System Optimisation and Radio Planning for Future LTE-Advanced

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy (PhD)

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Abstract

This work is related to wireless communication. In this Thesis three main issues are addressed for future cellular networks: power consumption, interference and mobility. These issues continue to be a burden on the system's performance as long as technology keeps evolving. In the presented chapters, the focus was to introduce greater intelligence to the LTE system algorithms and bring to them a dynamic and self-organizing approach.

The first approach concerns power consumption in wireless terminals. The currently applied solution to save energy is the DRX mechanism. It organizes the time when the terminal wakes up and starts receiving data, and when it goes into sleep mode in order to save its battery power. The current DRX is described as static or fixed which makes its parameters unsuitable for the nature of the bursty traffic. In this work an adaptive DRX mechanism is proposed and evaluated as the wireless terminal battery saving algorithm. The second approach is co-channel interference mitigation. To increase the system's capacity and avoid spectrum scarcity, small cells such as Femtocells are deployed and operate on the same frequency bands as the Macrocell. Although these small nodes increase the system capacity, however, the challenges will be in the femtocells planning and management in addition to the interference issues. Here a dynamic interference cancellation approach is presented to enable the Femtocell to track the allocated resources to the Macro-users, and to avoid using them. The third approach concerns mobility management in heterogeneous networks. The wireless terminal may have different mobility levels during handover which increases the handover failures due to failure in handover commands and aging of the reported parameters. This issue is presented in detail with the aim to avoid performance degradation and improve the reporting mechanisms during fast mobility levels. For this regard the presented method proposes more cooperation between the serving cell and the end-user so that the large amount of overhead and measurement are reduced.

Simulations with different configurations are conducted to present the results of the proposed models. Results show that the proposed models bring improvements to the LTE system. The enhanced self-organized architecture in the three presented approaches performs well in terms of power saving, dynamic spectrum utilization by Femtocells, and mitigation of sudden throughput degradation due to the serving cell's downlink signal outage during mobility.

Table of Contents

Abstract .... *i*

Table of Contents .... *ii*

List of Figures .... *vi*

List of Tables .... *ix*

Abbreviations .... *x*

Acknowledgement .... *xii*

Declaration .... *xiii*

1. Introduction *14*

1.1 Motivation 15

1.2 Challenges 17

1.3 Aims of research 19

1.4 Methodology 20

1.5 Contribution 21

1.6 Thesis organization 23

1.7 References 25

2. LTE Technology State of the Art *26*

2.1 The architecture of LTE, motivation for LTE 28

2.1.1 Technology history 28

2.2 System architecture 29

2.2.1 System Architecture Evolution (SAE) 29

2.2.2 Core network 30

2.2.3 Channels 31

2.2.4 Cyclic Prefix 33

2.2.5 System discovery 34

2.2.6 Modulation 36

2.2.7 Power control 38

2.2.8 Timing Advance 38

2.3 LTE processes 39

2.3.1 Fading 39

2.3.2 Channel Estimation ... 41
2.3.3 Measurement Window ... 41
2.3.4 Scheduling ... 42
2.3.5 Hybrid Automatic Repeat Request (HARQ) ... 45
2.3.6 Random Access (RA) ... 45
2.4 Technical challenges ... 47
2.4.1 Power consumption ... 47
2.4.2 Interference ... 47
2.4.3 Mobility ... 48
2.5 Summary ... 49
2.6 References ... 50

3. Adaptive Power Saving Mechanism -DRX- for LTE-Advanced ... 52
3.1 Power Saving for Wireless Devices ... 54
3.2 Related work ... 56
3.3 Preliminaries ... 60
3.3.1 Problem formulation ... 60
3.3.2 LTE DRX mechanism overview ... 62
3.4 Analytical study ... 67
3.4.1 Power consumption ... 68
3.4.2 Delays ... 71
3.4.3 Wake up optimising procedure ... 75
3.5 System model ... 82
3.5.1 Load-Monitoring algorithm ... 84
3.5.2 Decision-Making algorithm ... 86
3.5.3 Critical situation avoidance ... 88
3.5.4 The DRX extended mechanism ... 89
3.6 Proposed scheme implementation ... 91
3.7 Performance evaluation ... 94
3.8 Results and discussion ... 96
3.8.1 Application performance during DRX ... 99
3.8.2 Power consumption ... 106
3.9 Summary ... 113
3.10 References ... 114

4. Interference Management for Co-Channel Femtocell *118*
4.1 The Femtocell technology 120
4.2 Related work 122
4.3 Interference management 124
4.4 Power control 126
4.4.1 Power formulas in LTE 127
4.5 Interference over the control channels 129
4.6 PCFICH and PCI planning 130
4.7 Proposed scheme 132
4.7.1 Algorithm 135
4.7.2 Co-channel deployment 139
4.7.3 Search space and the candidate PDCCH 139
4.7.4 Macro-user tracing 140
4.7.5 Resource allocation 143
4.7.6 The Femtocell extended design 143
4.8 Designing the proposed model 145
4.9 System performance 149
4.9.1 The simulated scenario 150
4.10 Results 152
4.11 Summary 164
4.12 References 165

5. Mobility in Heterogeneous Networks *168*
5.1 LTE Heterogeneous Networks (HetNets) 170
5.2 Related work 172
5.3 Preliminaries 174
5.3.1 Introduction 174
5.3.2 The UE's measurements 176
5.3.3 Idle mode procedures: Cell search and reselection 177
5.3.4 Measurement GAPs 179
5.3.5 Measurement reports 180
5.3.6 The X2 interface 182
5.3.7 The handover process 182
5.3.8 Handover parameters 183

5.3.9 Radio planning and power control in dense deployment 185
5.3.10 Cell-Edge scenarios 186
5.4 System implementation 188
5.4.1 Radio Link Failure model 190
5.4.2 Speed dependent measurement 191
5.4.3 Requirements 193
5.5 Methodology 193
5.5.1 Parameters during mobility 196
5.5.2 Results and discussion 198
5.6 Summary 212
5.7 References 213

6. Thesis Conclusion and Future Work *216*
6.1 Conclusion 217
6.2 Future work 220

Appendix *222*
A. Node's parameters 223
B. Distance & Time function 225

List of Figures

Fig. 1-1 Key challenges to the evolution of LTE [3] 15
Fig. 1-2 Application demands [6] 16
Fig. 1-3 Data explosion challenges [10] 18
Fig. 1-4 LTE stack protocol [12] 22

Fig. 2-1 System Architecture Evolution (SAE) 29
Fig. 2-2 LTE System core network 30
Fig. 2-3 LTE channels 31
Fig. 2-4 LTE physical channels in the UL frame [5] 32
Fig. 2-5 Inter-symbol interference 34
Fig. 2-6 LTE system discovery and synchronisation process 35
Fig. 2-7 FDD Frame case [5] 35
Fig. 2-8 TDD Frame case [5] 36
Fig. 2-9 LTE modulation and coding [5] 37
Fig. 2-10 Frame structure for timing advance 38
Fig. 2-11 Fading phenomenon 39
Fig. 2-12 Received signal as a function to frequency 40
Fig. 2-13 Channel estimation 41
Fig. 2-14 The system bandwidth and subbands 42
Fig. 2-15 LTE scheduler and BLER for CQIs 1 to 15 43
Fig. 2-16 Effects of delayed feedback (1 ms delay) 44
Fig. 2-17 LTE HARQ process [16] 45
Fig. 2-18 LTE PRACH 46

Fig. 3-1 Today's large phone screens are power-hungry elements 54
Fig. 3-2 Recommendations for maximizing battery life 55
Fig. 3-3 DRX cycle and parameters 63
Fig. 3-4 DRX modes 66
Fig. 3-5 DRX RRC Connected state 67
Fig. 3-6 DRX timers for packets' arrival 68
Fig. 3-7 Power consumption according to packets' arrival 71
Fig. 3-8 DRX consideration of power and delays 72
Fig. 3-9 DRX delays for packets' arrival 72
Fig. 3-10 DRX analytical model 73
Fig. 3-11 Delays according to packet arrival 75
Fig. 3-12 Switching time for RRC Connected & RRC Ideal states 76
Fig. 3-13 The power amplifier in the transceiver circuit 76
Fig. 3-14 MPDU transmission 77
Fig. 3-15 Optimal wake up period model 78
Fig. 3-16 Power consumptions vs. Number of DRX cycles 79
Fig. 3-17 Delays vs. Number of DRX cycles 79
Fig. 3-18 Optimal operational point 80
Fig. 3-19 Delays and power consumption vs Inactivity timer (for packet's arrival) 81

Fig. 3-20 Proposed functions working layers ... 83
Fig. 3-21 The frame format ... 84
Fig. 3-22 DRX extended mechanism ... 90
Fig. 3-23 PHY & MAC layers for eNB and UE ... 91
Fig. 3-24 eNB process model ... 92
Fig. 3-25 DRX process model functions and transactions ... 93
Fig. 3-26 The simulated scenario ... 95
Fig. 3-27 Load monitoring statistics ... 96
Fig. 3-28 Transmitted and received timers values ... 97
Fig. 3-29 Inactivity timer in response to the estimated load ... 98
Fig. 3-30 Web browsing traffic ... 100
Fig. 3-31 FTP traffic model ... 100
Fig. 3-32 Video streaming traffic model ... 101
Fig. 3-33 Adaptive mechanism ... 101
Fig. 3-34 Cumulative average of dropped packets ... 102
Fig. 3-35 Video conferencing End-to-End delays ... 103
Fig. 3-36 FTP download/upload response time ... 103
Fig. 3-37 HTTP response time ... 104
Fig. 3-38 LTE uplink and downlink throughput ... 105
Fig. 3-39 UE’s cumulative power consumption ... 106
Fig. 3-40 Operational time for fixed and adapted scheme ... 107
Fig. 3-41 Battery estimated life time ... 107
Fig. 3-42 Battery capacity ... 108
Fig. 3-43 DRX real scheme ... 108
Fig. 3-44 DRX counter to enter long sleep ... 109
Fig. 3-45 Number of network re-entries (Scheduling Requests) ... 110
Fig. 3-46 Number of triggered cell searches ... 111
Fig. 3-47 Number of performed cell searches ... 111
Fig. 3-48 Number of handover triggers (Average per UE) ... 112
Fig. 3-49 Number of Grants ... 112

Fig. 4-1 Femtocell access through broadband connection ... 120
Fig. 4-2 Femtocell interference scenario ... 125
Fig. 4-3 Femtocell Dead-Zone ... 126
Fig. 4-4 eNB downlink OFDM signal ... 128
Fig. 4-5 Subframe structure from the control channels perspective ... 129
Fig. 4-6 Interference caused by the same PCI group deployment ... 131
Fig. 4-7 eNB downlink control and data channels ... 133
Fig. 4-8 Femtocell procedure to avoid interference ... 134
Fig. 4-9 Radio resource management (RRM) ... 137
Fig. 4-10 LTE UP link map [33] ... 141
Fig. 4-11 Packet of interest ... 143
Fig. 4-12 The Femtocell extended design ... 144
Fig. 4-13 Packets formats ... 145
Fig. 4-14 Coordinator process and node model ... 146

Fig. 4-15 Femtocell MAC layer 147
Fig. 4-16 Femtocell extended process model 148
Fig. 4-17 Femtocells in Macrocell network 149
Fig. 4-18 Frequency deployment 150
Fig. 4-19 The coordinator's simulated scenario 150
Fig. 4-20 The co-channel simulated scenario 151
Fig. 4-21 Interference duration 152
Fig. 4-22 Effects of interference 153
Fig. 4-23 Pathloss and the received signals by the Femtocell 154
Fig. 4-24 Distance between MUE and the Femtocell (m) and the changes in the received signals ... 155
Fig. 4-25 Macro-user reported wideband MCS 155
Fig. 4-26 Downlink SINR of three Macro-users 156
Fig. 4-27 BLER due to co-channel deployment 157
Fig. 4-28 Effect of Macrocell on the Femto-users 158
Fig. 4-29 CQI of the reported subbands by the Macro-user 158
Fig. 4-30 SINR of the affected subband 5 160
Fig. 4-31 Effect of Femtocell available resources on the Macrocell DL SINR 160
Fig. 4-32 Macro-user throughput in response to Femtocell's occupied resources 161
Fig. 4-33 Reported MSC for subbands 0 to 4 over time 162
Fig. 4-34 Average values of the reported MCS while passing Femtocell area 163
Fig. 4-35 MUE throughput 163

Fig. 5-1 Heterogeneous networks [3] 170
Fig. 5-2 Small cell properties 174
Fig. 5-3 Picocells range expansion 175
Fig. 5-4 UE measurement report 176
Fig. 5-5 Cell search stages 178
Fig. 5-6 Cell selection with DRX 179
Fig. 5-7 Measurement GAPs 180
Fig. 5-8 Measurement report triggering 181
Fig. 5-9 X2 interface establishment 182
Fig. 5-10 Handover process 183
Fig. 5-11 Handover parameters and inter frequency reselection 184
Fig. 5-12 Cell coverage planning 186
Fig. 5-13 Cell edge and irregularities 186
Fig. 5-14 SINR power boost 188
Fig. 5-15 The simulated scenarios 189
Fig. 5-16 3GPP defined trajectories 190
Fig. 5-17 EPC NAS model 191
Fig. 5-18 location based services 192
Fig. 5-19 Connected cells during mobility 194
Fig. 5-20 Fading and shadowing 195
Fig. 5-21 Macrocell issues/suspends measurements 196
Fig. 5-22 Downlink command for different mobility levels 197
Fig. 5-23 DL traffic and radio link failures during high mobility state 198

Fig. 5-24 Handover region with RSRP distribution 199
Fig. 5-25 Number of connected cells and average of connected time per cell 200
Fig. 5-26 Power statistics comparison between the two scenarios in high speed mobility 200
Fig. 5-27 DL received traffic for different measurement window sizes 201
Fig. 5-28 Reporting delays for different measurement window sizes 202
Fig. 5-29 Associated eNBs IDs 204
Fig. 5-30 Number of generated events in low speed mobility 204
Fig. 5-31 DL received traffic 205
Fig. 5-32 DL delays and received traffic for different measurement window sizes 205
Fig. 5-33 Power statistics comparison between the two scenarios in low speed mobility 206
Fig. 5-34 The cumulative number of measurement GAP triggers 207
Fig. 5-35 Power saving statistics in low speed mobility 207
Fig. 5-36 The simulated scenario of medium speed mobility 208
Fig. 5-37 Associated eNBs IDs and RLF in medium speed mobility 209
Fig. 5-38 DL received traffic in medium speed mobility 210
Fig. 5-39 DL received traffic in medium speed mobility 210
Fig. 5-40 Picocell and Macrocell RSRP 211

Fig. 6-1 The key requirements for 5G 220

List of Tables

Table 3-1 Operational power state values 81
Table 5-1 Handover Events 185

Abbreviations

3G	Third Generation
3GPP	Third Generation Partnership Project
ABS	Almost Blank Subframe
ACK	Acknowledgement
BLER	Block Error Rate
BW	Bandwidth
CC	Carrier Component
CCE	Control Channel Element
CCI	Co-Channel Interference
CFI	Control Format Indicator
CP	Cyclic Prefix
CQI	Channel Quality Indicator
C-RNTI	Cell-Radio Network Temporary Identifier
CS	Circuit Switched
CSG	Closed Subscriber Group
DCCH	Dedicated Control Channel
DCI	Downlink Control Information
DL	Down Link
DM-RSs	Demodulation Reference Signals
DRX	Discontinuous Reception
DTCH	Dedicated Traffic Channel
DwPTS	Downlink Pilot Time Slots
eNB	Evolved Node B
EPC	Evolved Packet Core
E-UTRA	Evolved Universal Terrestrial Radio Access
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FDD	Frequency Division Duplex
FFT	Fast Fourier transform
GBR	Guaranteed Bit Rate
GP	Guard Period
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat Request
HeNB	Home eNB
HetNet	Heterogeneous Network
HSPA	High Speed Packet Access
HTTP	Hypertext Transfer Protocol
ICI	Inter Carrier Interference
ICIC	Inter-cell Interference Coordination
IMS	IP Multimedia Subsystem
IP	Internet Protocol
ISI	Intersymbol Interference
L1	Layer 1
L3	Layer 3
LS	least Square
LTE /LTE-A	Long Term Evolution /LTE-Advanced
LTE-AS	LTE Access Stratum
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIB	Master Information Block

MIMO	Multiple Inputs Multiple Outputs
MME	Mobility Management Entity
MMSE	Minimum-Mean-Square-Error
MPDU	Mac Protocol Data Unit
NACK	Negative-Acknowledgment
NAS	Non-Access Stratum
Non-GBR	Non-Guaranteed Bit Rate
OFDMA	Orthogonal Frequency-Division Multiple Access
PA	Power Amplifier
PCFICH	Physical Control Format Indicator Channel
PCI	Physical Cell ID
PDCCH	Physical Downlink Control Channel
PDN	Public Data Network
PDSCH	Physical Downlink Shared channel
PGW	PDN Gateway
PHICH	Physical Hybrid-ARQ Indicator Channel
PRACH	Physical Random Access Channel
PS	Packet Switched
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RA	Random Access
RAT	Radio Access Technology
RB	Resource Block
REGs	Resource Element Group
RLF	Radio Link Failure
RRC	Radio Resource Control
RS(TP)	Reference Signal (Transmit Power)
RSRP	Reference Signal Received Power
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SAE	System Architecture Evolution
SGW	Serving Gateway
SIB	Service Information Block
SINR	Signal to Interference plus Noise Ratio
SMS	Short Message Service
SSS	Secondary Synchronization Signal
TCP	Transmission Control Protocol
TDD	Time Division Duplex
ToS	Time of Stay
TPC	Transmit Power Control
TTT	Time To Trigger
UDP	User Datagram Protocol
UE	User Equipment
UL	Up link
UMTS	Universal Mobile Telecommunications System
UpPTS	Uplink Pilot Time Slot
VOIP	Voice Over IP
WCDMA	Wideband Code Division Multiple Access

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Declaration

It is hereby declared that the thesis in focus is the author's own work and is submitted for the first time to the Post-Graduate Research Office. The study was originated, composed and reviewed by the mentioned author and supervisors in the department of Electronic and Computer Engineering, College of Engineering, Design and Physical Sciences , Brunel University UK. All the information derived from other works has been properly referenced and acknowledged.

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CHAPTER 1

Introduction

1.1 Motivation

Technology is changing; LTE technology was associated to releases 8 and 9, now LTE-Advanced supports wider bandwidths with low latencies to maximise the data rate and provide better Quality of Service (QoS) to end-users. Advanced modulation techniques, such as 64 QAM, support high data rates with multiple services. However, these data rates increase the data processing level of high bandwidth transfer, causing rapid consumption of the device's battery. The main focus of this thesis is enhancing power saving and mobility in heterogeneous networks, and mitigating interference. A novel and efficient adaptive power saving mechanism for LTE-Advanced is needed. The battery life of the end-user device serves as a limiting factor on the extent to which the system's performance can be optimised in terms of QoS and radio resources for 4G systems and beyond. The discontinuous reception process (DRX) was introduced by the third generation partnership (3GPP) [1, 2] to have control over the power consumed from the battery, by introducing idle periods in the radio receiver so that it turns off while there is no data being received from the serving cell. DRX performs best when longer cycles can be performed.

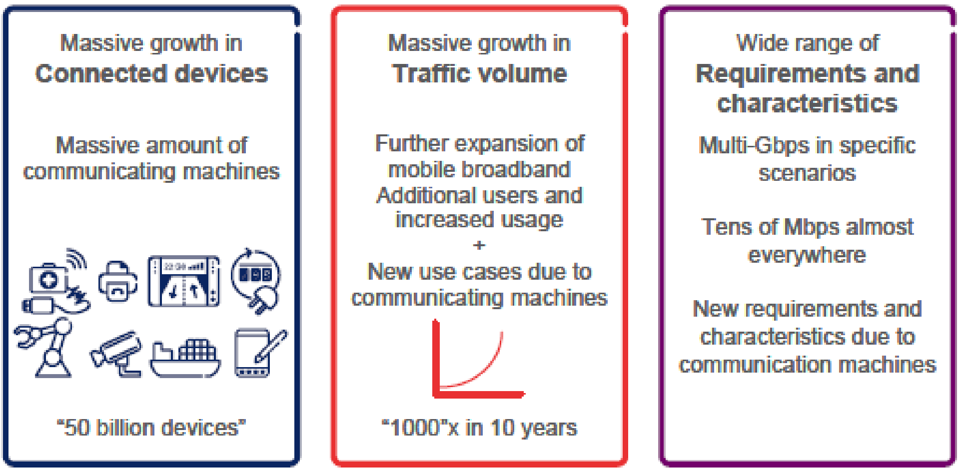

Fig. 1-1 Key challenges to the evolution of LTE [3]

Another important and challenging issue in LTE-Advanced is the massive growth in the number of connected devices and hence the transmitted traffic (Fig. 1-1). This is due to running applications and their characteristics. These challenges create the motivation to keep evolving the technology in order to produce enhancements and progression. There are many applications which do not demand an extremely high throughput, but they are characterised as 'always on', which has impact on the system's efficiency (Fig. 1-2). Mobile devices should enable the battery to last longer.

The growth in traffic requires an increase in the spectrum and spectrum efficiency in addition to introducing small cells to increase the network density. This provides a strong motivation for developing Femtocells and providing short-range coverage. One of the most typical deployments of Femtocells is the co-channel, where the same carriers are shared between the Femtocell and the Macrocell. Consideration must then be given to overcoming the interference in co-channel deployment, which cannot be mitigated efficiently by traditional network planning techniques [4]. Femtocells must be configured with self-control capabilities such as downlink (DL) power control and sensing. Power control may degrade the Femtocell's performance if it is applied aggressively by the Femtocell to avoid interference in co-channel deployment. Therefore it is necessary to introduce sensing capabilities to small cells, and also synchronisation with larger umbrella cells, so that the frequency bands allocated by the large cells can be avoided by the small cells. By enabling the small cells to sense the spectrum in co-channel deployment, this gives better scheduling efficiency to the Femtocell. Managing interference in a shared spectrum makes mobile broadband sustainable, and ensures that data throughput is improved dramatically with lower signals leaking out so that each user equipment (UE) gets the most bandwidth without the need for manual intervention [5].

Fig. 1-2 Application demands [6]

One of the most recent topologies to improve LTE technology is heterogeneous networks which enhance the network's capacity. Heterogeneous networks aim to improve the spectral efficiency per unit area by deploying Macrocells, Picocells, Femtocells and Relays in one mixture [7]. The goal is to introduce new mobility enhancements so as to improve and support seamless mobility between the Macrocell and the Picocell. In this framework, new rules are necessary to support the processes of handover and link adaptation, which require the measurement of the signal's strength and quality during UE mobility. Within this dense deployment, delays in reporting have adverse effects on the system's performance, and fast and accurate measurement and channel estimation are essential to improve the system's performance and meet the objectives of the heterogeneous deployment, in order to gain more capacity.

This research presents enhancements to LTE-Advanced technology. In addition to power saving, interference mitigation and mobility enhancement, the impact of the proposed work on the system's other processes, such as scheduling, random access and application performance is also introduced. The newly-added functionality and configurations are compatible with the 3GPP which standardised LTE technology.

1.2 Challenges

With the evolution of communication services and wireless diversity, mobile networks need to support the increasing demands. The LTE ecosystem for the next decade is expected to meet the market demands with a wide range of services and multiple devices [8].

The evolution of LTE networks creates many obstacles that need to be considered continuously. On the one hand we have applications with high data throughput, and on the other hand we have to handle this in a much more efficient way (Fig. 1-3). In this work we review the impact of new technology on the device's battery life, in addition to the interference and mobility requirements and configuration. The new technology has to satisfy the battery runtime constraints on the uplink transmissions. The maximum use of the network structure and high data rates are accompanied with fast evolution and development of mobile handsets. Mobile streaming of media services is expected to be widely used and video services will increase the traffic volume. The boost in end-user services such as gaming and web browsing, in addition to real time applications, creates a heavy burden on the battery life of the end-user device, and requires more consideration to reduce the power consumption. Limited resources cause segmentations and retransmissions upon the uplink and this consumes more power. The power-saving mechanism in the cellular system has to be upgraded and evolved to be able to meet the new demands of wide-screen devices and applications. Large devices equipped with new functions consume more energy and bursty, and the unpredictable nature of recent applications causes instability in the power-saving mechanism which operates in a static scheme. In the early stages of LTE systems, there were a small number of connected UEs with a small amount of data signalling and DRX was proposed to save power with its frequent transition into the idle state. However, with the increase in the number of UEs and signalling, the serving cell assigns the UEs to the 'always online' state which means a longer connection time and hence a dynamic adaptive DRX scheme is becoming a necessity [9].

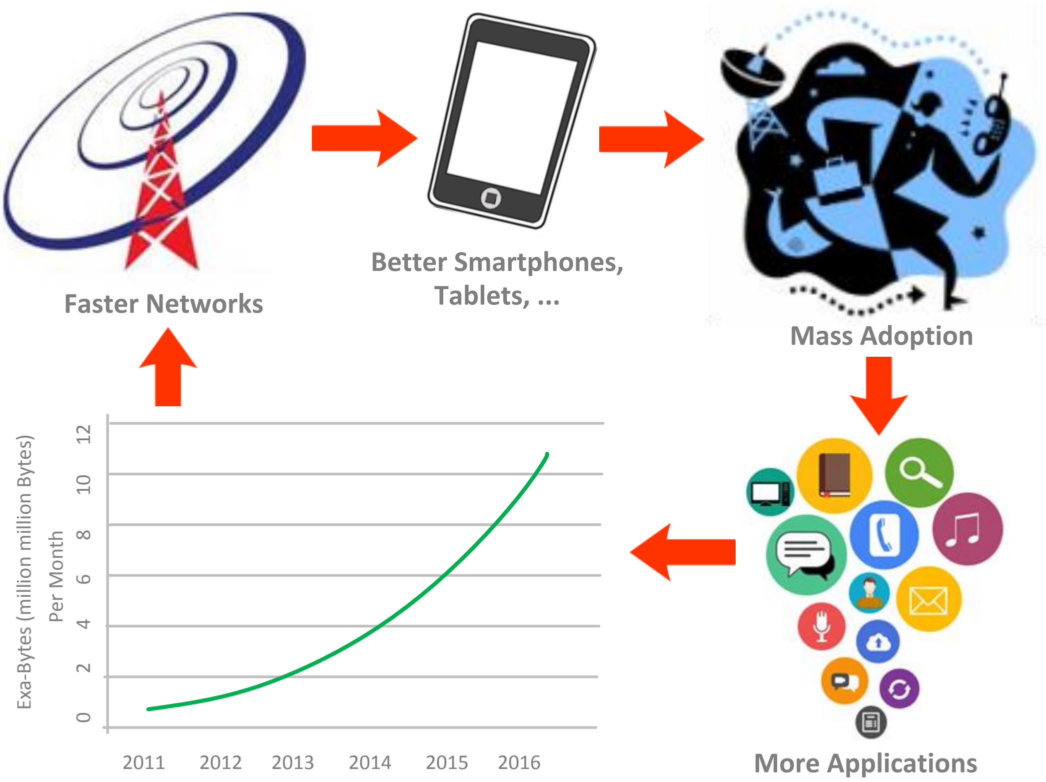

Fig. 1-3 Data explosion challenges [10]

Various forms of interference are a matter of concern and make the LTE system vulnerable, which may cause communication failures or could take down the whole LTE network [11]. One issue of major concern is co-channel interference originating from the Femtocell to the nearby Macrocell UEs. Sensing capabilities with power control on the downlink are essential to mitigate interference in OFDM systems. Using statistical methods such as fixed resources partitioning between the Macrocell and the Femtocells wastes resources, with the increase in the number of Femtocells deployed within the Macrocell coverage. Enabling the Femtocell to perform dynamic allocation while taking into consideration the Macrocell subcarriers' allocation has emerged as a very effective way to save resources and improve the signal quality at the cell edge between the Femtocell and the Macrocell.

The difficulty is that in future networks, multi-layer networks with different configurations will need to be synchronised together and maybe share the same spectrum, without introducing any interference or affecting the QoS. The large number of deployed cells increases the amount of handovers and requires more self-configuration, optimisation and more consideration to bit rates at the cell edge. The system's improved performance must be guaranteed under different mobility conditions and network layers. Hence, the handover performance is very important for the whole system. Signalling data is transmitted over a short period of time. If the UE is in a high mobility state, the impact of signalling caused by high mobility may cause radio link failures and affect other service characteristics. Also, high mobility affects the uplink feedback and may cause aging to the reported measurements from the UE and hence the response from the serving cell will not be suitable for the radio conditions.

Addressing these challenges is the main drive of this research; the presented methods improve the existing networks' and smartphones' performance in order to meet the growing demands of data and subscribers.

1.3 Aims of research

The aim of this research is to study the LTE standard and provide comprehensive solutions to mitigate future challenges. In LTE systems, due to technology evolution, there is a need to introduce self-optimizing and dynamic solutions, thereby introducing more intelligence into the current standard. This will make the network more adaptive and able to handle peak data demands and cope with increasing capacity requirements. Here we address three objectives:

- The first part of the present study investigates the power consumption of LTE mobile devices. The current power-saving mechanism in LTE systems (i.e. DRX) is studied in detail and the challenges of the static nature of this mechanism are presented. From this perspective an adaptive scheme that is able to deal with the fast- changing nature of the network load is presented. Unlike many other studies in this field, more consideration is given to the effects of the DRX mechanism on the system performance and other running processes. This is because this mechanism organises the LTE device's operation by introducing sleeping periods, in the form of periodic cycles, which if not taken into consideration may create a trade-off between power saving and delays.

- The second part addresses the system's capacity enhancement through the introduction of Femtocell technology. The Femtocell is utilised in co-channel deployment which addresses the potential interference with the Macro-users. The presented algorithm in this field considers enabling the Femtocell with a sensing and power control scheme, so that it will be able to quickly detect the presence of Macro-users and then perform dynamic resource allocation to its UEs. This supports the deployment of Femtocells in a co-channel scenario, and saves the spectrum resources compared to other proposed methods. Macro-users' protection and QoS guarantees of Femto-users are addressed in this section.

- The third part demonstrates the mobility issues in future LTE heterogeneous networks. The effects of different mobility levels on handover and link adaptation processes, where the UE performs measurements and reports the results to the serving cell, are presented. In this regard more attention is paid to the cell edge scenario where it is more likely that potential radio link failures and delays may occur. A management framework is proposed to deal with different mobility levels and adaptions in the network configurations, so that the measurement time is optimised and the handover from the small cell to the Macrocell is improved.

1.4 Methodology

The proposed algorithms operate in a dynamic manner so that the system self-adapts to different operational loads and conditions. Most of the procedures operate in the network Access Stratum (AS) layer in the serving cell and in the UE. The methodology for this research was proposed after detailed analysis of the current challenges with consideration given to multiple parameters in each studied area. The proposed solutions are simulated with different applications for each case. In the literature review we present many works related to the present study. The aim is to avoid the limitations and difficulties that may degrade the system's performance. One of the highlighted issues is the employed software, which is OPNET 17.5. The software enabled us to run simulations where processes of interest such as DRX, handover, random access and many others, interact together which makes the simulations more reliable and produces a wide range of results regarding parameters of interest such as throughput, delay, and the signal's strength and distribution.

In the three contributions, the serving cell, which is defined as a Macrocell, has the major rule in the proposed schemes. It monitors the signalling in the cell and adapts the DRX parameters in response to load changes. The Femtocell in the second contribution has sensing capabilities and adapts its scheduling procedures in response to the detected Macro-user's signal. For mobility, different configurations are simulated with consideration given to handover failures and the power consumed by measurements. The network adapts its configuration in response to the UE's mobility level.

The network topology consists mainly of a serving cell with the associated UEs. New attributes are created in all the simulated scenarios to monitor the parameters of interest such as dropped packets, Channel Quality Indicator (CQI) reported value and number of measurement GAPs so that the network performance in the regarded field can be tested efficiently. All the simulated networks are set up according to the 3GGP standards in terms of geographical areas and node parameter configurations. Various applications are deployed such as HTTP, video, FTP and voice to maintain data traffic and resource utilisation during simulations. Different configurations and scenarios are explored to show and evaluate the results of the proposed schemes, with the goal of introducing enhancements to the current addressed objectives in wireless networks for 4G systems and onwards.

1.5 Contribution

The proposed algorithms are incorporated in the LTE stack protocol over different layers; the procedures include sensing, measurements, scheduling and resource allocation in addition to the mobility functions (Fig. 1-4).

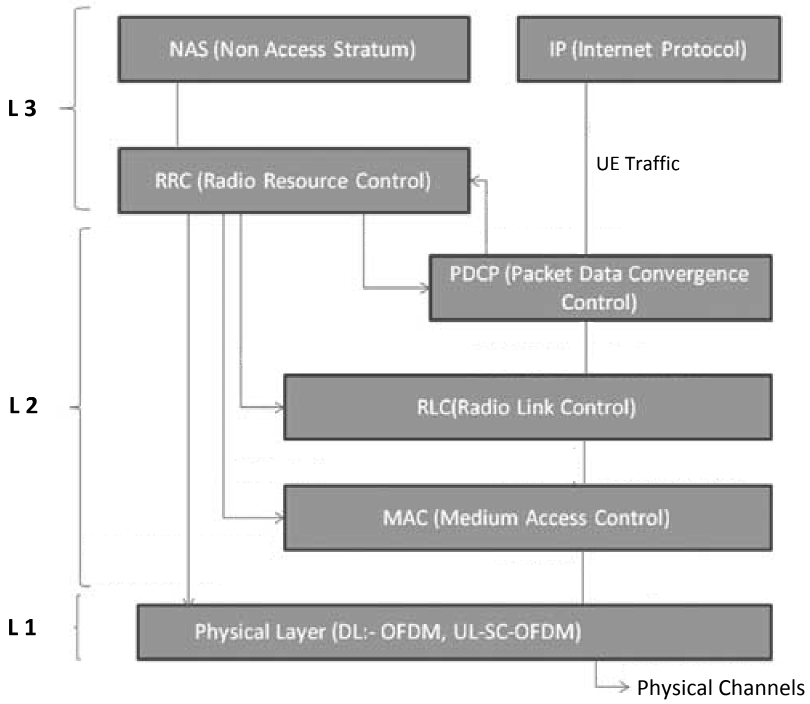

Fig. 1-4 LTE stack protocol [12]

In This work:

- The impact of the DRX process on the LTE system is analysed. Although DRX is created to save power, the evolving technology has extended the effects of this mechanism to the whole system and application performance [13]. In this contribution, a centralized adaptive scheme is proposed to avoid limitations, such as overhead and the trade-off between delays and power saving, with consideration to the performance of other running process such as HARQ, scheduling and handovers.
- A new structure of the Femtocell with a wireless backhaul are proposed. The Femtocell subband allocation depends on the monitored Macrocell UEs' activity and allocation. This scheme provides flexibility to create dynamic spectrum allocation to mitigate interference over the downlink. When this scheme is enhanced effectively, it can avoid interference by selecting subcarriers that are not allocated by the Macrocell to UEs near the Femtocell. In addition to avoiding interference, this has a positive impact on reducing the reliance on schemes that deploy power control and reduction techniques.
- Novel mobility schemes with accurate mobility estimation depending on positioning

are proposed to detect the mobility level of the connected UE and guide it to a suitable close target cell. Many proposals were introduced according to different mobility levels and all are compatible with the current 3GPP standard. Also the novelty includes presenting the effects of mobility on link adaptation, especially at the cell edge and during handover, between small cells and large cells in heterogeneous networks.

1.6 Thesis organization

The thesis includes six chapters, beginning with this introductory chapter where we outlined our work in 4G wireless systems. Each chapter starts with an introduction, and a literature review related to the work in the studied area of research, then after evaluating the performance we provide a conclusion of the chapter.

Chapter two provides an introduction to LTE technology and its main aspects. The LTE main processes are presented briefly, with some technical challenges, especially the processes that are directly connected to our work and mentioned later in the following chapters; therefore this chapter is the base to the following chapters 3, 4 and 5, where the new algorithms are applied to enhance the existing system.

Chapter three provides a review of the power saving mechanism in LTE systems, the DRX. The chapter starts with a comprehensive literature review of the DRX mechanism and its operation in the system. A comparison of the related work in this field is presented and highlighted. Then a novel adaptive power-saving scheme with its functions is introduced and explained with a mathematical analysis of the main process parameters. Variety of the results of the simulated network and the advantages of the proposed adaptive scheme are presented in detail, in addition to how the power is saved and the effects of this scheme on the whole system’s performance.

Chapter four highlights the deployment of Femtocell technology in LTE systems. In this chapter a technical background of the Femtocell and its challenges in 4G systems are introduced. At the beginning a new node in the network is designed, which performs as the wireless backhaul (co-ordinator) of the Femtocells. The main work is focused on the algorithm for interference mitigation in co-channel deployment on the downlink. The main algorithms are explained and introduced regarding power control, positioning, tracing and allocation. The results present the improvements in the received Macrocell signal at the Macro-user's location near the interfering Femtocell.

In chapter five, mobility issues and problems are discussed in detail. The literature review outlines the effects of mobility on handover and link adaptation. An extensive analysis of radio link failure between small cells and large cells is presented. The methodology is divided mainly into three sections, where each section is based on a UE mobility level – low, medium and high speed. The performance evolution section presents the effects of the proposed scheme regarding the reduction in the radio link failures and improvements in the battery life of the UE.

In chapter six the research findings are summarised and a conclusion is provided and an insight into future work in this area of research.

1.7 References

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CHAPTER 2

LTE Technology State of the Art

Introduction

In this chapter the main processes and technical issues of the Long Term Evolution (LTE) cellular system are introduced. In the following sections, the most common aspects of this system are explained from the technical point of view. This chapter represents an explanatory analysis and the technical background of this thesis. The performance of the LTE system, and the LTE main processes, will be analysed to show the main key features of the LTE system such as scheduling, system discovery, channels, and many other evolved processes that form the main aspects of 4G, and will continue to dominate the performance of 5G. The challenging issues concerning our studied LTE system are presented so that later chapters can devise ways to fix these issues, ensuring that the effects of the addressed challenges and technical problems are minimized.

2.1 The architecture of LTE, motivation for LTE

In the past, mobile communication networks were dominated by phone calls and the data transfer requirements were not really very big. A few years ago, these networks became dominated by emails, web pages, data files and applications. This has led to a huge growth in the amount of data which network operators are trying to transfer across mobile communication networks. In response to this problem, network operators are having to greatly increase the capacity of the mobile communication networks. One of the ways of achieving this is by improving the technology, so that information between mobile phones and the base stations can be transmitted and received faster than ever before. The main driver behind the introduction of LTE is a change in mobile communication technology, so that it runs faster to achieve higher data transfer rates. Another motivation for LTE is the reduction in delays to figures of around 20 to 30 ms, which are suitable for the more recent kind of applications such as interactive remote games.

2.1.1 Technology history

Mobile phones have gone through these generations: 1G, 2G, 3G and 4G. The first generation of mobile phones were the large analogue mobile phones from the 1980s. Mobile phones became really popular with the second generation in the 1990s, which brought with it the introduction of the Global System for Mobile Communications (GSM) which was the first mobile communication device, although it could only handle phone calls and text messages. The General Packet Radio Service (GPRS) (2.5G) enhanced 2G phones by adding data to the previous voice and Short Message Service (SMS). The design of GSM however did not permit the kind of high data rate communication required, and Universal Mobile Telecommunications System (UMTS) was introduced as the first 3G technology, known as Wideband Code Division Multiple Access (WCDMA), which is the name of the radio communication in most 3G systems.

In 3G networks, the architecture of the network has been kept more or less intact, but the nature of radio communication has completely changed in order to make it work faster. High Speed Packet Access (HSPA) is optimised for data, so that the average data rate is increased, provided that the application is willing to tolerate variations in the time at which the information arrives.

The objective of 4G was to speed things up further, and this led to the introduction of LTE. The designers of 4G have done two things: first they have completely changed the nature of the radio communication to make it go faster, and second they have changed the architecture of the network.

In 3G systems the system occupies a fixed bandwidth (BW) of 5 MHz. The use of a fixed BW means that the use of the spectrum is inflexible. For the spectrum regulator and network operator to allow for a higher data rate and more flexibility, LTE works in a variety of different BWs. There are different values supported: 1.4, 3, 5, 10, 15 and 20 MHz [1].

2.2 System architecture

2.2.1 System Architecture Evolution (SAE)

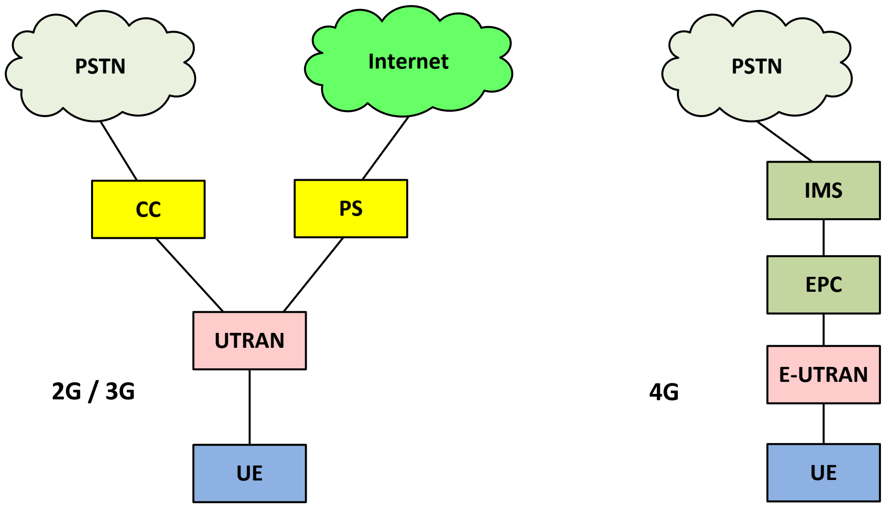


Fig. 2-1 System Architecture Evolution (SAE)

2G and 3G communication systems are supplied with 2 core networks: a packet switched core network which handles data, web pages and e-mails, and a circuit switched core network which handles phone calls. In LTE, the evolved packet core is a direct evolution of the packet switched domain of 2G and 3G networks, but there is no equivalent of a circuit switched domain. This determines how phones calls are managed in LTE.

Fig. 2-1 shows a basic diagram for 3G systems; there is a radio access network, a mobile phone and a core network with Circuit Switched (CS) and Packet Switched (PS) domains. The

CS domain is connected to the public switched telephone network, and the PS to the internet. In the 4G LTE, also shown in Fig. 2-1, the PS domain is the Evolved Packet Core (EPC), the radio access network is the evolved UMTS Terrestrial Radio Access (E-UTRAN), and the mobile is the UE. The EPC is designed to connect to the internet. In traditional 3G networks, phone calls are handled by the CS domains which contain the functions needed for setting up phone calls. LTE was designed for data applications, which is where most of the network traffic comes from. So LTE does not have a CS network. Phone calls over LTE devices are conducted with two main techniques; the first one, which is being implemented at the moment, is called CS fall back. Using this technique, an LTE mobile hands over to a 2G/3G cell, links with a CS domain of 2G/3G, and makes a phone call in that way. This leads to instance delays of several seconds when the UE sets up a phone call. The second technique is to make use of an extra network which is called an IP Multimedia Subsystem (IMS). The LTE network transports data packets from the network outside domain to the UE and knows nothing about the signalling function which is needed to set up phone calls. Those signalling functions are run by the IMS [2].

2.2.2 Core network

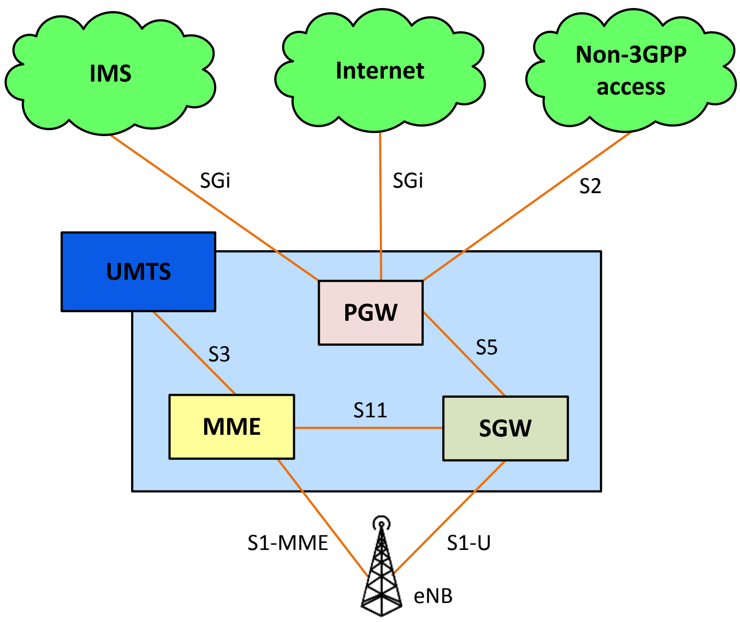


Fig. 2-2 LTE System core network

The system core network is shown in Fig. 2-2; there are a few devices within the EPC:

The PDN Gateway (PGW) is an interface to an external system such as the internet or the IMS. It is the first point of contact for data packets travelling from an external network into LTE. It also allocates an IP address by which that external network will recognise the mobile.

The Serving Gateway (SGN): It forwards data packets between PGW and eNB (it represents an intelligent high level router). Packets are sent in two steps (PGW/SGW) to handle roaming situations.

The Mobility Management Entity (MME) is used to pulse signalling messages around, and it also performs tasks such as authenticating a mobile. When a mobile switches on, it sends a signalling message to the MME and the MME authenticates the mobile, checking its identity and whether it is a genuine mobile, not an intruder. (SGN handles packets, MME handles signalling).

The amount of signalling depends upon the number of mobiles in the networks; the amount of traffic depends on the number of mobiles in the networks multiplied by the data rate per mobile. By separating the signalling function and traffic functions, it makes it easier to evolve the network as the requirements of the network grow.

S1 is split into 2 components to reflect the distinction between the MMEs and SGWs. The S1_u interface carries traffic between the eNB and SGW, and the S1_MME interface carries signalling between the eNB and MME [3].

2.2.3 Channels

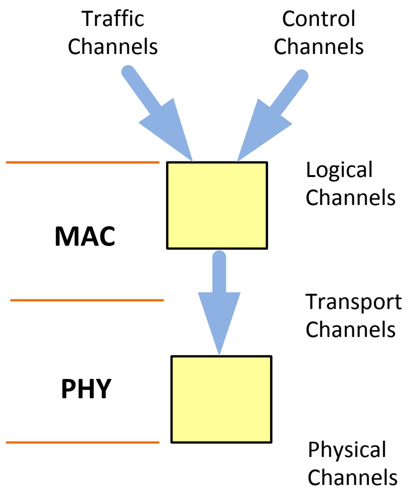


Fig. 2-3 LTE channels

Channels are streams of information which travel between different levels of the protocol stack and between a mobile and an eNB. There are logical, transport and physical channels (Fig. 2-3). Logical channels are streams of information flowing between the radio link control protocol and the MAC protocol. They are basically characterised by the type of information they transmit. For example, if the UE is interested in traffic like Voice over IP (VOIP) or web pages or emails, it is transmitted using the Dedicated Traffic Channel (DTCH). On the other hand, high level signalling messages like handover commands are set on the Dedicated Control Channel (DCCH).

The physical channels are best thought of as the information streams which the eNB sends to the mobile upon the downlink and which the UE sends to the eNB upon the uplink. The subcarriers are organised in such a way that, at any one moment in time, a particular subcarrier is transmitting on a particular channel. For example the Physical Uplink Control Channel (PUCCH) carries a low level feedback channel quality indicator (CQI) from the mobile to the eNB. The Physical Uplink Shared Channel (PUSCH) carries 2 types of data: firstly any data streams that the UE is interested in, such as VOIP packets, data files, emails and so on; secondly high level signalling messages, for example the messages which the mobile might send to the eNB during the handover procedure [4].

Fig. 2-4 shows the distribution of the physical channels in the uplink frame. It shows time and frequency with different power levels.

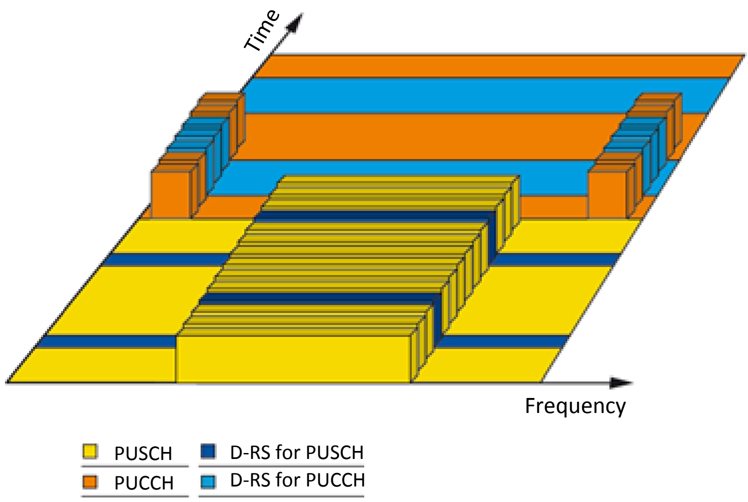


Fig. 2-4 LTE physical channels in the UL frame [5]

On the downlink, there is a similar distinction between these two channels, the PDCCH and the PDSCH. On the PDSCH there are two types of information: downlink data VOIP packets and web pages, and high level downloading signalling messages, for example mobile handover from one cell to another. Mobile transmissions on the PUSCH are always explicitly scheduled by the base station using scheduling commands on the PDCCH. The PUCCH is always at the edges, but the amount of space it occupies can vary. The Physical Random Access Channel (PRACH) can be anywhere depending on how the eNB has configured it. The Physical Broadcast Channel (PBCH) carries information about the BW, whether the cell is using 1.4 MHz BW or 5 or 20 MHz; the mobile discovers this by looking at the PBCH, transmitted once every frame.

Reference signals are used for 2 purposes: firstly for measuring the strength of the received signal so as to ascertain which subcarriers are good, and which ones are not suitable. The mobile inspects the reference signals which are scattered across the time and frequency map so that the mobile can easily find them and measure them. Secondly they help the mobile to process the information which it is receiving by briefly acting as a signal transmitted with a known amplitude and a known phase angle, which allows the mobile to undo the effect of amplitude and phase changes. On the downlink, the demodulation and sounding signals perform the equivalent tasks for the uplink [6].

2.2.4 Cyclic Prefix

Fig. 2-5 shows an eNB and a mobile; the mobile is receiving information upon more than one ray path. The reflected wave is longer than the direct one; therefore information will take a little bit longer to get from the eNB to the mobile via this reflected wave. In the figure, the received symbols on the reflected wave are a little bit delayed. The overlap between the symbols received on the different rays causes ISI. This causes difficulties and distortion to the mobile receiver. There are various different methods in LTE of dealing with Inter Symbol Interference (ISI), one method is called the Cyclic Prefix CP.

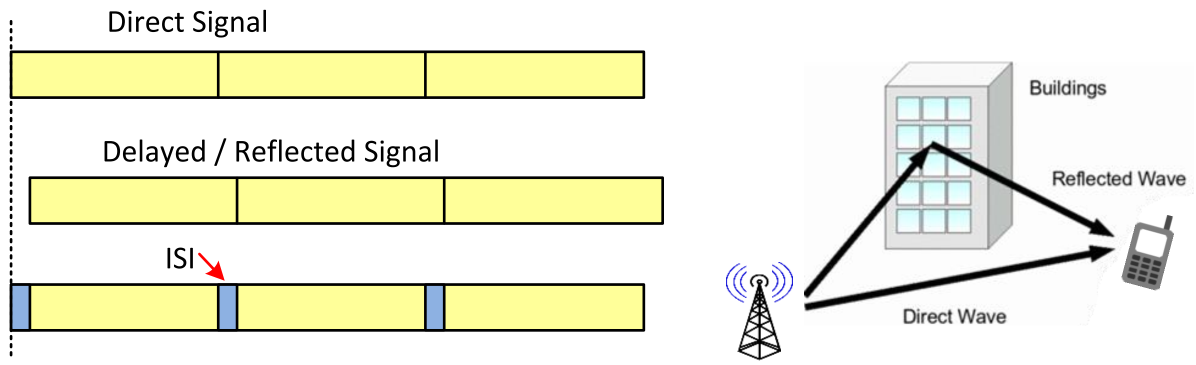


Fig. 2-5 Inter-symbol interference

A little gap is introduced between the transmitted symbols, called a guard period (GP). The guard period should be longer than the difference in the arrival times of the rays. The guard period is filled up with information which is transmitted at the end of the symbol (copy it back). Another advantage of this process is that the transmission would not be switching on and off several times per second [7].

The problem arises if the distance between the longest and the shortest path is greater than the 1.4 Km. Here there is an option of an extended cyclic prefix in which the CP is made 4 times longer, which increases the maximum distance to a range of 5 Km and this reduces the data rate even further.

2.2.5 System discovery

Primary Synchronisation Signals (PSS) and Secondary Synchronisation Signals (SSS) are standard transmissions which occur twice in every download frame. When a mobile switches on, the first signal the mobile looks for is the PSS. It defines an LTE eNB and it also provides the Physical Cell Identity (PCI) mod3. The secondary signal provides a reminder of the physical cell identity (called the identity group), and it also tells the mobile whether it is a TTD or FDD cell, and whether a normal or extended CP is used. The mobile can start to receive the reference signal and by looking at the PBCH it can discover the DL BW; the remaining part of the synchronisation process is shown in Fig. 2-6 [1].

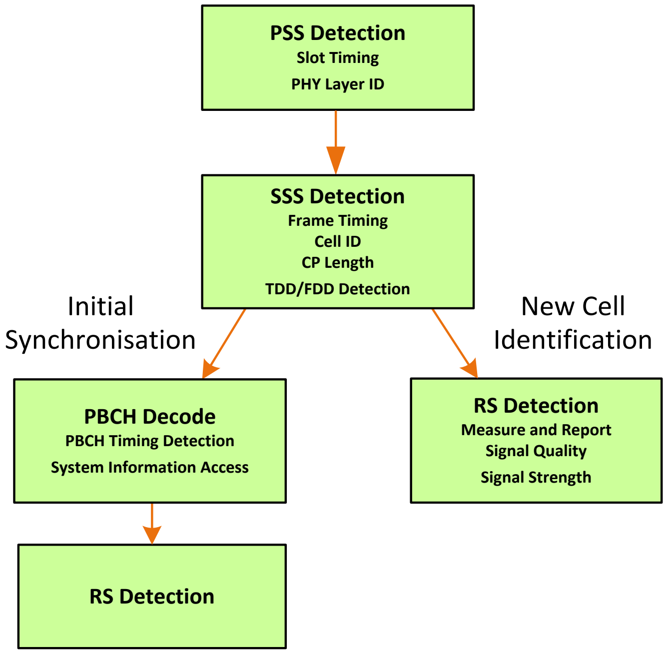


Fig. 2-6 LTE system discovery and synchronisation process

Fig. 2-7 represents the relative locations of the primary and secondary synchronisation signals in the case of FDD. The CP is usually 4.7 μsec long. That leads to the existence of 7 symbols in every slot. To account for big cells, sometimes the CP can be made longer by reducing the number of symbols per slot from 7 down to 6, thereby allowing extra time to make the CP longer. This produces an extended CP. The use of an extended CP reduces the symbol rate per subcarrier from 14 Kbps down to 12 Kbps. (The mobile discovers which one the cell is using, normal or extended CP, from the relative location of the primary and the secondary synchronisation signals).

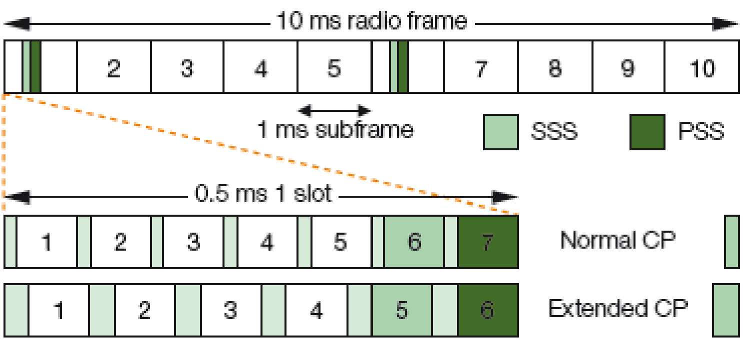


Fig. 2-7 FDD Frame case [5]

In TDD mode, the relative positions of the primary and the secondary synchronisation signals are different once again. The SSS is 3 symbols earlier. So by discovering the position of the secondary signal relative to the primary one, the mobile can discover whether FDD or TDD mode is being used, and whether it is a normal or extended CP (Fig. 2-8).

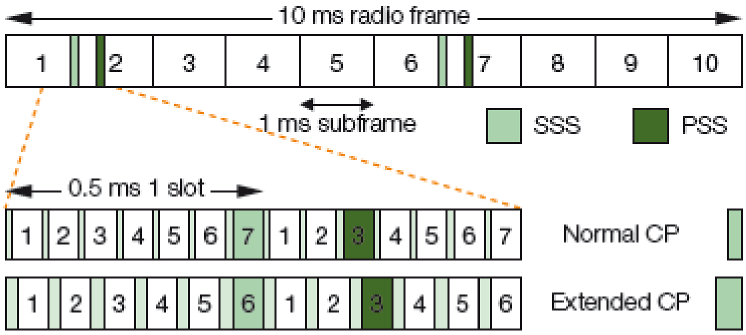


Fig. 2-8 TDD Frame case [5]

The eNB has to be configured with a low level ID called PCI. There are 504 numbers arranged in two 168 groups of 3 identities. The idea is that a mobile discovers the cell identity group from the secondary synchronisation signal SSS and the remaining numbers 1, 2, 3 from the primary synchronisation signal PSS.

