumstances have to wait 1.5 seconds, 50% more time.
- 10 seconds, would instead has to wait 10.5 seconds, a time increase of merely 5%.

Proving that performance loss would affect terminals with smaller packets more severely. This indicates that better constraints could be utilized if future behaviour was more consistent, as it would most likely be just as effective to serve a small packet in the energy optimized mode than to switch to the capacity optimized mode and shortly after switch back.
A worst case scenario where examining current load collapses is the moment that the mode changes. Since a possibility exists that traffic increases the instant a base station indicates a handover. This would result in performing a handover to a cell that has just become barred, requiring to perform another handover to a sector cell, decreasing the UE’s performance substantially. Had a decision instead been focused on the packets in the buffer; the base station would realize before transmitting if it would require to change mode. Allowing the site to be in the state most suitable for the expected data.

Fig 8.1 depicts what happens when a change of mode is instigated, observe that maximum bitrate to terminals is not immediately achieved and performance suffers from degradation. The delay is however not only introduced due to handovers, but also from protocol inefficiencies such as TCP slow start. Components has to also increase their output which can also cause a delay, but is in this case masked by the delay of changing to the capacity optimized mode.

8.2 Detection

The following circumstances describes the detection and transition between cells that have gone barred i.e circumstances of the energy efficiency enabler including dynamic psi-omni coverage.

Certainly a limitation in this study that introduces in fact a delay, is that the UE first had to detect a cell before attempting a handover. When a cell turns barred, any terminal becomes unable to attach to that cell, with the single exception of their corresponding serving cell. This causes the UE to wait until it has detected another cell that it can perform handover to, a cell that is not
barred. This affects both the transitions from a psi-omni cell to a sector cell and the other way around. Stated in [8, section 5.3.1.3], specifications of Rel-8, a terminal is allowed to blindly perform a handover by the request of the base station which could improve performance further.

Delay is preferably avoided but can be accepted when traffic is at its minimum i.e when changing from capacity optimized to an energy efficiency enabler, as there are no large data rates/packets required. However, the losses observed in performance in chapter 6 are most likely introduced when traffic increases. Because the need instead focuses on increasing data rate there will most likely be substantial effect compared to the case of when load is small in terms of delays.

8.2.1 Transition between sector and dynamic psi-omni

When transitioning between sector configuration and dynamic psi-omni there are as mentioned many factors that needs to be taken into account. One of them is that when either cell turns dormant and the other becomes active, it is crucial that all terminals finish their respective handovers. Otherwise, as mentioned in section 8.1, the possibility exists that a terminal might perform handover to a cell that turns barred before the handover gets finished. Mainly, handovers are rather avoided if not necessary. This behaviour confuses the channel estimation and certainly introduces larger delays for the UE. A solution considered to this problem, except for examining the buffer instead of the current load, is for the base station to check before changing mode if there are any terminals incoming before changing cells to barred. This can be done as the UE will receive a unique preamble from the BS, avoiding any risk of preamble collision. This allows the base station to know which terminals are currently connected and which terminals are on their way.
9

Further Research

9.1 Spectrum alterations

This study applies to using the same spectrum for both sector, capacity optimized mode, and dynamic psi-omni, energy optimized mode. Although it is possible to use different bandwidth spectrum on which mode. The main idea behind sector to psi-omni reconfiguration is to apply this change when there is very small traffic e.g. during the night, when in many regions there are often no traffic at all. Meaning that pilot signals stipulated by the LTE standards are the only requirement to support. Supplying higher bandwidth concede that more symbols can be used. In case of LTE, the mandatory symbols per subframe that will be used will count for many more than they would if the bandwidth was smaller. This would mean as there are more data to send, more power will be needed to support it. Hence, decreasing the bandwidth when traffic is non-existent would reduce the power consumed even more, as the pilot signals will be sent using less power.

Although this approach decreases the power consumption when there is only pilot signals to be transmitted, it will also trigger the change of mode much easier. Because using less bandwidth implicates that less symbols can be used i.e. less capacity, forcing the base station to change mode in order to handle even the slightest traffic. A further study would be to compare the gains and losses of using different bandwidths depending on mode. Would the user performance change? And as it would influence the conditions to change mode would the overall power consumption decrease or increase? Why this was not included in the original study is because the assumed energy that could be save would be sufficiently smaller compared to the concluded research, as well as to maintain the scope of the project from becoming to large.