Different concurrences of the physical cell ID are organised so as to be far away from each other for 2 reasons: firstly, to minimise interference in the data transmissions. Different cells tweak their transmitted data in different ways depending upon the PCI. If concurrences of the same physical identities are kept far apart, then the network can reduce interference within data transmissions in the cell. Secondly, when sending measurements reports, these reports refer in the first instance to the PCI, so there is a possibility of a mobile receiving a strong signal from two cells which are sharing the same PCI. This measurement report then becomes immediately ambiguous. This leads to degradation in the handover. It must be guaranteed that a particular eNB is only going to receive measurement reports from a particular PCI, which should only ever come from one cell.

2.2.6 Modulation

To receive the signal correctly, the mobile has to choose the correct received wave from 64 possibilities (64 modulations). That is fine if the SINR is high /has a strong signal. QPSK gives the lowest data rate but if the SINR is low, the mobile has 4 possibilities to choose, not 64, so there is much less chance of getting confused (Fig. 2-9).

The system adjusts automatically between these situations; if the SINR is high enough at the receiver, then the eNB transmits using 64 QAM to give the highest data rate. If the received SINR is low, then the eNB transmits using the QPSK which is a reliable transmission at a lower data rate. The base station uses the feedback, the CQI, to discover which modulation scheme to employ. The CQI tells the eNB two things: firstly which subcarrier (subband) to use, and secondly which modulation scheme the mobile can handle. The modulation scheme is dynamically adjusted depending upon the strength of the received signal [8].

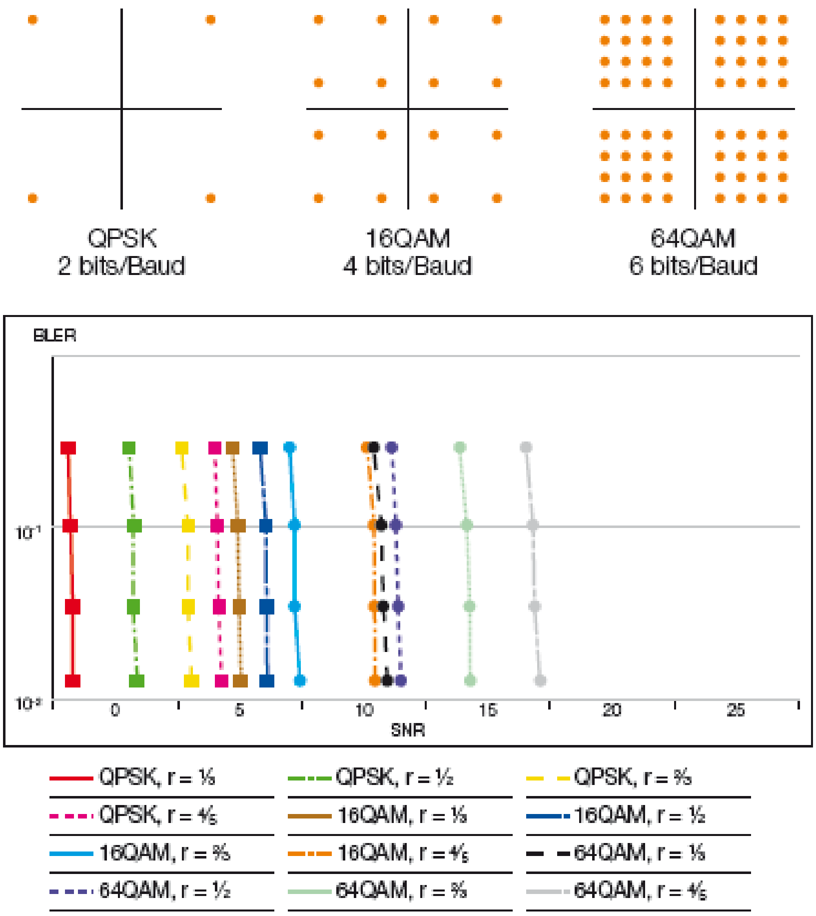


Fig. 2-9 LTE modulation and coding [5]

Modulation schemes are considered as coarse adjustments to the data rates; a fine adjustment is known as a coding rate. The coding rate is the number of info bits divided by the number of code bits (in the range of 0 to 1). A low coding rates gives a low data rate which is suitable for a low SINR.

Data rate = coding rate * 2 or 4 or 6 (number of bits per symbol X number of information bits per transmitted bits).

2.2.7 Power control

The eNB controls the power with which the mobile transmits, so that if the mobile is close to the eNB it only needs to transmit a low power signal. On the other hand, if the mobile is far away from the eNB, it needs to transmit a strong signal. The principle is that the mobile transmits the lowest acceptable power signal, thus maximising the mobile's battery life. The mobile computes its best estimate of its own transmission power and then the eNB adjusts that depending on the strength of the signal received (using the transmit power control command). The transmitted power will depend upon the number of subcarriers which are used for the UL transmission [1].

2.2.8 Timing Advance

Timing advance is the reason for the existence of the special switching subframes. The idea is that there are transmissions from mobiles from different locations up to the eNB. There are a nearby mobile and a distant mobile. In TDD mode it is very useful to have the transmissions from all the mobiles reaching the serving eNB at about the same time.

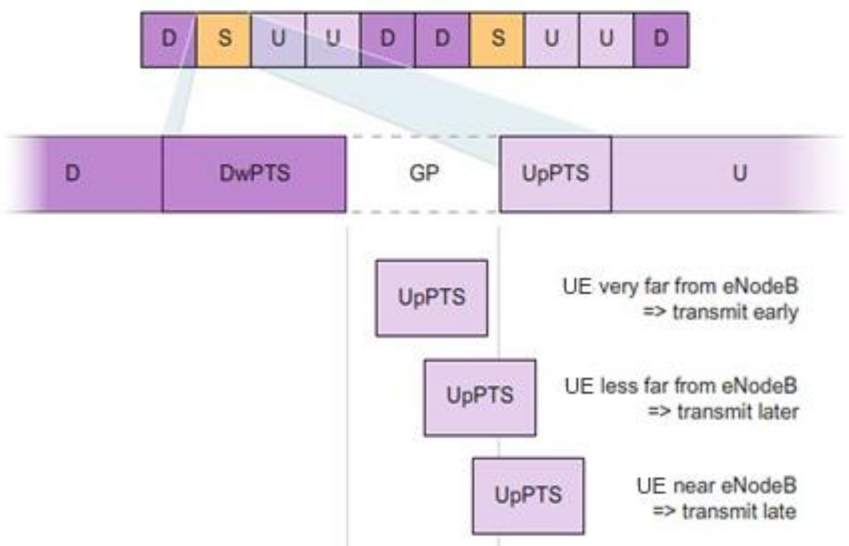


Fig. 2-10 Frame structure for timing advance

There are Downlink Pilot Time Slots (DwPTS) before the Guard Period (GP) and an Uplink Pilot Time Slot (UpPTS) after it. The distant mobile starts sending its uplink transmission a little bit earlier than nearby mobiles. The purpose of the GP is to allow for advancing the UP transmission times without any risk of overlap with the downlink information, which the mobile is receiving upon the same carrier frequency. But for transmission from the UP to the DL there is no need to do anything special because the advance in the UP time simply creates a gap where nothing previously existed (Fig. 2-10) [9].

The mobile sends Random Access (RA) transmissions; the eNB measures the arrival time then replies and initialises the mobile timing advance. Timing advance commands are actually organised by a higher level protocol (MAC protocol) and they are transmitted along with other signalling data messages on the PDSCH, such as the identity of the network that the new eNB belongs to, and the cell ID.

2.3 LTE processes

2.3.1 Fading

Signals travel on different ray paths from the transmitter to the receiver. One of the effects of this multi path is that if the receiver is picking up different signals from the transmitter, those signals can either add together and reinforce each other, or they cancel each other out, and that leads to a phenomenon known as fading (Fig. 2-11).

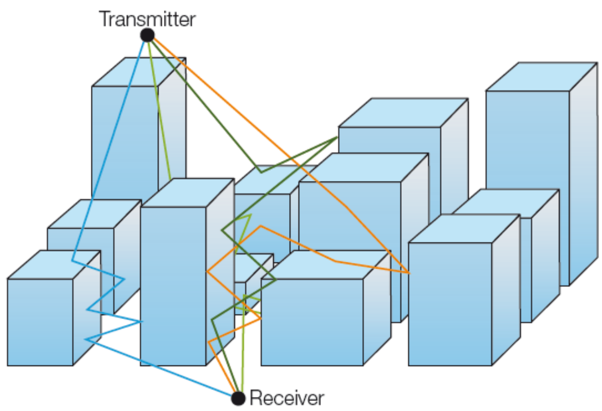


Fig. 2-11 Fading phenomenon

Fig. 2-12 shows a plot of the strength of the received signal as a function of frequency. The mobile is receiving information over many different subcarriers, and the mobile can detect that some subcarriers arrive with a strong signal, and other subcarriers arrive with a weak signal [10].

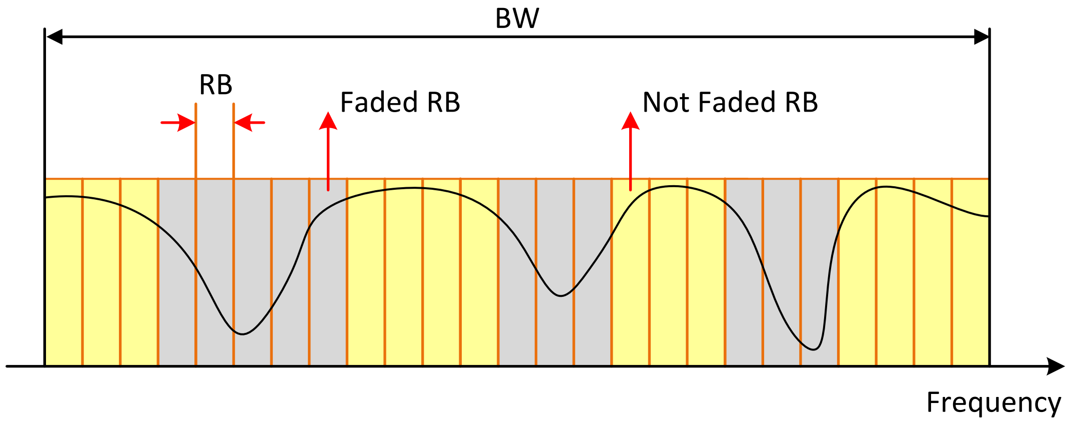


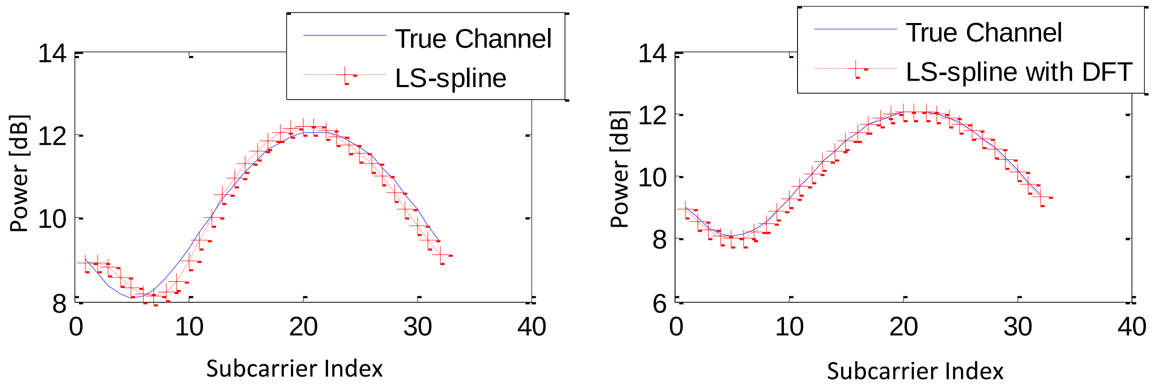
Fig. 2-12 Received signal as a function to frequency

If a base station is trying to transmit to different mobiles, it could transmit to one mobile on some subcarriers, and then leave other subcarriers for transmitting to other mobile phones within the cell. The data rate with which it transmits depends on the number of subcarriers that it allocates to a mobile. So if it is trying to transmit at a high data rate it allocates a lot of subcarriers, and if it is trying to transmit at a low data rate it just needs to assign a few subcarriers to the mobile. In this way the frequency spectrum is organised so that some subcarriers are used for transmission to one mobile and other subcarriers are used for transmission to another mobile. Mobiles can measure the strength of the received signal and report back to the eNB that it is happy with some subcarriers and not happy with the subcarriers in between, because the received signal upon those subcarriers is weak. At the same time, a second mobile may be carrying out a similar management and reporting back to the serving cell. The eNB can use this information to decide which subcarrier it is going to allocate to different mobiles within the cell. By doing that the eNB can selectively transmit to mobiles using the subcarriers on which the mobiles receive strong signals, and avoiding the subcarriers with a weak received signal [11].

2.3.2 Channel Estimation

In the OFDM system, reference signals (RS) are used to estimate the channel. When the signal is recovered at the receiver, the UE estimates the channel to report the downlink signal strength over the PUCCH (periodic) or the PUSCH (aperiodic). Many algorithms are used to estimate the channel such as Least-Square (LS) and Minimum-Mean-Square-Error (MMSE) techniques; however the performance depends on the SINR as shown in Fig. 2-13 [12].

SINR = 30 dB



SINR = 20 dB

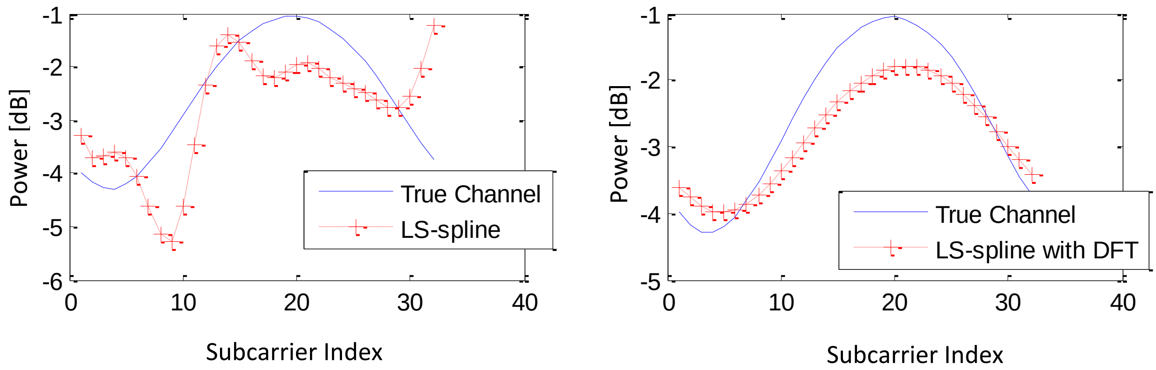


Fig. 2-13 Channel estimation

2.3.3 Measurement Window

There is a time window in the range of msec; during this window the UE measures the strength and quality of the DL signal of the serving cell and reports the measurement (of every subband) to the serving cell, so that it can find the best subband for this UE to use for transmission (Fig. 2-14).

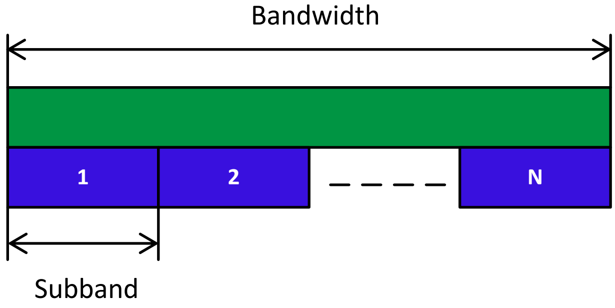


Fig. 2-14 The system bandwidth and subbands

During mobility, the UE aims to find the best eNB and maximise data throughput. The eNB depends on information reported by the UE to adjust the downlink parameters. Link quality is affected by time varying and frequency selective channels; one of the essential feedbacks is the channel condition reporting which is done through the Channel Quality Indicator (CQI). In this field, the UE has to estimate the channel and then reports the result back over the uplink to the serving cell. In general, the network performance shows improvements when the feedback process is fast and accurate. Fast measurement and feedback are required due to the presence of channel coherence time in a wireless environment, which causes Inter- Carrier Interference (ICI).

2.3.4 Scheduling

The scheduler in the eNB allocates resources to the connected UEs based on the reported CQI from the UEs and on the queues' availability (Fig. 2-15) [13]. Each UE is allocated a modulation level and then data is mapped to the physical resource blocks in time/ frequency distribution. If this allocation process has not been fulfilled quickly, then the effects of frequency-selective channel will not be mitigated properly.

CQI is a flexible feedback; it is an important value because it is independent and used with all antennas' configurations. This parameter is determined according to the target link quality (acceptable Block Error Rate - BLER) and the current measured SINR (wideband and subband measurements) - (SINR-BLER curves). The performance of the feedback depends on the situation of the UE in terms of speed and network load.

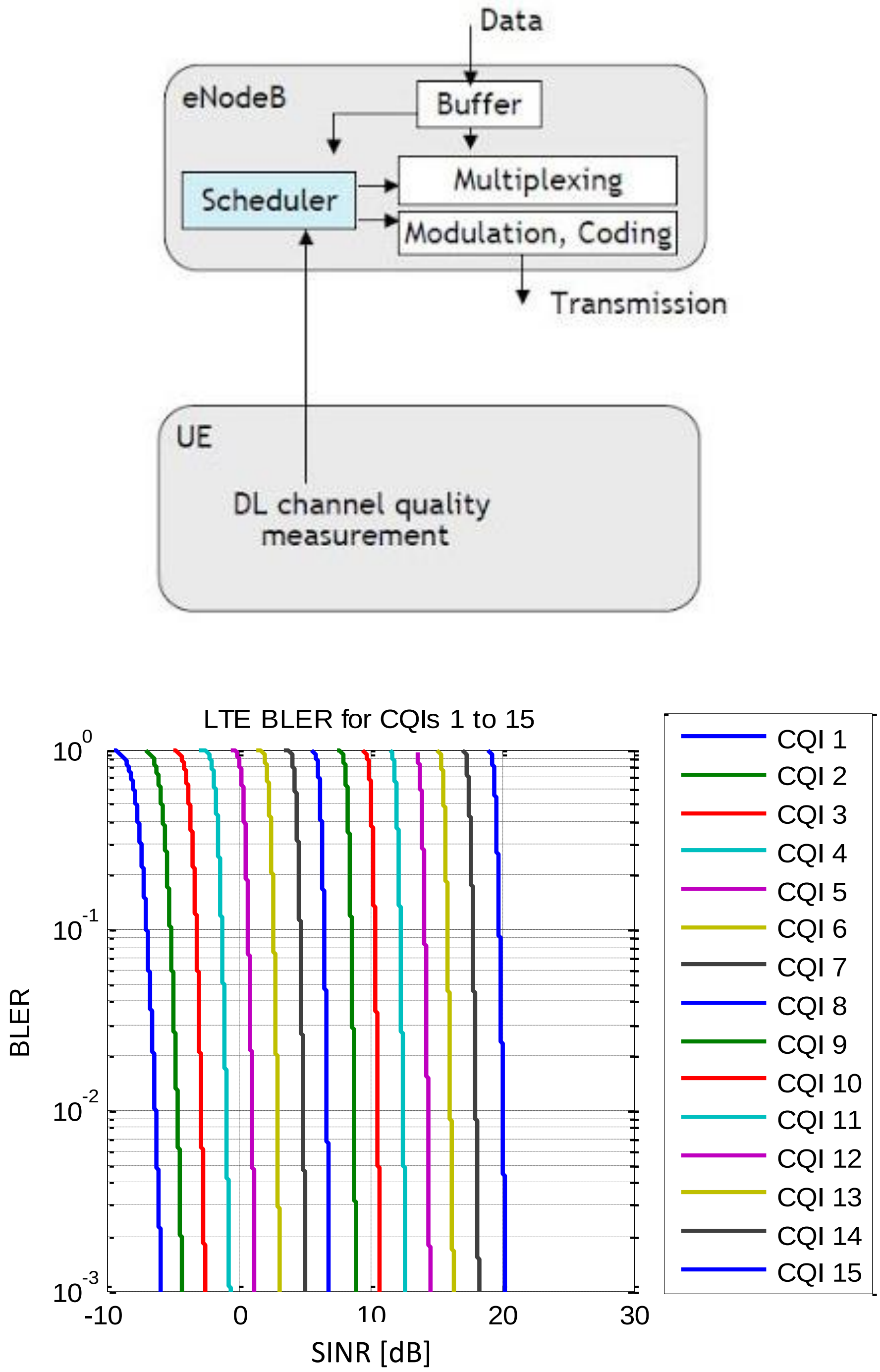


Fig. 2-15 LTE scheduler and BLER for CQIs 1 to 15

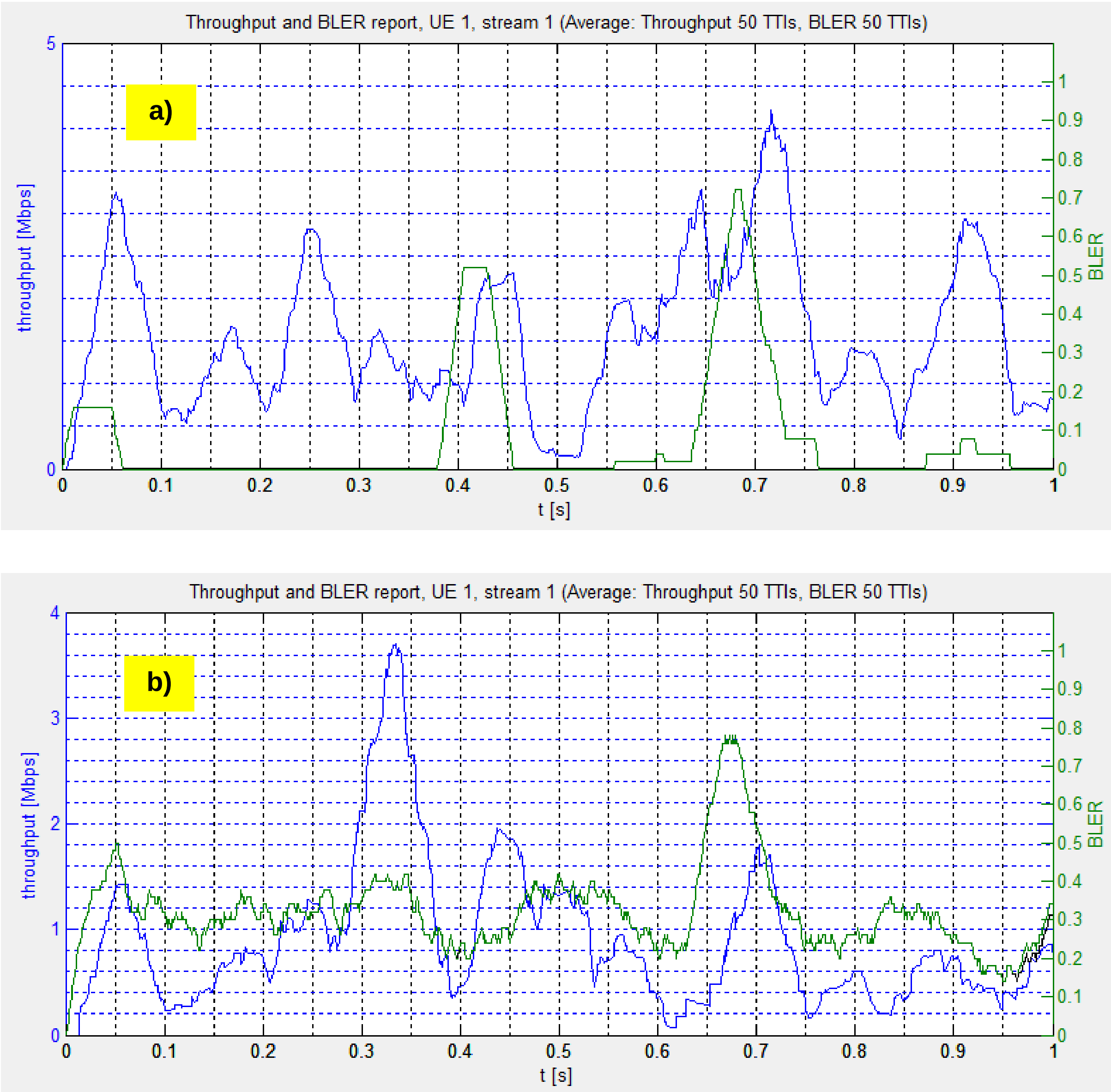


Fig. 2-16 Effects of delayed feedback (1 ms delay)

The channel coherence time and feedback delay are among the factors that affect link quality measurements [14]. These cause a mismatch between the current channel state and the reported state and as a result, BLER requirements cannot be fulfilled. Panel (b) in Fig. 2-16 shows throughput degradation and BLER increase due to feedback delay of 1 ms (compared to panel (a)).

2.3.5 Hybrid Automatic Repeat Request (HARQ)

The Hybrid Automatic Repeat Request (HARQ) process is one of the very essential components in the LTE system; the target error rate is 10% and it is the indicator of whether the transmission is successful or not. If the transmission is not successful, the receiver replies with HARQ NACK. The receiver keeps the original bits and combines them with the new received ones in order to increase the decoding probability (Fig. 2-17). The transmission is considered failed after 3 times, which is the maximum number of retransmissions of the HARQ packet [15].

Although the HARQ process has a fast response, it adds extra processing delays and it differs between FDD and TDD. With FDD it requires 8 subframes for the round trip times, while for the TDD, because there are different types of frames and subframes on which the transmission is scheduled, the ACK/NACK processing delays are assumed to be in the range of 3 subframes.

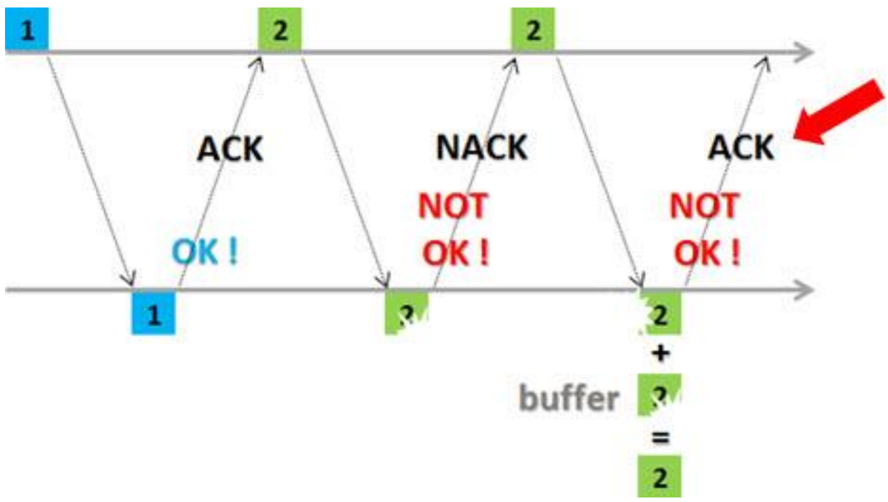


Fig. 2-17 LTE HARQ process [16]

2.3.6 Random Access (RA)

A problem occurs when a mobile is switched on and it would like to transmit data to the eNB, but the eNB doesn't yet know that it is there, and has no means of scheduling the mobile. The mechanism which will cater for the mobile, which it just switches on, is the Physical Random Access Channel (PRACH). The eNB reserves an individual region of the UL map for transmission upon the PRACH and here a mobile can connect (via a Hello Message) to the eNB without previous scheduling (Fig. 2-18).

A mobile just finds the region in which PRACH transmissions are permitted, and sends a little signal (Preamble) to the eNB. The eNB responds by scheduling the mobile for a normal transmission on the PUSCH.

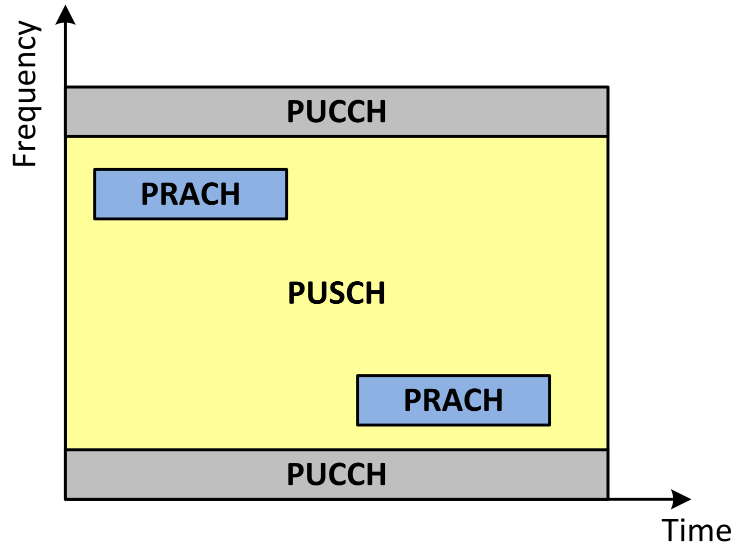


Fig. 2-18 LTE PRACH

The random access process is started at the UE side in the MAC layer. It is controlled by the Radio Resource Control (RRC); the MAC layer transmits RA preambles under control from the RRC. The worst case scenario of the RA procedure is when it is not successful; here the RRC is informed. RRC is informed about the unsuccessful procedure when the maximum number of preamble transmissions is reached, but the MAC layer continues to send preambles. The RRC layer may have different actions in response to the problem of reported unsuccessful RA procedures. The RRC response depends on the status of the connection of the UE and here timers have an essential role [17].

If this happens during the UE's handover process, the RA process is suspended upon the expiration of the T304 timer, and the UE will start the RRC connection re-establishment process. If this happens when the UE is connected and synchronised with the eNB and it has data to send, the RRC will consider this as a radio link failure, and the UE has to start the RRC connection re-establishment process again.

2.4 Technical challenges

LTE requires flexible frequency bands and reasonable terminal power consumption with simple network architecture. Listed below are some of the technical challenges that are continuously considered in all LTE 3GPP releases and specifications:

2.4.1 Power consumption

Power consumption in LTE systems has become a progressively more important issue due to many factors such as:

- The device's battery limitation in size and capacity due to the simultaneous decrease in size of the wireless terminals and widening of the screen.
- Battery evolution is slow; the technology relies on Lithium-ion technology.
- Increasing data rates and evolution in applications.

In this regard, the industry aims to reduce power consumption by developing the current primary sources of power consumption such as power amplifiers, CPUs, the display and the radio interface.

On the other hand, the power saving mechanism DRX was introduced to LTE in release 8, which has achieved significant power savings. Industry and telecommunication vendors are working to support this technology and adopt new solutions [18, 19].

2.4.2 Interference

Interference in cellular systems is one of the most common problems. Although each transmitting service is assigned a portion of the frequency, operators aim to increase the throughput by sharing the spectrum. The LTE system is designed so that each eNB uses the whole bandwidth with a frequency reuse of 1. Femtocells improve the spectrum efficiency, however, the new introduced components in the LTE network architecture, such as Femtocells, add further to the complexity of the development and deployment of the system. The key challenge is to improve the spectrum utilization by allowing the Femtocells to operate in a co-channel scenario, without making the Macro-users undergo too much co-channel interference [20].

There are many co-channel interference scenarios that limit the operation and deployment of Femtocells, such as:

- Macrocell interference with the Femtocell users.
- Macrocell users' interference with the Femtocell receiver.
- Femtocell downlink interference with the Macrocell users.
- Femtocell users' interference with the Macrocell receiver.
- Femtocell interference with the neighbouring Femtocells.
- Femtocell interference with the neighbouring Femtocells users.

In some scenarios the interference from the Macrocell to the Femtocell does not have a significant impact on the Femtocell's throughput [21].

2.4.3 Mobility

Mobility affects the active mode and idle mode handovers and wastes resources in the case of multiple radio link failures. LTE aims to optimise performance for different mobile speeds, with particular consideration given to speeds in the range of 3 to 160 km/h, measurement and measurement reporting, configuration for mobility, and scheduling [22].

Several practical issues may prevent the mobility procedure from functioning in a proper way, especially the heterogeneous deployment. The expansion of heterogeneous networks presents challenges due to the increase in the node numbers which creates confusion between cells of different sizes. The situation will have additional challenges with the presence of multiple vendors together in the same network [23]. In [20] it is mentioned that the link adaptation for LTE is not yet standardised, and the focus has been put on the LTE interfaces by 3GPP. This creates differences in the network performance in heterogeneous networks and makes it necessary to optimise the underlying link adaptation functionality in this field so that the scheduler's decision values are improved.

2.5 Summary

LTE-Advanced has the potential to enhance current deployments of 3GPP networks and to enable considerable new service opportunities. However, the standard may present many development challenges and success requires the availability of self-organising solutions that match the standard's fast evolution. This chapter summarise the essentials of the LTE processes and the main technical challenges in the area of our research.

The chapter starts with an introduction and motivation for LTE, and how it relates to previous communication systems such as 2G and 3G. It explains the important technical features, and looks at the architecture of the radio access network and the core network of LTE. Then the principles of radio transmission and reception in LTE are presented, followed by an illustration of how a mobile phone and a base station communicate with each other in different radio frequency scenarios.

In the following chapters we present a detailed analysis of the current challenges, in addition to introducing the proposed solutions so that these challenges can be met.

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CHAPTER 3

Adaptive Power Saving Mechanism -DRX- for LTE-Advanced

Introduction

3GPP has added new specifications to the power-saving mechanism in wireless networks. The discontinuous reception (DRX) in LTE has a major impact on saving the battery power of the UE. The operating timers in DRX control the transmission and reception activities of the wireless terminal device; it defines the time to wake up and when to enter the sleep mode. The research in this field regarding LTE-A is focused on making the power-saving mechanism more dynamic, in order to make it compatible with the transmission of higher data rates and different applications at the same time.

The goal is to render networks more intelligent, and close to self-organising, by modifying the main parameters according to certain situations; this intended intelligence may cause a huge undesirable overhead over the wireless interface because of the large activities in today's networks. In this chapter, we have presented a method for dynamic DRX for LTE-A. The proposed method is based on the self-organising capabilities of the serving eNB. Each eNB needs to be more aware of the surrounding environment by continuously checking some effective and dynamic parameters. The loaded eNB cannot serve the connected UEs as effectively as a half-loaded eNB. The load considered here is the signalling load. The simulation results show that the adaptive DRX has a positive impact on the UE's power consumption. In addition, by presenting the effects of the dynamic approach on other related processes such as handover and cell search, it is shown that by modifying the DRX process and making it a dynamic one, the adaptive DRX does not introduce any delays or overheads to the other vital processes for the UE in the LTE system.

3.1 Power Saving for Wireless Devices

Pervious portable devices were analogue ones. They were described as steady current consumers compared with digital devices that exhaust the battery through short, sharp bursts of activity. The latest generations of mobile phones are manufactured with a screen size of about 5 inches; these screens are considered to be power-hungry elements which require larger rechargeable batteries, rather than the normal thin ones (Fig. 3-1). Nowadays with the booming market of mobile phones and digital applications, customers are more interested in the short battery life of their mobile phones. A battery that runs strong all day long will be good news for consumers who give priority to battery life over other issues. Some manufacturers who work in the field of mobile technologies have switched to another way of increasing battery life.

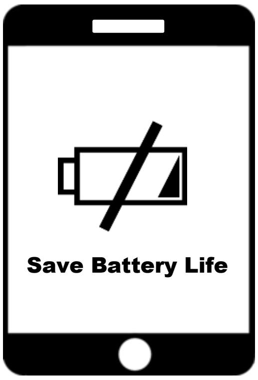


Fig. 3-1 Today's large phone screens are power-hungry elements

The new features include many ideas for saving energy. For example, Sony has introduced a new feature based on the mobile screen's situation itself. If the screen is off, the mobile will shut off its receivers automatically and resumes operation when the screen comes back on. Huawei's method for decreasing power consumption was to turn off the circuitry depending on the applications running on the device. Other vendors are working on new processors that consume lower energy than the current ones. For example the released Nivada Tegra 4 processor is said to consume 45 % lower energy than the Nivada Tegra 3 when operating in the same situation. Samsung released the Exynos 5 Octa processor which required the company to combine it with a larger battery so that new smartphone can win over the market [1]. Apple has focused on the heat/temperature factor in order to avoid degradation of the battery's performance [2].

The best possible performance of mobile phones' batteries is with Lithium-ion batteries. They provide longer battery life with lighter packaging. It is obvious that the lifetime of the mobile battery depends on the usage of the device. For example, watching movies or running other different applications are power-consuming compared with other activities such as text processing. There are many recommendations for extending the battery life, such as charging tips, using the device regularly with a minimum of one charge cycle per month to keep the charge carriers moving inside the battery and, more importantly, to avoid a 'dead battery', i.e., total battery depletion. Other recommendations concern the optimisation of the settings of the mobile device. These settings include, for example, adjusting screen brightness, closing background applications and turning off Bluetooth to minimise power consumption of the mobile device. These have a considerable impact on improving power saving but nevertheless they are not efficient or even practical as they limit and restrict the usage of the updated new features of the smartphone.

Fig. 3-2 Recommendations for maximizing battery life

Battery power consumption is influenced by the running applications which differ from one device to another. Despite all the above-mentioned optimal device settings (Fig. 3-2), the performance of a smartphone's battery depends upon two major factors: (a) the Discontinuous Reception (DRX) process, which is studied in this work and, (b) the running applications on the device such as the mobile web browser and the specific web page. This second factor is not covered in this study. Nevertheless, several studies can be found in the literature about the impact of specific web pages/applications on battery consumption, such as the study in Ref. [3].

Batteries are introduced to the market with advertising terms such as longer life, higher capacity, ultra-power, heavy duty, fast charge and others which do not reflect any real industrial meanings. The performance of the batteries depends on the mechanism that organises the device's way of using them, and battery consumption is influenced by the running applications in a way which differs from one device to another, according to the manufacturer and the model of the device. Statistics such as the amount of time spent in usage and standby states may help in improving the current device's battery life, as power consumption changes between these two states.

The DRX process was proposed by 3GPP for power saving and prolonging the mobile's battery life and has a major impact on saving the battery power of the LTE UE. DRX employs timers to control the transmission and reception activities of the wireless terminal device. It, therefore, defines the moment to wake up, or the moment to enter into sleep mode and thus shuts down the receiver circuitry for a short period of time – if, of course, there are no packets coming from the eNB.

The following sections outline the procedures used to characterize the power-saving mechanism implemented by the current days' smartphones and other portable devices, and also show how these procedures may vary according to many conditions during the network operation.

3.2 Related work

The new multimedia services and features of today's smartphones are considered the main cause of draining mobile batteries. In order to conserve mobile battery power, the 3GPP has defined and specified a new mechanism, the discontinuous reception process DRX, for power saving and prolonging a mobile's battery life. As mentioned earlier, the idea of DRX is to shut off the receiver antennas for a while when there are no packets to be received from the eNB, or to shut off the receiver and buffer the data for a short time.

Many studies have been conducted to propose an adaptive algorithm in order to bring enhancements to the current DRX method. In [4] a dynamic DRX algorithm has been devised for UMTS systems in order to find the optimum value for the inactivity timer and the DRX cycle. Algorithm entries were based on the traffic patterns received from the end-user. When there are packets pending for some UEs and they are busy with high bursty traffic, the announcement period is shortened. Many scenarios were proposed such as to make the mobile station send a “ready” indication to the base station to indicate that the load is low or acceptable for receiving the pending packets. However, these indications cause additional signalling overheads to the base station, in addition to the high probability of collision occurrence when the number of mobile stations associated with the base station is high. An adaptive mechanism was proposed in [5] where one User Equipment (UE) or a group of UEs – with a similar QoS – adapt the DRX periods independently from the other UEs. This method requires introducing new temporary management and identification parameters in order to avoid possible collision among paging occasions. Also in this method, the NodeB needs to keep a record or queue for each end-user in order to detect its traffic characteristics and checks whether the record is empty or not, in order to judge each UE’s situation. This is impractical in large cells where packet transmission reliability and delays are considered main concerns. In [6] authors focused on the applications with a bursty nature of packets such as web browsing. The proposed system monitors only one UE without considering the uplink control channel. When a UE starts receiving data, with or without scheduling, an average estimate of power consumption is calculated. This study assumes a low mobility environment in order to avoid delays on the CQI reporting mechanism which affects the actual scheduling demands, especially when the UE is in sleep mode.

In [7] the authors presented an overview of the evolution of wireless local area networks for different standards and the newly-defined modes and processes for power saving. Different types of classes were defined for different management and multicast regulations. One of these is based on the idea that when the end-user sends a sleep request, it will enter into a sleep mode for intervals that will be double the previous period each time the UE is allowed to sleep by the base station (BS). However, the UEs are not notified to wake up until a specific number of packets is received, which adds more delays compared to other schemes.

In [8] the research work is focused on presenting a DRX algorithm over multiple services with new characteristics according to a carrier aggregation scheme over multiple component carriers. When an application starts between the eNB and UE, the QoS requirements are negotiated and established. Then one DRX session is awakened for every carrier component (CC) individually and the other components are left in inactivity mode. This method saves energy over the inactive components, and different carrier components may operate with different settings. However, the mentioned algorithm is applied without considering the HARQ process retransmissions which, if taken into account, will cause explosion of traffic over the radio channels, especially when the channel conditions are not optimal or the UE is located at the edge of the cell.

In [9] an analysis of the UE's energy consumption was presented, depending on the allocation of resource blocks upon the uplink. During the simulation, the number of resource blocks was increased and the transmission power distribution was examined. The scheduling process is done either in the frequency domain, when the UEs are allocated small numbers of resource blocks, or in the time domain if the number of UEs is high and occupying a large chunk of the bandwidth where it is very efficient to shorten the transmission time. This method examined the feasibility of fast control channel decoding against various possible patterns of data traffic without any implementation of power consumption mechanisms. The results showed that when applying fast control channel decoding instead of discontinuous reception, some of the control signals will be missed or delayed. These control signals may contain reference signals in the downlink frame which deliver the reference points for the power from the eNB. When missing these signals, the UE will not be able to do the necessary measurements to figure out the downlink cell power and hence will not be able to estimate the uplink power and pathloss.

The approach in Ref [10] proposed a method to support LTE machine-to-machine communication just for delay-tolerant services and applications, where the device is set to sleep for a very long period. The presented idea is based on extending the value of the DRX cycle to a length that exceeds the defined value in the 3GPP specification group. Many scenarios were simulated with different values of DRX cycles for machine-to-machine devices, smartphone devices and the data reporting period scenario. The results show that large amounts of energy could be saved when applying a longer DRX cycle; however the trade-off of this method is the long response time of the device when the network is trying to reach the intended device. Ref [11] shows modelling of the DRX algorithm for the machine-type communications in LTE systems. A semi-Markov chain was proposed and the packet arrival rate was the key for the UE to change its state and also it is used for calculating the stationary probabilities in order to estimate wake up delays and energy-saving parameters.

In [12] the researchers propose an energy-efficient sleep scheduling in LTE networks where a new downlink scheduler is proposed that is aware of the QoS factors that affect the performance for both network and associated UEs. Real time and non-real time traffic applications and channel conditions are considered in the process of assigning resources to the UEs. The proposed scheme is based on achieving high throughput by only assigning the resources to the UEs who report good channel conditions. This opportunistic assigning process, which works by prioritising UEs, has a main drawback – 'fairness' – which requires more balance between the UEs' demands and their spectrum efficiency. This method introduces a huge signalling overhead in terms of estimating data rates and modulation schemes for every UE upon every sub-channel in addition to calculating the average throughput and the UEs' buffer state and finally processing services for guaranteed bit rate and non-guaranteed bit rate flows.

The study in [13] aims to autonomously adjust the DRX cycle in order to follow UE activity changes. Two counters are introduced in order to follow the silent and active periods at the UE and eNB. When any of the timers reach a pre-defined threshold, the DRX cycle is increased or decreased autonomously depending on the fact that both the UE and the eNB are aware of data transmission between them. In [14] the DRX optimisation is based on District Time Semi Markov. The traffic condition is estimated in a time period of one second in order to obtain the optimal DRX parameters configuration. The proposed power-saving strategy considers two scenarios in trade-off between latency and power saving.

In [15] an adaptive DRX scheme uses the actual number of awake and connected UEs to adjust the On Duration timer, and Channel Dependent Scheduling to adapt the inactivity timer. In this way, energy is saved. However, the number of connected UEs does not reflect the actual impact of the activity level of each UE, since some UEs may have voice calls and thus require fewer resources compared to other connected UEs who are running video sessions. Hence, a change in the number of less effective UEs causes DRX parameter modification, which may affect the performance of other more effective UEs.

Other studies [16, 17] presented an analytical and numerical analysis of DRX and power saving for LTE systems and previous technologies such as UMTS. The studies evaluated the power consumption over different configurations and assumptions for DRX parameters and over different services and applications. Many operational states and conditions for UEs were defined and described. Simulation results highlighted the importance of applying such energy conservation techniques in today's wireless networks and showed that the trade-off between power saving and delay constrains satisfaction.

In this work, the impact of the DRX process is analysed. Although DRX is created to save power, the evolving technology has extended the effects of this mechanism to the whole system and application performance, [18]. In this contribution, a centralised adaptive scheme is proposed to avoid limitations, such as overheads and the trade-off between delays and power saving, with consideration given to the performance of other running processes such as HARQ, scheduling and handovers.

3.3 Preliminaries

3.3.1 Problem formulation

3GPP LTE transfers data over wide bandwidths with lower transmission delays; this high speed data transmission drains the UE's battery. The rich 4G services and applications with their complex circuitry designs, which obviously require a lot of power, also add a more exhausting load to the UE's battery. Therefore optimising the power consumption of UEs' equipment is an important issue in today's wireless networks [19]. In the future, it seems that there will be good opportunities for improving the energy consumption efficiency of power-hungry devices. The DRX mechanism was proposed before the launch of LTE, and it has been applied in 2G systems such as GSM; it was then continued to be used in UMTS with more enhancements to achieve a longer battery life and power efficiency [20]. DRX for LTE has been introduced with many differences such as sleeping occasions over long periods, even if there is data being buffered which is dedicated to the intended UE. The algorithm is made more efficient by introducing new timers and setting a new specification; it is managed and controlled by the radio resource control (RRC). However, the static nature of the present LTE DRX algorithm causes degradation of system performance, especially with real-time applications in terms of packet latencies and connection re-establishments. After introducing multimedia applications, many developments were introduced to DRX without considering the effects on the QoS requirements. When considering the DRX process, this means taking into account the process configurations, the QoS needs and the power limitation of the end-user's battery. These three critical factors together have an essential role in achieving the required efficiency level and performance optimisation. The problem of DRX optimisation can be formulated by considering an eNB with a number of associated UEs. Each UE has been assigned a number of GBR and non-GBR flows and each flow has QoS demands in terms of packet loss and latency. The packet interarrival time may cause a serious problem for some sensitive delay applications if the interarrival time in-between is very short. This makes it very difficult for the network to predict the optimal time for the intended UE to be scheduled. Moreover, the scheduling process may trigger overheads upon both the uplink and the downlink when sending NACKs and retransmissions, especially over the downlink, which will cause extra delays and requires the UEs to be scheduled later or when they have been granted priorities by the network scheduling algorithms. The problem is how to find the optimum DRX parameters so that the available resources are scheduled and delivered to each UE fairly, and how to develop the current static DRX process to a dynamic DRX process without introducing any signalling overhead to the already saturated eNB, or without extending the specified values of the current 3GPP standard. Sometimes, the values of DRX parameters such as ON Duration timer, Inactivity timer and DRX cycle are optimised accurately; however, when applying these values on the DRX process in a real network, they hamper the QoS requirements and lead to critical situations which are not suitable for the UE. This raises a question about the best switching time estimation between the IDLE mode and the CONNECTED mode and how to avoid the miss-match between the theoretical principles and real implementation. The estimated transaction time between sleeping and waking up for UE in critical situations is in the order of tens of milliseconds [21]. This increases the overall energy usage and sometimes the energy consumed by one transaction exceeds the energy consumed in the IDLE mode. On the other hand, a detailed investigation needs to be carried out to optimise the operation of the RF transceiver which is the dominant part of the mobile station in terms of responsibility for the majority of the power consumption. In order to extend and exploit the usefulness of DRX and prevent the worst case scenarios, there is a need for a centralised dynamic DRX in which the network decides the times when the UE sleeps and when it wakes up to provide an accurate timing match. This gives rise to many questions, such as making decisions about the best period for sleep and wake up intervals, and what the result would be if the sleep interval is too short and the wake up interval is very long or vice-versa. Modelling the correct operating DRX process with different types of traffic, such as bursty or streaming, using real 4G LTE traffic is the main contribution of this proposed method and affords its superiority over the legacy technologies. The realisation of DRX is not a simple process because it requires a high level of synchronisation between the UE and the eNB, plus it needs to take into account critical situations, especially in the presence of many timers operating together. The presented algorithm must help to overcome the high power consumption, and the DRX parameters could be optimised depending on the LTE real network traffic and also depending on the actual channel condition. Dedicated physical channels in LTE have an essential role in separating data flows between the eNB and the UE, in addition to removing implementation complexity inherited from previous systems.

3.3.2 LTE DRX mechanism overview

3.3.2.1 Introduction

The nature of packet data traffic is sometimes very bursty where the transmitter sends packets over periods of times before it enters into silence for longer periods. For a receiver it is obviously helpful to monitor the control channel over the downlink in order to decode the dedicated subframes and receive the uplink transmission permissions or the downlink transmitted traffic. Clearly this continuous monitoring of the downlink control channel comes at the expense of a huge power consumption of the UE's battery. The complex design of 4G devices' circuitry requires inclusion of a mechanism of discontinuous reception (DRX) in order to reserve the energy of the devices' battery.

The DRX mechanism is based on DRX cycles on the UE's side. The configuration of the cycle on the UE terminal means that it is only active during regular periods. The smallest component of the DRX cycle is the subframe (which equals 1 ms duration). The UE monitors the downlink control channel for a list of subframes during one DRX cycle and shuts off its receiver circuitry for the rest of the cycle. This mechanism has a great impact on power consumption reduction. The amount of saved energy is directly proportional to the length of the DRX cycle. However, this requires a more aware scheduling mechanism so that the UE is scheduled during the active subframes.

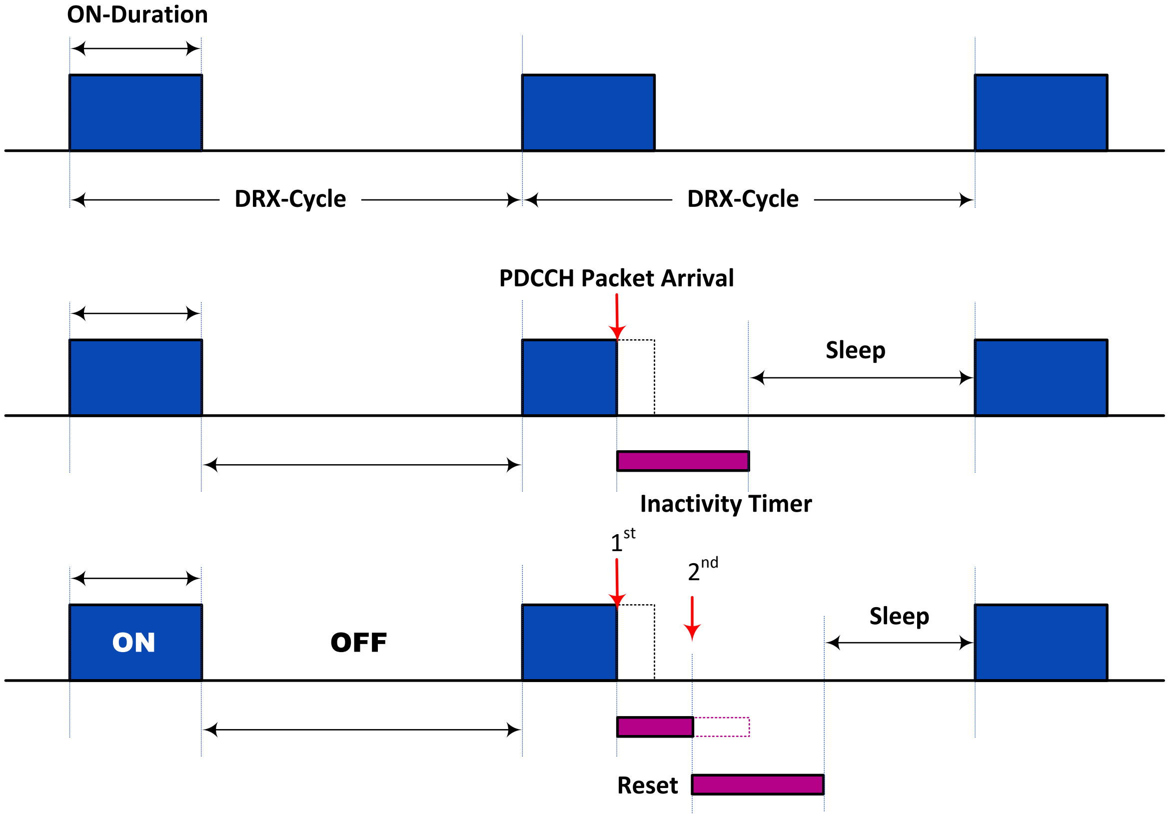


Fig. 3-3 DRX cycle and parameters

The matter of delays is critical in the DRX process. If the UE is scheduled and granted resources over the active period, what will happen if the active period expires and the UE enters into a sleeping period? This implies that the dedicated data is buffered and the UE needs to be scheduled again soon to complete transmitting the buffered data. The UE then has to wait for another cycle to complete transmission, while it may need just a few subframes to finish. This introduces unnecessary delays to the process. In order to avoid such delays, the UE is configured to stay active if it can decode the dedicated channel correctly. To do so, a new timer is introduced to the process and this timer is started, or re-set to zero, every time the UE discovers that there is dedicated data for it. For applications which transmit over regular periods and then hold for other periods, the DRX process is configured to operate over short cycles. This is very efficient with predictable applications and services. For example, the coding mechanism of voice could estimate when to deliver the packets of coded voice. Therefore the DRX cycle is set to a short period equal to the delivered packet period. For longer periods of silence between the voice flows, a long DRX cycle is applied to maintain the efficiency.

The impact of DRX on power saving during sleep and active periods is clearly shown in Fig. 3-3 which describes the DRX timing.

The DRX cycle covers two periods, the active period and the sleep one. The minimum cycle length is 2 ms (2 subframes). If the DRX parameters are configured on the UE but the UE is not following the DRX process, then the UE is considered to be in normal state or inactive state. The DRX state of the UE is defined through three states:

-DRX Inactive or Normal state: during this state the UE is in full operation where it can send and receive data.

-DRX Active: during this state the UE does not transmit over the uplink, but only listens to the downlink frame.

-DRX Sleep: during the sleep period, the UE does not have any activity over the uplink or the downlink. In this period the majority of the UE's battery power is saved.

3.3.2.2 DRX states during operation

During DRX operation, each state has different power consumption levels. There are various DRX states and many operating timers during the DRX process:

3.3.2.2.1 DRX Inactive (or Normal)

This state has the highest power consumption level. It is called normal because the UE is in normal operation during this state. The UE stops its DRX process in two cases: either if it has a higher level data to transmit over the uplink to the eNB, or when it receives data successfully over the downlink and starts the Inactivity timer.

- The UE starts the inactivity timer when it decodes the download control channel successfully. The minimum value of this timer is 1 ms.

- If the UE is in the normal state and running the inactivity timer, when it receives new downlink data, it resets the timer to zero and starts again.

- The UE returns to the power saving mode and starts the DRX process when the Inactivity timer expires without receiving any downlink data.

- The UE will not be able to avoid power consumption efficiently if it moves to the normal state when running the DRX process [22].

3.3.2.2.2 DRX Active

This state is very important to the UE. It is the first part of the DRX cycle; during this part the UE is considered active when it enters the RRC-Connect mode. The operating timer throughout this period is the On Duration timer and it is measured by means of subframes (the minimum value of On Duration is 1 ms). The UE's mission in this state is to receive the physical download control channel (PDCCH) and scan it to find out if there is any dedicated download control information for it. The successful arrival and reception of such data stops the DRX cycle and starts the Inactivity timer. Power saving starts to take place during this period as the UE is not transmitting any uplink data but just receiving the downlink information over the On Duration period.

3.3.2.2.3 DRX Sleep

The DRX sleep state is the second part of the DRX cycle, and it starts after the On Duration timer expires. The operating timer during this period is the Sleep timer. The eNB buffers the data during this period until the DRX cycle is active again. This period delivers maximum power saving as the UE does not transmit or receive any data over the uplink or the downlink. To avoid delays resulting from this state, the eNB will transmit packets to the UE over the downlink once it discovers any UE activities upon the uplink. If nothing interrupts the UE's sleeping period, a longer DRX cycle is configured. This is applied when the UE does not receive any data during the On Duration period following the first DRX sleep period. The UE will follow the same DRX functionality during a Long DRX cycle, but with a longer Sleep timer period. It is preferable that the period of Long DRX cycle is in the order of Short DRX cycle multiplications.

3.3.2.3 DRX mode

LTE modes are RRC-Connected and RRC-Idle mode, and it is possible to configure DRX on both modes. In the Idle mode the UE is just paged for the downlink data while in the connected mode, the UE is in full operation for transmission and reception, and the DRX may be initiated during the idle periods of packets arrival.

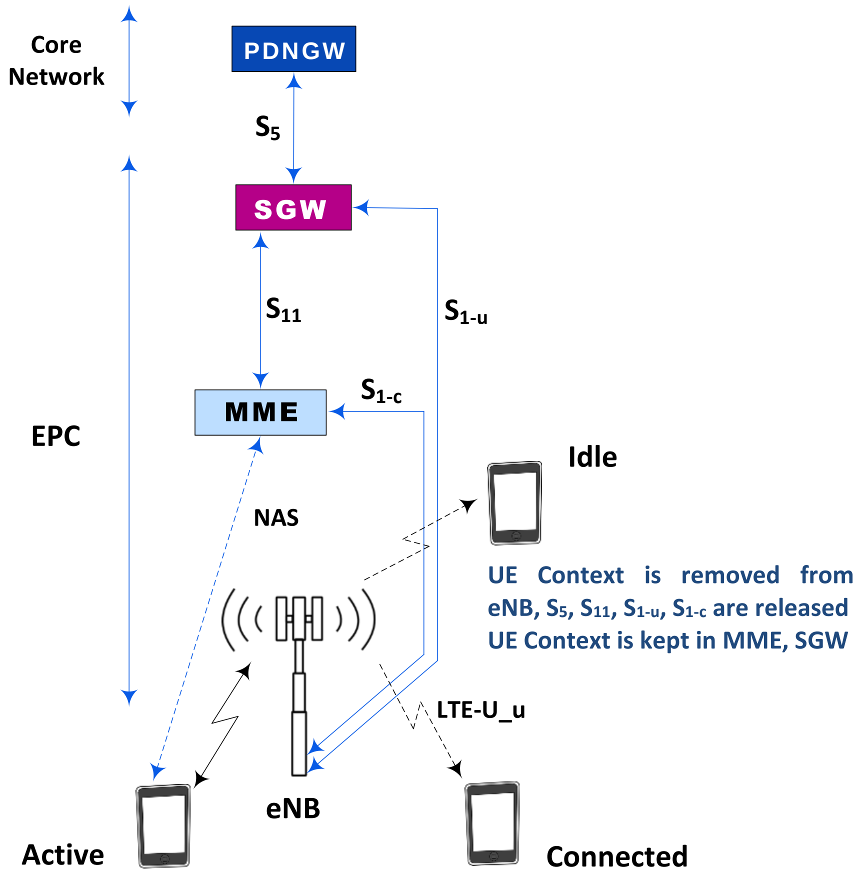


Fig. 3-4 DRX modes

Fig. 3-4 shows the different configurations of DRX modes with the EPC interface. The NAS, S1 and other RRC connections are active in the Connected mode while in the Idle mode, all the mentioned connections are removed.

3.3.2.3.1 DRX in LTE RRC-Connected state

DRX may be configured in the RRC-Connected mode automatically if the inactivity timer expires without arrival of any downlink data, or it can be configured by the eNB by sending the MAC Control Element of the DRX Command to the UE. For the start of the DRX process an offset is used and transmitted by the eNB to initiate the DRX on the UE. A RRC-Connection start up message is sent with the offset value. Upon receiving the offset value, the UE configures it at the start of the next frame following the reception of the RRC message. Both the UE and the eNB follow the same procedure to calculate the offset, and thus synchronisation is maintained [23] (Fig. 3-5).

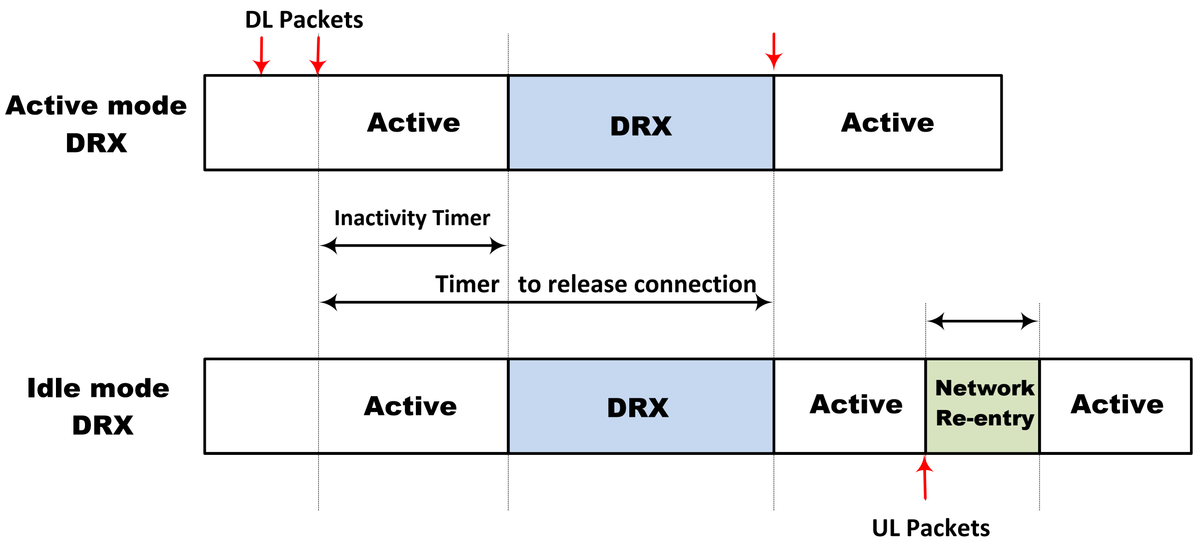


Fig. 3-5 DRX RRC Connected state

3.3.2.3.2 DRX in LTE RRC-Idle state

The eNB starts the process to release the UE context and the MME also releases the S1 connection (Fig. 3-4) upon receiving request from the eNB to do so. When there is data dedicated to the UE, it is paged by the eNB and the UE starts to activate its EMM connections. The SGW discovers the data dedicated to the UE, and then the EMM communicates with all associated eNBs to find out where the UE is located. Once discovered and reached, the UE is paged with the DRX parameters through the serving eNB [24].

3.4 Analytical study

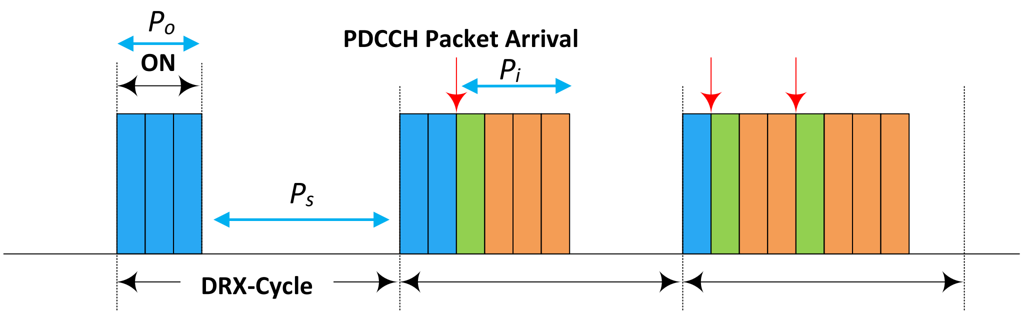
In [25, 26] the researchers conducted a mathematical study to calculate delays and power consumption. However, in the presented studies, Inactivity timer is not reset at the arrival of the message which is not accurate because the value of the sleeping period depends on the On Duration and the time elapsed from Inactivity timer in response to the message arrival. This will be considered in the following study in addition to taking into account the possibility that no message may arrive during the On Duration period.

3.4.1 Power consumption

The energy consumed by the UE for the arrival of one PDCCH message over one DRX cycle is calculated by adding together these values:

$$P_{DRX} = P_r + P_o + P_i + P_s \qquad (3.1)$$

- The energy consumed on the reception of the control message (over on TTI which equals to 1 ms) P_r
- The energy consumed over the On Duration period P_o (excluding the On Duration TTI(s) covered by the Inactivity timer and the one TTI of reception)
- The energy consumed over the Inactivity period P_i (taking into account the possibility that one or more message may arrive).
- The energy consumed over the sleeping period P_s



ON-Timer	3	2	1	0	0	0	0	0	0	0	3	2	1	0	0	0	0	0	0	0	3	2	1	0	0	0	0	0	0	0
IN-Timer	0	0	0	0	0	0	0	0	0	0	0	0	4	3	2	1	0	0	0	0	0	4	3	2	4	3	2	1	0	0

Fig. 3-6 DRX timers for packets' arrival

By considering all the arrival possibilities on the On Duration TTIs (Fig. 3-6), the average energy consumed over one DRX cycle is calculated by multiplying the power values P_{DRX} by their probabilities R and adding them up:

$$E_{DRX} = R_1 * P_{DRX-1} + R_2 * P_{DRX-2} + \ldots\ldots\ldots. + R_{ON} * P_{DRX-ON} \qquad (3.2)$$

The probabilities are calculated according to the arrival of the control message; if the message arrives at the UE on the first TTI (first subframe, n=1) of the On Duration, the probability is R_1 and so on. Therefore the value of R is the probability of decoding a valid control message during the On Duration timer and it is equal to (1/ON).

Where: "ON" is the value of the On Duration timer, "IN" is the value of the Inactivity timer.

Thus the average for each period is:

$$E_{DRX} = \sum_{n=1}^{Timer\ Value} R_n * P_{DRX-n} = \frac{1}{Timer\ Value} \sum_{n=1}^{Timer\ Value} P_{DRX-n} \qquad (3.3)$$

Derivation of the formula of P_{DRX-n} as a function of subframe number (n):

The energy consumed over the On Duration period P_o (taking into account the possible arrival of the control message) – μ indicates the total number of received messages ($0 \leq \mu$):

$$P_O = ON * P_a * \left(1 - \frac{\mu|\mu - 1|!}{\mu!}\right) + \left((n_1 - 1) * P_a + P_r\right) * \left(\frac{\mu|\mu - 1|!}{\mu!}\right) \qquad (3.4)$$

$$(P_a : operating\ power\ in\ active\ state)$$

$$\left(\frac{\mu|\mu - 1|!}{\mu!}\right) equals\ to: \ 0\ if\ \ \mu = 0\ or\ \ 1\ if\ \mu > 0$$

The energy consumed over the Inactivity period P_i (taking into account the possibility of no messages arriving, or one or more arriving) μ *is* the number of arriving messages during the inactivity period:).

$$P_i = \left(\left((\mu - 1) * P_r\right) + (n_\mu - n_1 - \mu + 1 + IN) * P_{in}\right) * \left(\frac{\mu|\mu - 1|!}{\mu!}\right) \qquad (3.5)$$

$$(P_{in} : \ operating\ power\ in\ normal\ or\ inactive\ state\ )$$

The energy consumed over the sleeping period P_s is:

$$P_s = \left(DRX_s - \left(IN - ON + n_\mu\right) * \left(\frac{\mu|\mu - 1|!}{\mu!}\right)\right) * \ (operating\ power\ in\ sleep\ state\ P_{sl}) \qquad (3.6)$$

Where DRX_S is the amount of time the UE is not sending/receiving any data while its DRX cycle is running.

The consumed energy over one DRX cycle is:

$$P_{DRX-n} = ON * P_a * \left(1 - \frac{\mu|\mu - 1|!}{\mu!}\right) + \left((n_1 - 1) * P_a + P_r\right) * \left(\frac{\mu|\mu - 1|!}{\mu!}\right)$$

$$+\left(\left((\mu-1)*P_r\right)+(n_\mu-n_1-\mu+1+IN)*P_{in}\right)*\left(\frac{\mu|\mu-1|!}{\mu!}\right)$$

$$+\left(DRX_{cycle}-ON-\left(IN-ON+n_\mu\right)*\left(\frac{\mu|\mu-1|!}{\mu!}\right)\right)*P_{sl}$$

$$P_{DRX-n}=\mu*P_r+\left(ON*\left(1-\frac{\mu|\mu-1|!}{\mu!}\right)+\left((n_1-1)\right)*\left(\frac{\mu|\mu-1|!}{\mu!}\right)\right)*P_a$$

$$+\left(n_\mu-n_1-\mu+1+IN\right)*\left(\frac{\mu|\mu-1|!}{\mu!}\right)*P_{in}$$

$$+\left(DRX_{cycle}-ON-\left(IN-ON+n_\mu\right)*\left(\frac{\mu|\mu-1|!}{\mu!}\right)\right)*P_{sl} \quad (3.7)$$

The average consumed power as a function to the DRX timers:

$$E_{DRX}=\frac{1}{Timer\ Value}\sum_{n=1}^{Timer\ Value}P_{DRX-n}$$

$$E_{DRX}(\mu)=\mu*P_r+\left(ON*\left(1-\frac{\mu|\mu-1|!}{\mu!}\right)+\left(\left(\frac{ON+1}{2}-1\right)\right)*\left(\frac{\mu|\mu-1|!}{\mu!}\right)\right)*P_a$$

$$+\left((\mu-1)*\left(\frac{IN+1}{2}\right)-\mu+1+IN\right)*\left(\frac{\mu|\mu-1|!}{\mu!}\right)*P_{in}$$

$$+\left(DRX_{cycle}-ON-\left(IN-ON+\frac{ON+1}{2}+(\mu-1)*\left(\frac{IN+1}{2}\right)\right)*\left(\frac{\mu|\mu-1|!}{\mu!}\right)\right)*P_{sl}$$

$$E_{DRX}(\mu)=\mu*P_r+\left(ON-\left(\frac{ON+1}{2}\right)*\left(\frac{\mu|\mu-1|!}{\mu!}\right)\right)*P_a$$

$$+\left((\mu+1)*\left(\frac{IN+1}{2}\right)-\mu\right)*\left(\frac{\mu|\mu-1|!}{\mu!}\right)*P_{in}$$

$$+\left(DRX_{cycle}-ON-\left(IN+\frac{1-ON}{2}+(\mu-1)*\left(\frac{IN+1}{2}\right)\right)*\left(\frac{\mu|\mu-1|!}{\mu!}\right)\right)*P_{sl} \quad (3.8)$$

In the case that no message arrives at all, this means that the value of μ is 0, therefore the average power consumption is:

$$E_{DRX}(0)=ON*P_a+\left(DRX_{cycle}-ON\right)*P_{sl} \quad (3.9)$$

One message arrives: (μ=1)

$$E_{DRX}(1) = P_r + \left(\frac{ON-1}{2}\right) * P_a + IN * P_{in} + \left(DRX_{cycle} - IN - \left(\frac{ON+1}{2}\right)\right) * P_{sl} \tag{3.10}$$

Two messages arrive: (μ =2)

$$E_{DRX}(2) = 2 * P_r + \left(\frac{ON-1}{2}\right) * P_a + \left(\frac{3*IN-1}{2}\right) * P_{in} + \left(DRX_{cycle} - \left(\frac{3*IN-1}{2}\right) - \left(\frac{ON+1}{2}\right)\right) * P_{sl} \tag{3.11}$$

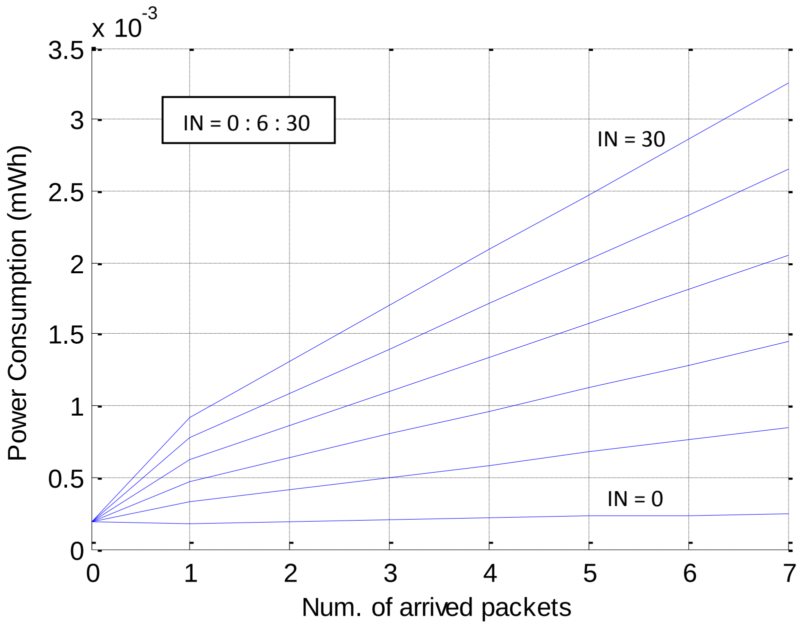


Fig. 3-7 Power consumption according to packets' arrival

From the previous formula, it is obvious that the arrival of more control messages will increase the power consumption dramatically and the value of the Inactivity timer has a great impact on power consumption, as illustrated in Fig. 3-7.

3.4.2 Delays

Calculating delays is different to calculating power consumption. When considering power consumption, the On Duration and Inactivity timers are not correlated since the arrival of a packet will automatically reset the Inactivity timer. However, when considering delays, the arrival of each packet depends conditionally on the arrival of the previous ones (Fig. 3-8).

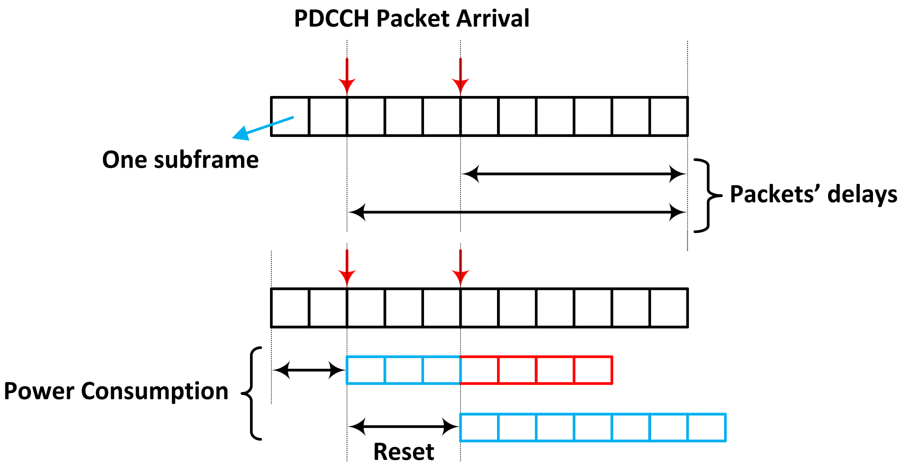
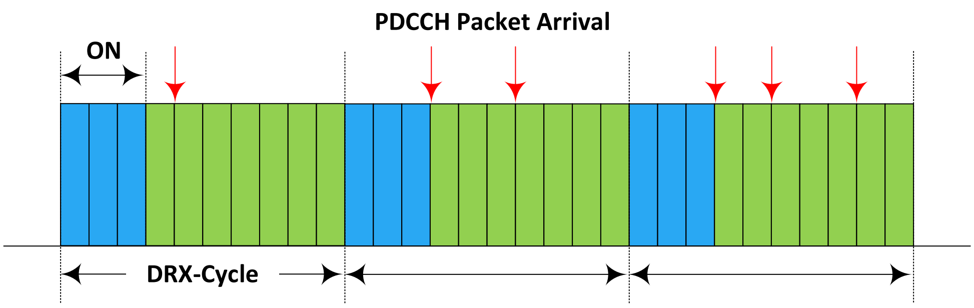


Fig. 3-8 DRX consideration of power and delays

While the DRX is running, messages may arrive during the sleeping period. The UE will not be able to pick up the message until the next active period. The time elapsed between message arrival and the next active period is an undesired delay and has an essential impact on the setting of the DRX parameters (Fig. 3-9).



ON-Timer	3	2	1	0	0	0	0	0	0	0	3	2	1	0	0	0	0	0	0	0	3	2	1	0	0	0	0	0	0	0
d_1	0	0	0	0	1	2	3	4	5	6	0	0	0	1	2	3	4	5	6	7	0	0	0	1	2	3	4	5	6	7
d_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	4	0	0	0	0	0	1	2	3	4	5
d_3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2

Fig. 3-9 DRX delays for packets' arrival

Delays depend on the sleeping period and the latter varies according to the number of messages arriving during the On Duration and Inactivity timers.

If the message arrives during the sleeping periods, the delay is equal to the number of subframes counted until the next On Duration period (Fig. 3-10).

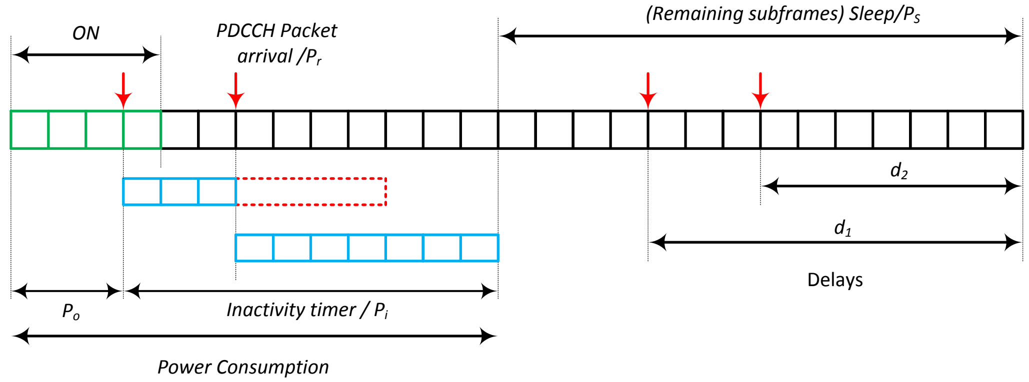


Fig. 3-10 DRX analytical model

Consider T as the duration of the sleeping period; the probability of message arrival upon the subframe number n is therefore 1/T. By considering all the arrival possibilities of one message during the TTIs sleeping duration, the average delay over T is calculated by multiplying the delay values d_n by their probabilities 1/T and adding them up:

Generalising the formula for K messages arrival during the sleeping period T:

If one message arrives:

$$D(1)_{average} = \frac{1}{T}\sum_{d_1=1}^{T} d_1 = \frac{T+1}{2} \tag{3.12}$$

In case two messages arrive, we have to consider all the possible arrival formulations that may occur:

$$D(2)_{average} = \left(\frac{1}{2}\right) * \left(\frac{1}{T-1}\sum_{d_1=2}^{T}\left(\frac{1}{d_1-1}\sum_{d_2=1}^{d_1-1}(d_1+d_2)\right)\right)$$

$$= \left(\frac{1}{2}\right) * \left(\frac{1}{T-1}\sum_{d_1=2}^{T}\frac{3d_1}{2}\right) = \frac{3(T)(T+2)}{8(T-1)} \tag{3.13}$$

When three messages arrive:

$$D(3)_{average} = \left(\frac{1}{3}\right) * \left(\frac{1}{T-2}\sum_{d_1=3}^{T}\left(\frac{1}{d_1-2}\sum_{d_2=2}^{d_1-1}\left(\frac{1}{d_2-1}\sum_{d_3=1}^{d_2-1}(d_1+d_2+d_3)\right)\right)\right)$$

$$D(3)_{average} = \frac{T(T+1)(7T+27)}{24(T-2)(T-1)} \tag{3.14}$$

When K message(s) arrive(s) during sleeping period T:

$$D(K)_{average} = \left(\frac{1}{K}\right) * \left(\frac{1}{(T-K+1)} \sum_{d_1=K}^{T} \left(\frac{1}{(d_1-K+1)} \sum_{d_2=K-1}^{d_1-1} \ldots\ldots\ldots \right.\right.$$

$$\left.\left.\ldots\ldots. \sum_{d_{K-1}=2}^{d_{K-2}-1} \left(\frac{1}{d_{K-1}-1} \sum_{d_K=1}^{d_{K-1}-1} (d_1 + d_2 + \ldots\ldots + d_K)\right)\right)\right) \tag{3.15}$$

$$D(K)_{average} = \frac{1}{K(T-K+1)} \sum_{d_1=K}^{T} F(K)$$

$$F(K) = \frac{1}{(d_1-K+1)} \sum_{d_2=K-1}^{d_1-1} \ldots\ldots\ldots. \sum_{d_{K-1}=2}^{d_{K-2}-1} \left(\frac{1}{d_{K-1}-1} \sum_{d_K=1}^{d_{K-1}-1} (d_1 + d_2 + \ldots\ldots + d_K)\right) \tag{3.16}$$

The value of T may vary according to the arrival of messages during the ON periods. If no messages arrive during ON periods; the value of T is equal to:

$$T(0) = DRX_{cycle} - ON \tag{3.17}$$

If one message arrives during the On Duration period at the n[th] subframe, the value of T decreases to:

$$T(1) = DRX_{cycle} - n_1 - IN \tag{3.18}$$

For μ message(s) arriving during On Duration period and Inactivity period, the general formula is:

$$T(\mu) = DRX_{cycle} - n_\mu - IN$$

$$T(\mu) = DRX_{cycle} - ON - (-ON + IN + n_\mu) * \left(\frac{\mu|\mu-1|!}{\mu!}\right) \tag{3.19}$$

The average value is:

$$T_{average}(\mu) = DRX_{cycle} - ON - \left(-ON + IN + \frac{1}{ON}\sum_{n_1=1}^{ON} n_1 + (\mu-1) * \frac{1}{IN}\sum_{n_{\mu-1}=1}^{IN} n_{\mu-1}\right) * \left(\frac{\mu|\mu-1|!}{\mu!}\right)$$

$$T_{average}(\mu) = DRX_{cycle} - ON - \left(IN + \frac{1-ON}{2} + \frac{(\mu-1)(IN+1)}{2}\right) * \left(\frac{\mu|\mu-1|!}{\mu!}\right) \tag{3.20}$$

The average delay formula:

$$D(\mu, K)_{average} = \frac{1}{K(T(\mu) - K + 1)} \sum_{d_1=K}^{T(\mu)} F(K) \qquad (3.21)$$

Fig. 3-11 shows the average delays according to the number of packets arriving during the ON and sleeping periods, as represented by equation (3.21).

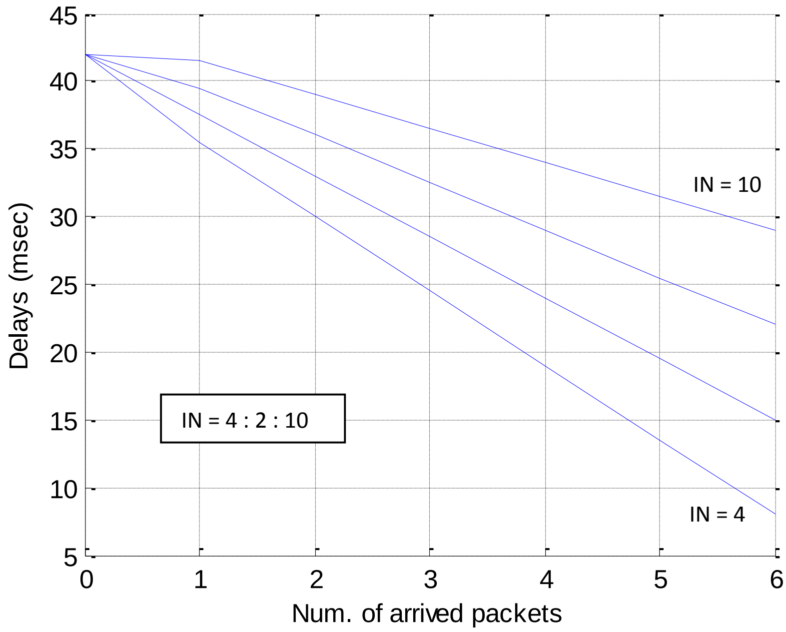


Fig. 3-11 Delays according to packet arrival

3.4.3 Wake up optimising procedure

In the ideal case for both the RRC-Connected and RRC-Ideal states, the UE switches from the idle to the active state without switching delays or any transitional power consumption. However, in real hardware circuits, there is a switching time that is not negligible, especially when implementing short DRX cycles where the UE transits more frequently between active and ideal states (Fig. 3-12).

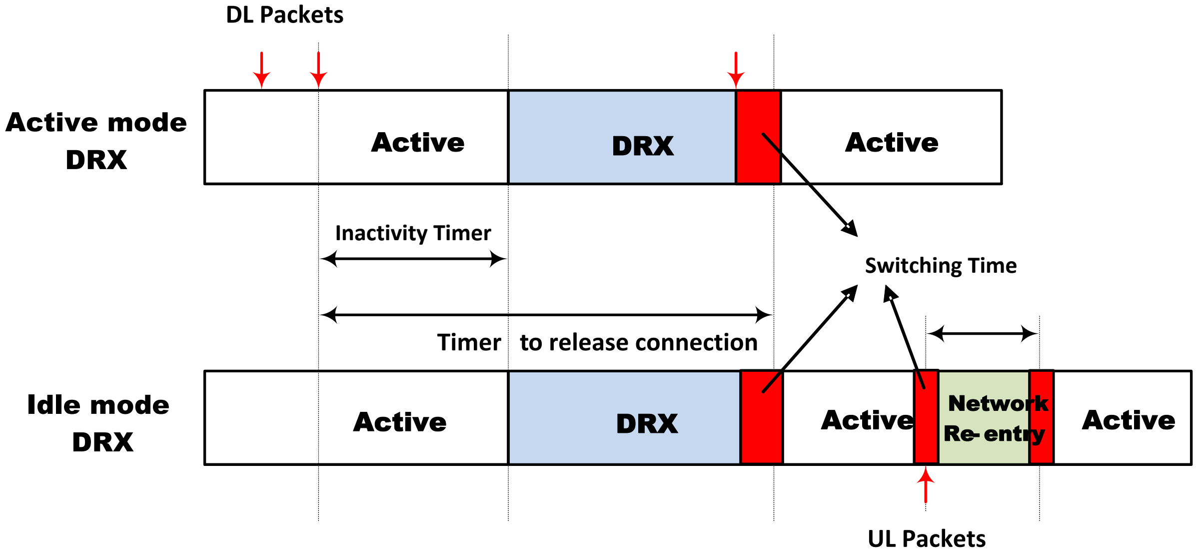


Fig. 3-12 Switching time for RRC Connected & RRC Ideal states

The transceiver in the UE consists of a series of consecutive circuits, including for example the coordinator, interleaver, mapper, modulator, and RF up convertor on the transmitter and the corresponding circuits on the receiver (Fig. 3-13). There is also the power amplifier which is responsible for most of the consumed power on the transceiver. All the aforementioned parts, and other parts, cause uncertainty over power consumption and associated delays. This circuit design makes switching between on and off periods totally different from the ideal proposed schemes; the difference is relative and manufacturer dependent. Each block or circuit in the transceiver diagram needs a raising time to reach stability and to start working normally.

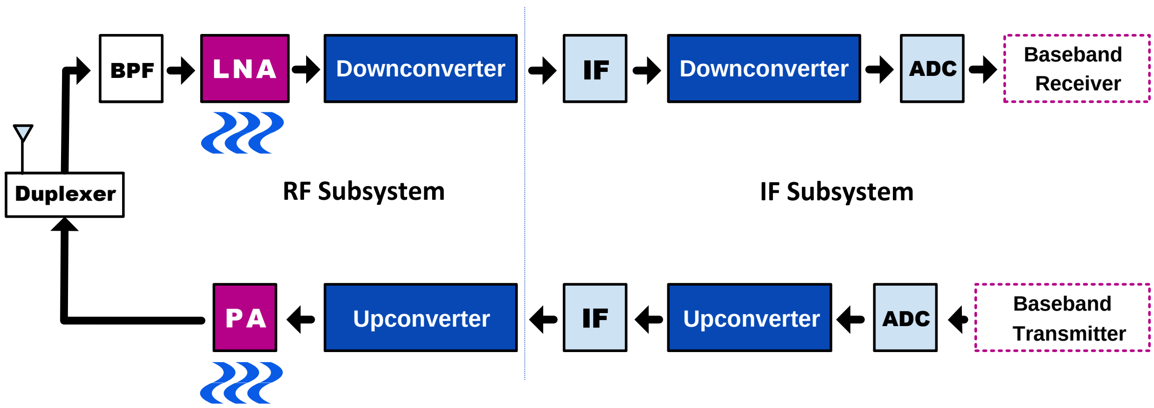


Fig. 3-13 The power amplifier in the transceiver circuit

The study published in [21] shows that due to the power management schemes (request/response process), the time needed for a wireless machine to wake up from a deep sleep state to an active state may be in the range of 2ms to 100ms. This transition period is accompanied with additional power consumption for every (ms) and the transition time, if it is high, may be equivalent to several DRX cycles and causes jitter.

Delays are expected during transmissions and receptions in wireless networks. There are processing delays which are difficult to predict and thus they are assumed for every packet. Every received packet undergoes delays during processing. In the LTE system standard, processing delays are assumed to be in the range of 3 subframes (or 3ms) for the reception of MPDUs and also 3 subframes for acknowledgment and non-acknowledgment for the hybrid automatic repeat request process [27]. The accumulated delays for a round trip time are expected to be at least 3 subframes for the TDD systems, depending upon the frame type, and about 8 subframes for the FDD systems (Fig. 3-14).

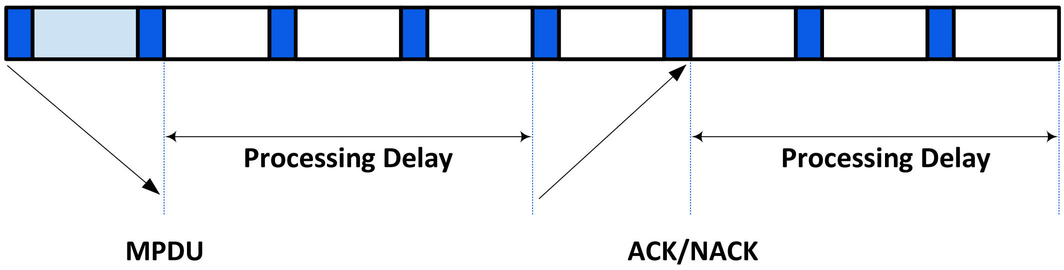


Fig. 3-14 MPDU transmission

Light sleep is proposed when the remaining part of the DRX mechanism is very short; therefore there is no need to go into deep sleep. When the UE is in light sleep mode, it turns off only part of its circuitry, hence reducing the time needed for transition from the sleep state to the active state. However, this will be at the expense of extra power consumption compared with deep sleep because some of the transceiver components are left on. To make the optimum use of light sleep advantages, it has to be performed over the shortest possible period. On the other hand, deep sleep saves energy more than light sleep; therefore it is useful when implemented. However it is better to be followed by a light sleep period in order to avoid any delays accompanied with the transition states.

The following example, (Fig. 3-15), shows the calculations of the optimal period when the UE has to truly wake up and start the active period in order to avoid DRX performance degradation.

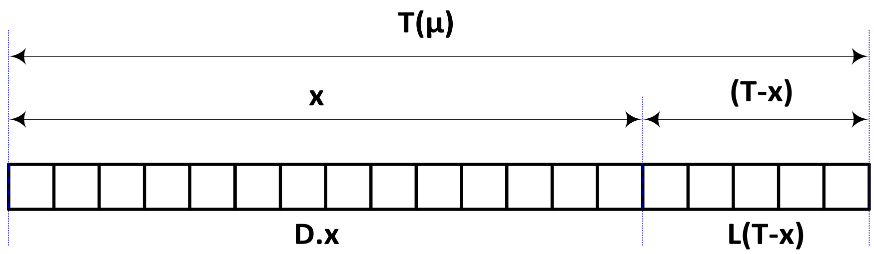


Fig. 3-15 Optimal wake up period model

$$Time_L * Power\ Consumption_L \leq Time_D * Power\ Consumption_D$$

$$L * (T - x) + 0.32 \leq D * (T - x) + 50$$

$$25T - 25x + 0.32 \leq 10T - 10x + 50$$

$$x \geq \frac{15T - 49.6\ 8}{15} \quad , \quad T - x \geq 2 \tag{3.22}$$

For light sleep, the actual measurements for power consumption and delays are:

$$P_s = \left(DRX_s - (IN - ON + n_\mu) * \left(\frac{\mu|\mu - 1|!}{\mu!}\right)\right) * P_l + 10\mu s * 32mW \tag{3.23}$$

$$(P_l\ is\ the\ operating\ power\ in\ light\ sleep\ state\ \ (\sim 25mW))$$

$$D(\mu, K)_{average} = \left(\frac{1}{K(T(\mu) - K + 1)} \sum_{d_1 = K}^{T(\mu)} F(K)\right) - 10\ \mu s \tag{3.24}$$

For deep sleep:

$$P_s = \left(DRX_s - (IN - ON + n_\mu) * \left(\frac{\mu|\mu - 1|!}{\mu!}\right)\right) * P_d + (transition\_time\ ms) * 25mw \tag{3.25}$$

$$(P_d\ is\ the\ operating\ power\ in\ deep\ sleep\ state\ = P_{sl})$$

$$D(\mu, K)_{average} = \left(\frac{1}{K(T(\mu) - K + 1)} \sum_{d_1 = K}^{T(\mu)} F(K)\right) + (transition\_time\ ms) \tag{3.26}$$

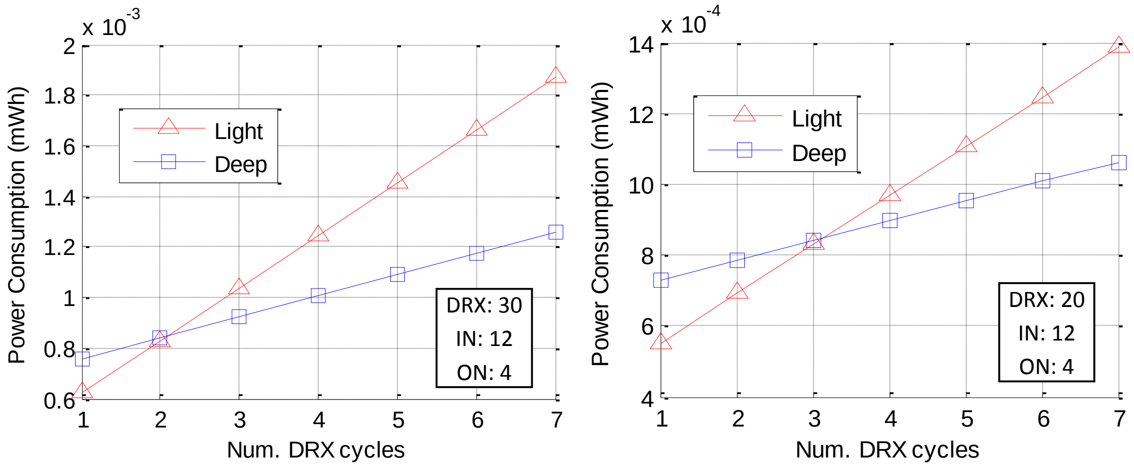


Fig. 3-16 Power consumptions vs. Number of DRX cycles

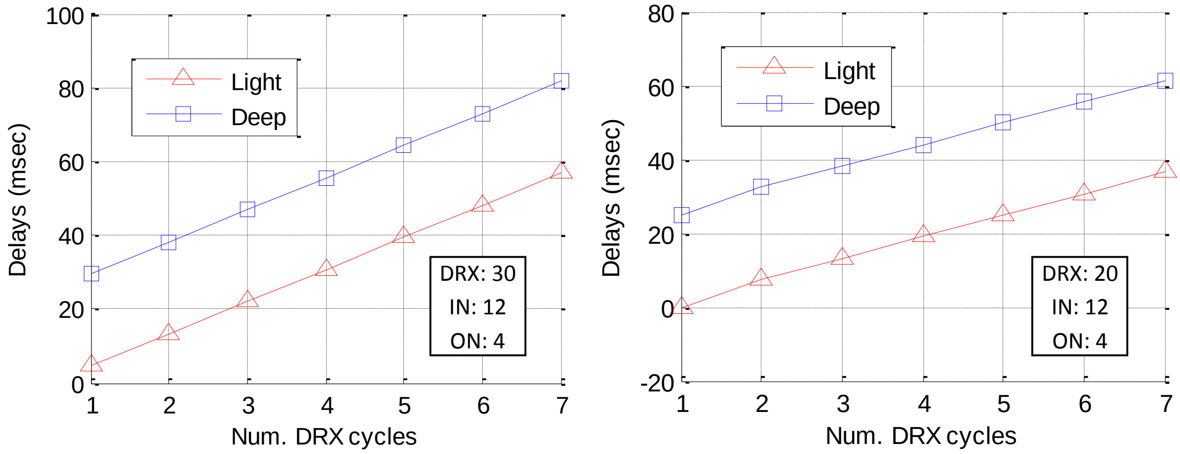


Fig. 3-17 Delays vs. Number of DRX cycles

When using multiples of short DRX, the number of cycles varies according to which number of cycles gives the lowest power consumption for a certain set of configurations. Fig. 3-16 and Fig. 3-17 show the power consumption and delays as a function of the configured number of DRX cycles for light and deep sleep scenarios.

Fig. 3-18 shows the simulated deep sleep scenario for delays and power consumption in response to the number of arrived packets. The optimal operational point that corresponds to the lower costs is changing according to the number of arrived packets. When more packets are expected to arrive and are being received successfully, a longer value is required for the Inactivity timer to be optimised.

The interarrival time of control messages may follow different patterns of distribution, depending on the application type. Some applications have bursty and correlated natures while others have exponential distribution or Poisson distribution.

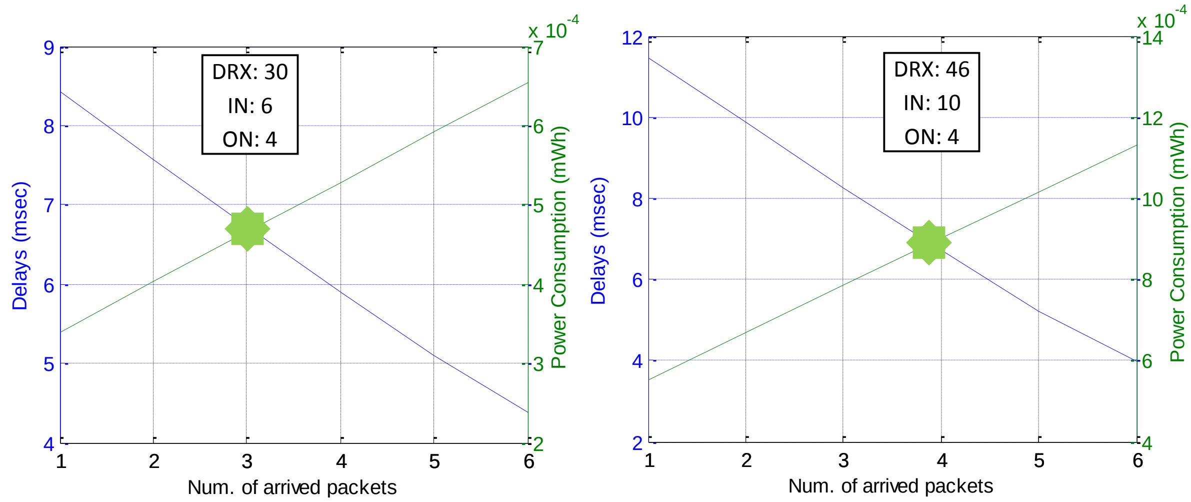


Fig. 3-18 Optimal operational point

Here we model packet arrival using Poisson distribution. In the proposed model, the packet may arrive with any possibility or may not arrive at all. Poisson distribution has the property of packet arrival with one arrival at a time, not simultaneous or bursty arrival; this property is suitable for modelling VOIP traffic. The number of arriving messages during the On-Duration and the following Inactivity periods is (μ) and the number of messages arriving during the sleeping period is (K). The expected number of control messages in one DRX cycle is (x=4). The average delay and power consumption will be:

$$Poisson\ distribution, \qquad P(\mu) = \frac{e^{-x}x^{\mu}}{\mu!}$$

$$D_{average} = \sum_{\mu=0}^{\infty} P(\mu) * D(\mu, K)_{average} \tag{3.27}$$

$$E_{average} = \sum_{\mu=0}^{\infty} P(\mu) * E_{DRX}(\mu) \tag{3.28}$$

Fig. 3-19 shows the optimal value for the Inactivity timer that corresponds to lower delays and lower power consumption with Poisson distribution. Different possibilities of packet arrivals are simulated. The figure shows that with more packets expected to arrive and be received, it is better for the inactivity timer to be extended to achieve both lower delays and lower power consumption.

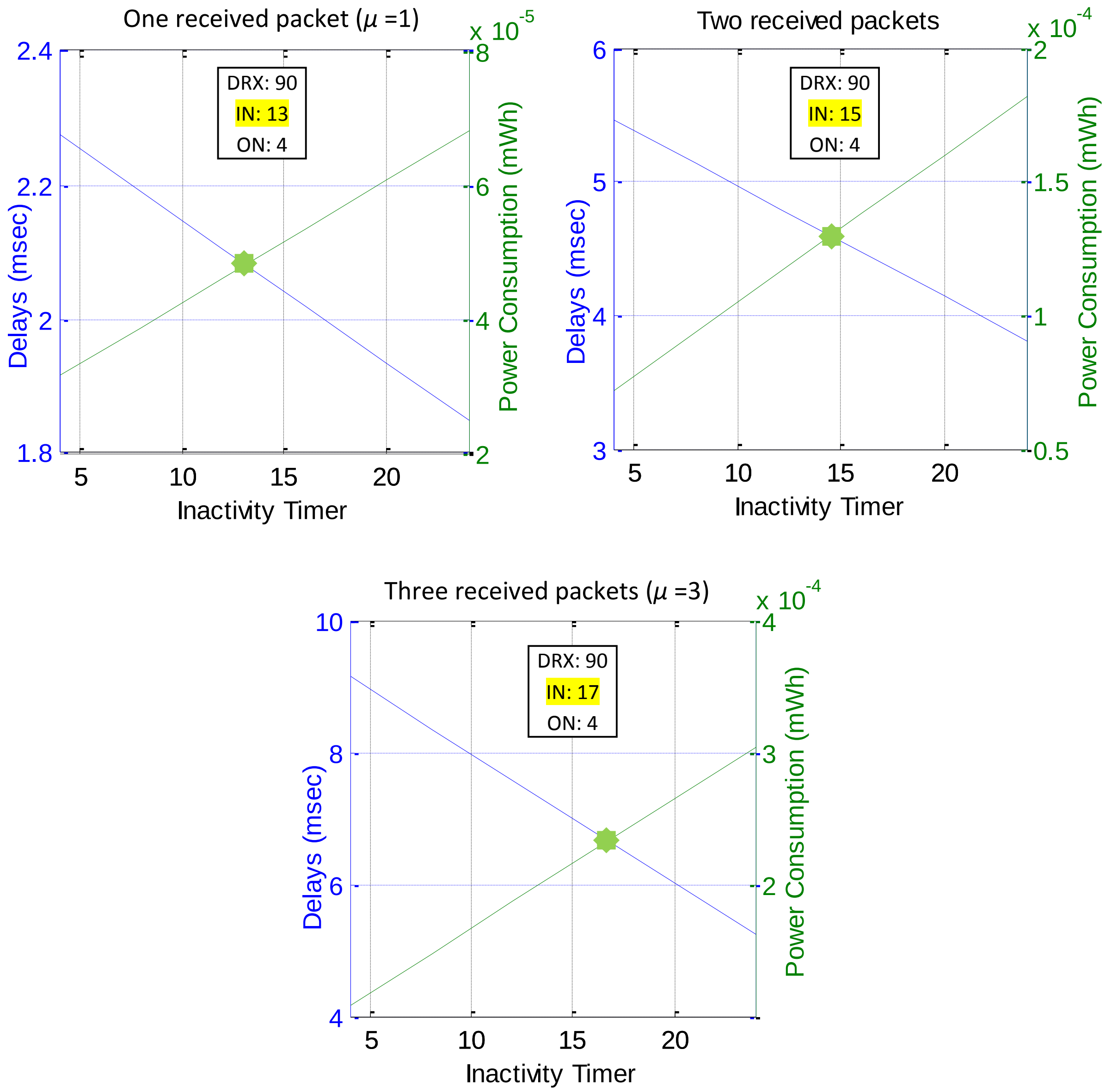


Fig. 3-19 Delays and power consumption vs Inactivity timer (for packet's arrival)

The values of (P_r P_a P_{in} P_s P_l) are average experimental values and the manufacturer's specification. The numerical values used for simulations are summarised in Table 3-1

Table 3-1 Operational power state values

Operational Power State	Value (mW)
P_r (Reception)	1
P_o (Active)	40
P_{in} (Normal)	100
P_s (Sleep)	10
P_l (Light Sleep)	25

3.5 System model

In this section, the incorporation of the new power-saving mechanism for the operating DRX over the eNB and UE in LTE is explained in detail. The main objective is to maximise the UE battery life and save energy in an efficient manner, with consideration given to the 3GPP standard QoS. This is achieved through an adaptive improved mechanism that considers most of the influencing factors in order to provide higher power efficiency.

The system model consists of an LTE system with a supported variety of real time services and non-real time services. Each service and application is associated with some QoS parameters such as packet delay, packet loss and other factors that affect the different types of services and cannot be exceeded or cannot be lower than a minimum level. The aim of these arrangements is to satisfy the requirements of the operating applications in such a way that firstly, the UE can highly optimise its power consumption and secondly it can avoid any performance degradation with the scheduling mechanism. To go through this, a new adaptive discontinuous algorithm is proposed and incorporated through the LTE-AS functions and the frame formulation process, along with the embedded algorithms and procedures within the UE's process model. The system load condition is monitored efficiently without introducing signalling or processing overheads between the physical layer and the NAS layer. This load status is exploited by the serving eNB in a centralised manner by adapting the power-saving mechanism parameters, and putting forward for consideration the critical positions and situations resulting from the adaptation process. This centralised mechanism is proposed in order to make use of all available extracted information from the transmitted frames upon the uplink and the downlink. This information is LTE deduced; it originates from real LTE network components and does not depend on theoretical assumptions or any external factors, so it is the best to describe the system situation and can be exploited in a highly efficient way during normal operation of the LTE system, together with all defined applications and the available scheduling mechanism. The load over the physical channels can be exploited by the serving eNB itself to determine the best way to adapt the power-saving mechanism without introducing any undesirable effects on the eNB's main functionalities. This new planning and optimising scheme makes the serving eNB more aware of the cell conditions and helps to ensure that the centralised proposed algorithm shares the adapted parameters normally over the air interface. The algorithm's main task is to count for and evaluate the presence of downlink control indicator (DCIs) and control channel elements (CCEs) within the transmitted frames and for all operating modules within the relevant process. The downlink subframe contains a number of CCEs together with other shared data. The new defined functions are specific to the data structure used by the proposed algorithm and are capable of working within the physical layer and the LTE-AS layer (Fig. 3-20). They access the frame generator at the eNB to extract the total CCE elements occupied by the DCIs in order to find out the real load.

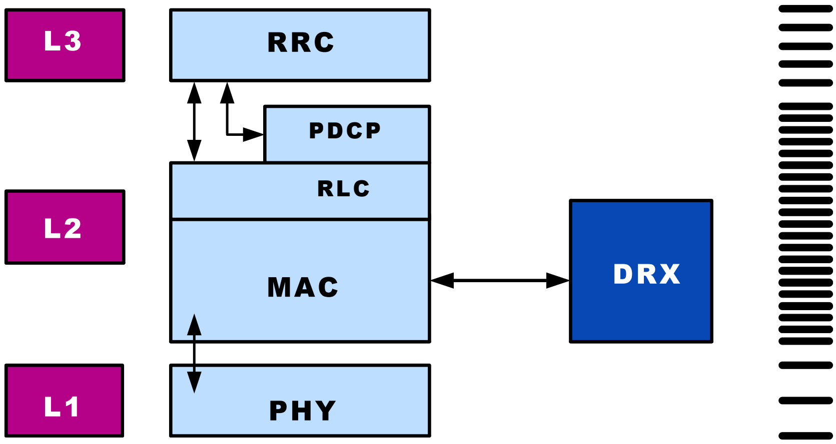


Fig. 3-20 Proposed functions working layers

The real time monitoring mechanism works together with the frame generator and starts measuring the load over the control channel between the eNB and the UEs; it reports this information continuously to an adaptive algorithm at the eNB which will make use of the available information to find the optimum values that satisfy throughput and delay requirements. Another algorithm is deployed in case light sleeping is decided. Light sleeping is proposed in order to avoid inconvenient situations where the UE is forced to shut off part of its circuitry if the sleeping period is short; this is very efficient at avoiding rebooting of the device, which consumes more energy and increases delays. The output of the two successive algorithms is new adapted DRX power parameters at the eNB's side. These new values are parsed with the connected UEs so as to maintain the desired requirements at the UE's end. This closed control loop is fully managed by the eNB and continues to operate on a regular basis over the air interface between the eNB and the associated UEs.

3.5.1 Load-Monitoring algorithm

The main function of the monitoring algorithm is to count the control channel elements' locations inside the PDCCH, where uplink grants and other data decoding requirements exist in combinations of time domain, frequency domain and modulation scheme. When a UE sends an RRC Connection request, it receives an uplink grant in the form of a DCI. The DCIs may be UE specific or common for all UEs and the existence of DCIs within the control channel is an indicator of active UEs inside the cell [28]. When the frame is formatted at the eNB in request to UEs' requirements, many functions may be implemented to measure the instantaneous load over the control channel. These functions span over different layers of the serving eNB in order to be compatible with standard functionality and to find the actual load without affecting the system's performance.

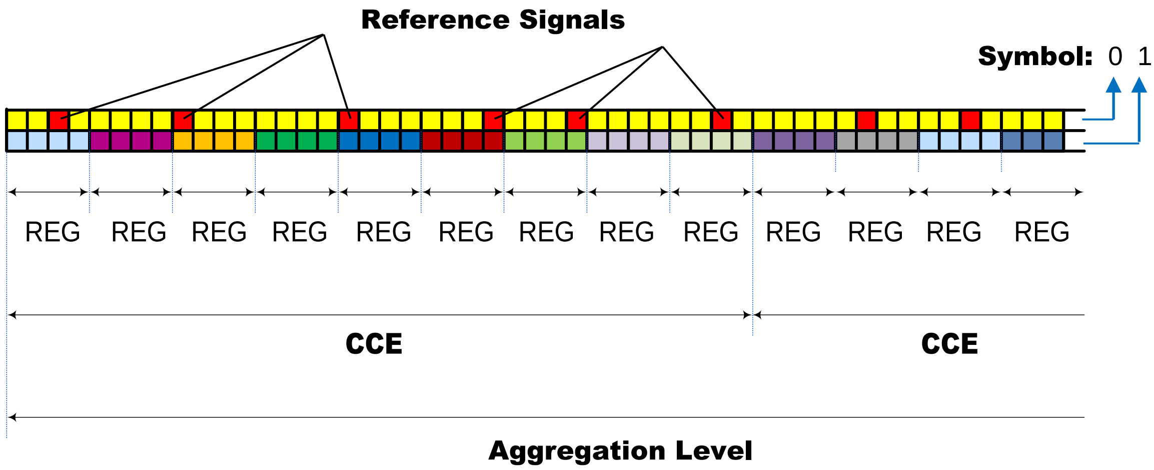


Fig. 3-21 The frame format

This is a very efficient way to find out the real load over the download control channel, as the control elements are the actual carriers of the DCIs. The mechanism of load measurement is initiated together with the subframe formulation process to check for the control elements allocated inside the downlink frame (Fig. 3-21). The eNB may sometimes lose DRX process synchronisation with the associated UEs, even if there is uplink traffic such as measurement reports because the uplink traffic is not always guaranteed. So the eNB needs to update its records about the UEs' state, clear the statistic lists of pervious subframes and reset the physical download control channel state.

Algorithm 3.1 on the following page describes the steps to find the load over the control channel.

Algorithm 3.1 : Load-Monitoring	
Start	
1	*Wait for the start of a new subframe.*
2	*Reset Allocation and Load Variables.*
3	*Call function to find max number of CCEs available.* *Find (size symbol, allocation Blocks per symbol, resource elements per block).* *Subtract the overheads (PCFICH size, Reference signals).* *RETURN: available CCEs = Total PDCCH RE/ (36 RE per CCE).*
4	*Call function to Track the number of CCEs occupied through the number of DCI.* *Access list updated by the downlink scheduler.* *Find (num of DCI(s), num of CCEs per DCI).* *RETURN: Occupied CCEs += num of DCIs*num of allocated CCEs per DCI.*
5	*Subframe end.*
6	*Calculate instant load percentage: (RETURN 4 divided by RETURN 3)*100.* *Accumulate the new estimated load value with the previous values.*
7	*Check forwarding threshold to avoid saturation.* *Threshold reached:* *No: Go to 1.* *Yes: Send statistics, Rest Accumulator, Reset threshold Counter, Call algorithm 2, Go to 1.*
End	

As mentioned before, the algorithm is triggered when the scheduler starts to build a new downlink map and the eNB starts to form a new subframe. This process is repeated at the beginning of every subframe. The algorithm depends on the available symbol times for the PDCCH to calculate both the total and available number of control elements. When done, the counter instantly forwards the statistics to the decision-making algorithm which plays the role of a management unit. The decision-making algorithm maps the received statistics on a look-up table with pre-defined values of DRX parameters which best suit the corresponding load values. Reporting the instant load may saturate the channel; therefore forwarding statistics and assigning values must be scheduled on a regular basis in order to avoid channel saturation.