9.2 Examining different values for timing and thresholds

Except for the discussion in section 8.1, I believe that the timing values and thresholds in this investigation can indeed be optimized. The constraints for
switching between energy optimized mode and an energy efficiency mode were certainly not chosen at random, but they were also not carefully optimized for each environment as that would have significantly broadened the scope of the study.

Specifics of when to change between sector and psi-omni cells is surely something that could be improved. Typically the traffic varies during day and night time. Changing the mode from sector to psi-omni coverage during the day might have larger consequences. For example, if the change would occur somewhere in the middle of peak hour, the amount of UEs having to perform handover to the psi-omni cell then back to sector deployment could cause big performance losses. This was also observed by forcing the sector deployment to a psi coverage the performance suffers significantly (see 6.1). To only allow low traffic hours is something that could be considered.

9.3 Using MIMO in psi-omni cells

An interesting approach for further studies would be to research how MIMO could perform in a psi-omni cell. Surely, this would increase the power consumption of this mode, and simultaneously, also increase the possibility of activating the psi-omni cell a longer time. The important aspect is to allow the psi-omni cell to stay active longer and not change the moment traffic increases. Because once again we arrive at the crossroad of, is it better to stay in an energy efficiency mode and complete the transmission? Or would it be better to change into a capacity optimized mode and provide higher data rates? As discussed in previous chapter, this can be solved by inspecting the packets in the buffer and proceed from that point of view instead of the current traffic, allowing the network to carefully dissect the upcoming traffic behaviour. Studying thereafter how much a psi-omni cell can handle and take that into consideration of when to switch is an attempt I believe to significantly enhance the downlink user throughput that dropped in this investigation.
References


[9] 3GPP TS 36.211 v. 8.9.0, 2010-01, "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (Release 8)".

Appendix

This chapter serves as a supplement to the results section, chapter 6. Additional data of how power consumption and downlink data rates changes in further traffic density scenarios is displayed here.

Rural environment

Rural - High traffic density

Fig. 1: 5th percentile of downlink user data rates in rural deployment with high traffic density.
Rural - Low traffic density

Fig. 3: 5\textsuperscript{th} percentile of downlink user data rates in rural deployment with low traffic density.
Suburban environment

Suburban - High traffic density

Fig. 4: Average power consumption (a) and downlink user data rates (b) in rural deployment with low traffic density.

Fig. 5: $5^{th}$ percentile of downlink user data rates in suburban deployment with high traffic density.
(a) Average power consumption per area unit.  
(b) Average downlink user data rates.

Fig. 6: Average power consumption (a) and downlink user data rates (b) in suburban deployment with high traffic density.

Suburban - Low traffic density

Fig. 7: 5th percentile of downlink user data rates in suburban deployment with low traffic density.
(a) Average power consumption per area unit.

(b) Average downlink user data rates.

Fig. 8: Average power consumption (a) and downlink user data rates (b) in suburban deployment with low traffic density.

Urban environment

Urban - High traffic density

Fig. 9: 5th percentile of downlink user data rates in urban deployment with high traffic density.
Scenario: Urban with High traffic density

(a) Average power consumption per area unit.

(b) Average downlink user data rates.

Fig. 10: Average power consumption (a) and downlink user data rates (b) in urban deployment with high traffic density.

Urban - Low traffic density

Fig. 11: 5\textsuperscript{th} percentile of downlink user data rates in urban deployment with low traffic density.
Scenario: Urban with Low traffic density

(a) Average power consumption per area unit. 

(b) Average downlink user data rates.

Fig. 12: Average power consumption (a) and downlink user data rates (b) in urban deployment with low traffic density.

Dense urban environment

Dense urban - High traffic density

Fig. 13: 5\textsuperscript{th} percentile of downlink user data rates in dense urban deployment with high traffic density.
Scenario: Dense Urban with High traffic density

(a) Average power consumption per area unit.

(b) Average downlink user data rates.

Fig. 14: Average power consumption (a) and downlink user data rates (b) in dense urban deployment with high traffic density.

Dense urban - Low traffic density

Fig. 15: 5\textsuperscript{th} percentile of downlink user data rates in dense urban deployment with low traffic density.
Fig. 16: Average power consumption (a) and downlink user data rates (b) in dense urban deployment with low traffic density.