3.5.2 Decision-Making algorithm

The instant load must be reported to another algorithm in order to make a decision and the DRX parameters updated to new optimum values. Upon receiving the load value, the decision-making algorithm accesses a look-up table to find the optimum parameter values that best serve the measured load and then passes those values to the associated UEs. The continuous permutation among different DRX timers' values must be achieved through fine steps in order to avoid degrading throughput and violating QoS requirements. The continuous reporting of the parameters to the associated UEs will not add any additional overhead to the wireless channel because the serving eNB has already allocated resources to announce the DRX parameters to the connected UEs and other UEs who request RRC Connect. The only difference is that the announced values are not fixed, but continuously updated.

Algorithm 3.2 describes the steps to making a decision according to the load value. This algorithm is independent from the subframe formulation process so there is no need to repeatedly perform it with every subframe. Therefore it is very efficient to incorporate it as an independent function that could be called upon when it is time for it. This way of management, separating algorithms and calling them when necessary, has the very important role of avoiding the overheads associated with these algorithms. An additional efficient step incorporated into this algorithm to avoid reporting overheads is to terminate the algorithm if there is no need to update the DRX timers. Hence the serving eNB does not need to update its record and pass the new parameters repeatedly. The load value is compared against multi-level thresholds in order to make it easier to find the best suitable parameters that could better serve the UEs, depending on the network's actual load. These thresholds are set according to the nature of the network and could be chosen either by simulation or by typical field measurements when performing network radio planning prior to installing new eNBs within the network.

Algorithm 3.2 : Decision-Making

Start

1 *Wait for function to be called.*

2 *Function called, cash the received load new value.*

3 *Access DRX parameters of interest.*

4 *Check load level: If:*

Lower than threshold1
Yes: Check DRX parameters.
If suitable with load value: don't update, Go to 1.
else: Update the timers' values to new suitable values,
Cash new values, Go to 5.
No: Continue.

Between threshold1 and threshold2
Yes: Check DRX parameters.
If suitable with load value: don't update, Go to 1.
else: Update the timers' values to new suitable values,
Cash new values, Go to 5.
No: Continue.

Higher than threshold2
Check DRX parameters.
If suitable with load value: don't update, Go to 1.
else: Update the timers' values to new suitable values,
Cash new values, Continue.

5 *Update eNB's DRX record.*

6 *Pass new DRX parameters for this eNB to all UEs in the cell.*

7 *Pass new DRX parameters to algorithm3.*
Go to 1.

End

3.5.3 Critical situation avoidance

This algorithm is performed on the UE's side in order to avoid any critical situations that may result from the adaptive behaviour of the DRX timers. As mentioned in the analytical study, in some situations it is better for the UE from the delay perspective to run light sleep rather than deep sleep [29]. The end of the Inactivity timer depends on the arrival of downlink packets and it is assumed that after an Inactivity period there will be enough time for the UE terminal to enter a sleep period. However, the bursty nature of the system makes the potential possibility of very short sleep periods high. Algorithm 3.3 is applied on the UE's side to minimise the effects of critical situations. This algorithm finds the instant remaining sleeping period, assuming maximum delay for packet arrival during DRX sleep. The value of the sleep period varies according to the number of messages arriving during the active periods.

From the previous equation (3.20), it is obvious that the UE can easily perform the calculations to find the amount of time remaining for the sleeping period. After this, the UE then has to undergo a Time-Energy trade off process to choose whether to go into light sleep or deep sleep. Therefore, algorithm 3.3 is implemented to mitigate transition latencies and boost performance. It is used to determine the best sleeping mode and the optimum length for the long DRX cycle as a multiple(s) of the DRX short cycle. This implementation will not add any processing overhead or additional power consumption on the UE's side because the algorithm does not require any uplink transmission from the UE, only to count for the end of the Inactivity timer and perform some steps for the DRX planning.

Algorithm 3.3 describes the steps to check for critical situations.

Algorithm 3.3 : Critical situation avoidance	
Start	
1	*Wait until algorithm is triggered.*
2	*Cash received DRX timer's values.*

3	*According to the received values:* *Calculate the critical sleeping period (in subframes).* *Find optimum DRX long cycle multiplication factor.*
4	*Track the Inactivity timer value, capture time when the timer ends.*
5	*Subtract the captured time from the DRX sleep timer, find number of subframes left.*
6	*If number_left ≤ Critical* *Run light sleep,* *Set the optimal DRX long cycle compatible with light sleep, Go to 1.* *else* *Run normal deep sleep,* *Set DRX long cycle according to received value from eNB, Go to 1.*
	End

3.5.4 The DRX extended mechanism

Now after the identification of the serving algorithms, it is very noteworthy to notice that the DRX cycle is kept constant for the QoS requirements as it is correlated to higher latencies. The Inactivity timer has the highest impact on the power consumption and much power could be saved through reasonable adjustment of the timer. The described adoptive algorithms operate separately in steps and they follow each other to add overall performance improvement. The serving eNB shares new configurations with the associated UEs within the cell through RRC signalling [30].

This centralised procedure enables the eNB to obtain instant comprehensive perception of what the radio channel is going to be and to adapt the UE's configurations according to the traffic intensity. The UE and eNB follow the following extended DRX mechanism (Fig. 3-22) where the system load is the main characteristic considered in the presented mechanism:

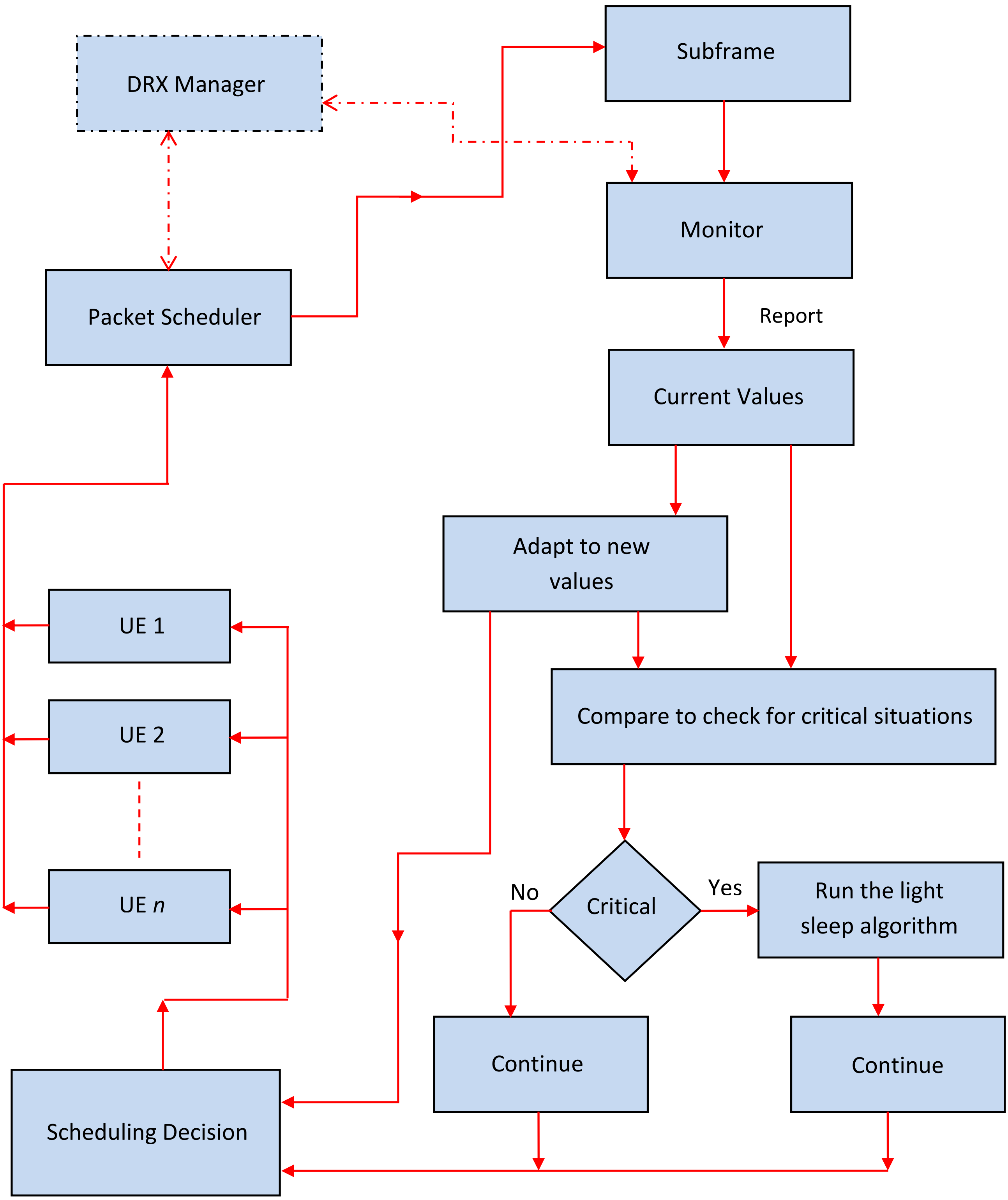


Fig. 3-22 DRX extended mechanism

3.6 Proposed scheme implementation

OPNET 17.5 is used to simulate the proposed scheme. It is the first version to support the DRX mechanism as the previous version 17.1 did not support power saving. It is a very robust simulation tool, especially for simulating LTE networks. The spatial multiplexing feature of MIMO systems is not yet supported by version 17.5. For the wireless link between the uplink and the downlink, there is no interference between the physical shared control channel and the physical download control channel and hence the assumption is that they do not interfere with each other and the interference is not accounted for in the physical profile. The proposed algorithms are integrated in the LTE-AS layer of the nodes.

Fig. 3-23 shows the lower parts of the node model for the eNB and the UE, where the parts shown are the LTE specific new layers. The rest of the layers – which are the higher layers – are not shown here but they are the normal layers as in the network OSI model starting from the IP, then the transport layer and so on.

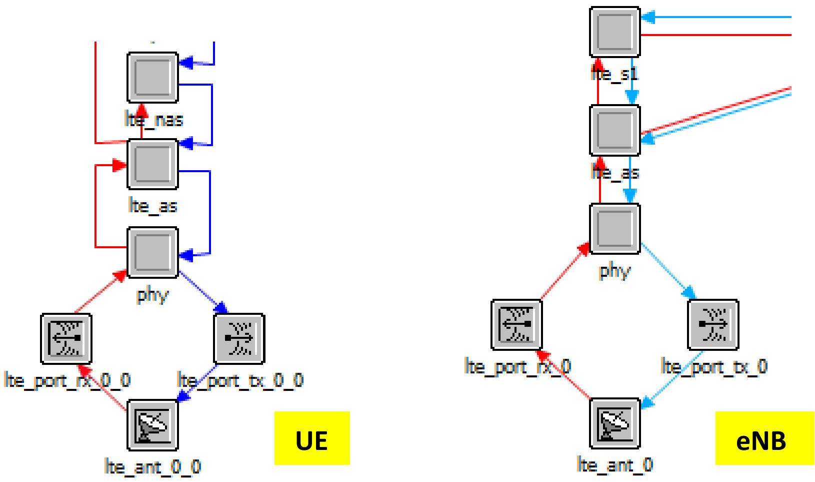


Fig. 3-23 PHY & MAC layers for eNB and UE

The access stratum (AS) layer is responsible for carrying data over the wireless link and managing IP connectivity for the LTE air interface [23]. All logical channels pass through the AS layer where they are manipulated in many ways such as multiplexing, mapping and HARQ. On the UE's side, a complicated process is performed especially when both types of DRX cycles are configured. The AS module does not invoke the DRX mechanism until it receives the RRC_Connection_Establishment notification that contains the DRX start offset. The AS module has many tasks to perform with the DRX such as discovering the UE specific

DRX parameters, checking if the DRX process is enabled and checking the status of the DRX process. In this layer, the DRX counters' status is updated continuously, and from it the parameters are published by the serving eNB. Also there are functions to trace the UE's DRX information and allocate memory for the parameters.

The DRX context is initialised for every UE by the access stratum which is also responsible for the initialization of the DRX synchronisation time and keeping the records updated by monitoring the DRX records for associated UEs every 200 ms. The subframe number needs to be recorded for the DRX process in order to be used later by the DRX logic for determining if retransmissions are possible for a specific UE or not.

When the subframe start is triggered, the algorithm starts as mentioned before. OPNET simulation procedures rely on what is called a process model where algorithms and work flows are implemented by coding and then they are compiled (Fig. 3-24).

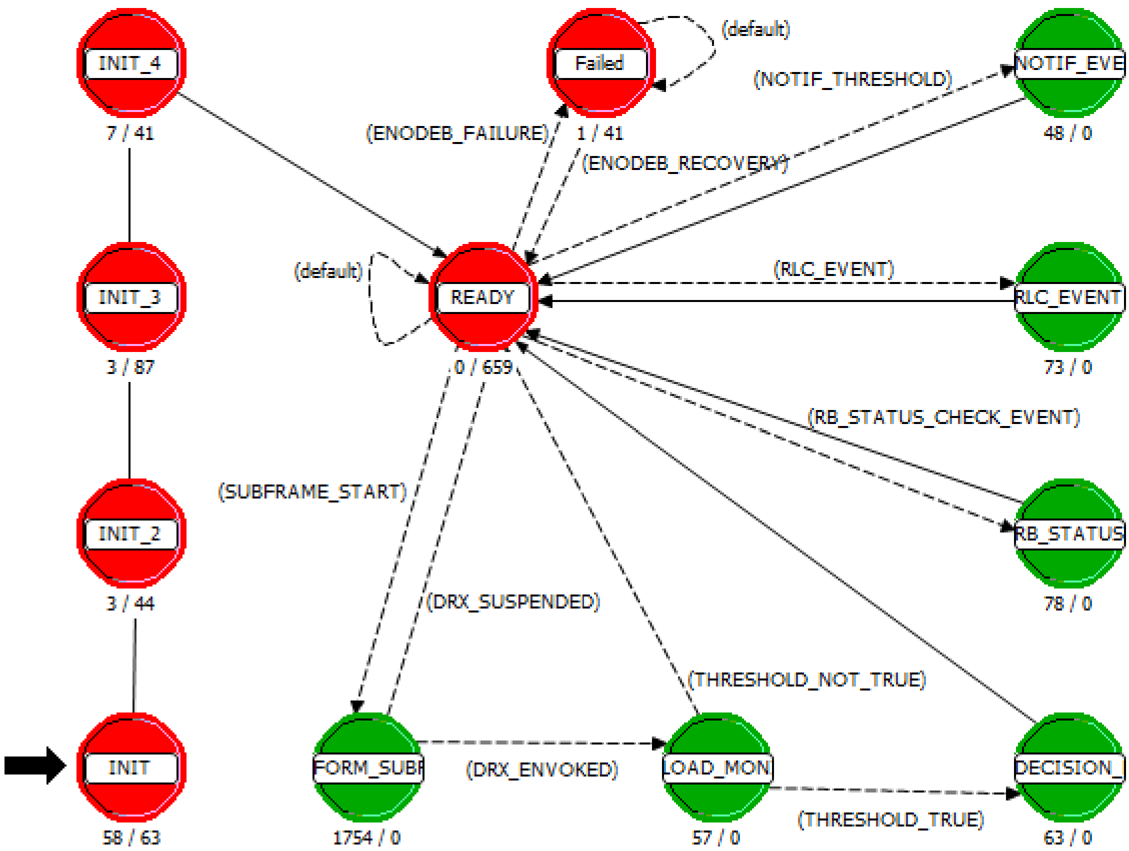


Fig. 3-24 eNB process model

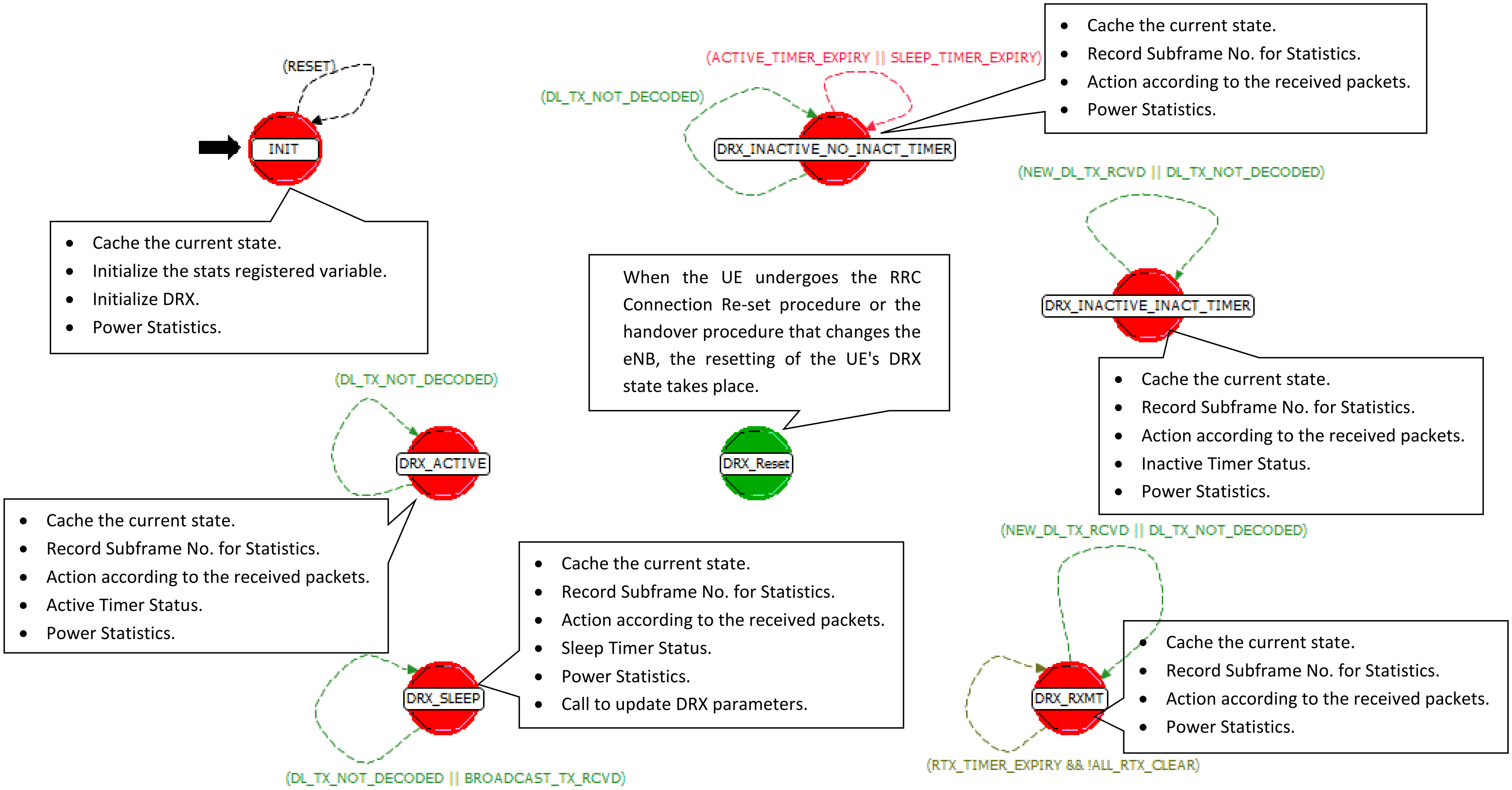


Fig. 3-25 DRX process model functions and transactions

When the process is initiated, it passes through many parameters' initializations until the whole module is ready. Then most time is spent on subframe formulation. As the module is getting ready to start subframe formulation, it synchronises the frame count so that the eNB and UE are in synchronisation with each other. While the module is in the READY state, it checks for the PUCCH signals which might be either a scheduling request from the associated UE or an HARQ ACK. It is very important to process the PUCCH signals from all the UEs because they are the source of the downlink stream and the network load. The subframe number of the very first allocation is used as the reference point and all UEs have to compute the time until the allocation of the next PUCCH. The DRX process (Fig. 3-25) is not started until the UE gets the RRC_Conn_Establish message from the eNB where it sets the offset for the UE [31]. The process may be suspended or invoked several times according to the UE's state, the newly received MPDU, or if there is a grant packet.

3.7 Performance evaluation

The performance of the proposed algorithms is simulated over an LTE network (Fig. 3-26). The performance of the LTE network is studied where the proposed schemes and algorithms explained earlier were coded in the process models of the existing eNBs. The LTE configuration parameters are set in an LTE configuration profile which controls the operation of the eNBs in the network. In order to run applications over the network, two entities were created, one for applications definition and the second for defining the profiles of UEs. All UEs are included in an application configuration entity which starts from the beginning of simulation until the end of it, and some UEs were added to another profile with different demands and starting times; in this way the load of the network is changed by deploying different profiles among the UEs. The model is tested with different types of traffic generated by the deployed applications such as FTP and HTTP and linked to the appropriate server.

<u>LTE Power Consumption:</u>

Simulation results concerning power consumption are presented in power tables which contain the information calculated at the end of the simulation, such as battery capacity which is the value of the battery capacity attribute (provided for reference) and estimated life time which is an estimate of the time it will take for the battery to be completely drained.

Network Topology and Application Configuration:

- 3 cells with cell radius of about 2.5 Km and an average number of 13 UEs per cell.
- UEs in the cells run DRX with short and long sleep time and have the DRX long sleep time as multiples of the short time.
- More than half of the UEs in the cell have voice application where the voice is continuous with the exponential interarrival time.
- All UEs have Video, HTTP and FTP applications with exponential interarrival time. UEs are arranged in profiles. Applications start after each other and last during the simulation time which was 100 minutes. This represents bursty traffic.

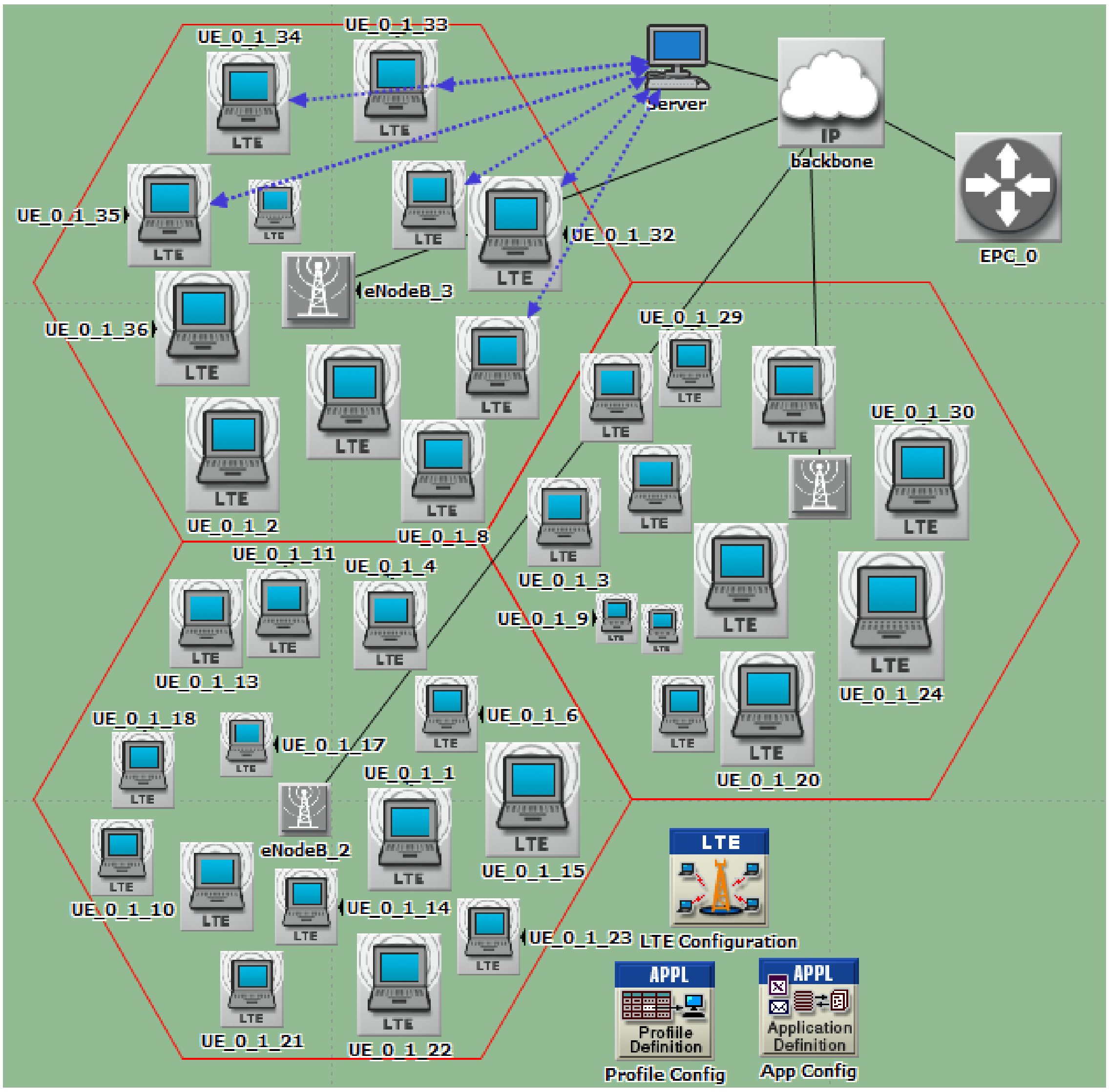


Fig. 3-26 The simulated scenario

3.8 Results and discussion

New statistics such as total power consumption, load, number of dropped packets, timers and others were programmed and introduced into the model in order to derive the performance over the simulation time and enhance the result. Also other existing statistics such as throughput, delay and connection re-establishments attempts were used to show the results of the incorporated scheme.

The actual load over the control channel is estimated and reported periodically through a function implemented to parse the eNB's DRX-related parameters and share them with the associated UEs. Fig. 3-27 shows a real load of an LTE network over the control channel. This load is not a data load but a signalling load; it is the load over the PDCCH and separated from the PDSCH upon the same subframe. The estimation is performed by sampling the actual load every 30000 subframes. The overlaid statistic in the figure shows by how much the actual and the estimated load are close to each other.

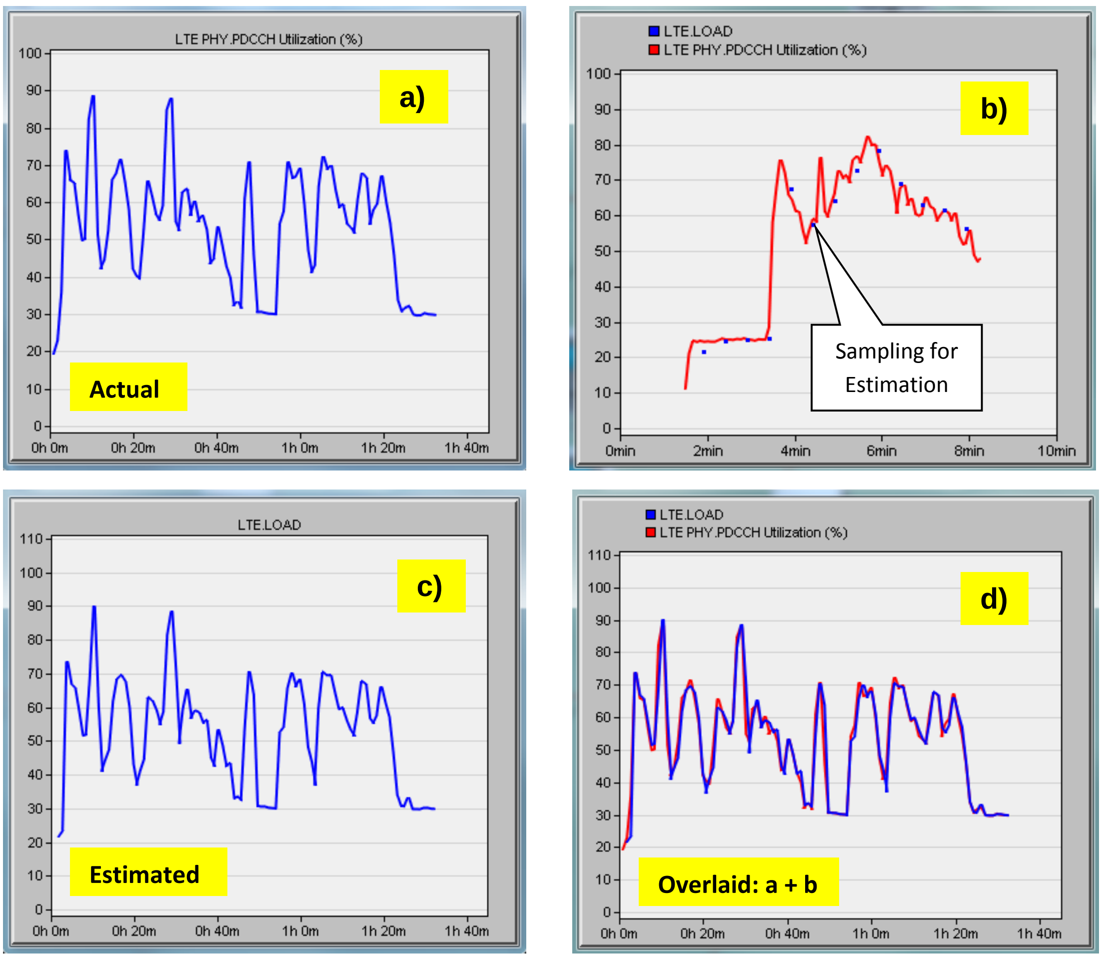


Fig. 3-27 Load monitoring statistics

As is mentioned in this chapter's literature review, the eNB uses this load to predict the optimum values of the DRX timers. The code in both the eNB and UE process model is modified in order to show the values of the DRX timers. Fig. 3-28 shows the ON duration timer value changing over the simulation time. It is generated by the eNB and transmitted to the connected UEs within the cell. The figure shows the overlaid statistic between the transmitted and received values which look identical.

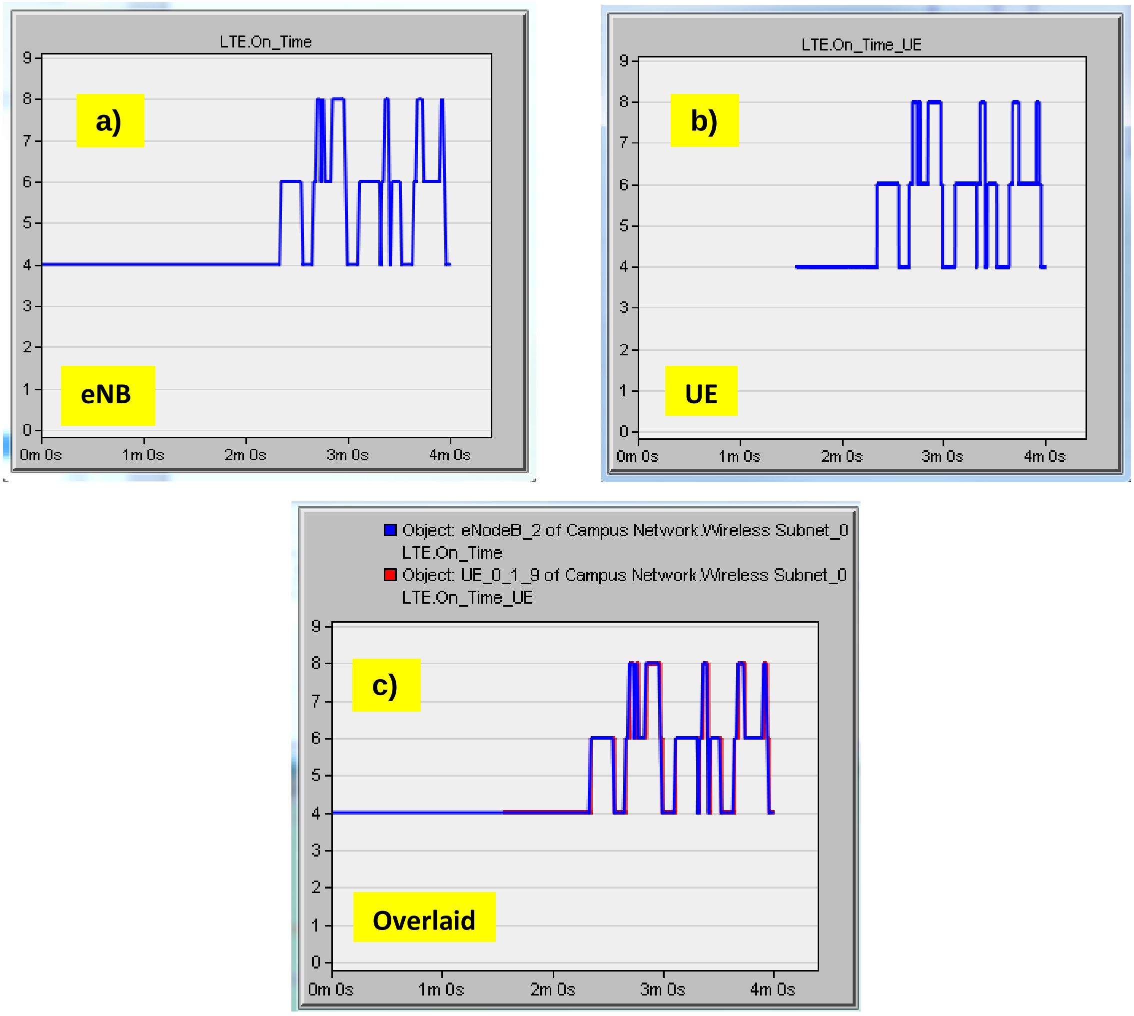


Fig. 3-28 Transmitted and received timers values

From the overlaid figure, it is obvious that the UE receives exactly the same transmitted signal values from the eNB. The signal in this example is switching between four and eight for the ON duration timer. The UE receives the values through the RRC connection set up, the RRC connection reconfiguration message (which is a command to modify an RRC connection and contains modification of the DRX configuration) and sometimes through the MAC-MainConfig [30, 32]. Updates may take place explicitly every 200 ms when running the

DRX process and OPNET supports updates at the time of the MPDU delivery to insure that updates take place for all UEs who receive downlink traffic.

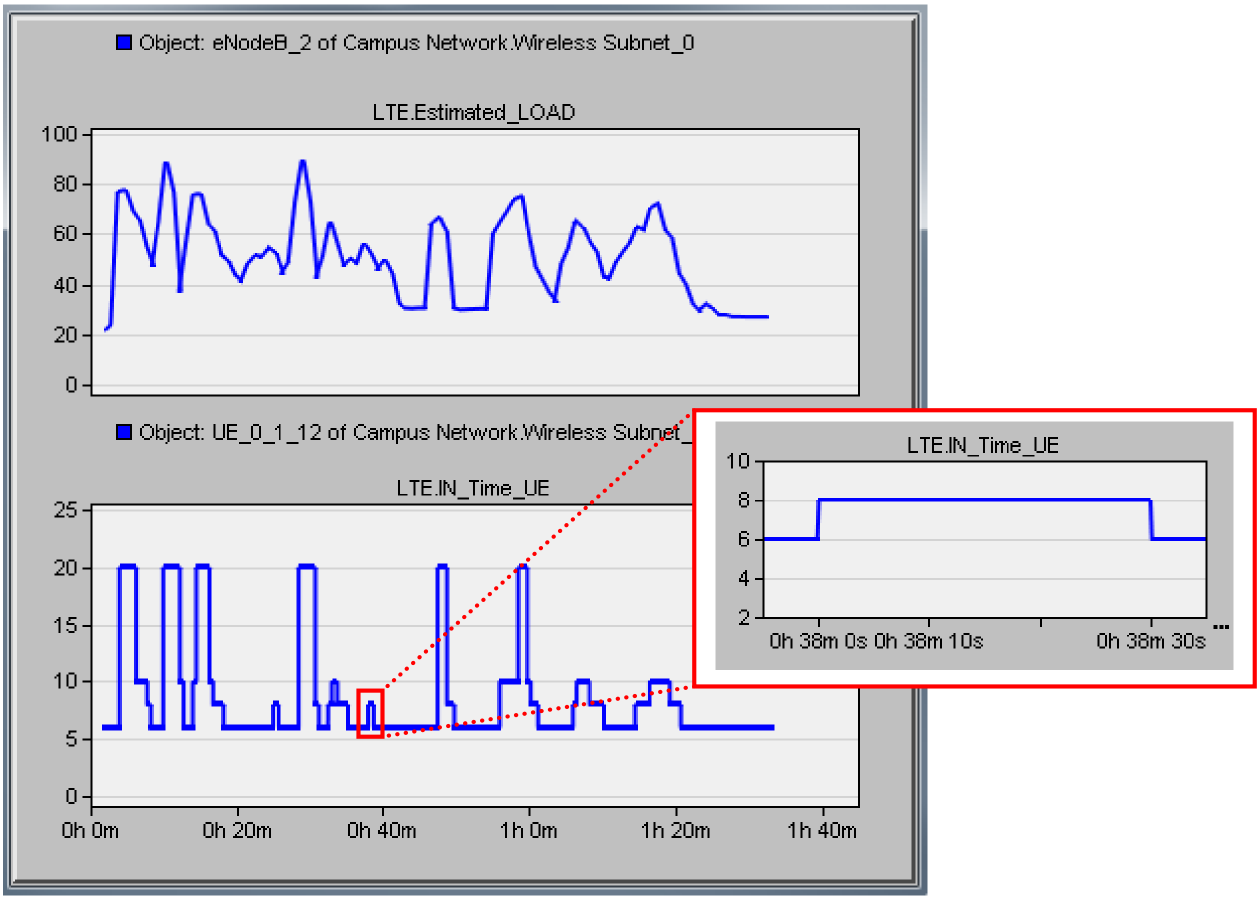


Fig. 3-29 Inactivity timer in response to the estimated load

Using the same DRX parameters all the time with various load levels is not efficient when the aim is to achieve better performance. Lower delays and lower power consumption levels could be realised when implementing an efficient adaptive DRX approach. Fig. 3-29 shows the Inactivity timer in response to the estimated load values. The implemented algorithm in the serving eNB adapts the Inactivity periods and reports the values to the associated UEs. For example, in the figure, the enlarged period equals 30 seconds which covers about 350 DRX cycles. This period matches lower power consumption because the corresponding period of the Inactivity timer is shorter and the UE has a higher probability of entering sleep mode earlier and starts energy saving (the UE may also be configured to another shorter period depending on the load value).

3.8.1 Application performance during DRX

This method has been included in four types of applications: FTP, voice, HTTP and video. The power consumption and application performance have been discussed for different traffic characteristics during the simulated LTE network with the proposed model and the current one. The performed applications are set to be started at random times and with different periods in order to create a variable load.
When running the simulation, a fixed number of voice calls were configured and maintained to represent real network performance with voice and data UEs. Data throughput is represented by traffic models of HTTP, FTP, and video streaming. These traffic models represent the transport protocols TCP and UDP. The TCP protocol performance depends on the acknowledgment ACK which has significant impact on network throughput and delays. Some of the results concerning the effects of the power-saving process on application performance will be demonstrated. The effects vary from one application to another; this is related to the nature of the application itself as every application has different traffic models and distributions. The type of service in some applications is applied to assign priority to the traffic and guarantees the quality of service (QoS) [33].

For web browsing traffic, shown in Fig. 3-30 the web page construction has a major impact on the performance – the pages requested from the remote server are represented by on-off slots and intermediate reading times. One requested page may result in multiple TCP connections because of the content of the page (text and graphics). The HTTP version 1.1 is used to characterise servers and browsers. The differences between this version and the previous versions lay in the implementation of TCP protocol, the way of fetching the objects of the web page and the download mode.

The FTP application is the file transfer protocol; it is a procedure for file transfer. The FTP traffic shown in Fig. 3-30 is characterised by a sequence of file transfers with inter-request times (time between subsequent file requests). The rate of requesting files is independent from the arrival of the response and a request can be sent without the arrival of the previous response. The FTP application is a two commands application, get and put. Get starts file transfer and data connection from the remote server, while the put command transfers the file and data connection to the remote server. The ratio of get commands to set commands can be modified so that the load over the FTP application session can be varied.

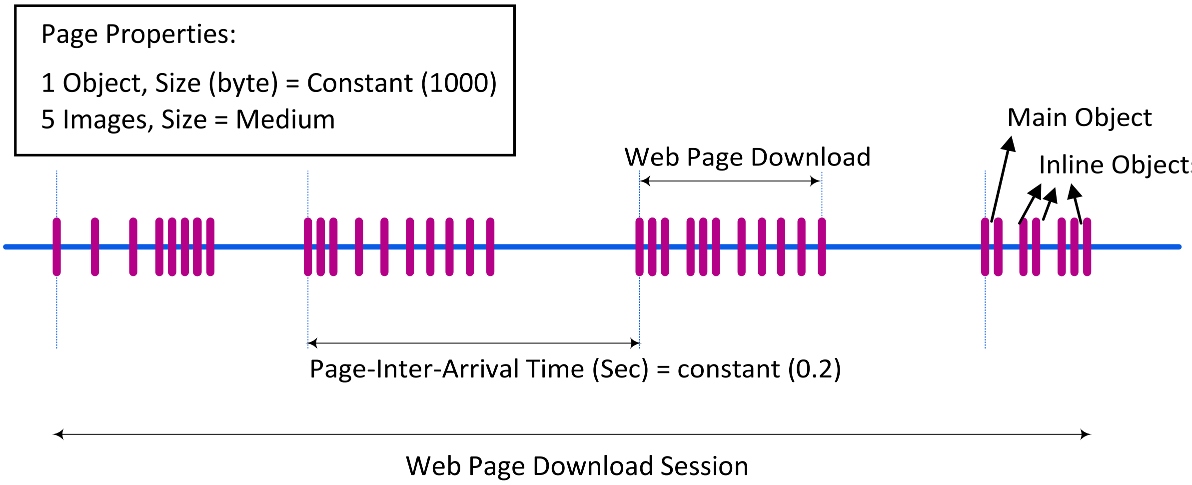


Fig. 3-30 Web browsing traffic

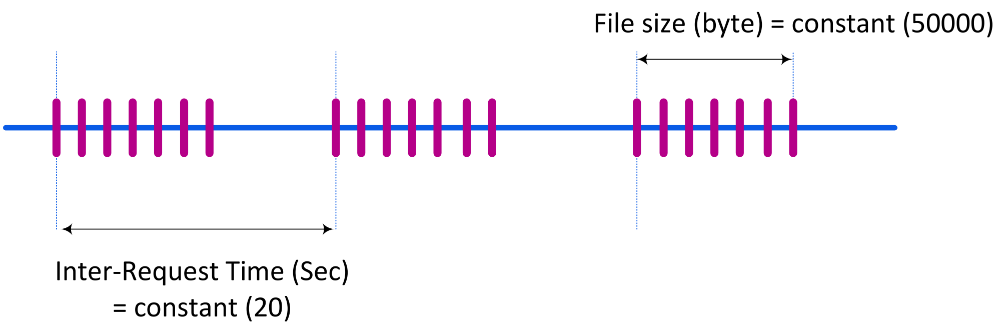


Fig. 3-31 FTP traffic model

Video streaming is one way traffic, while web browsing includes interleaving of the upload and download processes. Fig. 3-32 shows the traffic model of the video streaming as viewed by the eNB. Data arrive in frames (sliced into packets) on regular intervals – frames per second, and delays, are related to the encoding process. Buffering is used with video streaming to mitigate jitter and ensure that the display is not interrupted and is kept continuous. The transport protocol is the UDP and the performance of the application depends on the streaming interarrival times and the frame size information. TCP could be used but this will cause multiple independent sessions to be opened.

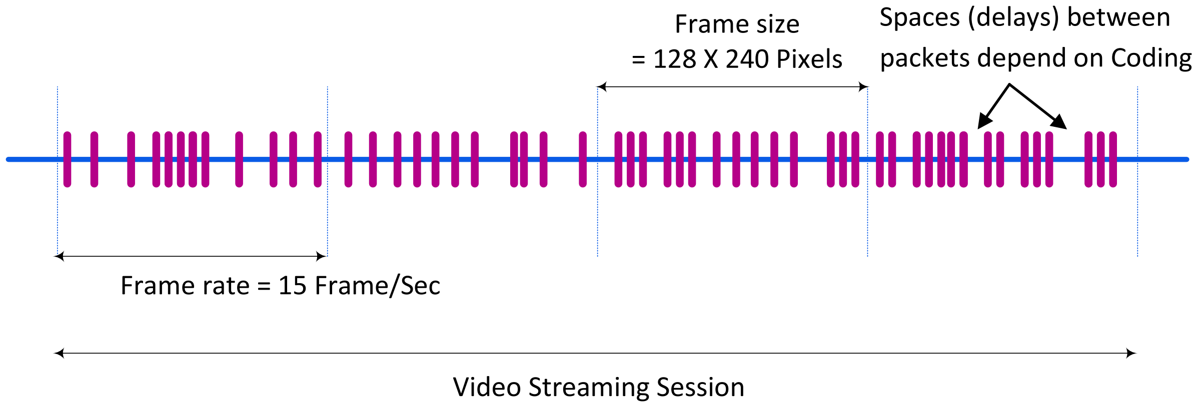


Fig. 3-32 Video streaming traffic model

When grants are allocated by the eNB, packets are expected to be sent to the scheduled UEs. If a packet arrives during the sleeping period, it will not be received by the UE and it is considered as a dropped packet. When the receiving device has the opportunity to receive the packet by allocating a longer period of reception, it will be able to receive the packet with higher probability, as shown in Fig. 3-33 [34].

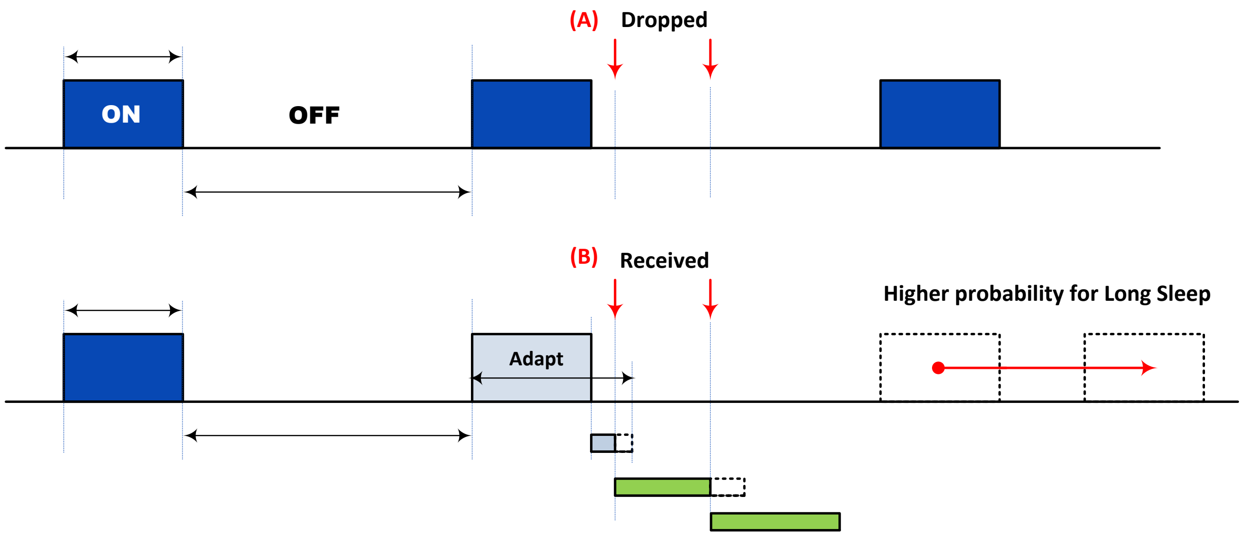


Fig. 3-33 Adaptive mechanism

A new statistic (LTE.DROPPED_PACKETS) is added to the UE functionality in order to count the number of broadcast packets that have been dropped by the UE while it is in the DRX sleep mode. Packets dropped upon the uplink and downlink traffic are not considered. Normally, when an MPDU packet arrives at the physical layer and is not decoded, it is passed to the HARQ channel and maybe many HARQ transmissions are required until the decoding is successful. Sometimes the packet includes a HARQ feedback and dropping the packet causes loss of DCIs which prevents the UE from distinguishing which HARQ process number was received. As a result, neither an ACK nor a NACK is transmitted back in response. If it does not receive either of these signals, the eNB considers this as a NACK which triggers unnecessary retransmissions of HARQ blocks and causes more delays, overhead and control signalling load. In many cases, when the retransmission timer expires, it causes the DRX process to be invoked irrespective of the UE's state (even if the UE is in DRX sleep mode) and forces it to start receiving packets [23]. Thus it is very efficient to reduce the HARQ activity level and free the HARQ process as much as possible so that this helps in reducing the number of HARQ retransmissions, avoiding the associated overhead and retransmissions accompanied with the HARQ process that consumes radio resources.

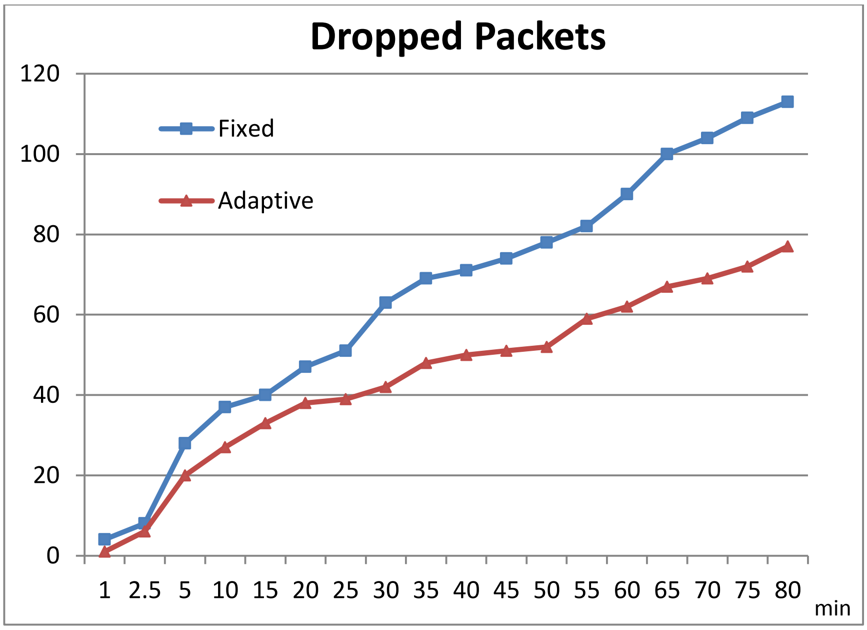


Fig. 3-34 Cumulative average of dropped packets

Therefore it is expected that there will be a decrease in the number of UEs' dropped packets during the sleeping period. In addition, the opportunity for a UE to enter a long sleep period will increase. By this approach the throughput is maximised. Fig. 3-34 shows the average number of dropped packets for 40 UEs, according to the figure there is a remarkable decrease in the number of dropped packets as a result of implementing the new method for the UEs operating during the 100 minutes of the simulation.

Fig. 3-35 shows a decrease in the end-to-end delays for video applications. The adaptive scheme performs well compared with the fixed one.

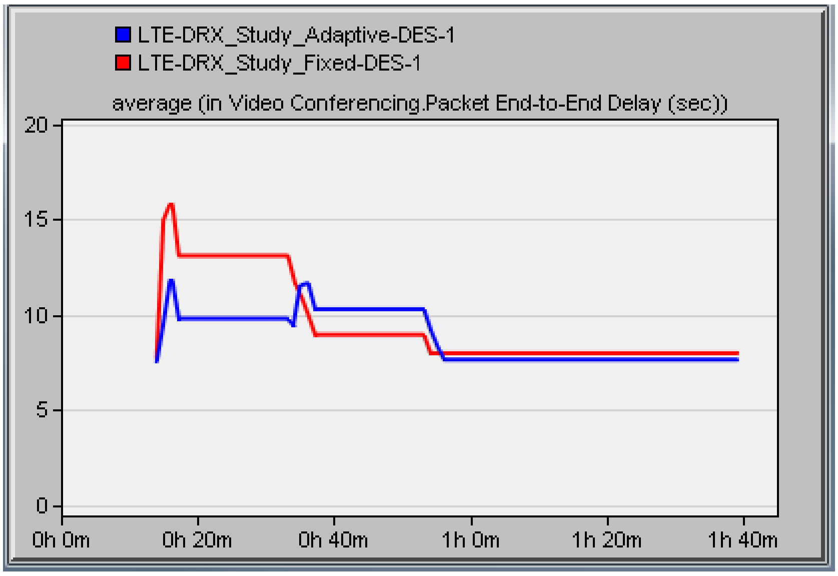
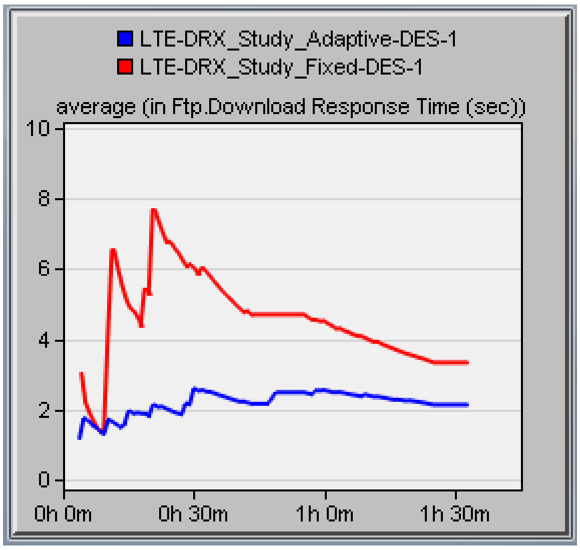


Fig. 3-35 Video conferencing End-to-End delays

The decrease in the number of dropped packets is very good from the perspective of throughput and delays. When considering other applications' performances, for example FTP upload/download response time shown in Fig. 3-36, the results show a noticeable improvement in the response time which means an improvement in the network's overall throughput. A lower response time indicates better performance.



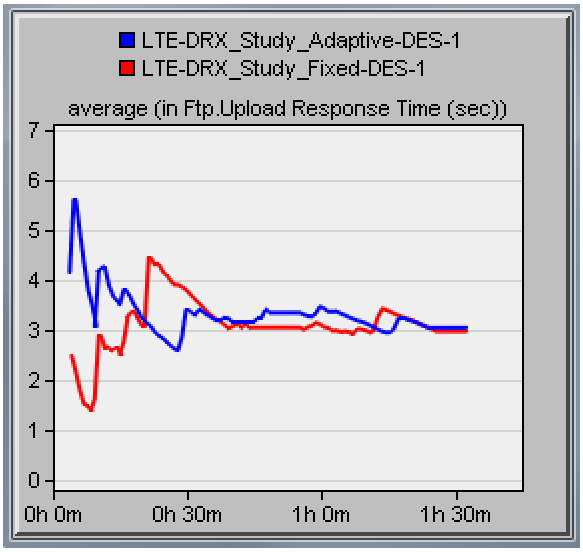


Fig. 3-36 FTP download/upload response time

From the DRX parameters point of view, longer ON Duration and Inactivity periods decrease delays, while a longer sleeping period increases delays because more packets are expected to be buffered and delayed. The adaptive scheme helps to balance related parameters. According to the figures, there is a very good improvement in the average downlink response time as it decreases from fluctuating between 4 and 6 seconds in the fixed scheme, to an almost steady value of around 2 seconds in the adaptive scheme. For the upload response time, the figure shows some improvement over the simulation and sometimes some drawbacks. This is related to some UEs' performance when they want to access the channel and the way the eNB serves them and allocates grants for transmissions. Sometimes repetitions of packets retransmissions for some UEs are given priority over scheduling new transmissions. Quality of service assigned for different applications' traffic has an essential role in determining which UEs are to be served preferentially.

For web browsing, the page response time is very important and it is considered as a key demand for web UEs for 4G systems. UEs care about page response time and can easily notice the delay when browsing the Internet. Fig. 3-37 shows a slight decrease in the page response time when using the adaptive method compared to the fixed DRX method. The standard web page response time according to some published statistics [35, 36] which satisfies UEs about the system's reactions is in the range of 0.1 second (best) to less than 1 second (still impressive but a delay starts to be sensed). According to the figure, the page response time is in the range of 0.28 second for the fixed approach and it decreases to 0.27 second for the adaptive one.

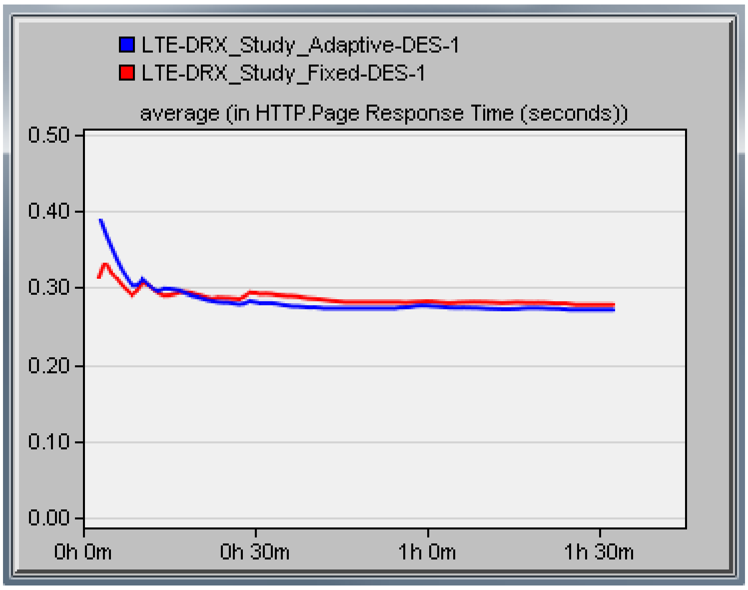


Fig. 3-37 HTTP response time

In general, energy saving is accompanied with a decrease in the throughput. Here the throughput could be maintained compared with the fixed method and sometimes enhance it. Normally, according to the scheduling mechanism at the eNB, bearer context requests and scheduling requests are sent from the UEs, and each UE is allocated a specific bearer. Hence there is a difference between one UE and another over the uplink and the downlink throughput, but the overall system throughput is stable and improving. Throughput stability is related to the improvements in packet delays and losses, in addition to the longer periods allocated to the UEs when the load is high and when the eNB is expected to transmit the packets. When implementing power-saving algorithms, a little throughput loss is accepted and QoS requirements (QoS Class Identifier) define a minimum level for throughput decrease and packet delay budget provided by LTE which should not be exceeded in order to maintain efficiency. It is very useful to guarantee the throughput by allowing the UEs to get higher chances to wake up when they are scheduled and granted resources. In the adaptive mode, the UEs have the ability to exploit the granted allocated resources in a quicker manner before the DRX process is invoked and UEs enter the energy-saving mode. Fig. 3-38 shows the LTE uplink and downlink throughput.

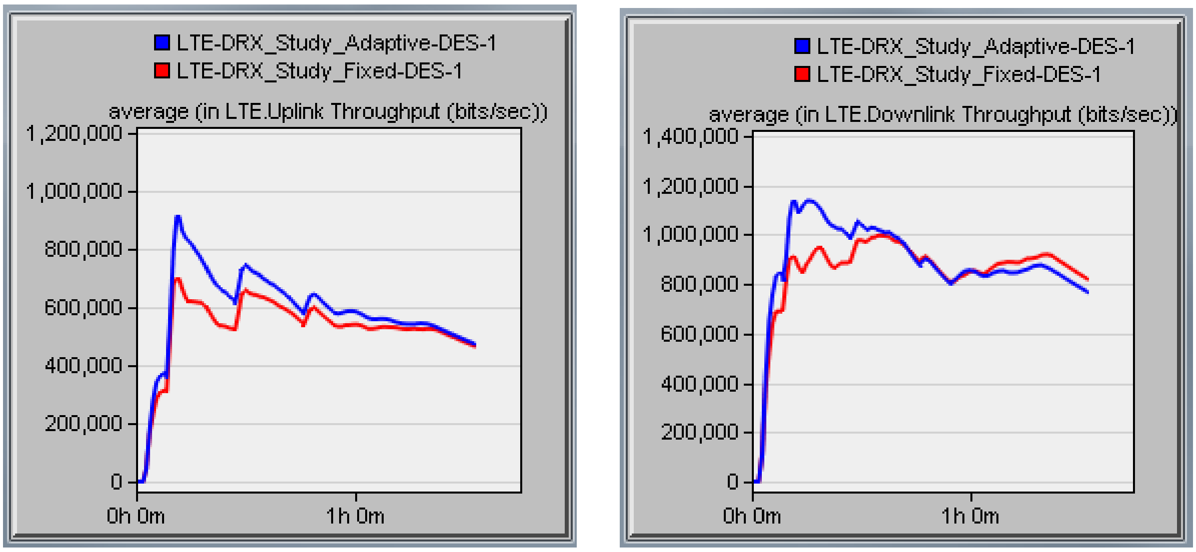


Fig. 3-38 LTE uplink and downlink throughput

During simulation and according to different application sessions, the throughput level between fixed and adaptive approaches is comparable. At the end of the simulation, the throughput is decreasing due to the exponential distribution configured for all application profiles.

3.8.2 Power consumption

The total_power_consumption statistic is calculated during the simulation through the sum of the device's:

- Operating_power_consumption.
- Transmission_power_consumption.

The operating_power_consumption, which is the total energy consumed during the simulation, is based on the time the UE has spent in every state and the given operating power consumption rate for each state as defined in the LTE configuration entity. The transmission_power_consumption is the total energy consumed by all transmissions during the simulation.

Fig. 3-39 shows the power consumption for one UE shown as an example of the power measurement procedure. The figure shows the consumed power during operation. The upper edge of the graph represents the power consumed during activity times and during this activity it undergoes a large number of drops to lower levels of power consumption which represent the power consumed during the sleeping period.

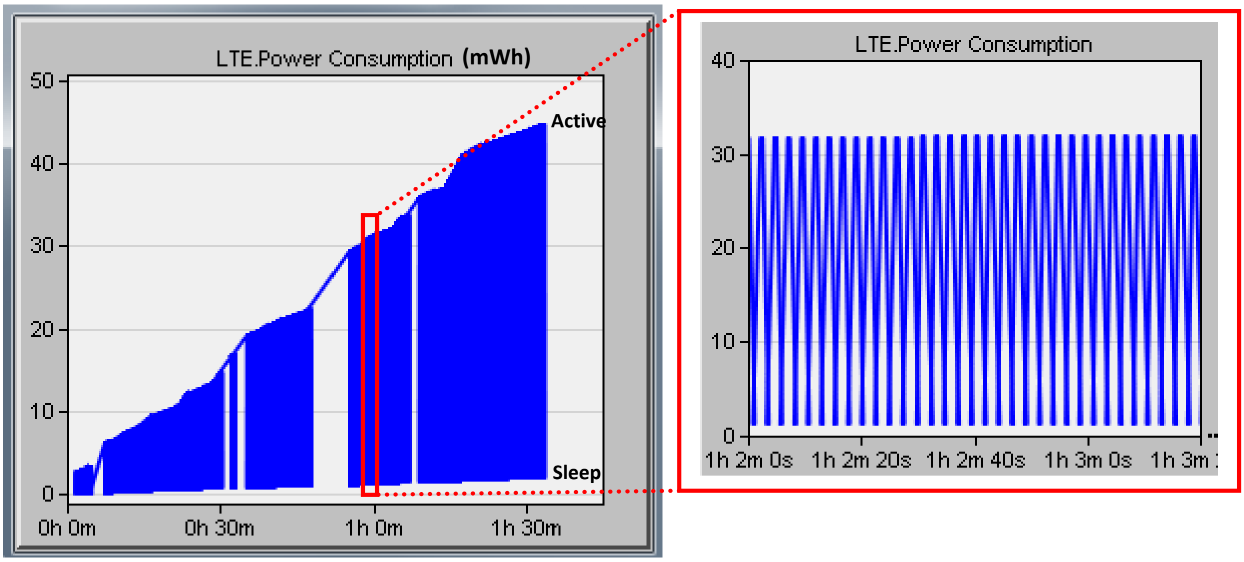


Fig. 3-39 UE's cumulative power consumption

Fig. 3-40 shows a comparison between the fixed and adapted scheme in average for 40 UEs in the network and the percentage of time spent in active, inactive and sleep periods. It is obvious that there is a decrease in the consumed power from the battery of the mobile device. This decrease in power consumption has an impact on the time remaining until the battery is completely drained.

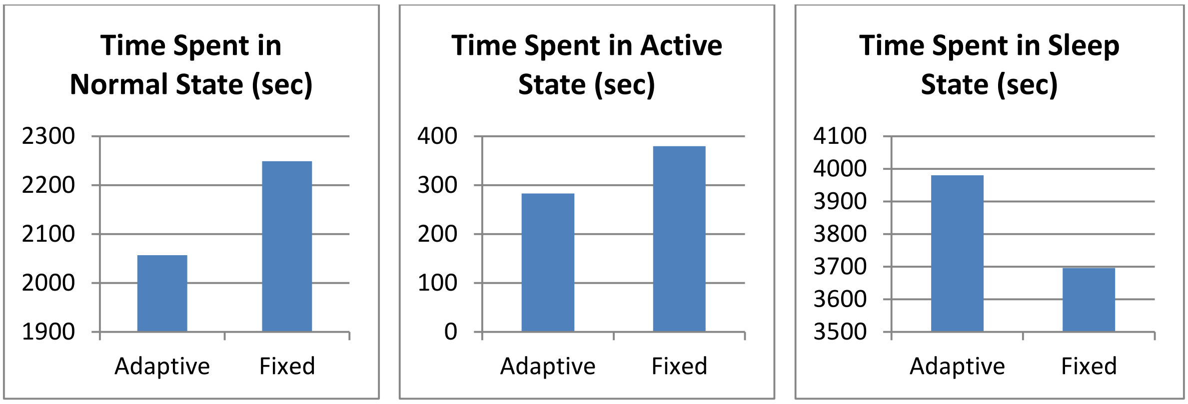


Fig. 3-40 Operational time for fixed and adapted scheme

Fig. 3-41 shows the average power consumption in the fixed and the adaptive scheme; it is clear from the result that the adaptive scheme has a better energy performance.

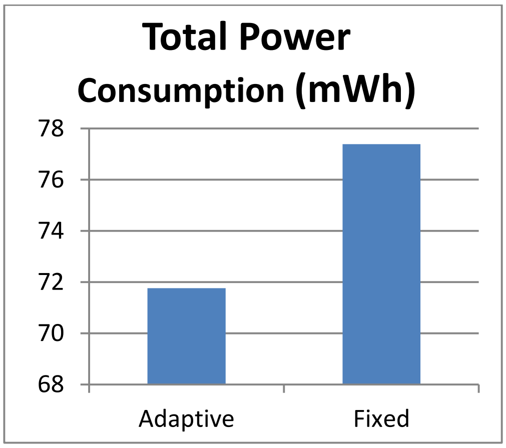


Fig. 3-41 Battery estimated life time

For example, the time saved from the battery life is estimated by the following:

$$Battery\ estimated\ life = \frac{Capacity\ (Wh)\ X\ Operation\ Time\ (sec)}{Total\ power\ consumption\ (mWh)} \qquad (3.29)$$

= (5X1000) X (5600/3600) / (77.5) = 100.36 Hours (Fixed)

= (5X1000) X (5600/3600) / (71.7) = 108.48 Hours (Adaptive)

According to the calculations mentioned before, on average the UE will have an additional 8.12 hours when applying the adaptive method.

In the simulation, the battery capacity is assumed to be 5Wh (or mAh). Fig. 3-42 shows some examples of standard mobile device batteries and their capacities [*]. The battery capacity increases with mobile devices' evolution in order to meet the increasing energy demands for the devices' operation.

Fig. 3-42 Battery capacity

--- [*] Internet Materials

Energy is saved due to three main reasons. The first reason is related to the relief of the effects of the RDX mechanism by making the process more optimised and adaptive. When the process is modelled comprehensively so that the mobile receives and transmits in an optimal way, this saves energy and reduces delays. Fig. 3-43 shows a real scheme for the DRX mechanism (compared to the ideal one). It is preferable and more efficient to reduce the number of switching and transition times of the transceiver circuitry in order to reduce the effects of transition time and the accompanied power consumption during transitions.

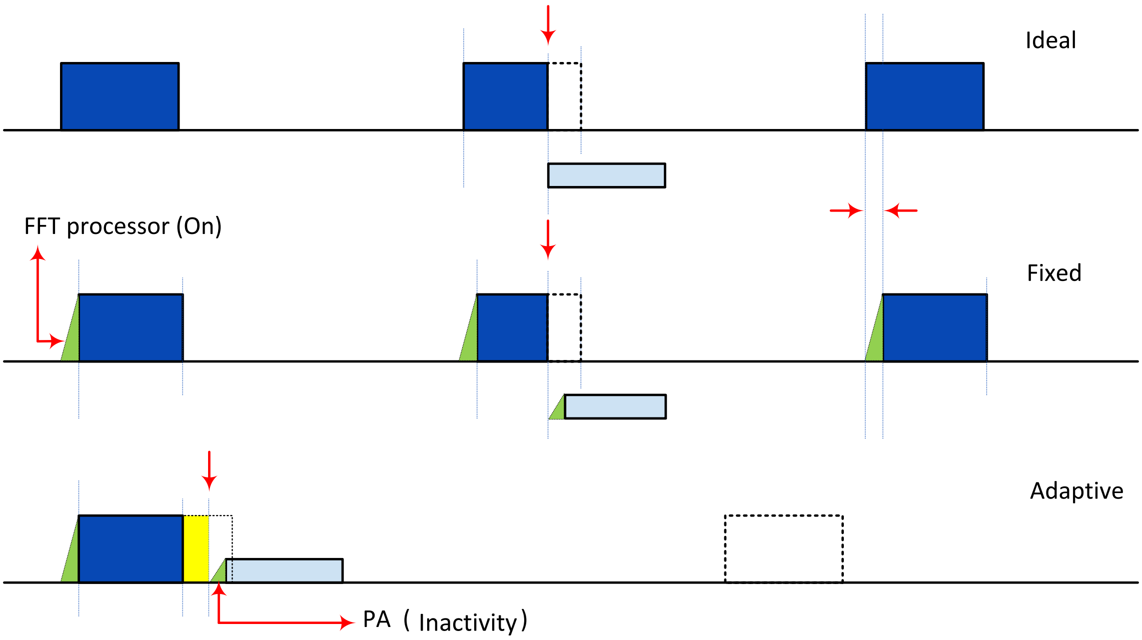


Fig. 3-43 DRX real scheme

From the definition of the DRX mechanism, during the On Duration period the UE is only receiving download transmissions, so power consumption is dominated by the FFT processor in the receiver circuit [37]. On the other hand, when the UE is in an Inactivity period, the power consumption is dominated by the power amplifier (PA) in the transceiver's circuitry. DRX timing is in "*msec*" and with thousands of transitions during operation, the effects of power consumption during circuit raise-up could not be neglected, even if the switching time is in the range of "*µsec*". Sometimes the energy consumed on one transition between the IDLE mode and the CONNECTED mode exceeds the energy consumed in the IDLE mode [29]. Fig. 3-44 shows an example of a very high level of transitioning a process can go through.

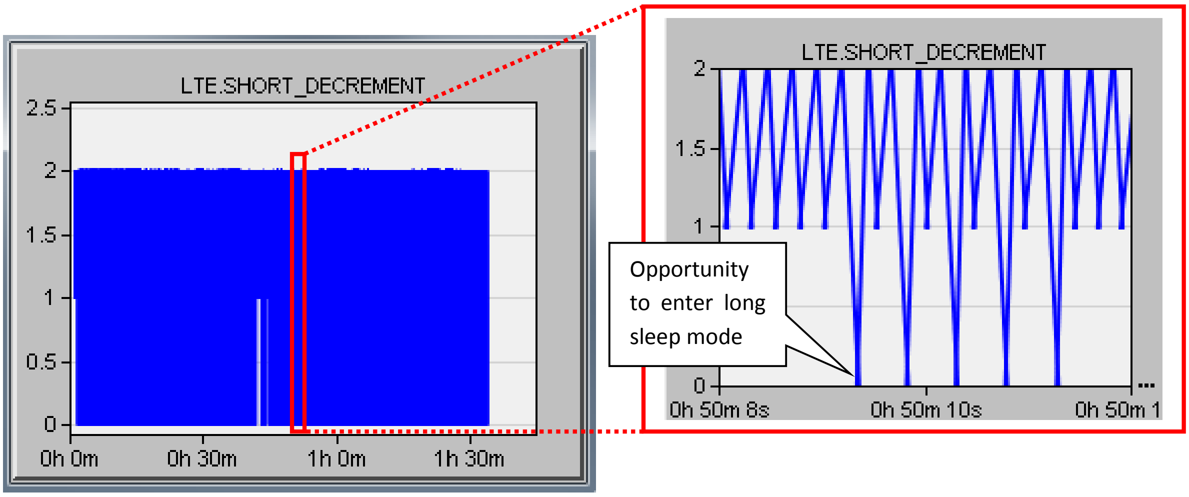


Fig. 3-44 DRX counter to enter long sleep

The second reason is related to the effects of the RRC connection request (generally known as msg3 transmission) and RRC state change effects (network re-entry). Fig. 3-45 shows the total number of RRC connection request attempts for every UE (average per UE). From the figure, the number of request attempts in the adaptive mode has decreased compared to the fixed one, which means a decrease in the amount of energy consumed on transmissions by the RACH. According to the DRX mechanism, when there is no traffic to be transmitted for a specific time period, the eNB issues the RRC connection release and UE enters the Idle mode. This sounds very useful for power saving, but if any data transmission is triggered, the UE must start the RRC session again and has to request the radio bearer creation procedure which requires more energy to be drained from the battery. The UE has to invoke the RACH procedure (or scheduling request transmission) with every RRC connection request attempt [32], and with every successful one, the UE has to reply with a connection establishment complete message, then it has to find the DRX start offset and invoke/start the process. When a UE goes into this operation, transmission and receptions steps are performed with the eNB, and this requires more operational power to be consumed as these steps are repeated for every attempt.

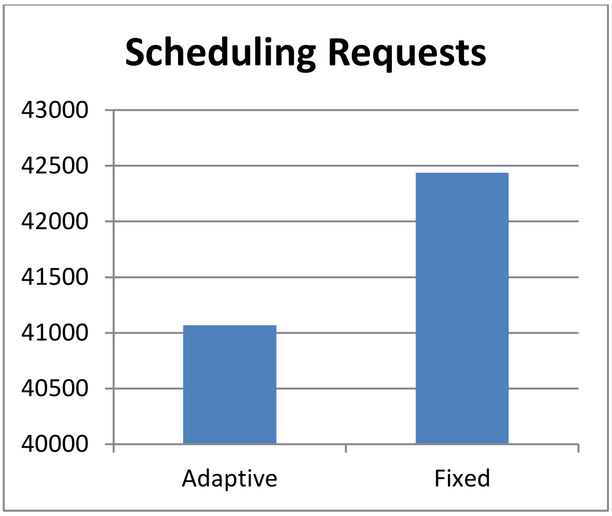


Fig. 3-45 Number of network re-entries (Scheduling Requests)

Another point is that the UE keeps retransmitting msg3 on the uplink in the random access procedure until it reaches the maximum allowed number of retransmissions or it receives a msg4 response from the eNB indicating a successful msg3 [38]. A large number of RACH invocations would not be efficient and this is considered to be one of the drawbacks associated with power-saving methods. So the power-saving method has to be optimised in order to reduce the number of RRC connection requests to a minimum level.

The third reason for saving energy is due to the cell search process [39]. This process combines procedures for measurement, evaluation, detection and then selection processes. All these procedures have a great influence on power consumption during the Idle mode. The cell search and select processes are configured to be performed and restarted in many situations, such as when the UE is turned on or when it is out of coverage, but one situation which has a significant impact on power consumption is when the UE, upon invocation from NAS, performs cell search for a serving cell regularly every certain number of DRX cycles [24, 40]. Cell search is a continuous process and from this perspective, it is more efficient to decrease the excessive cell search procedures and make the search intervals longer, to avoid the steps for restarting and re-scanning all available frequencies and bands which consumes time and power.

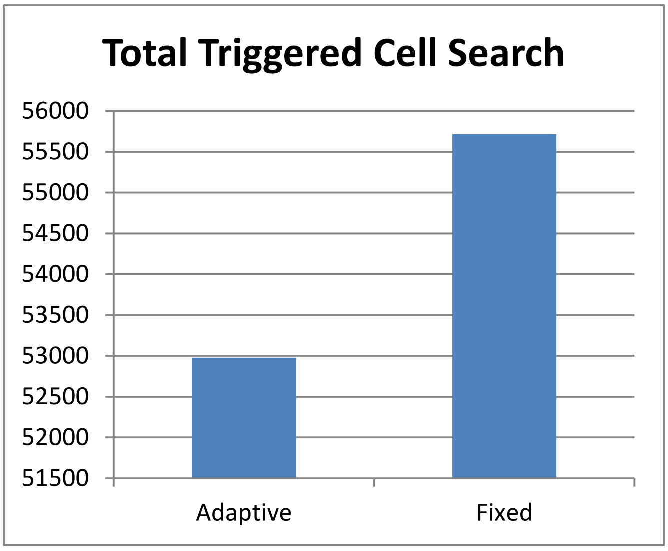


Fig. 3-46 Number of triggered cell searches

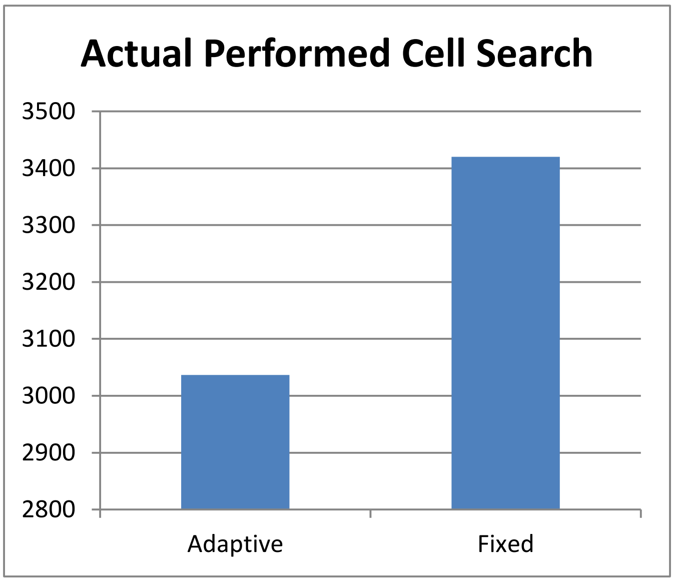


Fig. 3-47 Number of performed cell searches

Thus power consumption could be improved through optimising the cell search process when the UE enters long sleep periods and this implies that the UE performs a lower number of cell search processes and avoids additional related steps such as initialization, HARQ, RACH and DRX process updates. Fig. 3-46 and Fig. 3-47 show a comparison between the number of triggered cell search processes by UEs in the fixed and adaptive modes.

Other issues that consume power in mobile systems are handovers and retransmissions (due to errors and drops). The HARQ protocols increase circuitry power due to frequent retransmissions; with increased unnecessary retransmissions through the HARQ process, more power is consumed from the battery. Fig. 3-48 shows the decrease in the number of triggered handovers in the adaptive mode, and Fig. 3-49 shows the decrease in the number of allocated DL grants (DL HARQ ACK which requires processing power and sometimes are destroyed because they are not expected) and regular grants (UL grants).

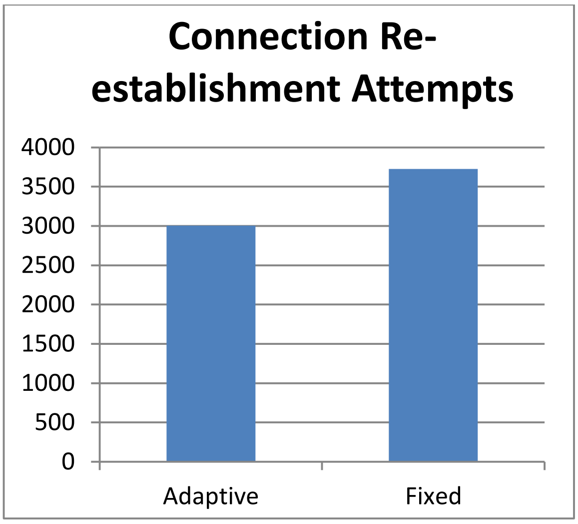


Fig. 3-48 Number of handover triggers (Average per UE)

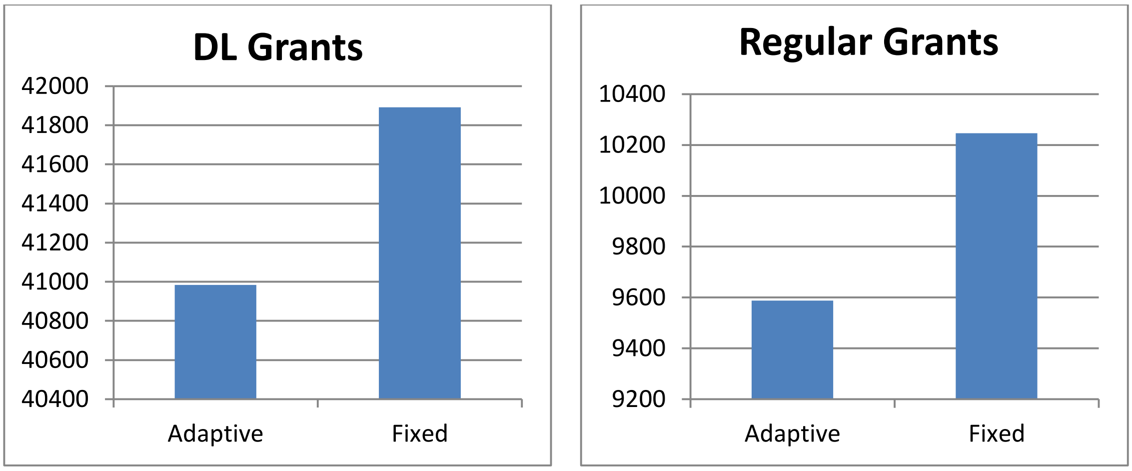


Fig. 3-49 Number of Grants

3.9 Summary

In this chapter, the DRX process for power saving in LTE systems is presented and studied with the basic states and procedures. The requirements for extending battery life and optimising the power consumption in 4G systems are introduced, and the main focus has been put on the DRX timers' configuration with its accompanied delays and power consumption. The impact of the Inactivity timer and other timers on delays, network throughput and energy savings has been presented through a comprehensive analytical study and simulation model. According to the network situation and the traffic load, using different DRX parameter configurations has been revealed to be necessary, and the system operated better than when keeping to one configuration state.

Additional functionalities have been introduced to the existing DRX mechanism in order to optimise the process and turn it into an adaptive mode. The main implementation took place within the LTE eNBs' and UEs' AS layers. Based on the load over the control channel, the serving eNB in every cell has the procedures incorporated to monitor the load and continuously adapt the RRC reconfiguration message on a regular basis to inform the active connected UEs about the new DRX configurations. Upon receiving the new configuration, UEs are adapted and start a new DRX cycle smoothly.

According to the results, the adaptive mode achieves significant power savings. The worst case scenario has been simulated and the network has been saturated in terms of transmission power and narrow available BW profile. The performance has been changing from one UE to another. Numerical results show the effectiveness of the adaptive algorithm for power saving compared with the currently existing fixed standard with respect to power consumption. However this sometimes happens at the cost of an accepted minimal variation in the throughput level or delay values, which vary among the UEs depending on the running applications.

As the DRX mechanism dominates the network performance for UEs and eNBs, the effects of the presented adaptive scheme appear on the other implemented processes in the LTE-AS layer such as cell search, handover, allocated grants and RRC Connection state. The adaptive scheme showed a positive impact on these running processes in the system, and over the wireless link, easing the congestion over the control channel by freeing it faster.

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CHAPTER 4

Interference Management for Co-Channel Femtocell

Introduction

The dense deployment of Femtocells within the Macrocell's coverage area is expected to dominate future LTE networks. Femtocells could be the solution for mobile networks when there is need for capacity relief. The challenges will be in the Femtocell planning and management when thousands of them are deployed. The deployed Femtocells have to operate in a co-channel deployment due to the scarcity of spectrums. This issue causes interference between the Femtocells and the Macrocell. Another important consideration is that the Femtocells are randomly deployed by the end-user not by the network operators. This causes extra overhead on the networks because of the co-tier interference between adjacent Femtocells. Issues such as co-channel interference, co-tier interference, cross tier interference between the Femtocells and the Macrocell, and power control, have been under research in order to avoid and eliminate interference. Here the centralised scenario among Femtocells to avoid interference is presented. Here the Femtocell is made self-organised under the coverage of the Macrocell on the same subbands.

In previous studies by other researchers, when deploying multi-Femtocells within the coverage of Macrocells, downlink power calibration and reduction techniques are condsidered to be fundamental in the management of the Macrocell Recived Signal Strength Indication (RSSI) variation. A dynamic allocation is proposeded to ensure that the Femtocells operate adaptively and monitor the spectrum countinuously in an efficient way without needing to establish communication between the Femtocell and the Macrocell over the wireless interface. Our studies showed that the Signal to Interference Plus Noise Ratio (SINR) could be improved, and therefore interference on the downlink could be avoided, if the Femtocell could trace and sense the presence of the Macro-user.

4.1 The Femtocell technology

The mobile phone industry has undergone significant evolution and introduced innovative services, leading to a competitive market. Operators are looking for new tecknologies that will help to serve this increasing growth. One of the current methods is to use broadband internet to increase radio coverage and network capacity by deploying Femtocell technology. Femtocells are low power, user-deployed base stations, designed for indoor coverage. Their spectrum is licensed by mobile network operators; their advantage is that they are able to enhance wireless services, and provide short distance radio access to mobile users. As studies have shown that the largest number of phone calls are still made from indoors [1, 2], Femtocells are a technology which can potentially bring large benefits to indoor wireless communications. One Femtocell provides coverage and support to a small number of users by utilising the customer's internet backhaul such as DSL to connect to the cellular network (Fig. 4-1).

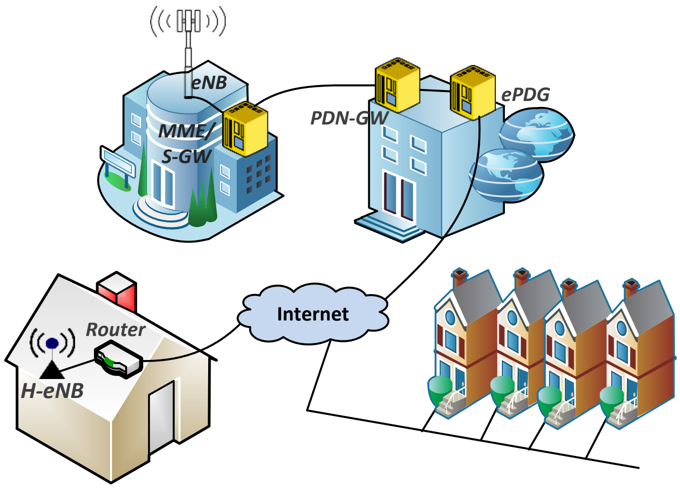


Fig. 4-1 Femtocell access through broadband connection

Femtocells are beneficial to network operators and users alike. For the former, it is useful to be able to offload traffic from Macrocells down to smaller base stations such as Picocells and Femtocells, as this enhances the system's capacity [3]. Femtocells are also utilised by service providers as a way of maintaining the quality of service and improving the UE's reception in situations where a high data rate is required. Due to their low power transmission, Femtocells reduce the amount of interference with other electrical devices, whilst providing improved indoor coverage. In addition, the battery life of the mobile device can be prolonged as it only needs to connect over short distances when connecting to a Femtocell, instead of to the nearby Macrocell [4].

Spectrum holes and scarcity are two of the main obstacles that affect network productivity, and indoor locations such as houses, companies and public spaces are the target of Femtocell technology in order to support and increase network coverage and capacity. Network availability, voice quality and data services will improve when deploying these cost-effective and small base stations. Femtocells are planned to be introduced into the market with self-configuration and self-optimisation capabilities. Hence the deployment of Femtocells in multi-tier networks requires a high level of interference management and power control. The unplanned dense deployment of Femtocells is expected to have a major impact on their characterisation in addition to their identification within the network. Other issues such as access control, access type and handover are also attracting more attention in order to optimise the performance of integrated Femtocells in LTE networks. The deployment of Femtocells is done by the end-user, who is required to register his new cell. The registration of the Femtocell could be done online through the website of the service provider, where the UE has the option to register a limited number of mobile phones in order to limit the access to his Femtocell; this is defined as a closed subscriber group (CSG). Alternatively, users can choose to access Femtocells through an open subscriber group (OSG) where the users can use the services of any Femtocell whose signal they can receive [5].

In this chapter the deployment of dense Femtocells in an LTE network is presented. The neighbouring Femtocells may suffer from their frequencies being overlapped, which causes the Femto-users (FUEs) to interfere with each other; this is known as co-tier interference. Cross-tier interference could also occur, when there is overlap between the Macrocell and the Femtocell signals on the downlink within the Macrocell coverage area [6]. Interference mitigation, Femtocell power control and resource efficiency are the issues to be investigated in the following sections in order to guarantee the QoS in OFDM Femto-networks and improve the spectrum utilisation in an LTE environment.

4.2 Related work

The deployment of low power nodes in heterogeneous networks has a beneficial impact on the system's capacity by bringing the transmitter and the receiver closer to each other. Femtocell technology is evolving, and the effects of Femtocells on non-Femto-users such as Macro-users have been a subject of much research. In order to reduce and mitigate the interference between Femtocells and Macrocells, many studies have been carried out based on the power control for the uplink or downlink, radio resource scheduling, Femto/Macro local information, UE measurements, cooperative approach, time/frequency allocation, QoS requirements, frequency division and frequency reuse.

In [7] the researchers proposed a method for power control of randomly deployed Femtocells. The system model is based on the idea of a constant Femtocell coverage area by enabling the control of pilot and data on the downlink. In the uplink, the transmission power of the UE is limited to a predefined value in order to guarantee that interference is at its minimum level for the existing Macro-users. In [8], a dynamic power control algorithm is proposed in order to reduce the interference level while maximising the indoor coverage. Because the Femtocell is limited in resources and bandwidth, the imbalance in the data load is related to the time-varying traffic. The aim of this scheme is to consider the load balance of the Femtocells so that the loaded Femtocell reduces its coverage area by adjusting transmission power and vice versa. In [9] the authors studied the leakage of pilot power into the adjacent areas and its effects on the mobility triggers. The goal is to reduce signalling overhead in a self-optimising scheme during the Femtocells' operation. The coverage of the Femtocell is adapted according to the available information reported from the UEs about mobility and also about changes in the pilot power. In [10] a distributed power management scheme is proposed which is based on utility and cost. Utility represents the SIR requirement and the cost represents the power consumption; an increase in the SIR is weighted against the cost. In this approach, the UE reduces its targeted SIR when it senses that traffic congestion has started to take place. The UE continues to reduce its SIR in response to traffic congestion and sometimes switches off transmission. As a result, this can degrade the QoS level. In [11] the authors described a communication mechanism over the X2 interfaces between the Macrocell and Femtocells for inter-cell interference coordination (ICIC). One example is that when a certain cell needs to transmit, it has to inform its neighbours about its transmission power level on the downlink. Another approach utilises the uplink, exchanging the measurements about interference levels among different cells.

In [12] the Macro-user's has to detect the presence of Femtocells by performing measurements during some time intervals. Then the UE checks for the available channel and determines the required SIR and the transmission power. The Femto-users have to adapt their transmission power in response to a distributed power control algorithm. This method requires a large amount of overhead on the Macro-user's side. In [13] the authors proposed a management framework in which the Macrocell determines and reports the transmission power for the Femto-users, in addition to the signal-to-interference ratio and the maximum allowed transmission power of the Femto-users. This interaction requires a large amount of signalling over the wireless interface, and the X2 interface as well. In [14] the authors proposed a decentralised resource allocation scheme for hybrid networks. In this scheme the available radio resources are divided into time and frequency domains. The Macrocell can select and use all the resources, while a Femtocell, when it wants to transmit, selects only a subset from the available frequency resources in a random way. The aim is to minimise the probability of interference occurring for every resource block. In [15] an interference mitigation scheme was proposed, based on transmit beamforming. The victim UE connects to the interferer Femtocell for control exchange, just for the Femtocell to change the beamforming weights, in order to reduce the interference level experienced by the victim UE. This approach would be very complicated in situations where a large number of UEs exists. In [16] a Femtocell management model was proposed, where resources are allocated to Femtocells and Macrocells orthogonally in time and frequency. However, this approach requires a high level of synchronisation between the different cells in addition to the overhead caused by the large amount of signalling. In [17] the cognitive approach has been proposed for Femtocells in LTE systems. The Femtocells share information among them about pathloss and then the interference is estimated and the Femtocell selects a component carrier according to mutual interference levels.

In [18] a type of dynamic technique for interference avoidance between Macrocell and Femtocells was put forward. The proposed scheme is a combination of power control and the handover process. When the Macro-user is discovered to be under interference from a Femtocell, the Macrocell will perform intra handover so that the UE is assigned to a different channel with lower interference. This also applies to the Femtocells, for changing their allocated channels. In [19] the authors presented a method for interference control based on clustering, bandwidth division and power control. Femtocells are allocated different frequencies in a frequency-reuse manner, according to the cluster position and interference level.

4.3 Interference management

Interference management, particularly when Femtocells are densely deployed, is a challenging issue. However, the dense deployment of low power nodes is one of the main features of future 4G networks. It is therefore vital to the efficiency of the system that the performance of these nodes does not undermine the activity level of the primary UEs of the system, the Macro-users. A feature of Femtocells is that they are deployed without planning; therefore a Macro-user operating close to a Femtocell may experience severe interference, as can the other neighbouring Femtocells [20].

Interference management is essential in Femtocell dense deployment schemes; Femtocells have to operate in a coordinated way. Fierce competition for the available radio resources among Femtocells is unacceptable; firstly it may waste resources, and secondly it does not guarantee the required QoS level. Interference management is even more important when there is a Macro base station that may share all or part of the bandwidth with the Femtocells. Already-existing base stations and users may experience interference from the Femtocells, as they can be deployed by the user at any time. Therefore any interference management scheme must afford priority to the Macrocell and its users.

The presence of small base stations within the coverage of larger ones changes the architecture of the cellular system. As the Femtocells are deployed within the coverage of the Macrocell, this can cause interference within the same tier or on different tiers. The two worst examples of interference are: co-channel interference (when the Femtocells and the Macrocell share all or part of the BW) and interference on the downlink of the Macro base station when the Femtocells operate in a closed access system. Network operators may prefer co-channel deployment as is provides a higher system capacity, but it is also most likely to lead to interference. Fig. 4-2 shows some expected interference scenarios in a two-tiers LTE system.

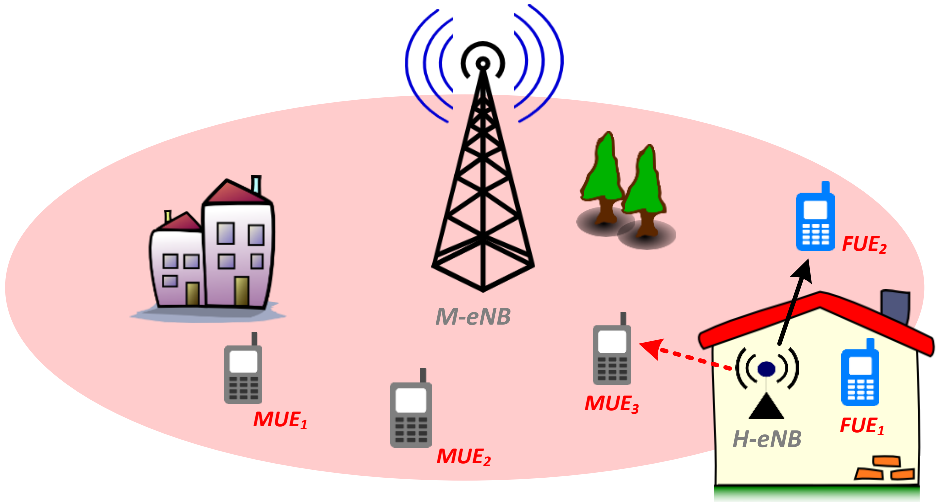


Fig. 4-2 Femtocell interference scenario

The figure shows cross-tier interference, where the Femtocell causes interference on the downlink signal of the Macrocell to the Macro-user (MUE), and the Macro-user also causes interference on the uplink signal to the Femtocell. As mentioned before, in closed access Femtocells where some of the UEs around the Femtocell are not served by its coverage, the level of interference could be worse.

In an OFDM system, the interference level varies depending on the subcarriers' allocation. Small areas with weak coverage and the presence of spectrum holes are the main motivations for Femtocell technology in order to improve the QoS in these situations. In an effort to compensate for the spectrum scarcity, Femtocells are deployed in a cognitive functionality [21, 22] so that they share the same subbands as the Macro base station within the same coverage area. One other challenging issue is the uplink interference at the Macrocell edge. At the cell edge the Macro-user has to transmit with high power due to its position far from the Macrocell and to overcome path loss. If a Femtocell is located in a position that is at the Macrocell edge, it will receive a large amount of interference from the Macro-user.

4.4 Power control

Power control is very important in 4G systems. The power leaks between neighbouring Femtocells due to the dense deployment, and hence this creates dead zones (Fig. 4-3). The random installation of Femtocells makes it difficult to manage the Femtocells planning without any kind of self-control or intelligence added to the Femtocells. The changing environment and also the location of the Femtocell, without any prior knowledge available of other Femtocells within the network, make it very important to equip the Femtocell with some kind of sensing capabilities.

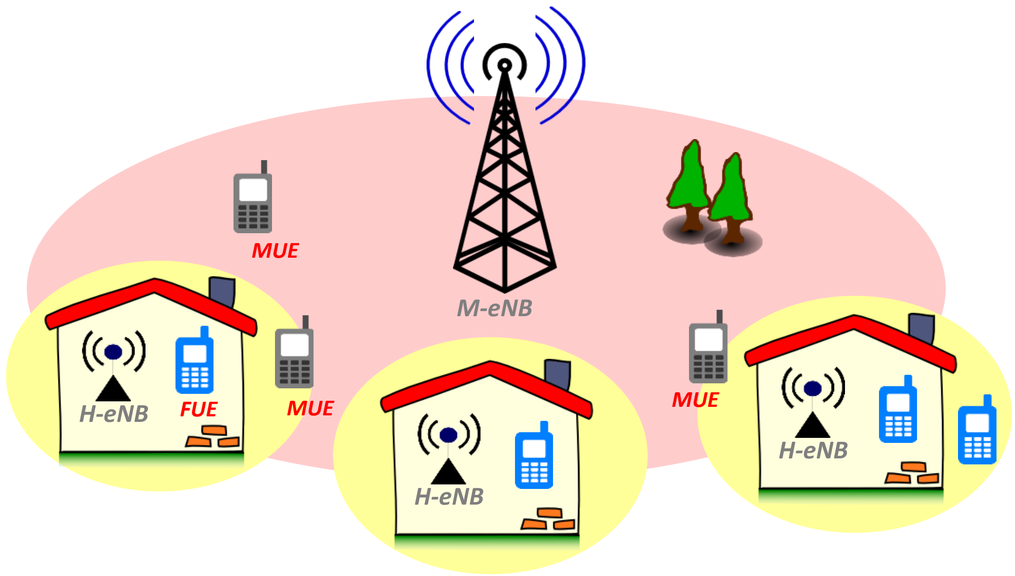


Fig. 4-3 Femtocell Dead-Zone

Power control for Femtocells has been proposed as a method for interference avoidance. Normally the distance between the Femto-user and the Femtocell is short and hence the Femto-user does not transmit at high power. However in 4G systems, power control is essential to avoid dead zones in addition to avoid power leakage between adjacent carriers in the case when there is spectrum splitting. Applying power control in an optimised way helps to protect the Macro-users and improves the indoor cellular coverage. However, network instability can be caused when the channel is changing quickly, and this makes power control methods time-consuming. Furthermore, power control requires a high level of cooperation between different nodes, and so in general it is a difficult technique to master. Adaptive power control is proposed to avoid interference caused by the constant power transmission, in addition to avoiding the dead zones around the Femtocell in the case of co-channel deployment. The Femtocell's transmitted power is adapted according to the surrounding environment and the observation of the Macro signal. However, adaptive power control is not enough in the case of dense deployment and additional procedures must be performed.

Power control must be done carefully as it entails a trade-off between providing sufficient coverage and reducing cross-tier interference. Cross-tier interference depends on the distance between the Femtocell and the Femto-user and adjusting the transmitted power must guarantee that the UE is still connected with the Femtocell. In order to avoid any overheads in 4G multi-tier networks, the best choice is to introduce intelligence and self-organising capabilities to Femtocells. Fast and accurate sensing is one of the most important features that a Femtocell must have in order to equip the node with better knowledge about the surrounding environment.

4.4.1 Power formulas in LTE

Power control in LTE systems is a complicated process and includes many parameters; it can happen around 1000 times per second in order to handle energy drops or increases at the receiver. It has two main phases, the first is during call set-up and the second is during normal connection. Power control at the set-up, or when turning the mobile on, is very important, since on the one hand the signal should not have such a low power that it will not reach the receiver at the eNB, and on the other hand, it should not be too strong or it will cause interference. The eNB plays a major role in organising this issue, by transmitting its reference signals and information about the power allowed to be transmitted by the UE.

On the uplink, the serving eNB sends the power commands to the UE through TPC between the eNB and the UE.

Fig. 4-4 shows how the downlink OFDM signal in the LTE system is formulated from a power point of view. The energy is determined per resource element; in the figure, the reference signals (RS) are cell specific and have the highest power values and additionally, their power is constant for all subframes [23].

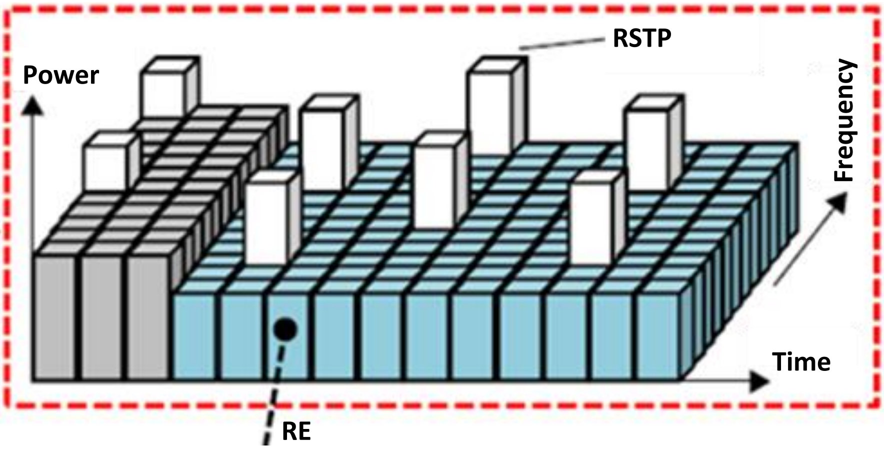


Fig. 4-4 eNB downlink OFDM signal

Power control formulas [24], for some channels, are summarised as the following:

$$P_{PRACH} = \min\{ P_{CMAX},\ PREAMBLE\_RECEIVED\_TARGET\_POWER + PL\}\ [dBm] \quad (4.1)$$

$$P_{SRS}(i) = \min\{P_{CMAX},\ P_{SRS\_OFFSET} + 10\log_{10}(M_{SRS}) + P_{O\_PUSCH}(j) + \alpha(j)\cdot PL + f(i)\}\ [dBm] \quad (4.2)$$

$$P_{PUCCH}(i) = \min\{P_{CMAX}, P_{0\_PUCCH} + PL + h(n_{CQI}, n_{HARQ}) + \Delta_{F\_PUCCH}(F) + g(i)\}\ [dBm] \quad (4.3)$$

$$P_{PUSCH}(i) = \min\{P_{CMAX}, 10\log_{10}(M_{PUSCH}(i)) + P_{O\_PUSCH}(j) + \alpha(j)\cdot PL + \Delta_{TF}(i) + f(i)\}\ [dBm] \quad (4.4)$$

$$PH\ (i) = P_{CMAX} - \{10\log_{10}(M_{PUSCH}(i)) + P_{O\_PUSCH}(j) + \alpha(j)\cdot PL + \Delta_{TF}(i) + f(i)\}\ [dB] \quad (4.5)$$

(i) is the subframe number , (j) is a factor which could be 0 or 1 – it is determined by the higher layer depending on the scheduling Grants.

In order to avoid the maximum transmission power as much as possible, the power is determined as the minimum value available between the maximum value and the other values. The maximum value is the UE's transmission power defined as 23 dBm; the other factors that specify the power for each channel are the bandwidth (the number of resource blocks), the calculated pathloss (estimated depending on the reference signal and the RSRP), F(i) and delta_push are the TPC command received from the DCI 0, P_o is provided by the higher layer and it is related to the RRC Connection set up and reconfiguration. Delta _TFI is provided by the high layer and it is related to the SIB2 [25].

4.5 Interference over the control channels

In the OFDM system, the frame structure spans the time domain and the frequency domain. From the perspective of the time domain, every subframe contains resources organised in the data dedicated channel (PDSCH) and the control dedicated channel (PDCCH). The PDCCH carries the downlink-allocated resources, and the PDSCH conveys the data to the UEs (Fig. 4-5). The relationship between the data and control spaces is inversely proportional. The more space occupied by the PDCCH, the less space remains for data and therefore the throughput will be lower. If a large number of UEs are served by the eNB, the PDDCH will be larger, so in every subframe the system has the chance to support either the capacity or the network throughput [26]. However, the PCFICH, which is the first control channel, will also need to be taken into consideration. As the essential part of the control channel planning and structuring in the time domain, it needs to be planned and designed in an optimal way to ensure the best planning of the control channels. It is located in the first OFDMA symbol and contains information about the other control channels in the subframe.

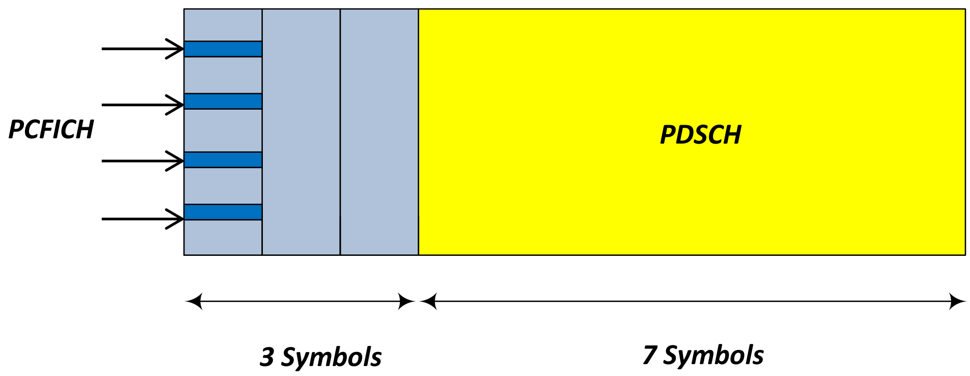


Fig. 4-5 Subframe structure from the control channels perspective

In the Femtocell scenario, as a result of the close distance between the transmitter and the receiver, the channel between the Femtocell and its UEs is considered in a good state and the low number of connected UEs indicates that there are a low number of control channels to be mapped. The PCFICH exists only in the first symbol, so it is possible to resize the symbols without losing data. For example, the Femto-layer therefore has one OFDM symbol, and the other subframes are left for data transmission.

On the uplink, the UE has to also generate and transmit uplink sequences, the demodulation reference signal and the sounding reference signal. There are 30 possible different reference signals. Interference between the Femto-users and the Macro-users exists in some locations. Every Femtocell has to consider an interference margin because of the existence of Macrocells UEs around it. This interference margin implies that the Femto-user has to transmit at a higher power in order to keep a good throughput. The amount of interference caused to the Macro-users by the Femto-users could reach a high level and exceed the interference margin of the Macrocell.

Regarding the frequency domain, the available bandwidth is the key in this aspect (the number of available subcarriers and hence the available resource blocks [RB]). The control format indicator (CFI) is located within the PCFICH, and indicates the PDCCH's occupation of the OFDMA symbols. The location of the PCFICH is distributed equally in distance over four REGs in the frequency domain. The positions of the REGs in the bandwidth are a function of the Physical Cell Identity (PCI). Each cell has to have been allocated a different PCI so that the UEs will not identify two cells operating on the same frequency as the PCI.

4.6 PCFICH and PCI planning

The PCI parameter is likely to play an important role in enabling the self-organising capabilities, depending on the configuring options of different LTE eNBs. The purpose of differentiating the cell from its close neighbours through its PCI configuration is to make sure that the reference signals (RS) of different cells are located in different positions, because the reference signals are coded depending on the value of the assigned PCI [27]. The PCI is defined depending on the physical layer cell identity group (N_1 from 0 to 167) and the physical layer identity (N_2 from 0 to 2).

$$PCI = 3N_1 + N_2 \tag{4.6}$$

In 3GPP they have defined formulas for generating and mapping the reference signals of the resource elements in the downlink frames, and also for mapping the primary and secondary synchronisation signals of the OFDM symbols and slot number, according to the frame structure (depending on a normal or extended cyclic prefix).

The goal of PCI planning is to pay attention to the primary and secondary synchronisation signals (PSS and SSS), in addition to the reference signals. In LTE standardisation there are 504 different PCI values; these 504 possibilities are a product of the manipulation between 3 PSS sequences and 168 SSS sequences [28]. Two cells transmitting the same PSS causes interference on the downlink. In the LTE standard, they have distributed the PCFICH locations according to the available bandwidth and the PCI. If two cells are planned to have the same PCFICH location, UEs will suffer from interference, especially at the cell edge. It will then be difficult to decode the PCFICH and hence there will be difficulties in decoding the other control channels, the PDCCH and the Physical Hybrid ARQ Indicator Channel (PHICH).

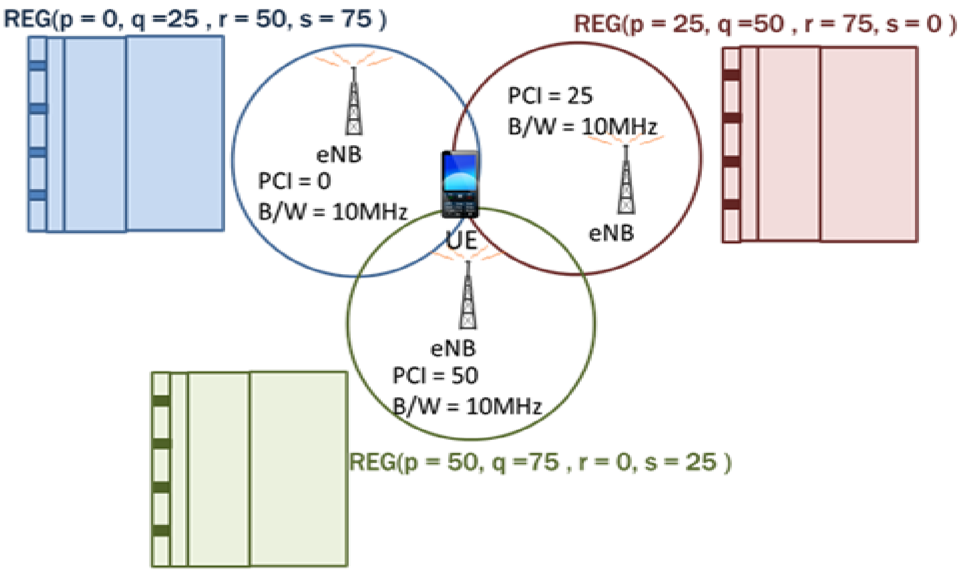


Fig. 4-6 Interference caused by the same PCI group deployment

As mentioned in the previous sections, the location of the PCFICH depends on the available bandwidth. For example, in the case of a 1.4 MHz BW, the number of subcarriers is fewer and hence, in the time domain, the PDCCH requires more space to be transmitted.

In the frequency domain, PCFICH requires 16 resource elements (4 REGs).

The location of the PCFICH is in the first symbols of the OFDM subframe.

The number of available resource blocks is N_{RB}

The number of the subcarriers in one resource block is N_{SC} = 12 subcarrier.

The mapping formula is given as:

$$\text{Value 1:} \quad P_1$$

$$\text{Value 2:} \quad P_1 + \left(\frac{1}{2} N_{sc}\right) * \left(\frac{1}{2} N_{RB}\right)$$

$$\text{Value 3:} \quad P_1 + \left(\frac{1}{2} N_{sc}\right) * \left(\frac{2}{2} N_{RB}\right)$$

$$\text{Value 4:} \quad P_1 + \left(\frac{1}{2} N_{sc}\right) * \left(\frac{3}{2} N_{RB}\right) \tag{4.7}$$

$$\text{Where :} \; P_1 = \left(\frac{1}{2} N_{sc}\right) * \; PCI \; Mod \; (2 * N_{RB}) \tag{4.8}$$

According to Fig. 4-6 where PCI = 25 and BW = 10 MHz, we have the subcarriers numbers:

$$\text{Value 1:} \quad 6 * 25 \; Mod \; (2 * 50) = 150$$

$$\text{Value 2:} \quad 150 + (6) * (25) = 300$$

$$\text{Value 3:} \quad 150 + (6) * (50) = 450$$

$$\text{Value 4:} \quad 150 + (6) * (75) = 600 \tag{4.9}$$

Therefore neighbouring cells should be planned with attention being paid to the deployment of the PCI in order to avoid collision between the synchronisation signals and to guarantee better throughput [29].

The PCI value becomes a problem when deploying the Femtocell randomly, therefore attention must be paid to enabling the Femtocell to automatically assign itself a unique PCI.

4.7 Proposed scheme

Regarding 4G Femtocells, the random deployment by the end-user and the ad-hoc nature of the Femtocell positioning indoors makes it difficult for the cellular operator to control the planning of the new low power base stations (the HeNB). This will be considered and resolved for the design of these 4G Femtocells.

In this section the new algorithms that have been proposed for the Femtocell in order to have interference management and adaptive power control are presented. The aim here is to enable the Femtocell to update itself based on its sensing of the spectrum and the Macrocell's downlink signal.

The drawback of power control is that if the Femtocell reduces its transmitted power by a large amount in order to reduce the interference level, this may result in a degradation of the signal-to-interference plus noise ratio SINR at the Femto-user's side. There are other methods of interference management, such as spectrum splitting among the Femtocells, but these are also not efficient and waste resources. There is a need to develop a new interference management mechanism which does not rely on power reduction techniques.

Within each subframe there is a control region and a data region. Fig. 4-7 shows an interference case where there is collision between the control region of the transmitted frames (or subframes) and the control regions of the other transmitted frames from another node operating on the same frequency band. In order to avoid interference or reduce it to the lowest possible value, a method which is able to protect the control region has to be proposed. The control signals are randomly distributed within the control region and they represent the scheduled UEs. If the control region is corrupted, the receiver will not be able to decode the information contained in the control region to find its resources and as a result it will not be able to access the network and thus the UE is considered as a blind. Sometimes in the case of severe interference, the UE may not be able to connect to the serving base station (Femtocell or Macrocell). If the data region is corrupted in some places, the retransmission mechanism (HARQ) could help in a very efficient way to restore the corrupted data through multiple re-transmissions and resource partitioning.

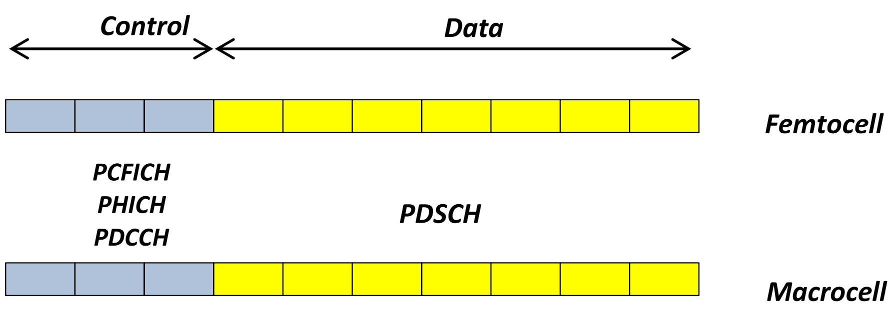


Fig. 4-7 eNB downlink control and data channels

A Femtocell has to search for the presence of Macro-users nearby. If detected, the Femtocell has to adjust the structure of the transmitted subframes so that they do not cause any collisions with the Macrocell downlink transmissions (Fig. 4-8).

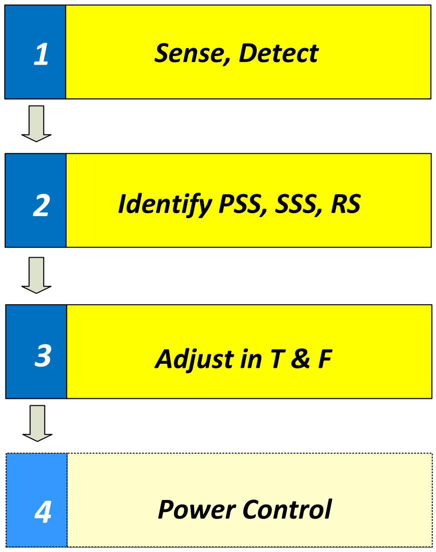


Fig. 4-8 Femtocell procedure to avoid interference

4G Femtocells have to be equipped with spectrum sensing capabilities to be aware of the surrounding environment. Reducing interference at the cell edge improves the SINR without the need for a high level of power control. Power control is a part of the LTE standard and it is carried out by the both eNB and the UE by exchanging Transmit Power Control (TPC) commands either to decrease or increase the power of the transmitter.

Femtocells plan for a small number of UEs so the complete control region is not required, meaning that it could be thinner compared with larger base stations, and much more flexible. The PCFICH tells the UE about the length of the control channel (in the first symbol only), so it is very important to protect it. The PHICH tells the UE about the uplink transmission, whether it is successful or not (first symbol or all symbols), and the PDCCH tells the UE where it can find its data.

Here we are not going to implement any procedures to change the size of the control channels, although resizing the control region has no impact on the UE's capability to receive and decode the subframes, and will not affect the throughput as the number of UEs connected to the Femtocell is small.

The required self-organising procedures for the Femtocell mainly include spectrum sensing and power control. The Femtocell has to detect the subcarriers allocated to the Macro-users in its vicinity and then avoid allocating them to its Femto-users. The Femtocell can allocate subcarriers allocated at the same time to the Macro-users who are relatively far from the Femtocell. However, detecting and allocating specific subcarriers is not straightforward and requires synchronisation in addition to considering different accompanied interference types. This methodology, which includes sensing, detecting and sharing, is performed efficiently; this makes it preferable over other methodologies proposed for Femtocell technology such as cognitive radio. Cognitive radio does not employ this cooperation between large and small cells; in addition it only provides a limited spectrum to the secondary network. To avoid co-channel interference (CCI) from the Femtocell to the Macrocell, the subcarriers allocated to the Macro-users are not used by the Femtocell.

The proposed work implies that, first, the Femtocell determines whether there is a connection to the Macrocell through either a wireless backhaul or through an X2 interface. This connection is very useful for exchanging information with the Macrocell; the Macrocell may send the scheduling information and the candidate subcarriers to the Femtocell. In that case the Femtocell has a connection with the Macrocell, which reduces the size of the Femtocell's efforts to perform measurements on all the subcarriers and limits these measurements to the group of subcarriers that could be utilised by the Femtocell. On the other hand, the Femtocell may send its information regarding the sensed spectrum to the Macrocell. Comparing the spectrum sensing results from the Femtocell with the scheduling information from the Macrocell helps to create spectrum opportunities.

4.7.1 Algorithm

The simplest method for interference management is to first enable the Femtocell to be aware of the surrounding radio environment. The Femtocell can perform measurement using a listening module to receive the downlink reference symbols (or pilot symbols) of the Macro eNB. The position of the reference symbols is known in the LTE OFDM time/frequency structure of each slot. Those reference symbols help in estimating the channel.

The radio frequency measurements performed by the Femtocell are considered similar to the measurements performed by the UE (Victim Macro-user) in the surrounding area of the Femtocell. Many factors may affect the accuracy of the performed measurements such as the power of the transmitted signal, switching the Femtocell off, and changing its location from a place deep inside the building or close to the window. All the previously mentioned factors may lead to a possible mismatch; therefore the Femtocell has to keep performing the radio measurements on a regular basis in order to avoid any possible mismatch in the radio frequency measurements performed by the UE.

In order to guarantee the accuracy of the sensing, additional sensing made by the Femto-user could be exploited when necessary. This is very important at the cell edge of the Femtocell, where the Femtocell itself cannot detect the signal of the Macrocell. For example, this case occurs if the Femtocell is located in the centre of a hole within the Macrocell's coverage. Therefore sometimes it is very efficient to enhance sensing by taking into account the measurement reports forwarded by the Femto-user (measurement reports in cellular networks are important especially for the handover process as they include information about the neighbouring cells).

For spectrum sensing and detection, many options could be utilised for the detection process such as defining a power threshold to determine the UL signals of interest. The threshold value depends on how successful the Femtocell is at finding suitable carriers. A higher threshold means that the Femtocell selects the UEs which are very close, while a lower threshold implies that the Femtocell considers more Macro-users which results in a low number of subcarriers being assigned to the Femto-users.

After this, the Femtocell identifies the close Macro-users and the available subcarriers. The Femtocell may discover subcarriers unused by the Macrocell, in addition to subcarriers that are allocated to distant Macro-users. Femto-users are limited in number compared to Macro-users and this creates a considerable number of subcarriers that could be utilised by Femto-users. By accurately selecting the subcarriers, the Femtocell interference on the Macrocell downlink is avoided.

The Femtocell uses the measurement reports reported by the Femto-user to be certain about its measurements and sensing of the surrounding environment (Fig. 4-9). The

Femtocell senses the Macro-eNB's presence (far) or the Macro-user's presence (near).

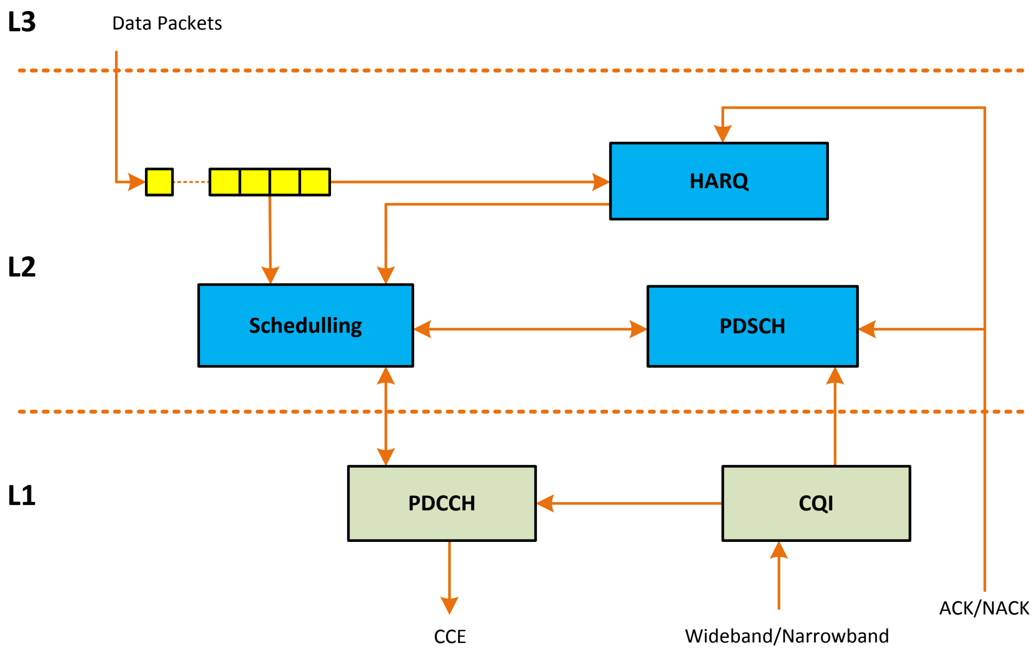


Fig. 4-9 Radio resource management (RRM)

The functionality of the centralised scheme using the controller depends on the geo-location services where the newly deployed femtocell will report its location to the controller along with its assigned bandwidth value. The controller upon receiving the femtocell information will create the neighbour list of this femtocell according to the relative distance between each neighbour and the new femtocell. Assuming that the femtocell has a radius of d, the neighbour cell will be at a distance of 2d and the maximum distance between three femtocells to avoid the case of confusion where no cell has two neighbours with the same PCI. For each newly added femtocell, the controller creates three lists for the neighbours; the first two lists are for the PCIs and BWs of the neighbour femtocells within a distance of 2d where the third list is for the PCIs of the femtocells within a distance of 4d of the new femtocell. The occupied subcarriers by the neighbours within 2d distance are determined by equations (4.7) and (4.8) and there locations must be avoided by the new femtocell in order to avoid overlapping. It is obvious that the larger bandwidth the femtocell has, the less overlapping is probable to take place.

	Algorithm 4.1: Sensing Phase
	Start
1	*Femto plug in.*
2	*First phase initialisation. Initialise measurement module. Measurements by the Femtocell. Initiate the cell search to start cell search*
3	*Synchronisation signal from an eNB is audible. This eNB needs to be evaluated further.* *Give preference to the preselected eNB.* *Calculate overlap:* *(Overlap <=0) → do nothing* *(Overlap >0) → Keep the range of subcarriers*
4	*Detect the frame timing from PSS and SSS signals and the DL bandwidth from MIB.*
5	*Inputs: Femtocell Location : (x,y,z), Femtocell BW: FBW* *Calculate relative distance D={d_1, d_2, d_3, ….d_k} for k existing F-eNB to this femtocell:* $d = \sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2}$ *For i = 1 to k : If d_i <= 2d_{max} :* *Add PCI of femtocell i to the PCI_{list} : $PCI_{list} = PCI_{list} \cup PCI_i$* *Add BW of femtocell i to the BW_{list} : $BW_{list} = BW_{list} \cup BW_i$* *Create the group of occupied subcarriers G according to equations ….* *$G = G \cup \{p_i, q_i, r_i, s_i\}$ for F-eNB$_i$* *If d_i <= 4d_{max} :* *Add PCI of femtocell j to the $PCI_{list\text{-}max}$: $PCI_{list\text{-}max} = PCI_{list\text{-}max} \cup PCI_i$* *Determine min integer m>=0 : $m \notin G$* *Case FBW : { 1.4, 3, 5, 10, 15, 20 MHz}* *m <= {72, 180, 300, 600, 900, 1200} respectively* *sn = m* *According to (4.7) and (4.8):* *Find max PCI_n : ($PCI_n \notin PCI_{list}$) && ($\{p_n, q_n, r_n, s_n\} \not\subset G$) && ($PCI_n \notin PCI_{list\text{-}max}$)* *else { m=m-4 , re-assign s_n , recalculate PCI_n }* *Update controller database with (x,y,z), FBW, PCI_n, Return PCI_n*
6	*Find the RA resource in frames, which is in even frames. Compute our RA-RNTI for this scheduled preamble transmission.*
7	*If Femtocell is switched off → go to 1: Reset the scanning information and restart the cell search.*
	End

The unique locations for the PCFICH depends on the assigned bandwidth, for the bandwidths of {1.4, 3, 5, 10, 15, 20 MHz} there are {72, 180, 300, 600, 900, 1200} subcarriers and {3, 7, 12, 25, 37, 50} PCFICH locations respectively. In order to guarantee far deployment of the PCFICH locations, the search in the algorithm is started from the top of the bandwidth for the value of Sn then the other locations are calculated according to the equations … once the PCIn value is determined for the safe PCFICH locations, it is checked for the confusion case for the PCIlist-max if the value of the PCIn is already used before, the calculations must be repeated for new value of m.

4.7.2 Co-channel deployment

In order to allow the Femtocells to acquire a unique PCI, one method is to depend on the coordinator so that the Femtocell sends the value of the detected Macro PCI to the coordinator and then the coordinator saves it and returns the value of a unique PCI to the Femtocell. The communication over the X2 interface does not cause an overhead on the communication line between the Femtocell and the co-coordinator. It is very useful to reduce the overhead from the wireless interface and offload it to wired connections between the different nodes (over the X2 interface). A central coordinator is the best way to distribute PCI offset to the connected Femtocells. A centralised scheme is better than the distributed one, especially with regards to stability. For example, when the Femtocell discovers another Femtocell and reports it to the coordinator, or when the owner changes the location of the Femtocell in his house, this may cause saturation over the air interface in the distributed scheme.

4.7.3 Search space and the candidate PDCCH

There are many places in the PDCCH on the downlink subframe where the UE can search for its dedicated resources. Each search space is a group of CCEs where the UE has to look for its resources on the PDCCH. The structure of the downlink frame is not always the same and it may contain different types of PDCCH locations; this depends on many factors such as the aggregation level and whether the PDCCH is UE specific or common.

In the MAC layer, the radio network temporary identifier (RNTI) identifies the PDCCH allocations which carry the DCIs. This identifier is used by the user when it monitors the search spaces in order to distinguish between a common search space and an UE specific search space. The DCIs with general network information are broadcasted on common search space such as paging, uplink power control and random access, while the DCIs with user-specific allocations are carried in the UE's specific search space.

4.7.4 Macro-user tracing

Femtocells' planning is challenging to manage, given their random installation. Self-control or intelligence is therefore required. As the Femtocell has no prior knowledge of other Femtocells in the network, it is essential to provide it with some kind of sensing capabilities.

The Macro-user can suffer from severe interference when it enters into the Femtocell's coverage area, particularly if the Femtocell is transmitting on the same frequency bands as the Macrocell. It must therefore avoid operating on the same subcarriers as those assigned to the Macro-user within its vicinity, which means that the Femtocell must keep track of the Macro-user as long as it is within the range of -or close to- its coverage. Interference could be avoided if the Femtocell was able to track the Macrocell's downlink signal and find out which resources are dedicated to the victim Macro-user [30].

The UE can be identified in the LTE system by different keys while it is connected with its serving eNB. UE identifiers are allocated to the subscriber during RRC_Connection setup, and the Femtocell uses one of these to track the Macro-user. A unique identifier, the Cell Radio Network Temporary Identifier (C_RNTI) is allocated by the eNB to the UE at the moment when an attach procedure is initiated between the UE and the eNB. This identifier is 16 bits and it can be generated in three states, depending on the connection status of the UE: temporary during the random access procedure; permanent during contention-free random access; or semi-persistent when the UE will use the same resources for a longer time during the whole connection.

The UE depends on the C_RNTI to track its data on the downlink within the cell and this makes the C_RNTI a very important identifier for marking RRC messages during connection [31].

During the simulation, the Femtocell is programmed to receive Macrocell and Macro-user's signals. In order to trace the Macro-user's dedicated resources on the downlink, it then has to locate the Macro-user's C_RNTI, and continue to track it periodically. The femtocell discovers the interference-free resources of far macro-users; in addition, it exploits the channel dependant scheduling to predict the future resources of the victim nearby macro-users and avoids utilising them. On the Macrocell uplink channel, the Femtocell detects and demodulates the control channels and the data channels. Fig. 4-10 shows the uplink channel for subframes in the LTE system. The Femtocell has to discover this information [32]:

- The uplink occupied subbands.
- Determining the UEs who occupy the discovered subbands.
- Determining the nearby Macro-users according to distance from the Femtocell.

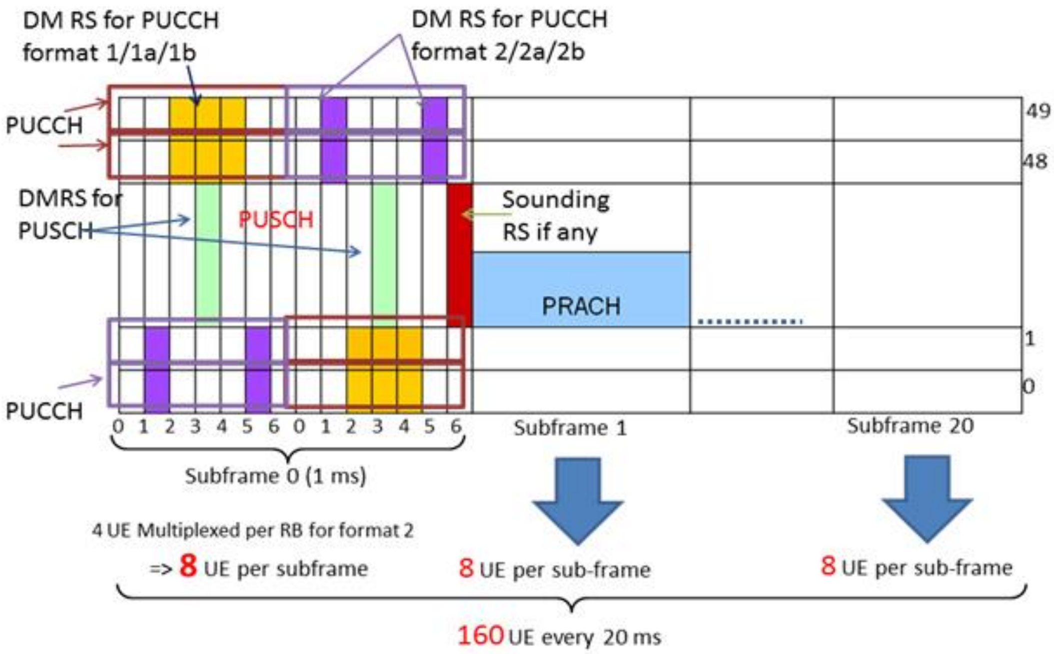


Fig. 4-10 LTE UP link map [33]

The determined Macro-users are the UEs of interest and their subcarriers must be avoided by the Femtocell. Note that Macrocell scheduling is always changing due to the channel-dependent scheduling procedure in LTE systems; hence the Femtocell must keep continuously scanning to avoid any failures.

The Femtocell has to be synchronised with the Macrocell by finding the start of the Macrocell's transmitted frames. After synchronisation and system discovery, the Femtocell has to keep the acquired scheduling information for future usage and comparison in case there are any scheduling changes. Uplink sensing is performed using an energy detector to find the nearby users. The discovered Macro-users are added to a list which is continuously updated.

Algorithm 4.2: Tracing the Macro-user	
	Start
1	*Macro-user Detection* *No signal detected → do nothing.* *If a Macro-user detected → find its C-RNTI on the UL.* *Monitor the MeNB on the downlink to find the resources of the MUE of interest.* *Compute the start of the next subframe.* *Find out the subframe number of the next subframe.* *Arrival of packet: Extract the packet for necessary information: Get the minimum frequency and bandwidth from the TDAs of the packet.* *Get the minimum and maximum frequencies of the overlap band.* *(Sub-channel count is the amount of blocks in the entire packet)*
2	*Access the UL grant DCI for this UE,* *Keep our C-RNTI.*
3	*Extract the RNTI information from the DCI if we are not going to discard it.* *For PHY layer, check the C-RNTI's and if they do not match, just drop the packet.* *Is this UL grant for us : if (rcvd_rnti == c_rnti)*
4	*Calculate the downlink power transmission of the Femtocell based on the received power of the Macrocell.* *Do not reduce the Femtocell power (to protect the Femto-users); instead use the power formula, the Macro-user will send its preferred subband measurements.* *When Macro subbands are detected, transmit normal Femtocell power or maximum power*
5	*Repeat the same procedure for other Macro-users if found in the Femtocell's vicinity.*
	End

The Femtocell transmission power P_F on the downlink is:

$$P_F = \max(P_{F,min}\ ,\ \min(P_{F,max}\ , P_M + PL - SINR_{Target\ at\ MUE})) \tag{4.10}$$

Where:

max: to satisfy the Femto-users and min: to protect the Macro-users. ($P_{F,min}$ and $P_{F,max}$) are the min and the max Tx power of the Femtocell (-10dBm and 20dBm respectively). P_M is the Macrocell signal power received by the Femtocell. PL is the calculated pathloss between the Femtocell and the Macro-user. $SINR_{Target}$ is factor (in dB) to satisfy the target minimum *SINR* at the Macro-user.

4.7.5 Resource allocation

When the CQI is reported for wideband mode, only one value is reported for the whole bandwidth to the serving cell. On the other hand when the feedback is for subband mode, the bandwidth is divided into bandwidth parts. The UE selects a particular subband from each part and sends the measured CQI of this band and its position to the serving eNB.

When the network is synchronised, the Femtocell can calculate and detect the start of the Macrocell's subframes or the UE's subframe, and capture PUCCH signal packet.

```
sr_pkptr = op_pk_create_fmt ("lte_pucch_signal");

/* Populate the packet fields.

cqi_to_send = lte_ue_as_cqi_determine ();
op_pk_nfd_set_int32 (sr_pkptr, "cqi",      cqi_to_send);
op_pk_nfd_set_int32 (sr_pkptr, "c_rnti_info", c_rnti);
```

Fig. 4-11 Packet of interest

In Opnet software, the UE reports each subband k times between two widebands. k here is defined as 1. The Femtocell detects the Macro-user at a certain distance and decodes the packet of interest (Fig. 4-11). The Macro UE reports the CQI value for each subband including the wideband [34].

4.7.6 The Femtocell extended design

The following flowchart (Fig. 4-12) shows the interaction among the Femtocell entities and the task of each one. The tasks are placed in the order of operation. The Femtocell will operate normally while also continuing to sense the surrounding area and update itself. After each sensing session the Femtocell will update the scheduler of the free available resources on the shared channel that could be allocated to the Femto-users.

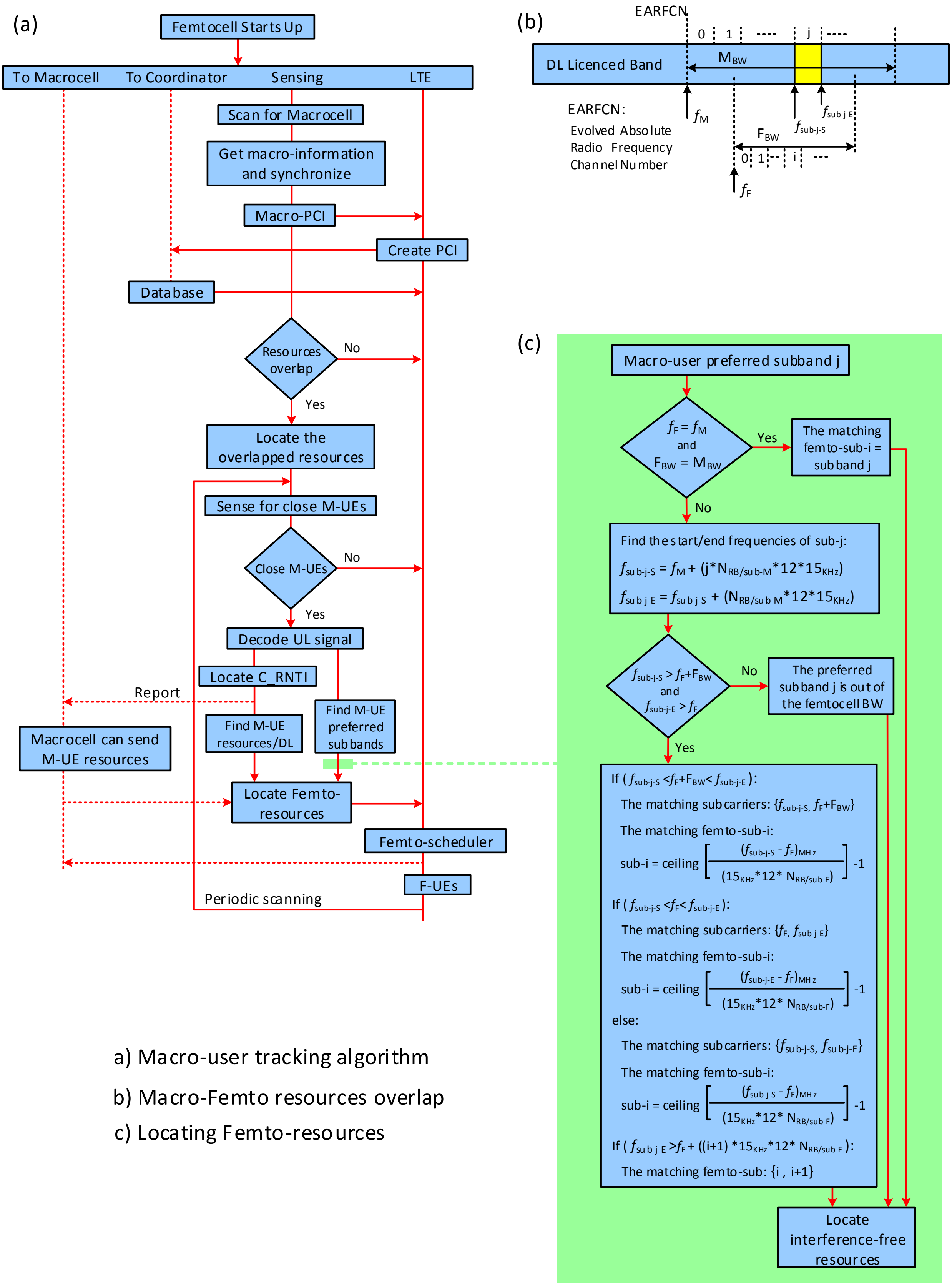


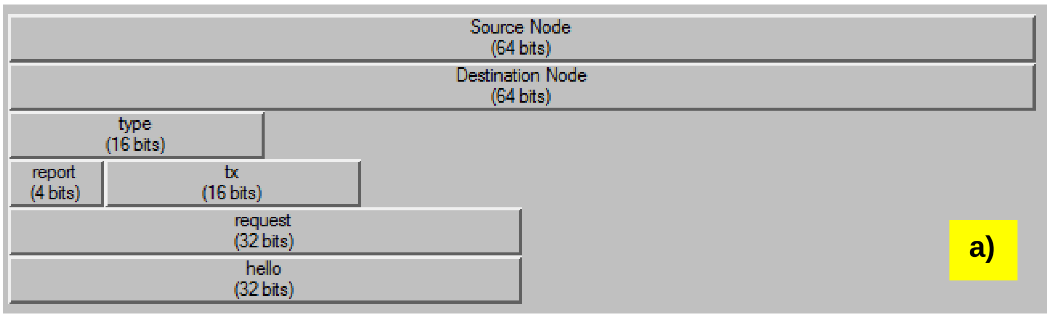
Fig. 4-12 The Femtocell extended design

4.8 Designing the proposed model

Here we are going to explain about the components of the proposed model. Femtocells will establish communications over the X2 interface and over the wireless interface. Each Femtocell is assumed to have a wired connection to the Femtocell coordinator – which is the ADSL cable – in addition to that, the Femtocell is enabled with a sensor attached to the LTE-AS layer.

The coordinator has a simple design and it is equipped with an interface to communicate with the connected Femtocells. Its MAC layer is equipped with a wireless interface and a wired one. Each interface supports different types of packets. (The wireless interface is used to send control-Hello-signals to the Femtocells in the region). The coordinator's MAC layer has a database to save the information received from the Femtocells.

The packet format between the Femtocell and the coordinator (in both directions) is designed to enable the Femtocell to report the interfering Femtocells, depending on cell ID, and to report the value of the PCI. Fig. 4-13 shows the packets' formats used for reporting by the UEs and the Femtocells. The Femtocell uses two types of packets; the first one is to request the PCI and the second one is to report an interfering Femtocell.



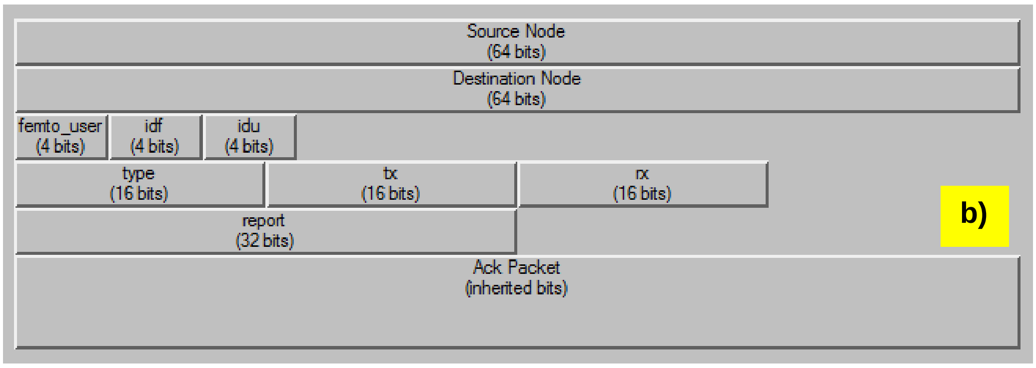


Fig. 4-13 Packets formats

The OPNET 17.5 tool is used to simulate the proposed design. The design of the coordinator is almost like the design of the gateway; it is triggered when it receives a packet from the Femtocell on the wired interface.

In the process model shown in Fig. 4-14 the coordinator is triggered with the PK_ARRIVAL event and the received packets from the newly-added Femtocell are processed in the state of FROM_FMETO.

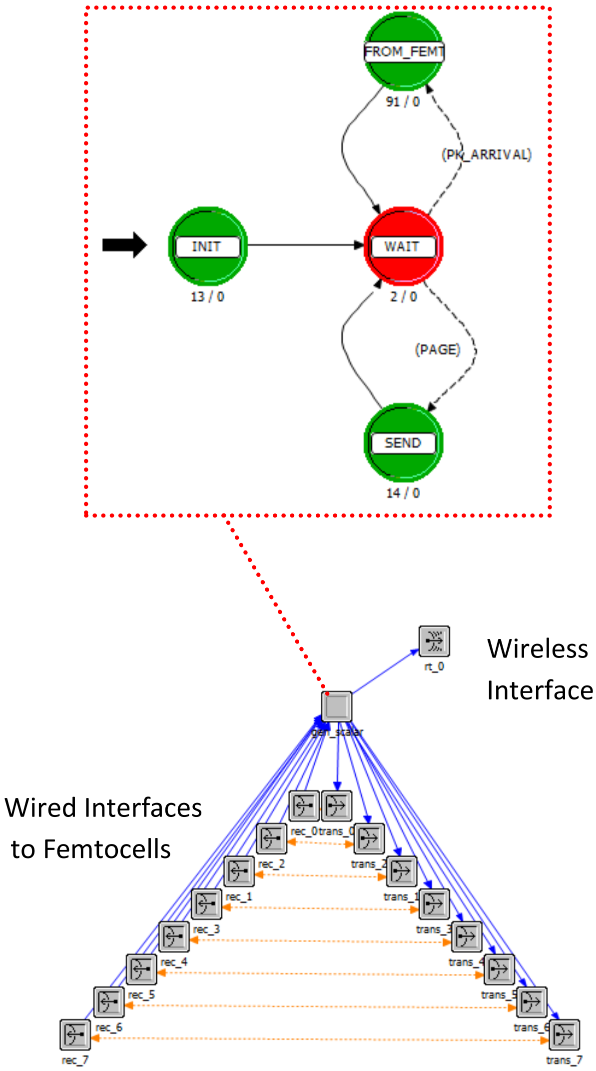


Fig. 4-14 Coordinator process and node model

In order to provide an efficient mechanism and to avoid unbalancing the standard, the OPNET command ((op_pk_deliver)) is deployed to put the packet on the desired stream without the need to use the Kernel Procedure packet oriented streams. This is very useful to interconnect modules that belong to different layers of the network such as the physical layer and MAC layer.

The MAC layer of the Femtocell has been modified and equipped with a sensing module in addition to the reporting module, and a wired interface between the Femtocell and the coordinator (Fig. 4-15).

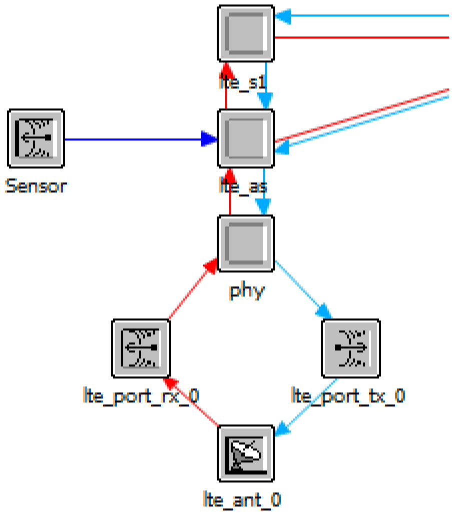


Fig. 4-15 Femtocell MAC layer

The process model deployed inside the lte_AS module is extended in order to incorporate the sensing capabilities and to add connections to the coordinator. Fig. 4-16 shows the process model with the wireless and wired sections. At the beginning the Femtocell process model is initiated and then it connects to the coordinator in the first phase. After receiving a response from the coordinator it moves to the READY state which is the wireless connection phase.

While the process model is in the READY state, it keeps updating itself by receiving updates from the wireless interfaces. Any new updates will drive the process to move to the UPDATES state where the process refreshes its records with the newly-received updates from scanning and moves again to the READY state.

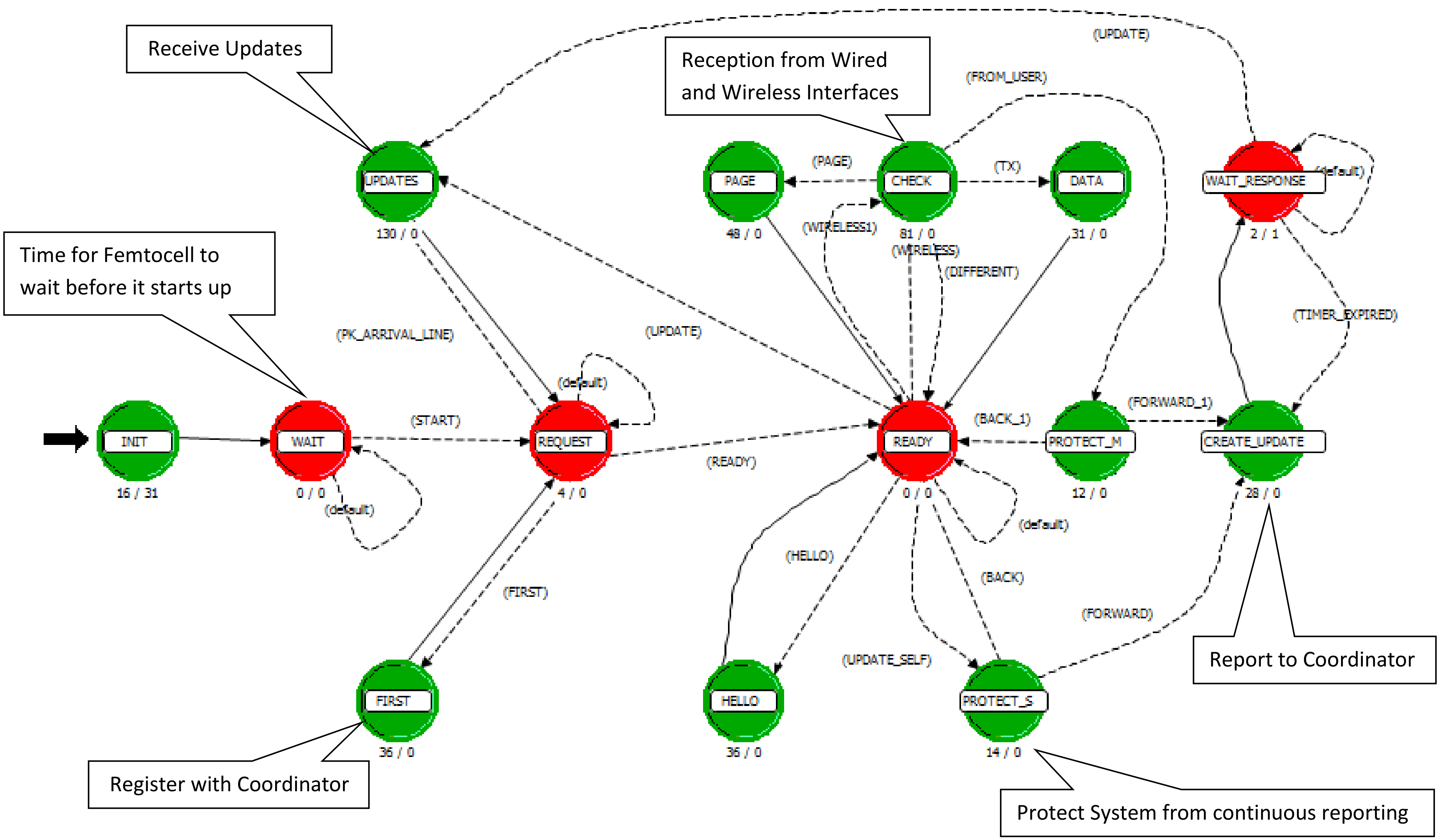


Fig. 4-16 Femtocell extended process model

4.9 System performance

In this scenario, the performance of the Femtocells in a Macrocell network is studied; twelve Femtocells are deployed within the coverage of a Macrocell (Fig. 4-17). The running application is video streaming. Interference is due to overlapping frequencies between the Macro-eNB and the Femtocells. In the network topology, each Femtocell is assigned a 1.4 MHz physical profile overlapped with the 5 MHz physical profile of the Macro-eNB. Each Femtocell has 3 to 4 UEs. For the application configuration, each Macro-user will send and receive video traffic to another Macro-user.

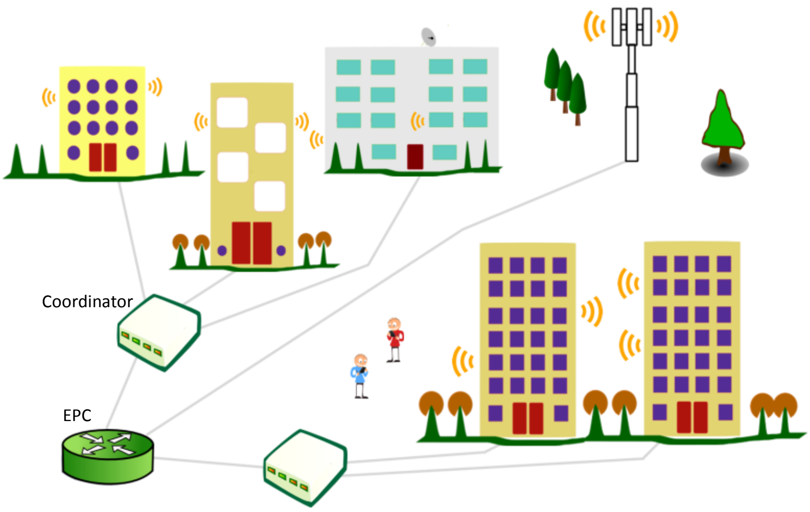


Fig. 4-17 Femtocells in Macrocell network

In order to generate interference on the Macro-users, Femto-users are configured to run traffic flows to the server.

(One traffic flow has a load of just 240 Kbps. There are about 2 to 3 traffic flows in the uplink direction and the same in the downlink direction per Femtocell.)

To study the effect of interference on the Macro-users and the efficiency of the proposed scheme, mobility is enabled on the Macro-users' profiles. Some of the Macro-users will move across the Femtocells' coverage areas.

4.9.1 The simulated scenario

This scenario is about interference mitigation; first, the allocated frequency and the deployed cells are shown. The central Macrocell has been allocated a 5 MHz bandwidth. This bandwidth is shared with a large number of Femtocells; many of which are allocated 1.4 MHz and the rest will be allocated a 3MHz and a 5 MHz bandwidth. All Femtocells and the Macrocell are deployed with FDD frequencies (Fig. 4-18).

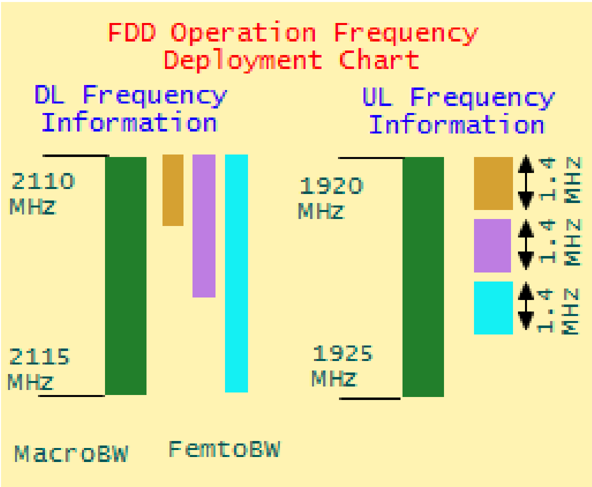


Fig. 4-18 Frequency deployment

Fig. 4-19 shows how Femtocells are grouped and connected to the coordinator in addition to different numbers of UEs are connected to each Femtocell.

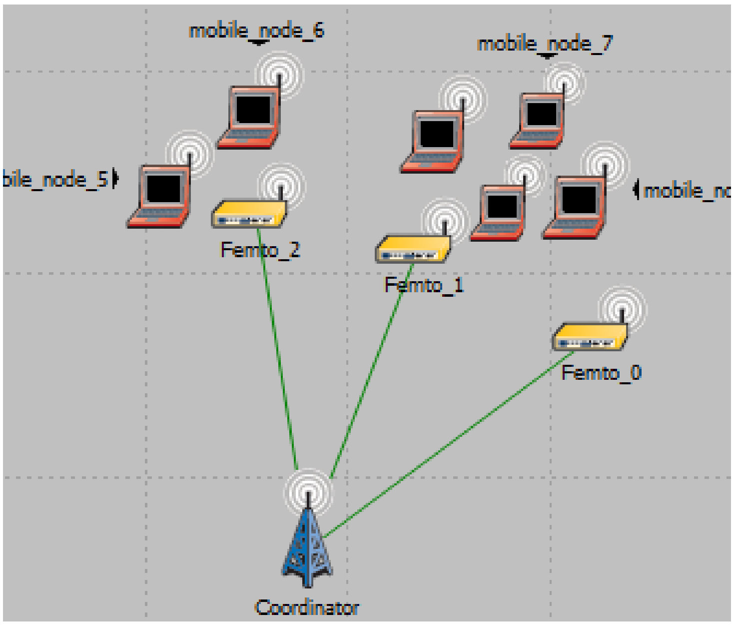


Fig. 4-19 The coordinator's simulated scenario

The following figure shows the full simulated scenario, the physical profiles are deployed in the LTE attributes for each cell in the area. Each group of cells is connected to one EPC to improve the simulation time.

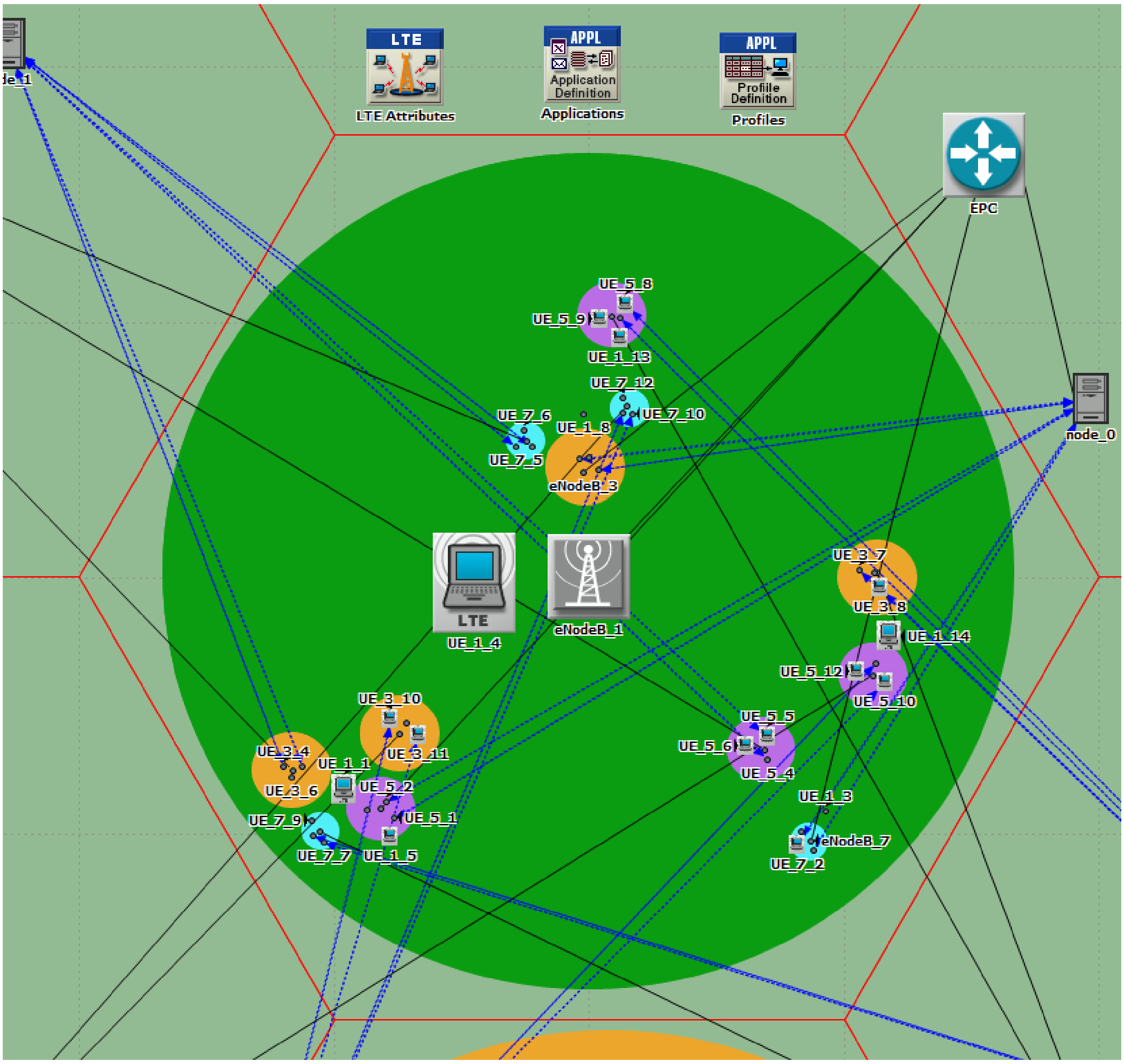


Fig. 4-20 The co-channel simulated scenario

The simulated area extends over 2 Km and the distances between Femtocells are in the range of 40 to 100 meters. Some Femtocells are installed after a certain period and some of them are switched off in order to change the radio frequency environment (Fig. 4-20).

4.10 Results

In this section figures regarding the reporting mechanism over the X2 interface between the Femtocell and the coordinator are presented. The Femtocell is configured to sense its surrounding area for the presence of the Macrocell and other Femtocells, and to report any neighbouring cell with the same PCI. When initiated at start-up, the Femtocell connects to the coordinator to acquire a PCI. The following figure represents the situation when two Femtocells have the same PCI.

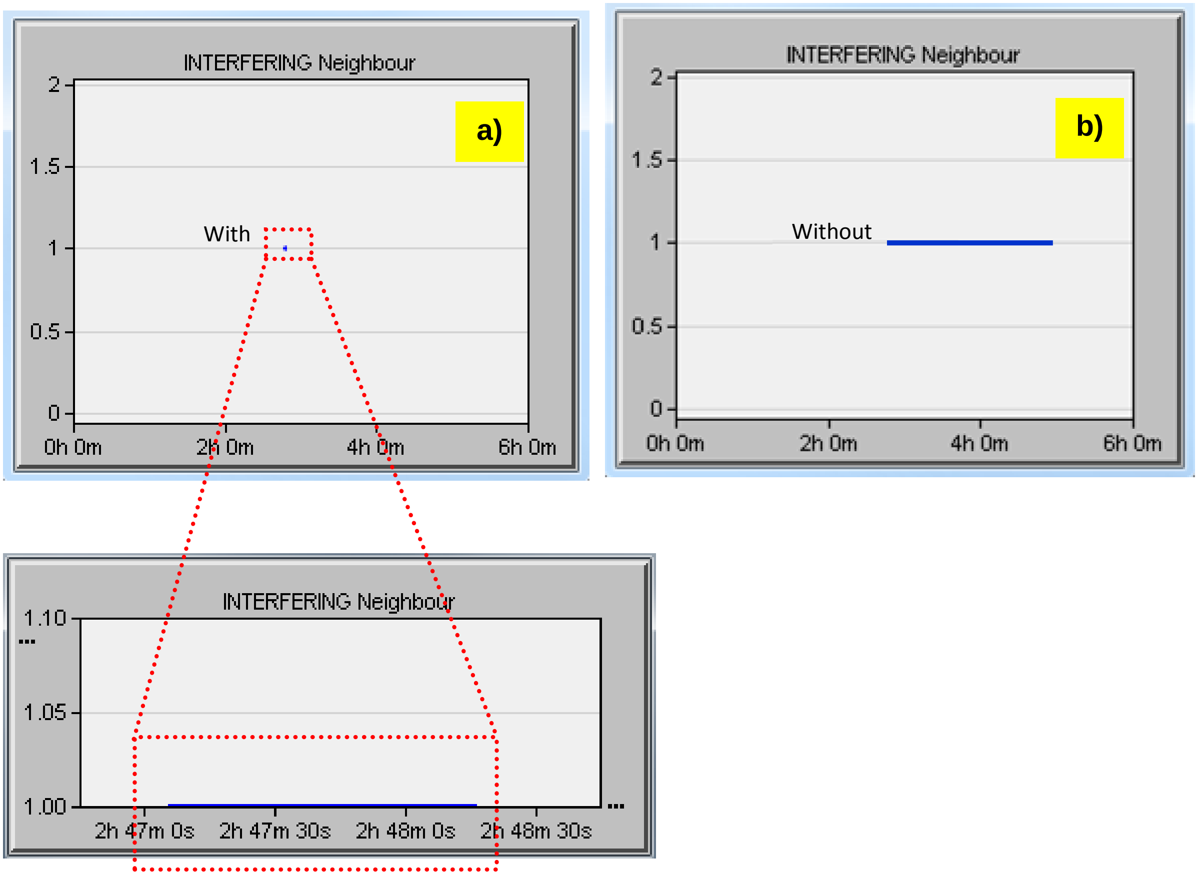


Fig. 4-21 Interference duration

Panel: a in Fig. 4-21 shows that the Interfering neighbour of Femtocell 0 (victim) could be detected. The dot represents the ID of the Interfering Femtocell which is Femtocell 1. (Without the reporting mechanism, the interference will continue and a line will replace the dot as shown in panel: b). During the simulation, Femtocell 1 is programmed to be installed with the same PCI as Femtocell 0 (this means that it will interfere with Femtocell 0). Femtocell 0 detects the signal of Femtocell 1 and as a result it forms a packet and sends it over the wired interface to the coordinator (shown in Fig. 4-19). The coordinator extracts the information from the packet and makes contacts with the reported Femtocell (Femtocell 1).

Fig. 4-22 shows the number of transmitted packets between the victim UE and its serving Femtocell over the simulation time.

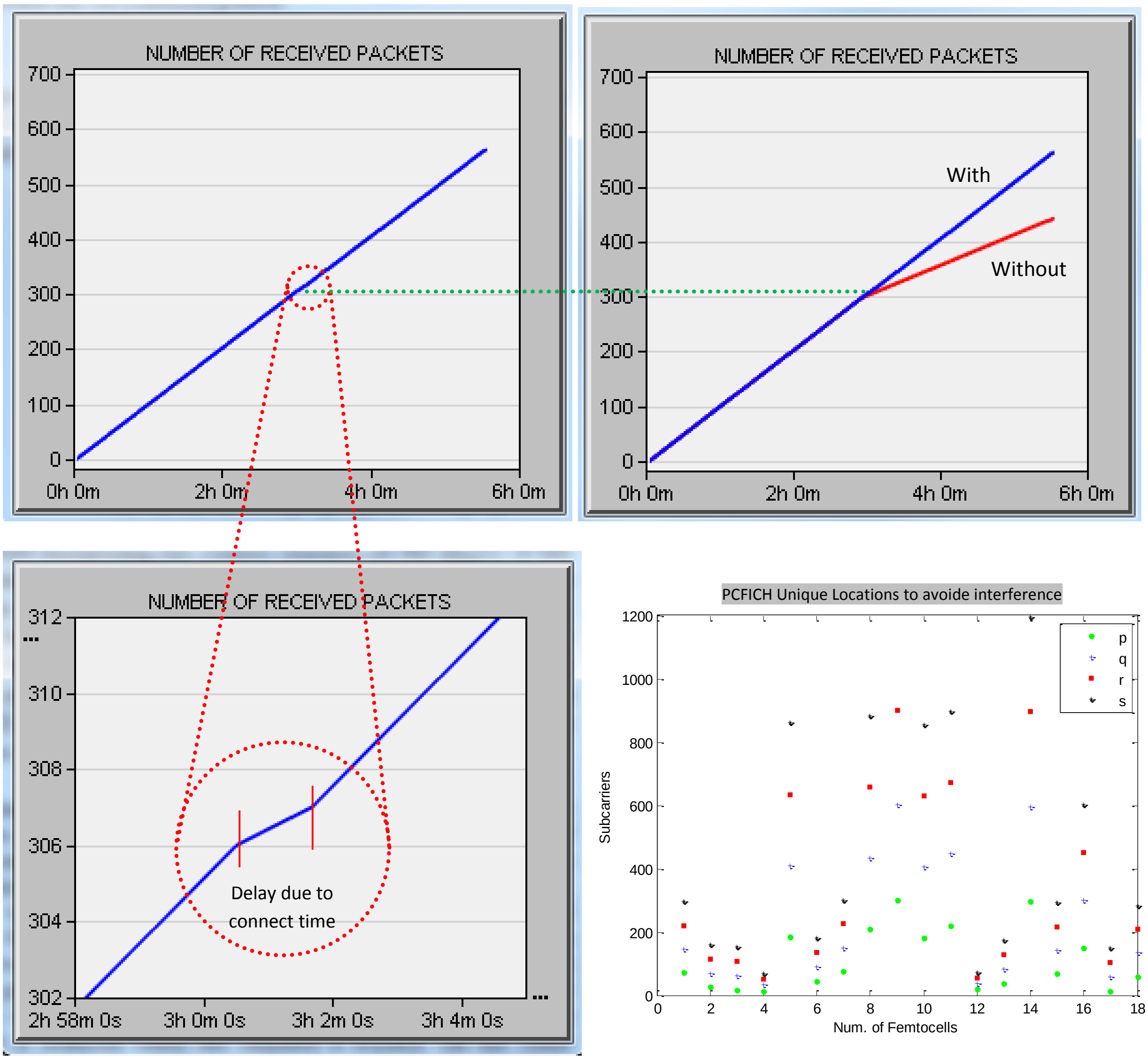


Fig. 4-22 Effects of interference and PCFICH locations

The figure shows how the number of received packets decreases due to interference from the newly installed Femtocell. When the Femtocell connects to the coordinator, the interference is mitigated and the number of received packets increases. The delay shown in the figure is over the period during which the victim Femtocell reports the Interfering neighbour and connects to the coordinator to allocate a new PCI.

With this mechanism it is guaranteed that no interference due to PCI clashes and collisions among the neighbouring cells will occur.

Now in the next section the effects of the presence of Femtocells within the Macrocell's coverage area are investigated. In this situation of co-channel deployment, the Macro-user is subject to severe interference when it exists in (or close to) the Femtocell's coverage area.

The proposed Femtocell design is introduced here in this section. The Femtocell is programed to trace the Macro-user when it is in its vicinity. We have introduced a new statistic to OPNET in order to show how the Femtocell keeps tracing the Macro-user. In the simulated scenario, the Macrocell's transmission power is 27 dB; the Femtocell performs sensing to detect the radio environment.

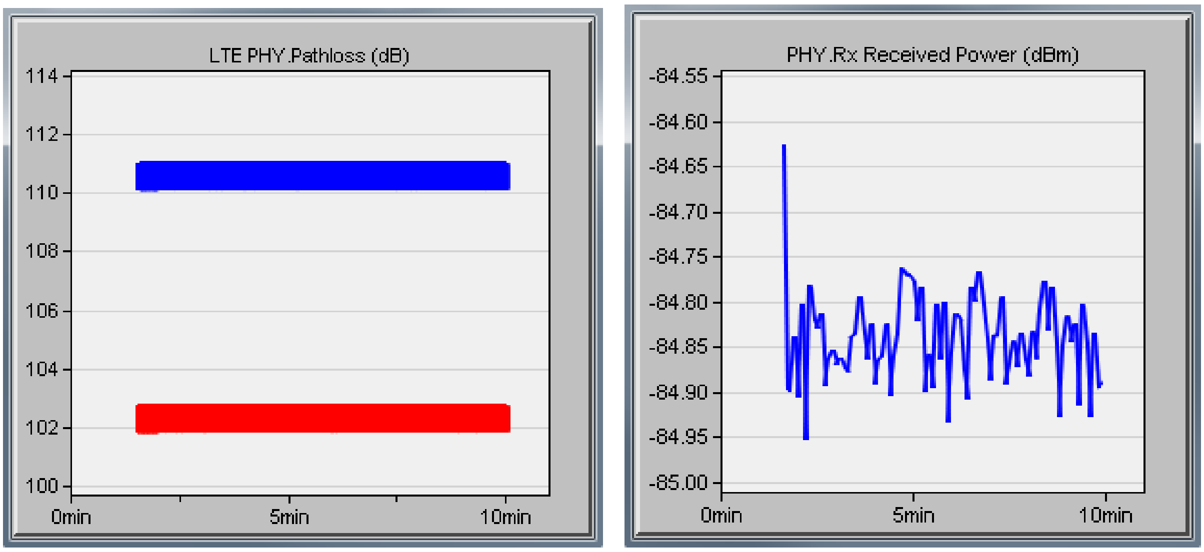


Fig. 4-23 Pathloss and the received signals by the Femtocell

Fig. 4-23 shows the signals detected by the Femtocell sensor and the estimated pathloss. The estimated pathloss is in the range of 102 to 111 dB. Considering the maximum pathloss, the power of the received Macrocell signal is around -84 dB.

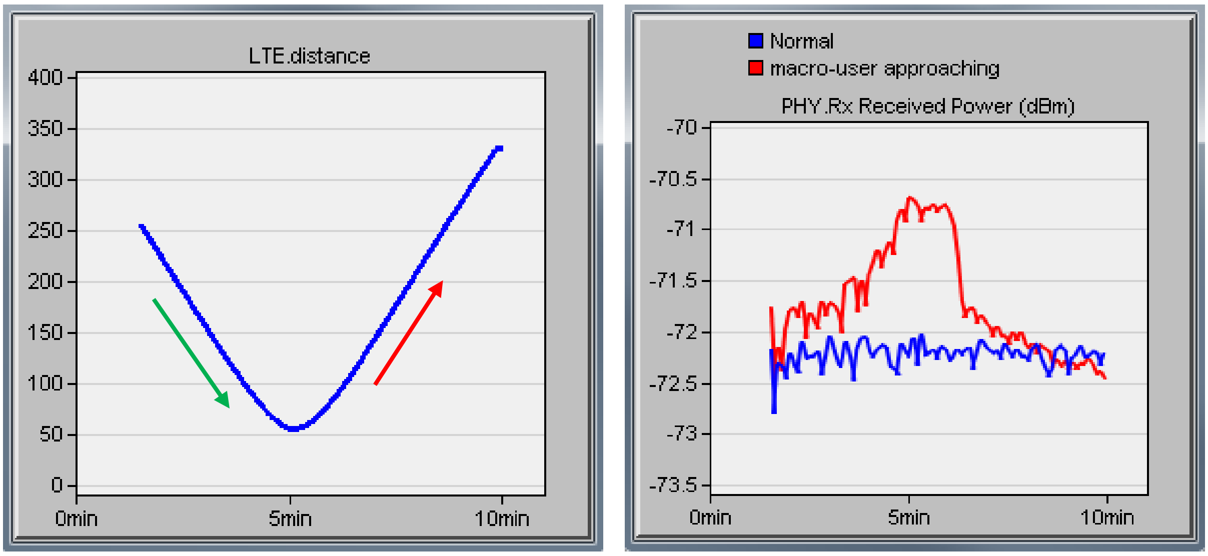


Fig. 4-24 Distance between MUE and the Femtocell (m) and the changes in the received signals

The Femtocell detects the Macro-user when it is at certain distance. Fig. 4-24 shows the estimated distance of the discovered Macro-user in meters. The Macro-user enters the Femtocell coverage area at a speed of 4Km/h. In the simulated scenario, the Macro-user is moving towards the Femtocell and passes across its coverage area. Then it moves away from the Femtocell. Due to co-channel interference, the throughput and the downlink SINR of the Macro-user decreases as long as it is inside or close to the Femtocell's coverage area.

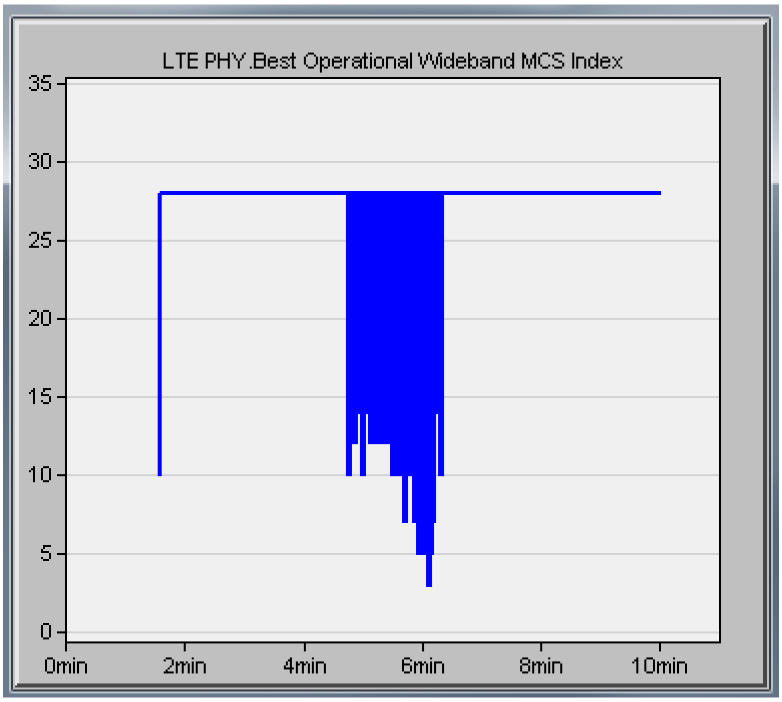


Fig. 4-25 Macro-user reported wideband MCS

Fig. 4-25 shows the effects of the Femtocell on the Macrocell's signal quality at the Macro-user's side; the figure shows the reported wideband MCS (the wideband's reported value is used by the serving Macrocell to differentiate the best reported subband by its UEs. IT does this by calculating the metric for the subbands, which depends on the difference between the reported subband MCS and the wideband MCS, and the allocation size block).

The Macro-user, while it is far from the Femtocell, reports a very good signal value of MCS of 28. The figure shows the tracked reported value during mobility near the Femtocell's area. When the Macro-user is close to the Femtocell, the MCS reported value starts decreasing and then undergoes a sharp decrease between when the Macro-user enters the Femtocell's coverage area and when it is very close to the Femtocell.

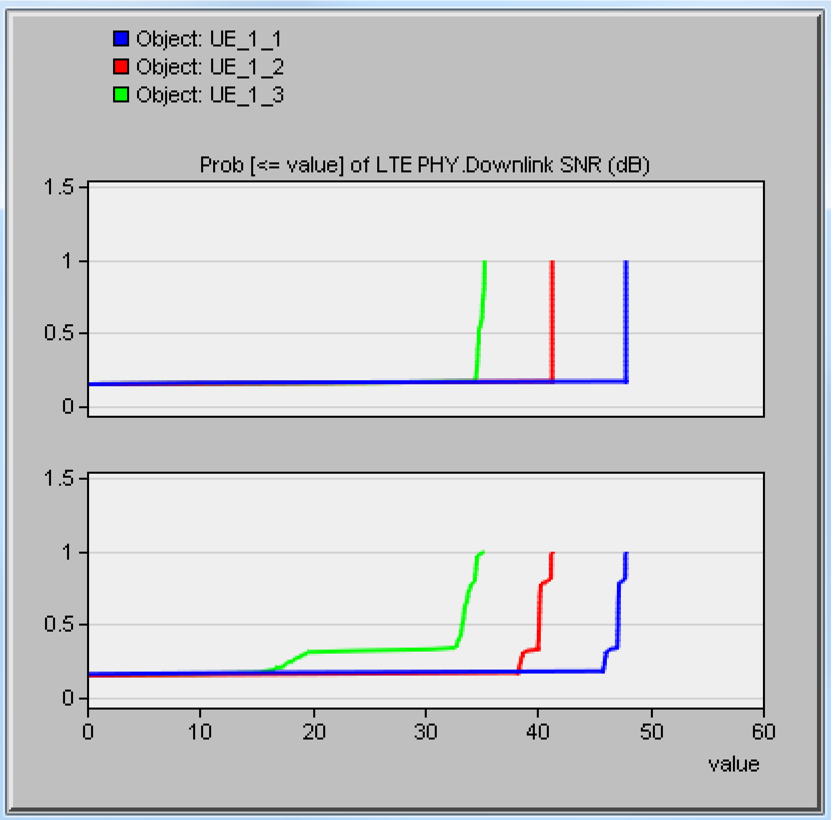


Fig. 4-26 Downlink SINR of three Macro-users

Fig. 4-26 shows the downlink SINR of three Macro-users. One is relatively close to the co-channel Femtocell (UE 1-3) and the others are at different distances from the cell edge of the Femtocell. All Macro-users are running the same application with the same parameter configurations. The figure makes a comparison between two cases: with and without the presence of the co-channel Femtocell. According to the figure, there is a significant decrease in the downlink SINR (CDF distribution) at the Macro-user side in the presence of the co-channel Femtocell. The drop of the SINR value of the close Macro-user is around 20 dB on average.

When comparing the BLER, Fig. 4-27 shows the downlink Block Error Rate (BLER) at the Macro-user's side. The figure shows that in the presence of the Femtocell, the BLER increases dramatically and exceeds 10% which is the critical value and the value recommended for a successful reception of the BLOCK [35, 36]. As a result, the SINR at the downlink is lower than the required value for successful reception and the Macro UE will not be able to decode the received blocks and it therefore will start dropping them.

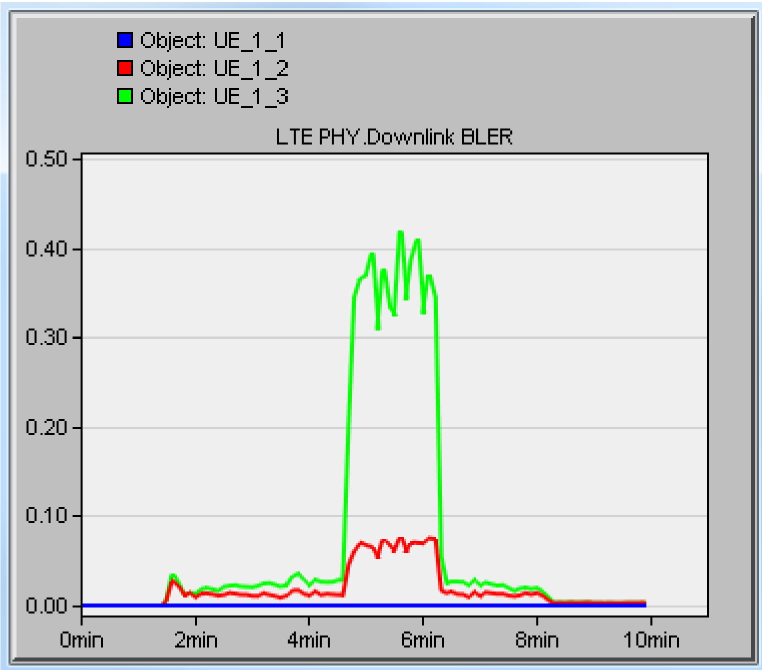


Fig. 4-27 BLER due to co-channel deployment

The assumption is that the Femtocell is far enough from the Macrocell's centre. The effect of the Macrocell on the Femto-users is presented in Fig. 4-28. It compares two cases: when the Femtocell operates in a co-channel situation, and when it operates on different frequency bands. The figure shows an average for 5 Femto-users. The BLER in the co-channel deployment is acceptable and in the range of 10% or less which is within the 3GPP standard value. Therefore the Femto-users still have a good SINR at their side due to the short distance between them and their serving Femtocell. The Femtocell does not have to reduce its transmission power (i.e. no need to decrease power).

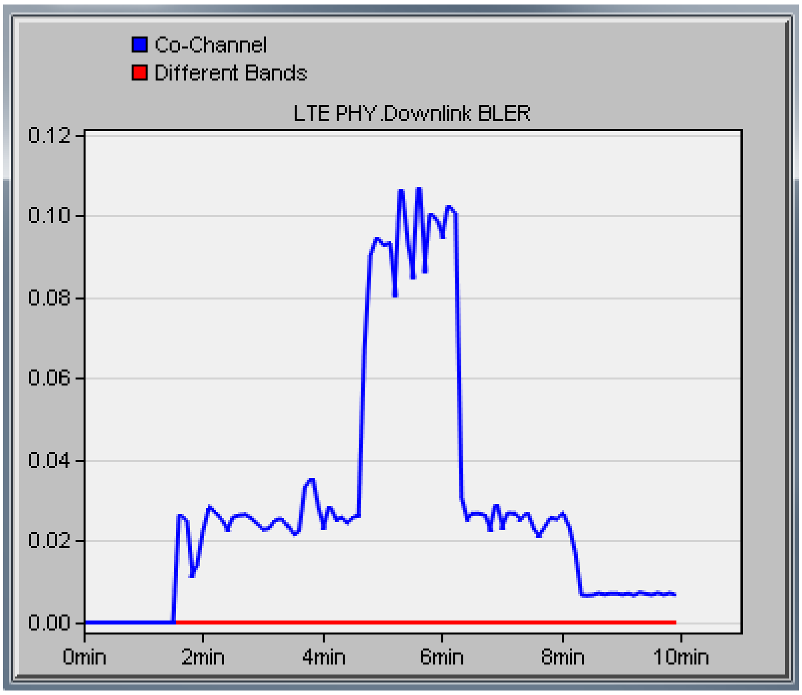


Fig. 4-28 Effect of Macrocell on the Femto-users

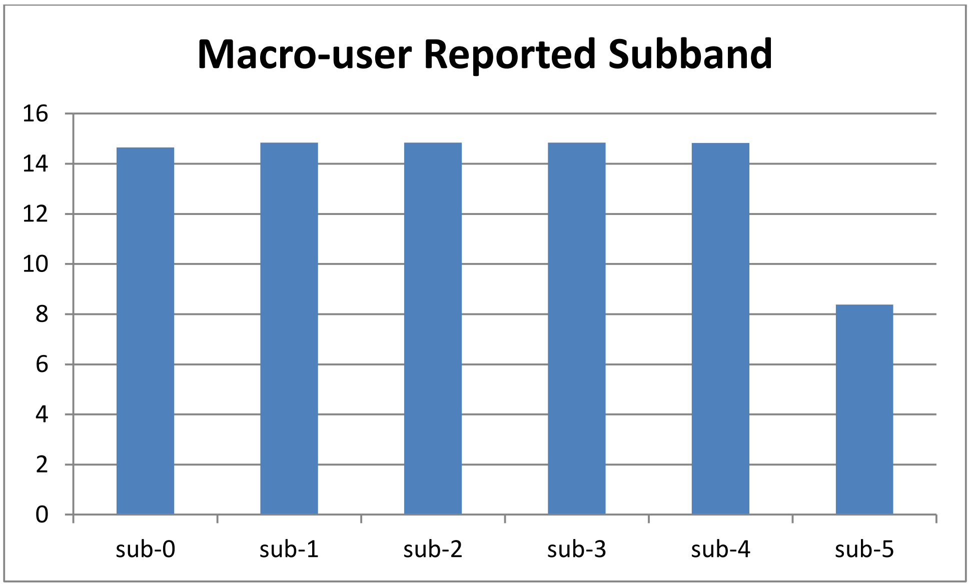


Fig. 4-29 CQI of the reported subbands by the Macro-user

The Femtocell detects the Macro-user's uplink transmissions; the reported CQI value shows that the Macro-user has reported a low CQI value for the subband 5. This subband is, for now, the target for the Femtocell.

Fig. 4-29 shows the reported values of the Macro-user subbands. On average, the subbands from 0 to 4 have good values and their subcarriers are suitable for the Macro-user's allocation. It is clear that subband 5 is not preferred for the Macro-user. The Femtocell can allocate subcarriers from subband 5 to its UEs. The Macro-user, upon reporting a low CQI value, will not be scheduled on subband 5. Here the Femtocell can find out on which subband (or over which part of the BW [37]) the victim Macro-user is scheduled. It is very efficient for the Femtocell to perform and maintain synchronisation with the Macrocell to detect its downlink map. When the Femtocell detects the Macro-user's C_RNTI, it can find its resources on the Macrocell downlink map. This gives flexibility to the Femtocell to decide on which co-channel bands it can schedule its Femto-users without any potential interference. Also this provides the Femtocell with dynamic allocation in contrast to the fixed allocation mentioned in some studies, and hence the Femtocell could be allocated all available bandwidths if no Macro-user is in its vicinity, which saves resources and makes efficient use of the Macro and Femto spectrum.

In LTE systems, there is flexibility in assigning the resources to the UEs. The serving cell allocates subcarriers to the UEs on a 'up from the bottom' or 'down from the top' way. This is determined according to what the associated UEs prefer through the reported metric. The metric is calculated depending on the difference between the reported CQI value of the subband and the wideband. If the majority of UEs prefer the top subbands, the scheduling starts from the top and vice versa. This could be very helpful in the presence of small cells in co-channel deployment. For example, in the scenario reported in Fig. 4-29, a Femtocell allocates subcarriers to its UEs starting from the subband of index 5, while the Macrocell allocate resources to the Macro-user of interest starting from subband of index 0. This can be planned while deploying the system. If an X2 interface exists between the Femtocell and the Macrocell, this could be more flexible.

The most affected subband is subband number 5, which can be used by the Femtocell. During the monitoring period, the SINR distribution of subband 5 experiences a sharp decrease in the received SINR value, as shown in Fig. 4-30, due to co-channel interference. This subband is not preferred for the Macro-user.

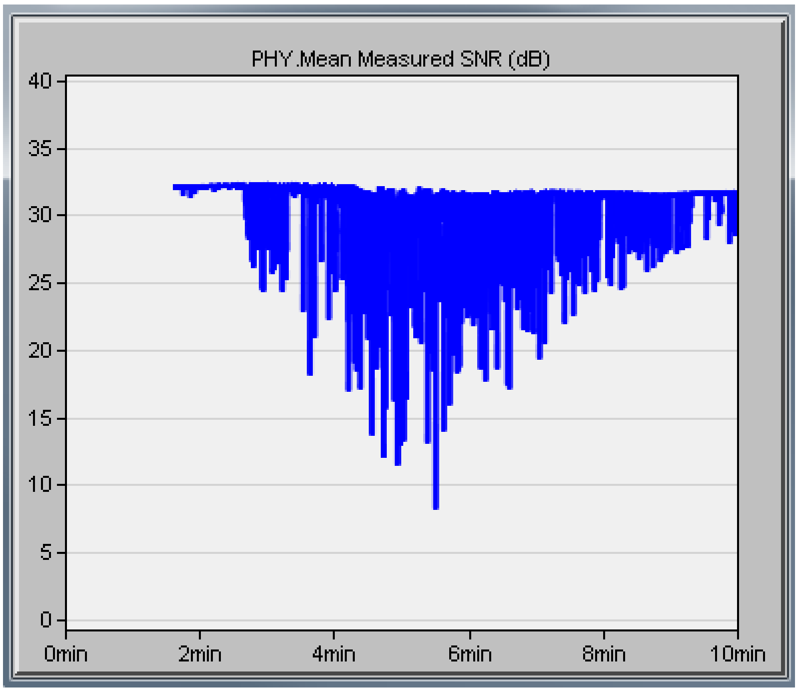


Fig. 4-30 SINR of the affected subband 5

Fig. 4-31 shows the value of the downlink SINR of the Macrocell signal at the Macro-user's side while passing through the Femtocell's area. The figure compares different situations depending on the available resources that could be utilised by the Femtocell. If the sensing results at the Femtocell side indicate that there are few resources (<6 RBs) that could be allocated to the Femto-users, this means that the Femtocell has to allocate resources that have been allocated to the Macro-users which causes interference on the Macrocell DL signal. This interference causes a decrease in the Macrocell downlink SINR to a low level.

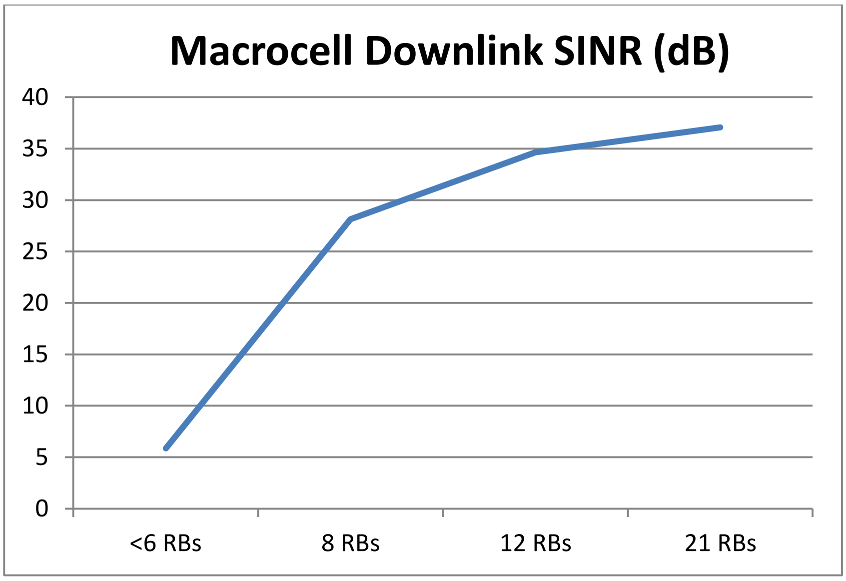


Fig. 4-31 Effect of Femtocell available resources on the Macrocell DL SINR

In the second scenario which is 8 RBs, it is clear from the figure that there is an improvement in the Macro DL SINR value to an acceptable level (~ 28 dB). This indicates that if there is at least one subband (6 or 8 RBs) available for the Femtocell to operate on, this reduces the Femto-to-Macro interference significantly. The DL-SINR improves even more when there are more available resources that have not been allocated to nearby Macro-users. For the same consideration we have plotted the Macro-user throughput vs the number of Macro-users and Femto-users. As explained before, the more Macro-users there are near the Femtocell, and the more Femto-users there are, have an impact on the Femtocell's procedures and allocation chances. Fig. 4-32 shows the Macro-user throughput near the Femtocell's coverage area. If the number of Macro-users near the Femtocell area increases, more resources have to be allocated by the Macrocell to its UEs, thus lower resources are left to be allocated safely by the Femtocell. The Femtocell in this situation may use resources already allocated to the nearby Macro-users, depending on the number of Femto-users and their running applications.

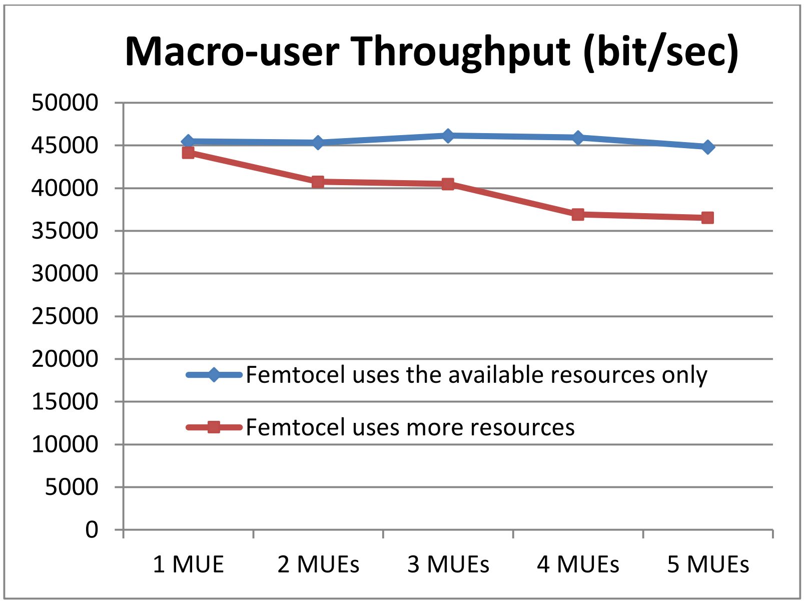


Fig. 4-32 Macro-user throughput in response to Femtocell's occupied resources

In co-channel interference, the interference affects Macro-users more than Femto-users due to their far distance from the Macrocell and the accompanied pathloss. It is preferred that the Femtocell operates in a strict way and empties the occupied subbands as much as possible to give more choices to the Macrocell to schedule the victim Macro-users on their preferred subbands. This is due to the fact that there are a large number of Macro-users waiting to be scheduled and it is not always guaranteed that the UE will be scheduled on its preferred subband. On the other hand, and in contrast to the Macrocell, the Femtocell serves a low numbers of UEs (and maybe no UEs in some situations). By doing this, more Macro-users can exist with the Femtocell in co-channel deployment as long as the Femtocell does not occupy more subbands. Once the Femtocell starts switching to the other subbands, the effects appear clearly on the Macro-users' throughput.

The maximum number of subbands that could be occupied dynamically by the Femtocell in co-channel deployment can be decided by the radio planning procedures, taking into account the total number of available subbands and the nature of the Femtocell's deployment.

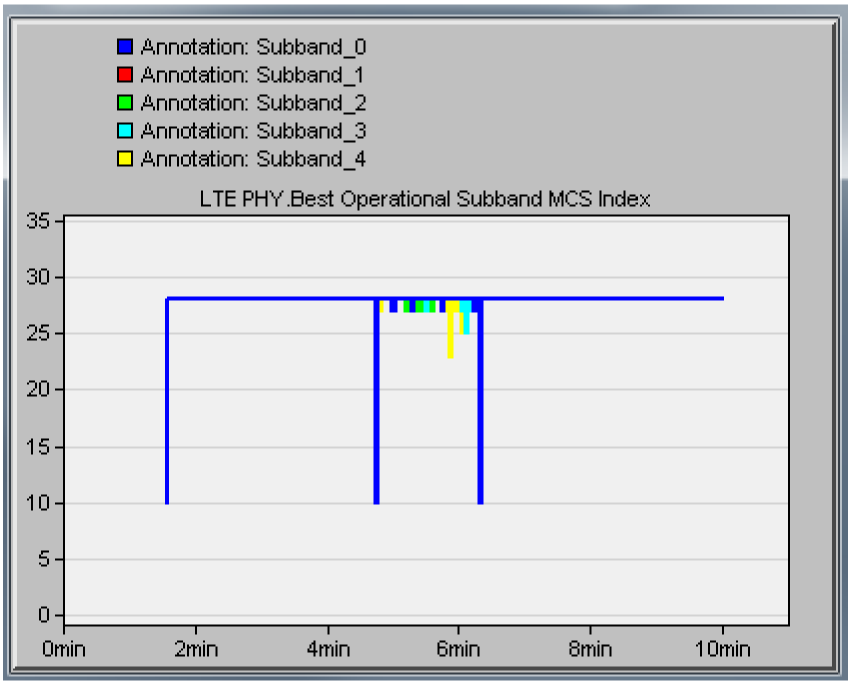


Fig. 4-33 Reported MSC for subbands 0 to 4 over time

In the case that the Femtocell has dedicated subband 5 for its UEs, it has to keep this subband and not switch to other subbands without prior knowledge of whether or not they are occupied by possible nearby Macro-users. Doing this means that other subbands are protected from co-channel interference in a dynamic way. Fig. 4-33 shows the reported values from the Macro-user over subbands 0 to 4. The Macro-user is reporting high MCS values over time; this implies that the Macrocell is now able to schedule it on one of these subbands, depending on its running scheduling algorithm.

Fig. 4-34 shows the average values of the reported MCS. The five subbands (sub-0 to sub-4) are suitable for scheduling the Macro-user.

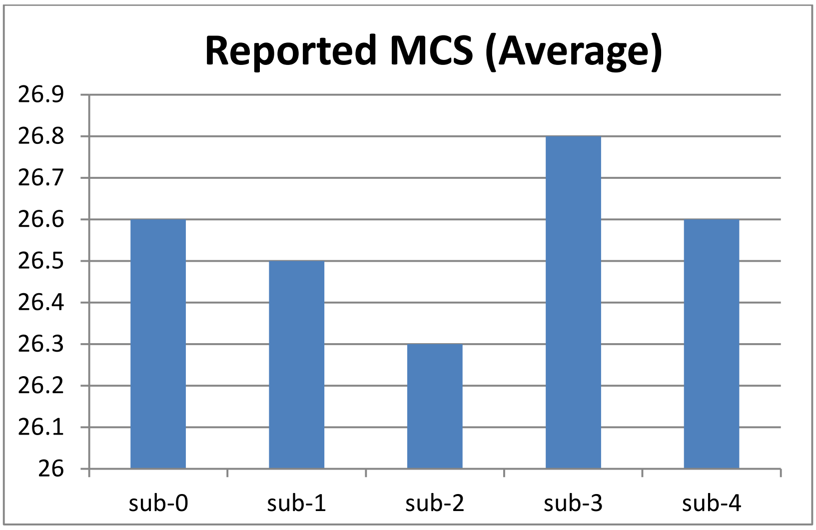


Fig. 4-34 Average values of the reported MCS while passing Femtocell area

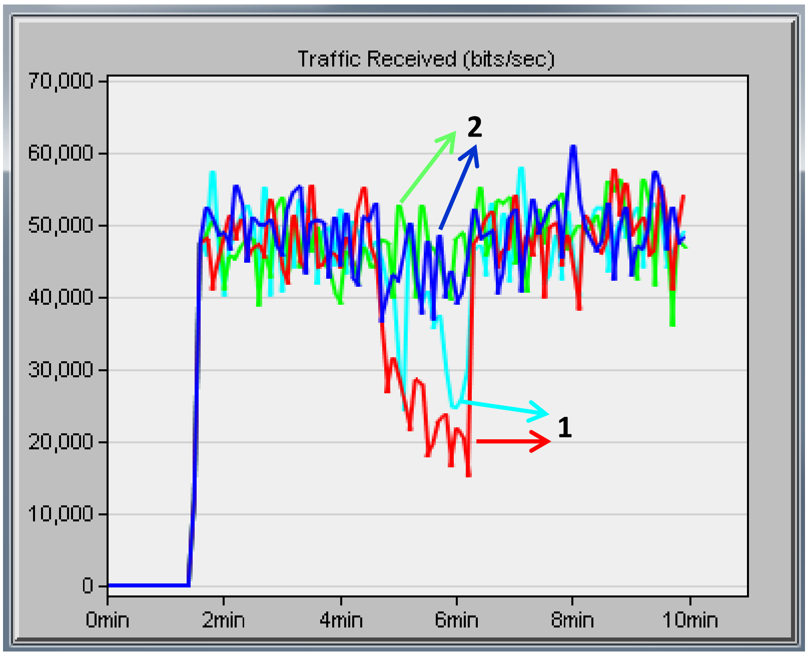


Fig. 4-35 MUE throughput

shows the throughput of the Macro-user over time. Throughout is stable and it starts to decrease as the Macro-user becomes closer to the Femtocell. The throughput decreases sharply when the Macro-user is close to the Femtocell (state 1). When the Femtocell starts tracing the Macro-user and performs the interference avoidance scheme, improvements start to appear in the throughput (state 2). According to the figure, the throughput has different levels of improvement when the scenario is simulated many times. Throughput improvements depend on how many frequency resources are free on the Macrocell side that could be utilised by the Femtocell.

4.11 Summary

In this chapter, a new mechanism for Femtocell dense deployment has been proposed in order to provide larger capacity and coverage benefits. This mechanism requires equipping the Femtocell to sense and detect the RF of the surrounding cells. Then the new challenge was to avoid interference for co-tier and cross-tier deployment with neighbouring Macrocells and neighbouring Femtocells.

In order to control the Femtocell's coverage and avoid trade-off with the Femtocell's transmission power, an efficient method to avoid interference in co-channel dense Femtocell deployment within the Macrocell's coverage was introduced, while protecting the Macro-user and avoiding SINR decreases at the Femto-user's side. The importance of control channels and PCI planning were illustrated. The Femtocells have been arranged so that there is collaboration among them through a centralised scheme, instead of the distributed scheme, to avoid saturating the wireless interfaces. This study showed that the co-tier interference among Femtocells operating in the co-channel scenario could be handled using the centralised scenario. The central coordinator has the main role in the reporting mechanism as it has a connection with every Femtocell in its domain. The centralised mechanism is preferred to the distributed one studied in previous works, because it has the advantage of offloading the signalling overhead from the wireless interface.

In the presented work, the main contribution is a presentation of co-channel interference in Macro-Femto networks. It was demonstrate that a dynamic, subcarrier-tracing based Femtocell could perform well regarding throughput improvement and interference reduction, without the need for power control or to reduce/control the Femtocell's coverage area trade off. The impact of the Femtocell's interference on the Macrocell's downlink signal depends on the position of the Macro-user related to the Femtocell vicinity and to the available frequency resources that could be utilised by the Femtocell. Sensing and detecting is needed in cases of dense Femtocell deployment for better performance when there is spectrum scarcity and co-channel deployment. It has been shown that Femtocells are able to avoid utilising the same sub-carriers that have been allocated to the Macro-user. With this dynamic algorithm, there is less need for Femtocell transmission power calibration and proper Femtocell placement.

4.12 References

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CHAPTER 5

Mobility in Heterogeneous Networks

Introduction

In this chapter the UE performance during mobility is analysed, the focus is put on two issues: the first one is related to signalling and the second one is related to data transmission, i.e. handover and link adaptation. Handover is a process where a UE moves between cells in order to connect to the strongest available cell, and link adaptation is a process introduced to improve data transmission between a UE and the serving cell. It has been shown that both processes experience degradation during mobility and this is worst at the cell edge. This study focuses on the cooperation between the cells to make mobility more flexible and seamless on. The presence of an X2 interface has a positive impact on reducing handover delays and reducing signalling over the wireless interface, and also provides direct connections between serving cells. Many parameters were considered during mobility in addition to the performed measurements and events. The reference signals on the downlink are the main drive for handover triggers. These reference signals are the fingerprints of the serving cells. During mobility, the serving cell has to be aware of the continuously arriving reports from the connected UEs. It must respond quickly to the UE's situation according to the data transmission and handover completion requirements. For link adaptation during mobility, the window measurement size and the reporting intervals have a significant impact on the data traffic. The effects of the window size during mobility are analysed at the cell edge and near the centre, in order to find the best parameters for data transmission enhancement.

In HetNet, where different sizes of small cells are present together with Macrocells, the new procedures for mobility optimisation show improvements in the system performance in terms of radio link failures, handover delays, power consumption and throughput.

5.1 LTE Heterogeneous Networks (HetNets)

In LTE heterogeneous networks there are a large number of small sells such as Microcells, Picocells or Femtocells camped on the coverage of larger cells such as Macrocell (Fig. 5-1). This evolution in network topology improves the radio link performance and the spectrum efficiency [1]. The spectrum configurations could be different among cells, or could be in co-channel deployment. One of the main incentives of heterogeneous networks is an increase in capacity, and the enhancement of the coverage of the LTE system. At the cell edge, the Macrocell coverage may not be as strong as expected due to many factors such as path loss and different types of fading. The small cells are deployed at the cell edge to enhance the coverage, and they are also deployed inside the cell in hotspots to increase the possibility of traffic offloading from larger cells to small ones [2].

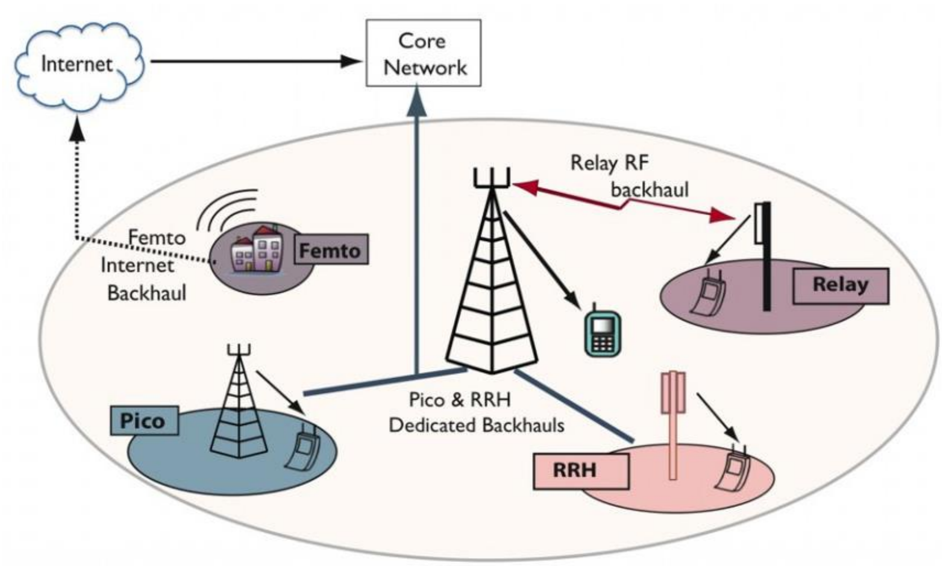

Fig. 5-1 Heterogeneous networks [3]

The UE's main concern is to receive the desired signal in terms of strength and quality. The UE has the option to connect to any cell – large or small – when the signal of this cell meets the selection criteria of the eNB. Another important consideration is the UE's speed when passing across or close to the small cell. Sometimes the variation of the UE's speed makes the load variation rapid, due to the small number of UEs connected to small cells.

Now, mobility enhancement is under consideration for LTE-Advanced [4]. In the new cell topology of the LTE system, mobility is challenging due to the changes in the cell size and radio channel conditions each time the UE connects to a new cell. The UE may pass through the deployed cells with different speeds and this affects the robustness of the handover process in some situations where there is low SINR and interference between the small cells. The interference distribution differs among the handover regions and this makes the handover triggers different at the cell borders.

Deploying a large number of small cells increases the site density. In this situation, if the mobility patterns and techniques have not been reconsidered in comparison to pure Macrocell deployment, the mobile terminal's handover rates increase because the number of handovers is inversely proportional to the cell size. High handover rates imply that there is an increase in the signalling load, and this has a negative impact on the terminal throughput as there is no data transmission during the handover period. In heterogeneous networks, the inter-layer radio resource management could be complicated when the selection process is performed frequently, in addition to a high percentage of radio link failure due to failure in the handover process [5].

Mobility also has a major impact on the channel condition measurements and the utilisation of the data channel. High mobility makes the channel fast-varying and frequency-selective [6]. This impacts on the channel feedback process reported by the UEs to the serving eNB upon the uplink and introduces delays to the feedback procedure. The reported CQI value on the uplink –and its corresponding MCS – for one location may not be suitable at another location and also may differ among small and large cells' coverage. Channel estimation and reporting is delay sensitive and the reported SINR values may be different from the actual values that occurred prior to the uplink transmission. Until the throughput is recovered and the CQI value is reported, there will be HARQ delays and higher retransmissions rates over the wireless link due to a sharp decrease in the node throughput.

Due to the inherent delay and therefore non optimal selected parameters, the performance of heterogeneous networks could undergo high potential degradation if consideration is not given to the mobility level of the UE, compared to Macro-only network scenarios.

5.2 Related work

In the LTE system, the mobility management procedures such as handover and cell reselection are becoming more complex due to the dense deployment of different types of cells. Many studies have examined the mobility robustness and handover issues in heterogeneous networks. Multiple-layer network scenarios have been proposed in order to improve mobility performance between large and small cells in different environmental conditions. Research has focused on different topics such as signal strength during handover, interference and the SINR, in addition to cell's priorities assigning and UE positioning.

In [7] the study proposed mobility robustness optimisation based on exploiting the measurement reports. The aim is to find the best target cell by updating the handover trigger mechanism, taking the SINR into account. SINR parameter monitoring is introduced in order to consider the interference variation and interference distribution within the handover region. The handover preparation and triggering is controlled depending on a defined SINR threshold. In [8] the research proposed two schemes to improve the handover performance during the process of Picocells leaving and attaching. The idea is to perform the handover from a small cell to a large one and vice versa quicker, in addition to controlling the attaching/leaving process to/from Picocells to avoid unnecessary handovers. In the simulated scenarios, the number of UEs attached to the Picocells is monitored to find out the number of handover failures and the length of Time of Stay (ToS). In [9] the UE controls the handover timing; the study proposed a two-step handover based on early preparation and quick handover command transmission. The UE continues performing measurements and waits to find the optimal target cell and the handover timing after receiving the handover command. Then an indication message is sent to the source eNB from the UE to execute the handover immediately with the selected target cell. The source eNB acknowledges the UE and forwards data to the target eNB. In [10] the authors proposed an inter-eNB coordination-free algorithm to optimise the handover parameters. The serving eNB depends on the C-RNTI to monitor the UE and the handover signalling. The serving cell monitors the UE's states and detects ping-pong states, too early handovers and too late handovers, and also finds a trade-off between the handover failures and ping-pong rates. It then adjusts the cell handover parameters according to the variance in the interference levels among different cells. In [11] based on the Markov mathematical model, the researchers modelled the UE state during the handover process to find the optimal handover criterion with consideration given to path loss, channel outage and fading propagation. The handover performance model was controlled by a timer countdown, depending on the SINR threshold. This timer is the Time To Trigger (TTT) timer, the countdown is aborted and the process is stopped if the SINR is improved above the threshold. On the other hand when the measured SINR changes along the UE's trajectory, if the SINR decreases below the threshold and continues to do so, the UE switches off its cell and connects to a new one. In [12] the researchers proposed a technique based on Inter-Cell Interference Coordination (ICIC) with a metric to detect the handover failure and evaluate the ping-pong state. In this technique, the co-channel scenario is assumed between Picocells and the Macrocell. Mobility is evaluated depending on the handover counts and the cell reselection threshold during a time window. Picocells employ the Almost Blank Subframe (ABS) method on some of their resources, so the Macrocell exploits these blank resources to schedule UEs with high mobility and protect them from Picocells' interference. On the other hand, Picocells schedule low mobility UEs during the blank subframes of the Macrocell.

The effects of cell range expansion, combined with inter-cell interference coordination on handover performance, were evaluated in [13]. Cell range expansion has an impact by increasing the number of connected UEs to the Picocells and thus impacts the traffic offload gain. The study linked the cell range expansion technique to handover performance, and ascertained the application range that could keep the handover failure under a certain percent. In [14] the handover decision scheme was investigated in a three layer network to reduce the frequent handovers. The study is based on priority and dwell probability. In some scenarios, higher probability is given to the handover process to the Femtocell, in order to reduce unwanted handovers. When assigning these probabilities, this information gives pre-knowledge about whether or not the UE is camping on the Femtocell, and this is very important for the handover decision. In the case where there is no pre-knowledge, prediction was used instead which is based on a history record. In [15] the researchers proposed a handover algorithm based on dwell time, in addition to the available data size that a UE can receive from the cell (large or small). The evaluations of the dwell time and data size are performed when the UE is at the cell boundary. According to the data that the UE receives, it hands over to the cell from which it can receive more data, otherwise it stays connected to its serving cell. In [16] the study investigates the handoff between the Macrocell and the Femtocell layers based on the UE's state and the SINR, taking into account the power difference between the two layers. Instead of received signal strength (RSS) as in a conventional handover, the UE hands off to the cell of the higher SINR. In [17] a novel handoff decision algorithm is proposed to manage the mobility of the UE towards the Femtocell. In this algorithm, the values of the RSS of the source and target cells are combined to generate an adaptive offset. A combination factor is introduced to weight or not the Macrocell's RSS over the Femtocell due to the power difference between the cells. The Femtocell's RSS should be greater than a threshold in order to guarantee a good combination and better connection according to that threshold's value. Other studies such as [18] consider the location of the UE to adapt the handover parameters, while in [19], the study is based on the large asymmetry in the cells' transmitted power.

5.3 Preliminaries

5.3.1 Introduction

Small cells are defined as low power nodes compared to typical base stations. They are attracting interest due to the services that they can provide in the licensed spectrum. Small cells have many advantages such as low power consumption, low transmission power, low deployment cost, and they are easily coordinated with the network (Fig. 5-2).

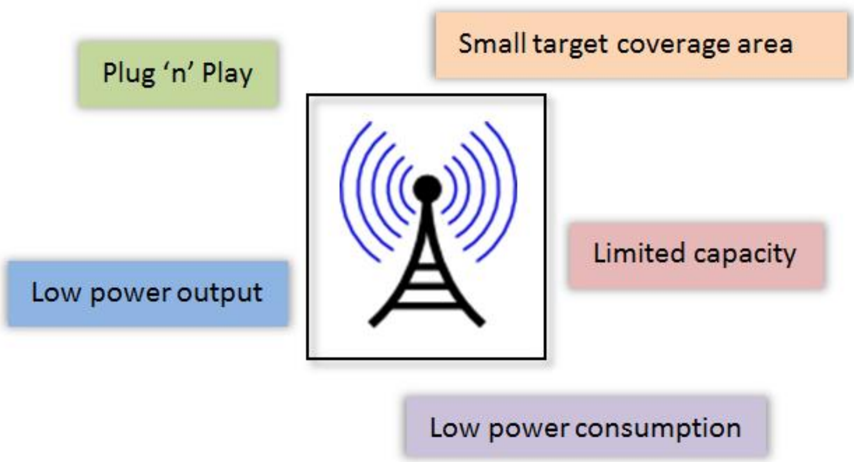

Fig. 5-2 Small cell properties

One significant addressed property of the deployment of small cells is something called Range Expansion, where the coverage of a small cell is extended in order to: a) have more UEs camped on the small cell, and b) compensate for the other cells' coverage in case one cell goes into a fail state (Fig. 5-3). This provides better services to the UEs and increases the offload from the large cells. On the other hand, the presence of these different types of cells in HetNets with other advanced technical features imposes challenges in mobility management and thus requires more advanced techniques in order to manage the dynamic changes in the spectrum and control the resulting interference.

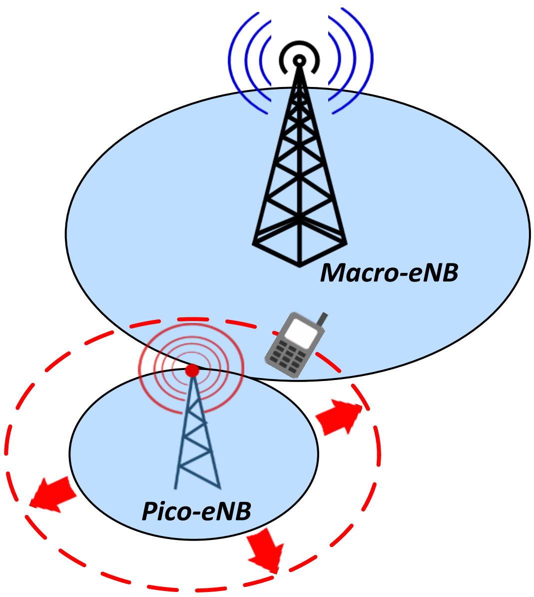

Fig. 5-3 Picocells range expansion

Heterogeneous networks provide the following services and advantages:

- Providing short distance connections between the UE and the serving cell, which reduces the potential interference and saves the power consumed on transmitting over longer distances;
- Offloading services from the large to the small cells at the coverage holes;
- The large number of small cell deployments provides efficient reuse of the spectrum;
- From the network management side, small cell planning has fewer overheads and a lower cost;
- A small cell has a low power consumption and can be switched off for some periods if no UE is attached to it.

HetNets implementation challenges:

- The unplanned nature of small cells requires coordination and interference mitigation procedures, especially at the cell edge with Co-tier and Cross-tier interference;
- In the case where some small cells operate in restricted mode, the near subscriber cannot have access to the cell;
- Handover and mobility issues;
- Self-organising and integration with multi heterogeneous RATs.

5.3.2 The UE's measurements

The UE measures the eNB's reference signal (RS) and reports the measurement to the eNB. The measurements go through two layers of filtering; L1 and L3 of the UE. The measurement's configuration includes the objects that the UE performs the measurement on such as inter-frequency, intra-frequency or inter-RAT measurements. The reporting configuration defines the reporting criteria and format. The measurement GAPs are also provided along with the measurement configurations. The UE may measure the serving cell in addition to the listed cells, and also new detected cells [20].

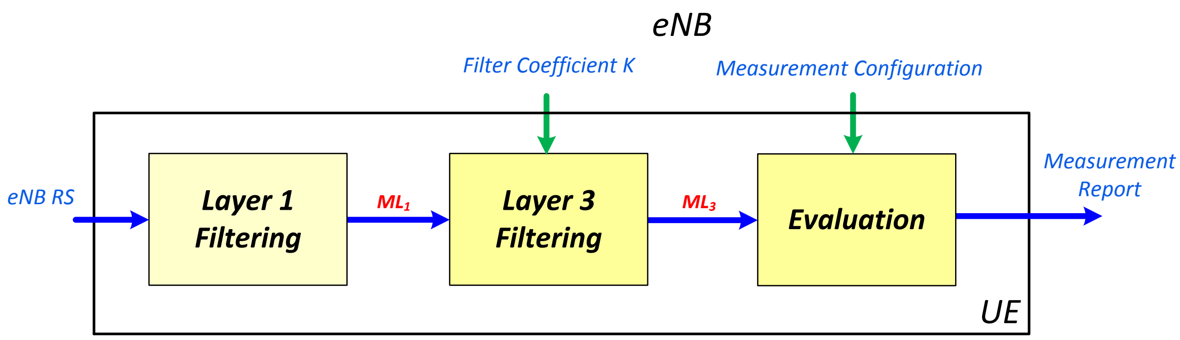

Fig. 5-4 UE measurement report

When the UE starts to make the measurements of the serving cell and target cell reference signals, it performs filtering of the measured values with consideration to their recent history. The filtering parameter is given by the serving eNB. L3 filtering is specified in RRC

Connection Reconfiguration and it is a very important parameter to avoid problems with the handover process (with frequent handovers) (Fig. 5-4).

The filtering formula is expressed as:

$$F_n = (1-a) \cdot F_{n-1} + a \cdot M_n \tag{5.1}$$

F_n is the updated filtered measurement result

F_{n-1} is the old filtered measurement result

M_n is the latest received measurement result from the physical layer

a is $1/2^{(k/4)}$, where k is the filter coefficient

In the filtering formula, the value of k is used to give weight either to the current value or to the old value. When k is equal to 4 then the value of "a" is equal to ½; in this case both the new measurement and the last one have half weight.

When k has a high value, the old measurement will have a higher weight and vice versa. Also a higher value of k has a positive impact on eliminating fast fading effects when there is a sudden change on the cell's RSRP. This will avoid the handover process to a cell with good RSRP for a short time, and then trigger handover again to another cell.

5.3.3 Idle mode procedures: Cell search and reselection

5.3.3.1 Cell search

Cell search is one of the major processes in cellular networks and it has the same logic among different technologies and generations. This process has a remarkable impact on the power consumption of the mobile station. The UE has to perform measurements, evaluation and finally detection during the idle mode. The UE has to scan and tune to certain frequencies and then perform measurements on the signal in the first step, followed by evaluation and detection. The detection of the cell requires synchronization to be able to decode the cell ID and the information block MIB/SIB (Fig. 5-5) [21].

Basically, when a mobile is on standby, it is going to spend most of its time asleep in a low power state. It wakes up at regular intervals; at the moment it wakes up, it does two things:

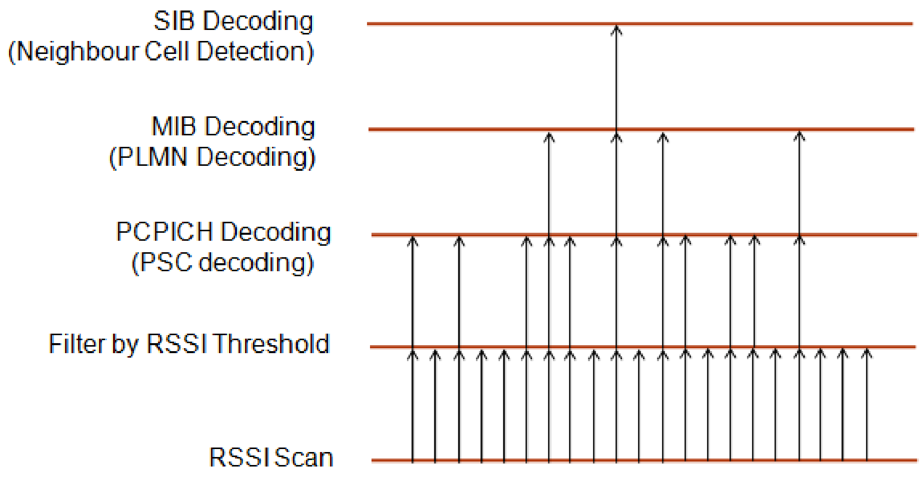

Fig. 5-5 Cell search stages

The first is to listen to the paging messages which the network might be sending to it, for example, the UE might be still be hooked up to an email server in the standby state and the email server is completely unaware of the fact that the UE is on standby and spending most of its time asleep. However, the exact moment when a UE wakes up is carefully calculated, the UE knows what time it is going to wake up, the network will send it a paging message and the UE will move to the connected state.

The other thing that happens when the UE wakes up is that it will measure the strength of the signals from the cell it is currently listing to, to make sure that the strength of the signal is still good enough, and if it is not good enough it might go and look for another cell to attach to.

When a UE switches on, it tries to detect which networks are nearby. It searches for all of the LTE cells and examines the synchronisation signals from their PBCHs, reads their system information, and discovers the identity of the networks which are nearby. It then chooses a network to connect to from the networks that it can see. In the second step of the 'power-on' stage it chooses a single cell from the selected networks and in the third step it does a procedure called "attach" in order to tell the network that it is switched on.

When the UE is in standby mode, the UE searches around for networks and listens for the strength of the signals from surrounding cells. It does that using cell reselection, continuing to listen to the cells around it and choosing a cell whose signal is good enough.

5.3.3.2 Cell reselection

Usually a UE only listens to a cell which it is currently in. The UE wakes up once in every discontinuous reception period and it measures the strength of the signal (Fig. 5-6). If the serving cell doesn't satisfy the selection criteria, the UE initiates the reselection process of the neighbouring cells and starts the measurement and evaluation process. The UE evaluates the reselection criteria of the discovered frequencies as described in [22].

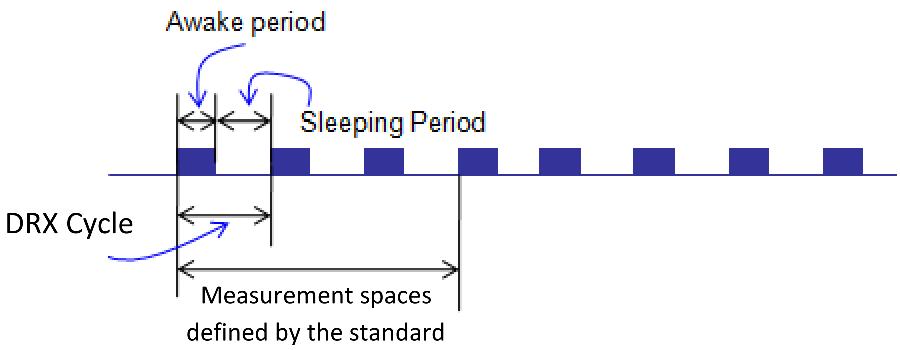

Fig. 5-6 Cell selection with DRX

In the connected state, the main issue is that the UE is actively communicating with the eNB and in this state the UE's behaviour is very different. The main difference relates to mobility behaviour. In the cell reselection procedure, first the UE measures the signal strength of nearby cells and uses them internally. Following this the UE makes measurements as before but it reports the results of those measurements back to the eNB, and it is then up to the eNB to decide to hand over the UE from one cell to another [23].

5.3.4 Measurement GAPs

If the neighbouring cell is on the same frequency (intra) as the original one, then the UE can transmit at any time. If the neighbouring cell is on different frequency (inter), here the situation is different, because normally a UE can just listen to one frequency at a time and cannot measure the new cell at the same time as communicating with the old one.

Therefore, for measurements of neighbours on a different frequency, the original cell injects measurement GAPs into the transmitted stream, and these are little periods during which it does not transmit anything to the UE on the downlink and does not schedule a UE upon the uplink. During the measurement GAPs, the UE can move across to different frequencies and make a measurement, without losing anything from its serving eNB (Fig. 5-7).

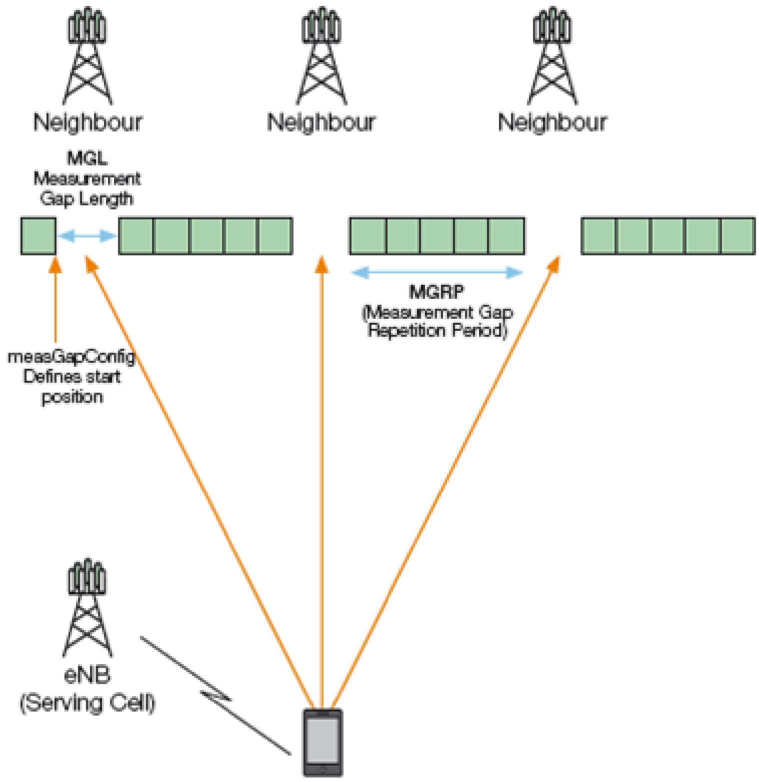

Fig. 5-7 Measurement GAPs

5.3.5 Measurement reports

The UE reports measurements up to the eNB; the eNB tells the UE the circumstances in which it should send a measurement report. The UE starts to take measurements and when the correct moment arrives, it sends a measurement report up to the eNB.

In general, measurement reports work as follows:

In RRC connected state, measurements can be sent periodically from the UE to the network at regular intervals but the measurements are usually triggered by some kind of event taking place.

As a UE moves away from one eNB towards a second, the strength of the signal from this new eNB is rising. This time the UE is measuring the signal from both eNBs continuously, which it can do because the UE is transmitting and receiving and the measurements are not much of an overhead. Secondly, this process is important because the UE needs to be communicating with the best cell, in order to procure the strongest signal so that it can transmit and receive with the highest data rate and the fastest modulation scheme.

The UE notices that the strength of the signal from the neighbouring cell has grown a little bit stronger than the strength of the signal from the current cell, and that triggers a measurements report (after Time to Trigger (TTT) which is a time value used to ensure that there is no fluctuation in the measured signals for a certain time; as a result ping-pong states are avoided). However, it is then up to the eNB to hand the UE over, so a few moments later the eNB might send a command to the UE which basically tells it to hand over, and only then would the UE switch to the other cell (Fig. 5-8).

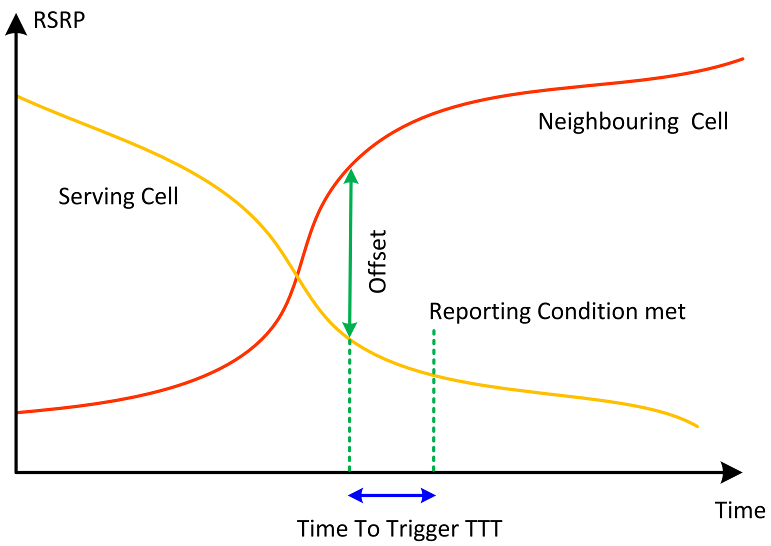

Fig. 5-8 Measurement report triggering

5.3.6 The X2 interface

The role of the X2 interface is signalling during handovers. If the network wants to hand over a UE from one eNB to another, X2 is also involved in transporting the data packets which are forwarded during the handover. The EPC requests the IP address of the new eNB, then the new eNB replies with its IP; this IP address is used to automatically establish X2 connections between the two eNBs without the need for manual intervention. eNBs can automatically establish X2-based connections between each other, based upon the measurement reports of the new eNB the UE is sending back (Fig. 5-9).

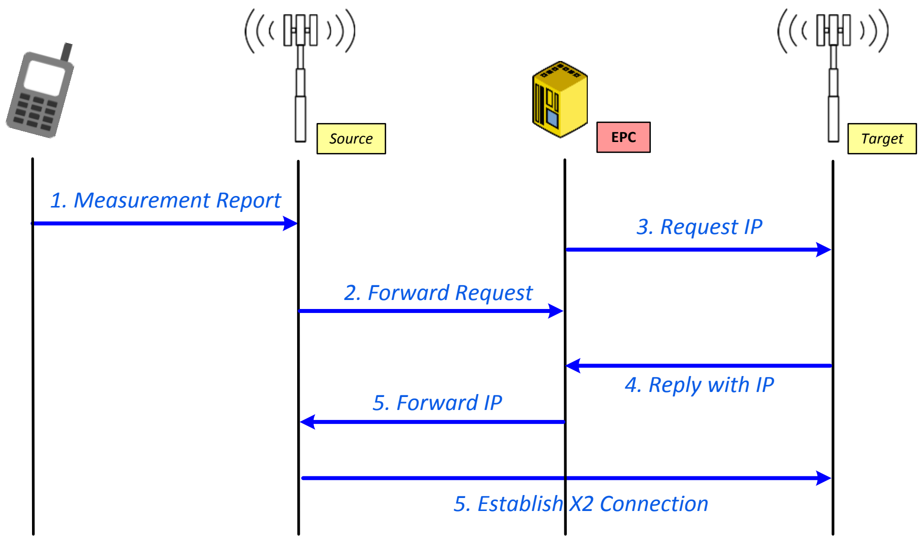

Fig. 5-9 X2 interface establishment

5.3.7 The handover process

Handover is the process through which a UE which is in RRC connected state (actively communicating with a network) hands over from an old eNB to a new eNB. When a UE is moving away from the eNB to which it is connected and towards a new one, the first thing the UE will notice is that the signal from the new eNB is getting stronger, and eventually the UE will send a signalling message called a measurement report back to the old eNB and this measurement report indicates that it is getting a stronger signal from the new eNB than the signal which it is getting from the old one.

The strength of the signal from the old eNB will be dropping, and the strength of the signal from the new eNB will be rising. There will be a measurement event, which will be triggered when the strength of the signal from new eNB becomes a bit stronger than the strength of the signal from the old one. That will trigger the measurement report (1). The old eNB, on the basis of the measurement report, decides whether to hand the UE over to the new eNB; it sends a message over the X2 interface to tell the new eNB to serve the UE (2). The new eNB replies with an acknowledgment (3).

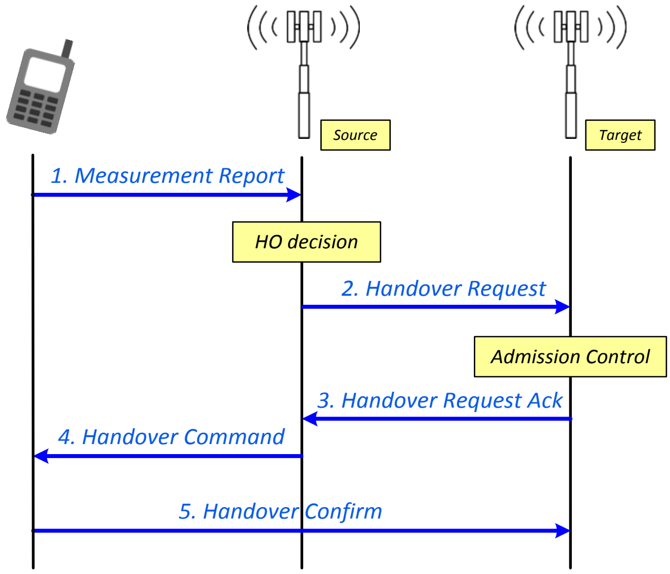

Fig. 5-10 Handover process

If the new cell is congested then it can reject the UE; if the new cell is slightly congested then it may take for example the voice, but not the video which requires a higher data rate. This triggers the old eNB to send a message down to the UE indicating handover to the new cell (4). The UE reconfigures itself, synchronises with the new cell and sends a message up to the new cell (5). These steps deal with the radio access network processes (Fig. 5-10) [20].

5.3.8 Handover parameters

Handover in the LTE system requires optimisation of many parameters in order to guarantee a seamless, efficient and robust handover process. This becomes challenging when the environment changes as the UE moves between different cells. Many parameters are involved in the handover process, related to both time and power. The change of the signal strength above or below a pre-defined threshold during the time window is referred to as an "event". Mobility is triggered by an event, and there are many defined events for the LTE system. For example, Fig. 5-11 illustrates the case of handover event trigger where the UE performs measurements on a possible target cell; if a neighbouring cell becomes better than the serving cell with an offset, then the UE will create a measurement report and send it to the serving cell [24].

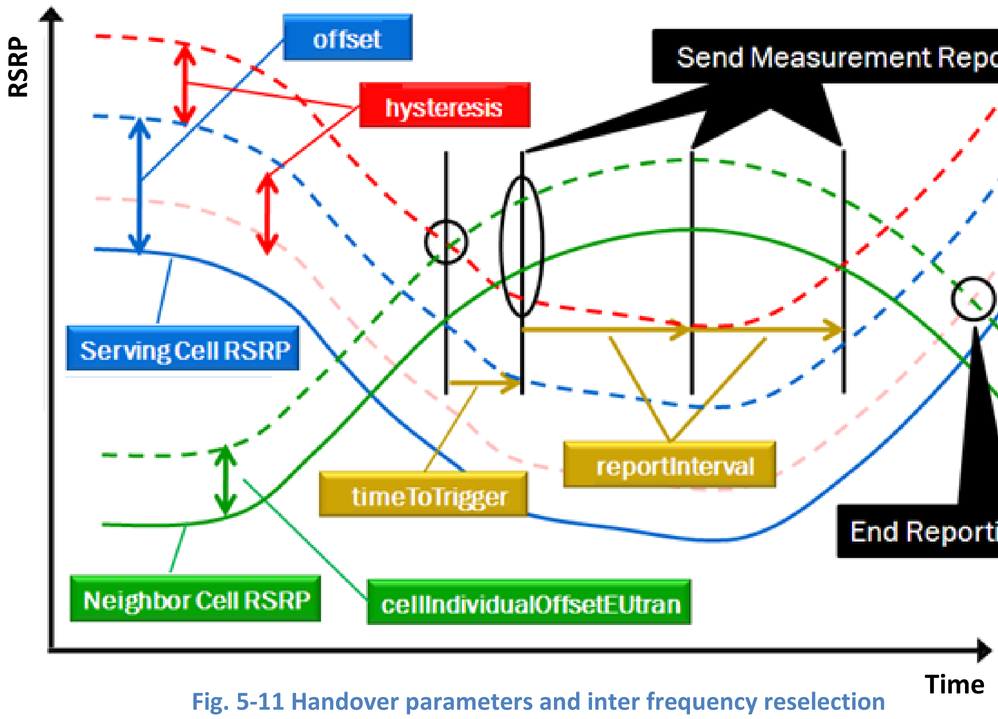

Fig. 5-11 Handover parameters and inter frequency reselection

Parameters that are involved in this process are:

- The Offset: this is a value that is used to weight the serving cell over the neighbouring cell. This means that the higher the offset, the more the handover is delayed.
- The Hysteresis: this value is used to ensure a strong neighbouring cell by making the neighbouring cell worse than its measured value.
- Cell_Individual_Offset_EUtran: this parameter is applied on the neighbouring cell's side to increase its credit and make it more attractive with higher values of these parameters [25].

The following equation explains the relation between the handover parameters:

$$RSRP_{target} > RSRP_{Serving} + offset + hysteresis - cell\_individual\_offset\_Eutran \quad (5.2)$$

This equation must be true for a time period of TTT for the UE to send the first report.

Another involved parameter is the reporting_interval which is a timer started when the UE does not receive a handover command from the cell. If the cell does not respond, the UE keeps sending the measurement report until the expiration of that timer, until it reaches the allowed number of measurement reports to be sent to the eNB which is the reporting_amount.

The network has predefined types of measurement reports called events. These events are shown in Table 5-1:

Table 5-1 Handover Events

Event Type	Description
Event A1	Serving becomes better than threshold
Event A2	Serving becomes worse than threshold
Event A3	Neighbour becomes offset better than serving
Event A4	Neighbour becomes better than threshold
Event A5	Serving becomes worse than threshold1 and neighbour becomes better than threshold2
Event B1	Inter RAT neighbour becomes better than threshold
Event B2	Serving becomes worse than threshold1 and inter RAT neighbour becomes better than threshold2

5.3.9 Radio planning and power control in dense deployment

The downlink power is fully controlled by the eNB in LTE systems, thus there are no power formulas specified in the 3GPP standards. It is up to the eNB to allocate power to subcarriers over the resource blocks (RB).

When the Macro-user undergoes interference, one of the eNB's ways to reduce the effects of interference on the Macro-user's side is to increase the aggregation level by increasing the transmitted parity bits in the transmitted subframes, thus improving the SINR conditions on the receiver's side. In general, this adjustment in capacity has no impact on the throughput of traffic that has tolerance against delays. On the other hand, some types of traffic are delay-sensitive, such as voice over IP (VOIP), and hence the capacity of the Femtocell's PDCCH has to be adjusted carefully. However this is not efficient with the presence of randomly deployed small nodes within the Macrocell coverage. The environment has a very important impact on the power allocation and radio planning to extend coverage and capacity. With Femtocells, path losses are almost ignored and the UE transmits with lower power.

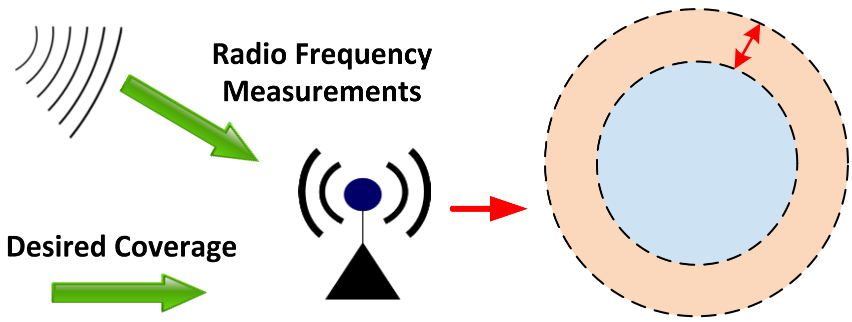

Fig. 5-12 Cell coverage planning

When setting up a new cell, engineers plan for the interference margin but it is not enough in the case of dense deployment and high potential interference. Network density solves the coverage issues but on the other hand, the potential interference increases (Fig. 5-12).

5.3.10 Cell-Edge scenarios

When deploying cellular networks, the cell edge is considered circular or hexagonal, and the frequency planning is carried out on that basis. This assumption is very idealistic and causes the most severe interference scenarios and SIR degradation at the cell edge, especially when a co-channel is deployed.

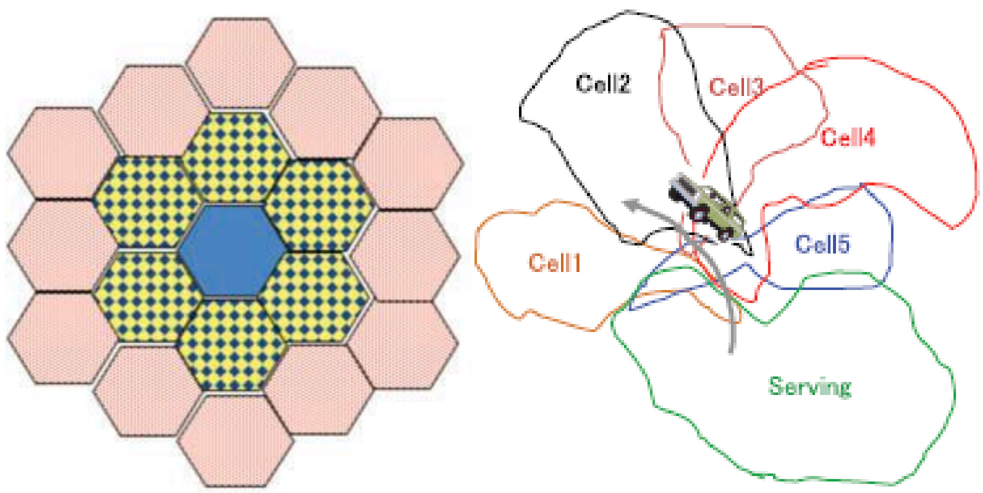

Fig. 5-13 Cell edge and irregularities

Field engineering and test drives are essential for radio planning and cell deployment, however in some scenarios such as dense deployment, fast mobility, adverse weather conditions and others, the SINR at the cell edge is not as good as it was planned to be.

Dissimilarity and irregularity among cells borders make it very difficult to estimate the SINR distribution and the caused interference from neighbouring cells, and sometimes from far cells that have line of sight (LOS) with the victim cell or the current serving cell [26] (Fig. 5-13).

$$SINR = \frac{S}{N + \sum_{k=1} I_k} = \frac{S}{N + I} \tag{5.3}$$

Where: $I = \sum_{k=1} I_k$ is the total interference received from the neighbouring cells

UEs at the cell edge may suffer from uncertainty about the best received signal; they may receive signals from different nearby cells. In this case the UE considers the received signals from the nearby cells as interference, which makes it very difficult to trigger a handover. The interference received by the UE is the sum of the power of the nearby cells and thus the interference (I) is high and the SINR is very low. The situation can worsen if the UE is moving quickly; moving at high speed from one cell to another delays handover to a better cell because there is always a new candidate cell and the cell edge SINR will always swing and show variation.

The SINR is one of the main parameters that should be considered regarding interference and cell edge issues. The relationship between the power of the signal and the interference from the other cell is mutable and the SINR has many scenarios and approximations depending on the cell's location and coverage.

One scenario is that when the cell is considered to be far from the neighbouring cells, the interference could be neglected, and the signal-to-interference-plus-noise ratio is considered as signal-to-noise ratio only.

$$\text{SINR} \approx \text{SNR} \tag{5.4}$$

This is a very simple scenario and the thermal noise N can be mitigated by increasing the power of the signal. Fig. 5-14 shows the effects and the efficiency of a 6dB power boost of the SINR of -5 dB

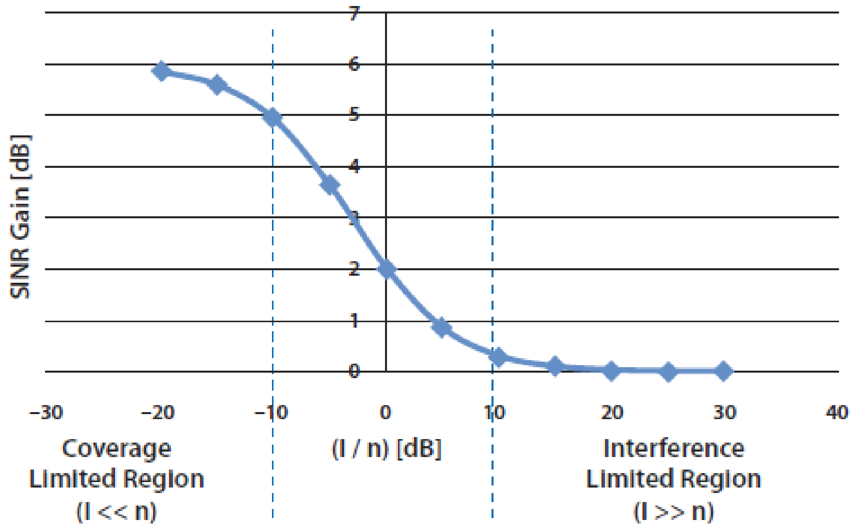

Fig. 5-14 SINR power boost

The second scenario is when the interference from neighbouring cells is high and dominant. In this case each cell may suffer interference from its neighbours. Increasing the transmitted power will make the situation worse.

5.4 System implementation

For this study, the simulated scenario is a heterogeneous network consisting of 6 Macrocells each 5Km apart, so that the total distance is about 25 Km. 30 Picocells are dropped at different locations (randomly & equal-distance) near and far from the cell centre to improve the coverage at the cell edge and at the boundaries between the cells (Fig. 5-15).

An IP flow is created between the UE and the server to maintain resource utilization and data connectivity during mobility.

The considered speed of the UE ranges from 3Km/h (slow) to 160Km/h (fast).

The simulation was configured to have different phases depending on the UE's speed and other parameters. A large number of small cells are deployed within the coverage of Macrocells, and the UE path was drawn randomly so that it would receive different strength signals during mobility. Some small cells would be in a very good situation for handover; others might be good or not suitable for handover. The random path also makes the time for camping different from one cell to another, regardless of the cell's RSRP.

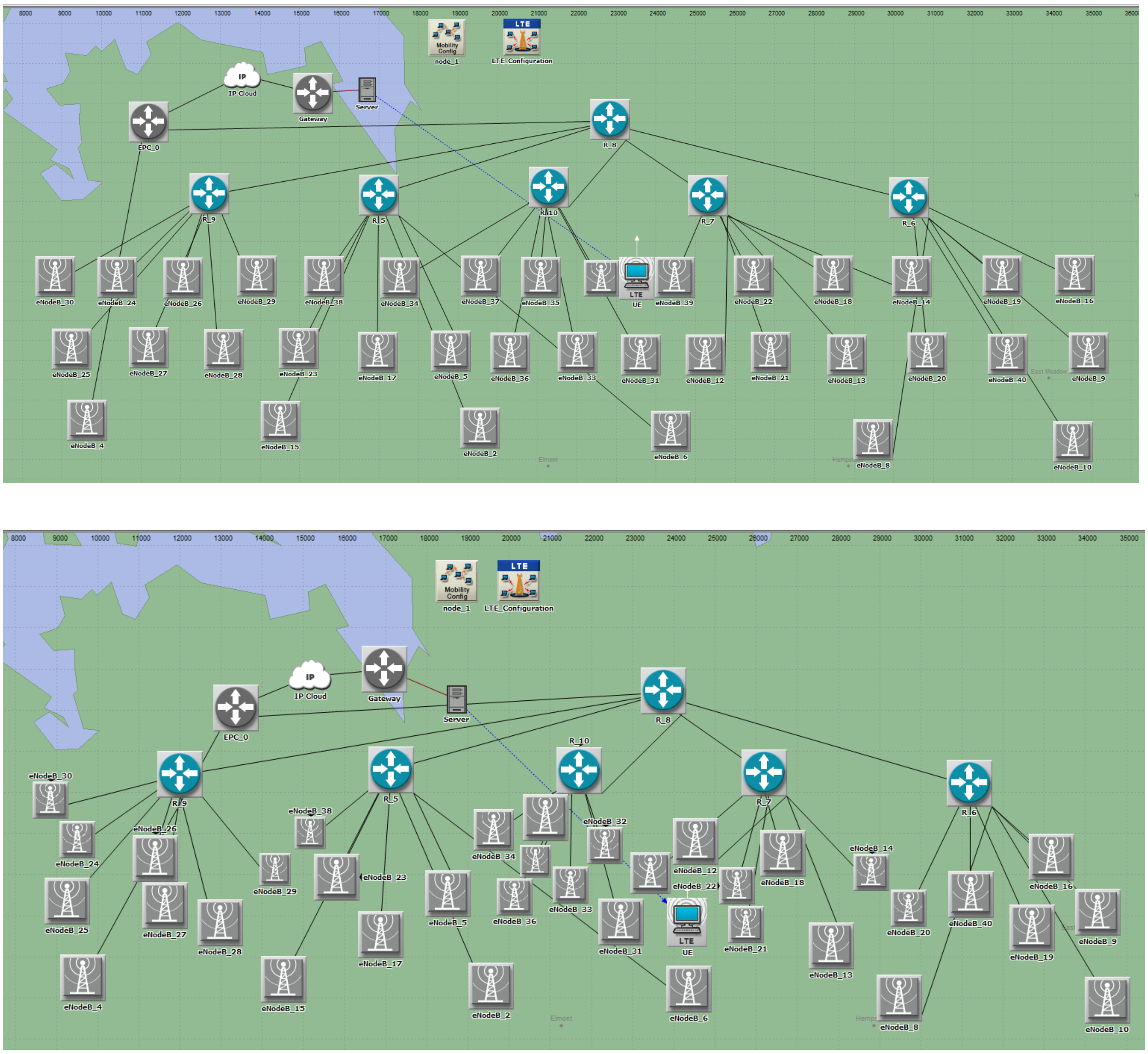

Fig. 5-15 The simulated scenarios

In 3GPP [27] UE placement and trajectories was defined for mobility and simulation calibration, one trajectory is at the cell edge and the other is inside the cell, and both of the trajectories traverse across multiple cells (Fig. 5-16).

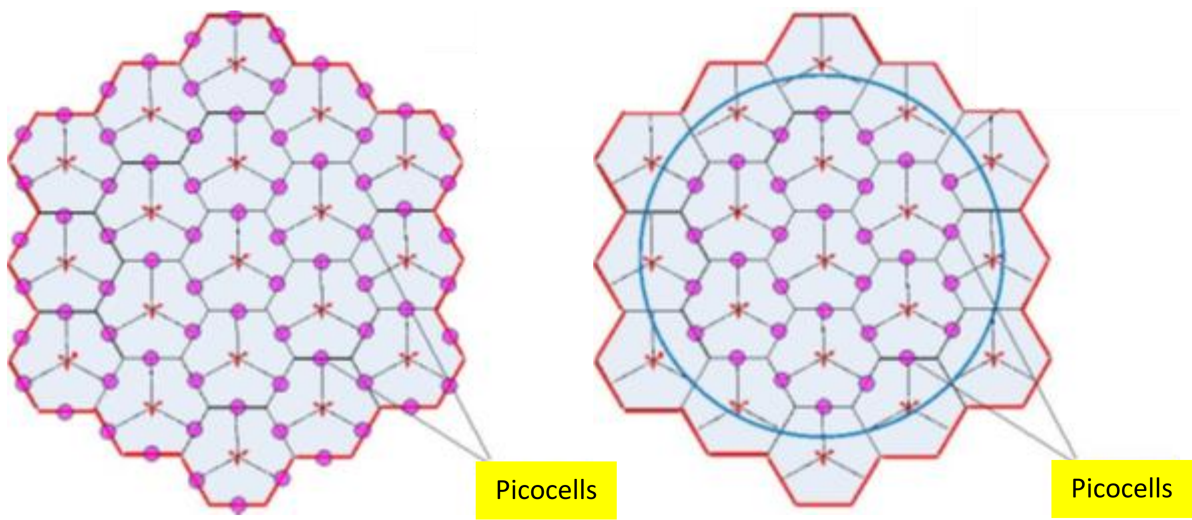

Fig. 5-16 3GPP defined trajectories

5.4.1 Radio Link Failure model

Fig. 5-17 shows the process model for mobility, in this model, the following processes are supported [28]:

- Scheduling requests over PUCCH.
- Random Access procedure via RACH.
- Period for measurement GAP.
- RRC connection re-establishment.
- Cell search and selection.

The radio link failure is counted for these states:

- Handover failures.
- Scheduling request failures.
- Random Access failures.
- Timer T310 expiration.

After recovering from the radio link failure, the UE has to move to the cell-selection state to establish a new connection [29].

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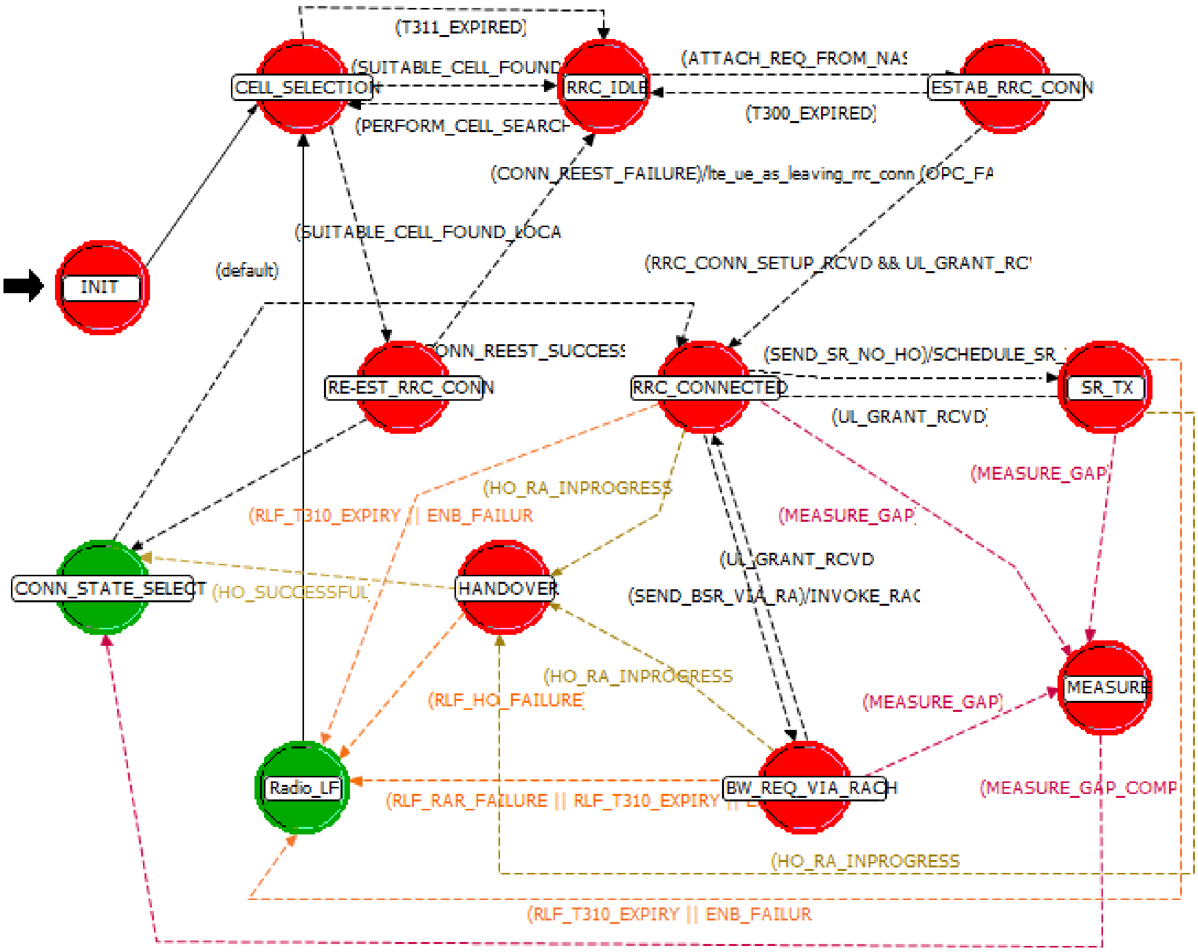

Fig. 5-17 EPC NAS model

5.4.2 Speed dependent measurement

In network-controlled mobility, the network controls the handover parameters' optimisation. However this requires considering the UE's mobility situation by estimating the UE's speed. Much research has been undertaken to find out the speed of the UE while connecting to the serving eNB. In future LTEs the mobility issue will be enhanced by the aid of positioning techniques. In 3GPP the mobility state is defined depending on the number of handovers during a set time window.

In location-based services, there are different proposals on how to calculate the location of the subscriber; they differ in how accurate or complex they are. The simplest method is cell identity where the UE reads the Cell Id (CID) from the system information broadcast, and then sends this information to the network and the network will know the location or address. The accuracy here is determined by the cell size (Fig. 5-18).

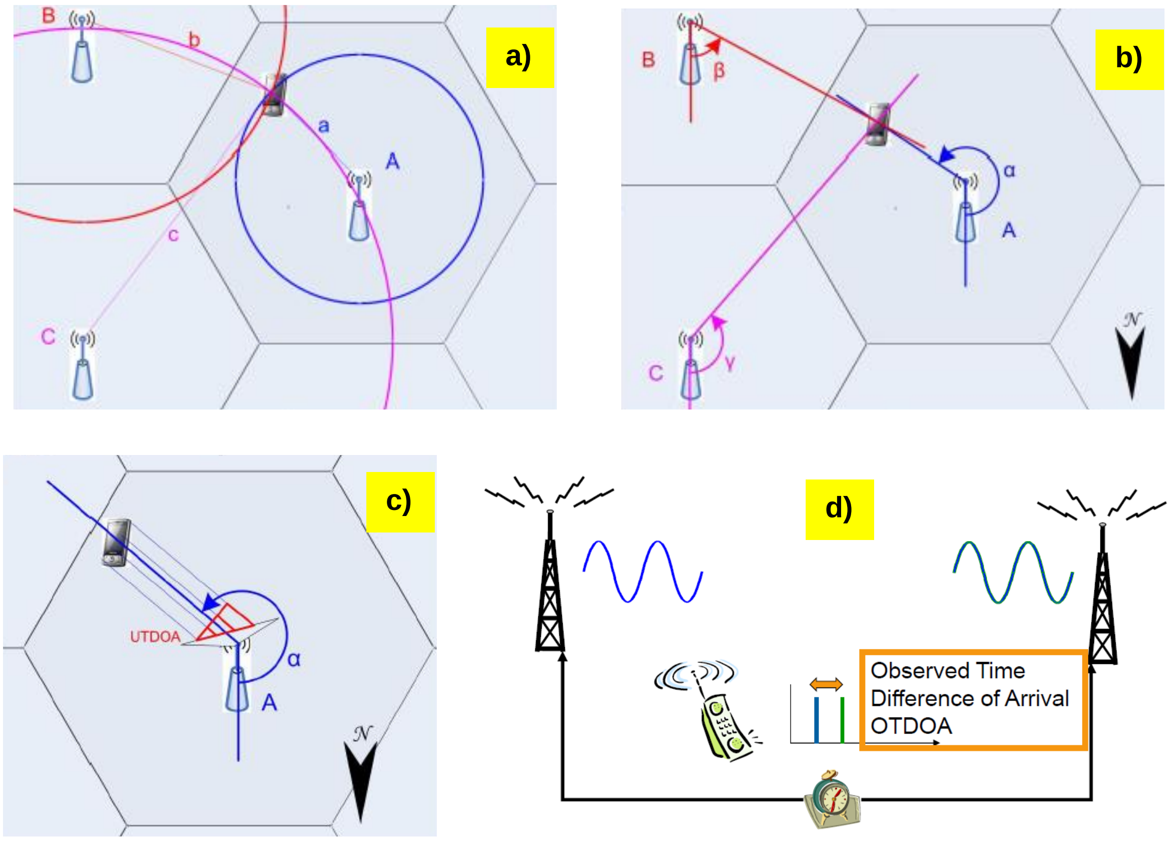

Fig. 5-18 location based services

Another method to estimate position, and hence the mobility level, is based on additional radio measurements after the UE establishes a radio connection [30]. The distance is estimated by measuring RSRP, timing advance, time of arrival and round trip time. This gives accuracy as a circle and provides a “ring” estimation (panel: a). In order to increase the distance accuracy level to a “locatable point” (panel: b), several neighbouring cells could measure the UE’s uplink signal and measure the delay time upon request from a location coordinator which involves neighbouring cells measuring the delay time. The location coordinator then sends the information to the serving eNB, which means it can estimate quite accurately the position of the UE. Another method, such as calculating the angle of arrival, requires a phased array antenna (panel: c). At the base station this would work perfectly in line of sight, however the network has to support this kind of antenna.

UEs can assist in the estimation of location and positioning (panel: d). The UE measures a certain kind of signal from one cell and also measures the reference from a second cell, and if the network is synchronised the UE can measure the time delay (difference) between both cells. This method would be enhanced further with the presence of three cells [31].

5.4.3 Requirements

UEs with different states of mobility must have seamless and robust mobility between Macrocells and other smaller base stations, otherwise offloading will not provide benefits efficiently.

In order to enable and enhance mobility in LTE networks, some factors must be considered such as:

- Small cell discovery;
- Mobility estimation;
- Network solution and UE assisted solutions.

The presence of Picocells within the coverage of the Macrocell creates hotspots; large numbers of hotspots will be created in the simulated scenarios where the UE moves randomly within the Macro coverage at the edge and also at the centre.

The impact of Picocells on the system's performance is simulated and handover is evaluated through handover delays and failures. The measurement report triggers cover all the possible events (periodic, A1, A2, A3, A4, A5). Also the figures provided show when the UE is out of coverage (or not connected for a period of time).

5.5 Methodology

When the UE is reported to be in high mobility state, this may degrade its performance when it passes across a large number of cells, especially when the cells have small coverage areas which the UE can pass very quickly after connecting. It will then restart the attach procedure with another cell.

The proposed method is based on the UE's mobility level. When the serving cell finds out that the connected UE is moving at a high speed, it has to move this UE to the prune list if this user is reported as reaching the mobility level threshold for this issue. In the simulated scenario all the serving cells (large and small) are interconnected with EPC. The prune list contains only the Macrocells connected to this Evolved Packet Core (EPC). The serving eNB will hand over the UE to Macrocells only and not to any other cells.

In HetNet, large numbers of small cells create large numbers of cell boundaries. This, in addition to the handover overhead, has an adverse impact on the cell reselect process and increases the signalling overhead. Another issue is that the low power transmission of small cells and the high power transmission of Macrocells creates a difference in power transmission, and degrades the cell edge performance due to interference , handover failure and ping pong states. Fig. 5-19 shows the cell IDs that the UE is connected to during mobility. The figure shows large numbers of handovers with a short time of stay under each cell (each line represents the time of stay under each eNB), and large numbers of radio link failures occurred during mobility (RLF is shown when the UE is connected to cell of ID -1). Radio link failures describe the performance of the handover during mobility in the simulated scenarios; the radio link failures will be presented in panels in addition to disruption in the received traffic.

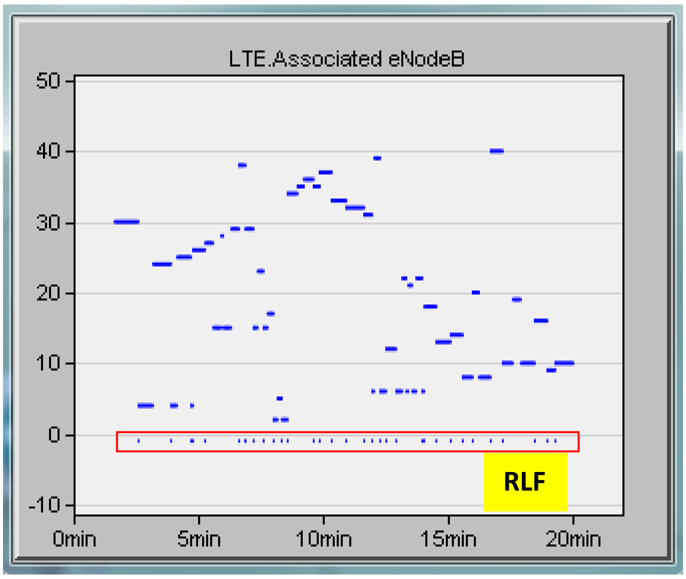

Fig. 5-19 Connected cells during mobility

Small cells are avoided in high speed UEs for two reasons; the first one is instability. When handover is performed to a small cell, there will be a short time of stay within its coverage (when the UE moves fast compared to the cell size then the UE has to find a new cell and starts new measurements). The second reason is to avoid instantaneous changes in the load of the small cell because there can only be a limited number of users connected to a small cell.

For a normal (low) speed UE, enhancement will be focused on detecting small cells. Handover commands could be configured on the UE, or on the serving cell, and then signalled to the UE. In HetNet one addressed issue is the location of the small low-power node; the UE doesn't know where the small cell is and it has to keep performing measurements which is not efficient for the battery's power consumption [32]. Due to the low level of mobility, this requires a long period of measurements until the UE starts sensing the signal of the cell, and it still doesn't know if it is small cell or not without prior knowledge [33].

In a wireless communication environment, when the UE is in a high mobility state, it travels a large distance and as a result large scale fading would be the main cause of the received signal's degradation, because it is a function of distance. In this case, degradation in the link quality must be avoided. A highly mobile UE has to report- the average band faster to make the environmental measurements close to long term fading, and to avoid short term variation of the signal caused by small scale fading [34] (Fig. 5-20).

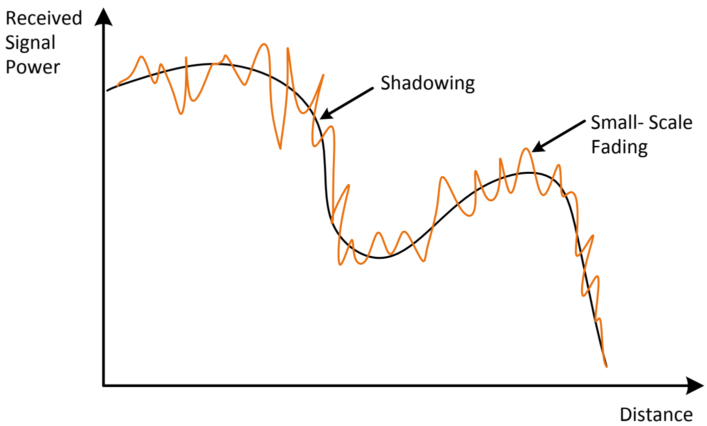

Fig. 5-20 Fading and shadowing

Two issues are addressed with small cells: the first one is that the UE needs to offload data to a small cell but it does not know when the small cell is available so it has to do inter-frequency measurements. The second issue is how long the UE will camp under the discovered small cell.

Small cell handover is suspended when the UE is in high mobility, then the measurement GAP is made for a longer time (longer but less frequent). As the UE is under the coverage of the Macrocell, the measurement GAP is triggered when the UE arrives at the edge of the Macrocell (Fig. 5-21). Network offloading will not be affected as that procedure is only applied on high speed UEs. In Chapter Four a function is implemented at the eNB to find the distance of the UE from its serving cell. The eNB keeps contacting the EPC to update its records about the location of the small cells.

The normal measurement GAP for inter-frequency measurement affects the UE battery's power consumption. The aim of continuous measurements is to enable the UE to discover new cells quickly when the signal quality of the serving cell is lower than a defined threshold. When the UE is moving among small cells, the signal quality of the cell will decrease quickly if the UE travels at high speed; therefore fast measurement with evaluation processes are needed to search for and switch to a new cell. The same situation will be repeated if the new cell is a small one too. The presence of these small cells together with the large Macrocell means that the measurement process impacts the system's performance adversely if the UE is highly mobile.

In order to reduce this impact, firstly these measurements are proposed to be made less frequent, depending on the mobility state monitored by the serving eNB. The UE will be forced to camp on the Macrocell for the longest period possible. The serving cell issues the measurement period, taking into consideration the fading and shadowing effects mentioned in [35]. After a certain distance the link quality of the serving cell suffers from shadowing and fading and here the serving cell will issue a measurement GAP for the UE to start searching for new Macrocells, if it is still in a high speed mobility state (Fig. 5-21). These less frequent measurements enable the UE to avoid the overhead of handovers to smaller cells and ping-pong states among them, so the UE will be configured by the network to use a set of all the measurement GAPs.

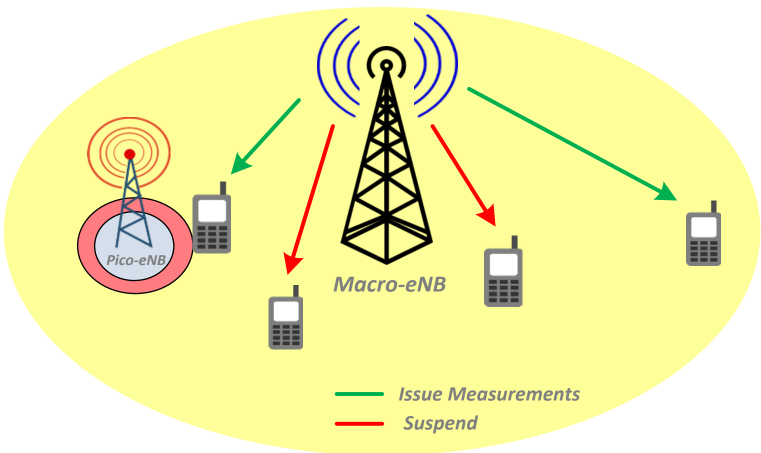

Fig. 5-21 Macrocell issues/suspends measurements

5.5.1 Parameters during mobility

The following diagram (Fig. 5-22) demonstrates the interaction between different entities and the downlink command of the LTE system with different mobility levels.

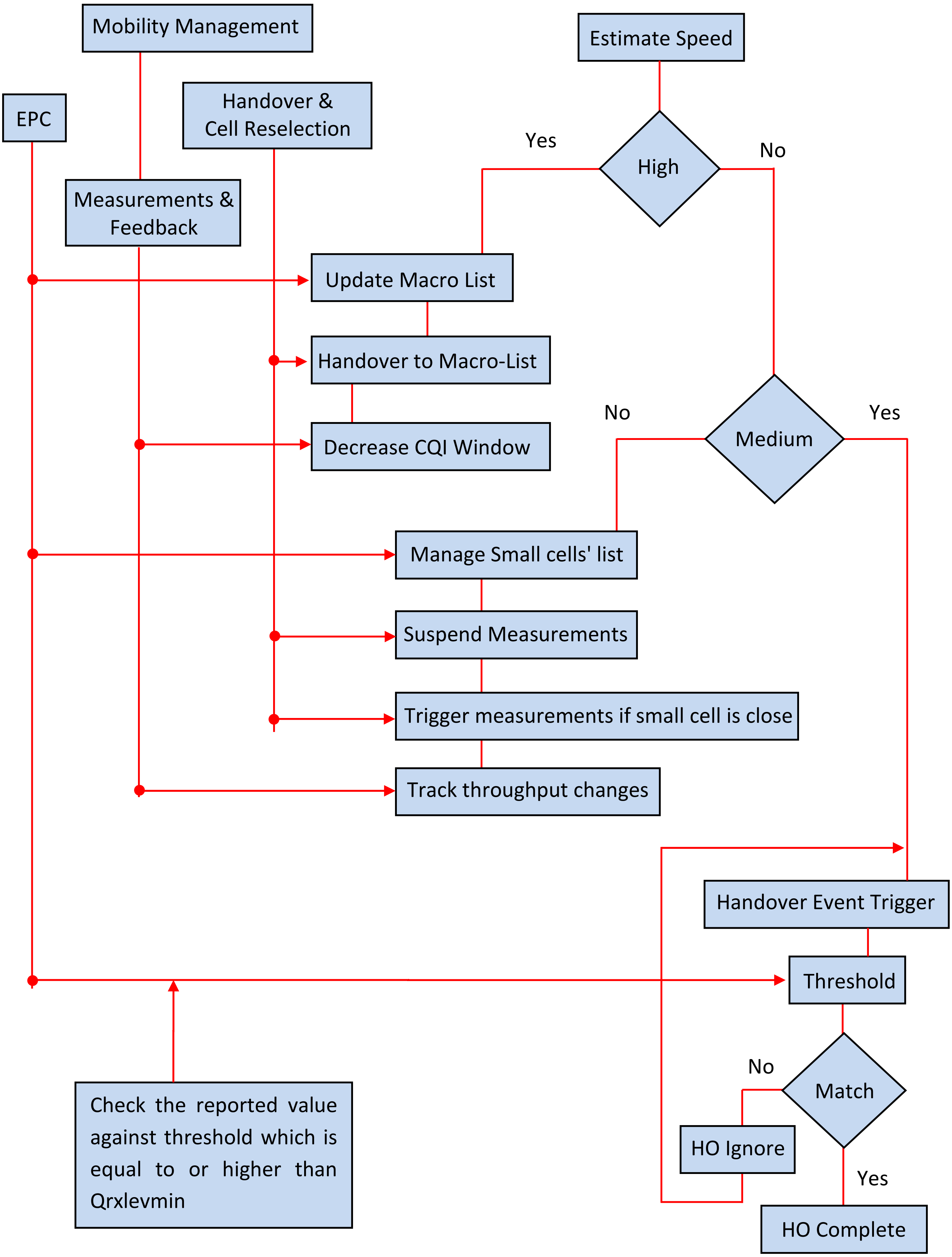

Fig. 5-22 Downlink command for different mobility levels

5.5.2 Results and discussion

The results consider 3 mobility levels, High (>60 km/h), Low (<30km/h) and Medium (30-60 km/h). Although small cells provide coverage at cell boundaries and create hotspots, this can have drawbacks when the UE moves at high speeds. In the first scenario, the UE is suspended from handover to small cells and measurements are made less frequently. Fig. 5-23 shows the received traffic during the high mobility scenario.

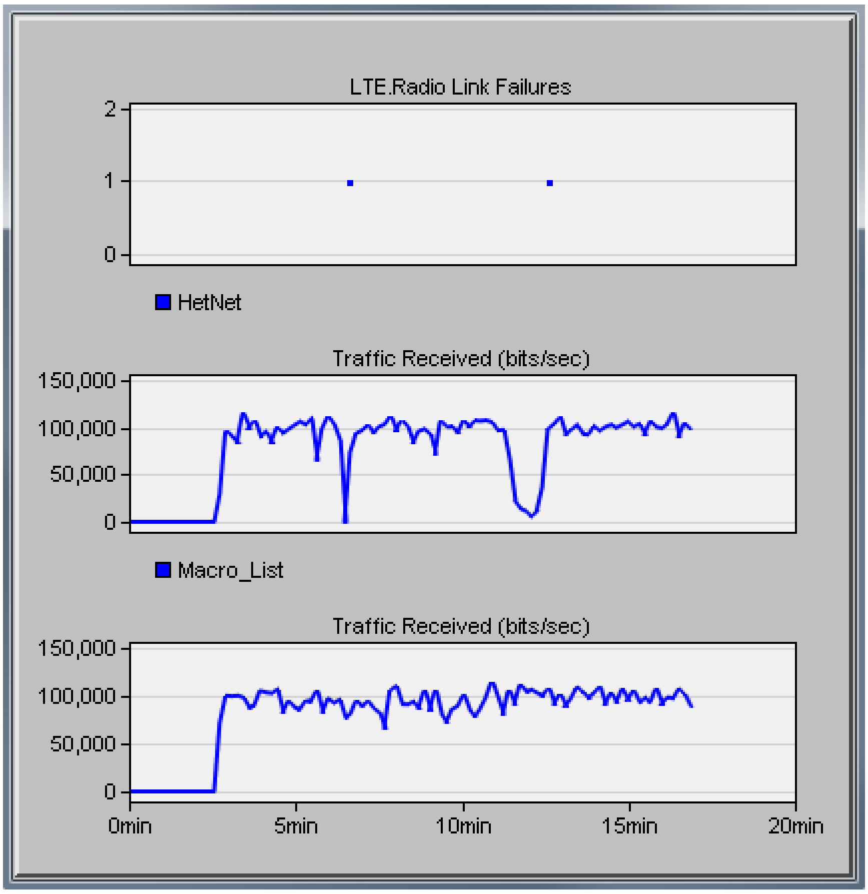

Fig. 5-23 DL traffic and radio link failures during high mobility state

The figure shows a comparison between two simulated scenarios at high mobility. The first scenario is the Normal HetNet scenario and the second one is the Macro-List scenario which includes forcing the UE to connect to the prune list of Macrocell if the UE is in a high mobility state. The first panel shows the radio link failures that caused the sharp decrease in the received traffic. The second panel shows how the node throughput undergoes remarkable degradation because of the radio link failures. This is due to handover failure between the small cell to the Macrocell. Due to high mobility, the UE is connected to the Macrocell and then after short period, it has to trigger handover at the cell boundary. The UE leaves the cell's coverage before handover is complete, and as a result it will not be able to receive from the Macrocell because its signal is lower than the accepted threshold. It will also not be able to receive from the small cell because handover is not complete.

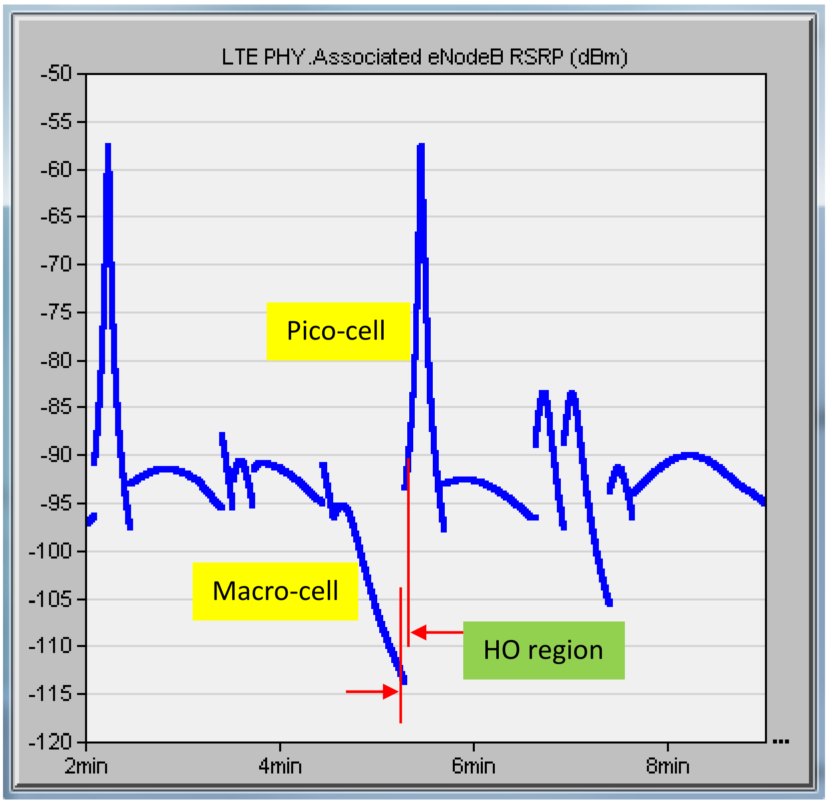

Fig. 5-24 Handover region with RSRP distribution

Fig. 5-24 shows RSRP distribution during mobility. The handover region from the Macrocell to the Picocell is very narrow and it is approximately between 2 and 8 meters. This handover region was not large enough for the UE to complete the handover successfully when passing the handover region at this area. The signal from the serving cell was very weak, so the UE did not receive the handover complete command due to PDCCH outage, and this caused handover failure. Regardless of the radio link failure and its effects on the transmitted data, sometimes the received traffic during mobility looks equal in both scenarios (HetNet and Macro-List scenarios shown in Fig. 5-23). However there is an important issue that should be referred to, which is the consumed power from the UE's battery. The negative effect of the large number of connections established, and multiple handovers, can be explained from the DRX side.

Fig. 5-25 shows the number of eNBs that the UE established connections and associated with, and the average connected time per cell for the two simulated scenarios at high speed mobility. In the Macro-List scenario, it is obvious that the UE has connected to a smaller number of eNBs with a longer period of connection.

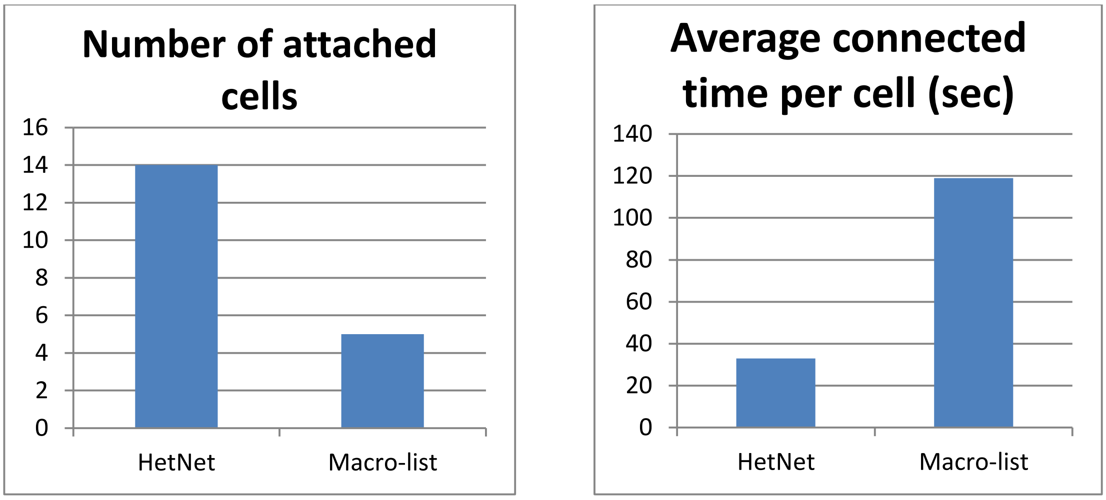

Fig. 5-25 Number of connected cells and average of connected time per cell

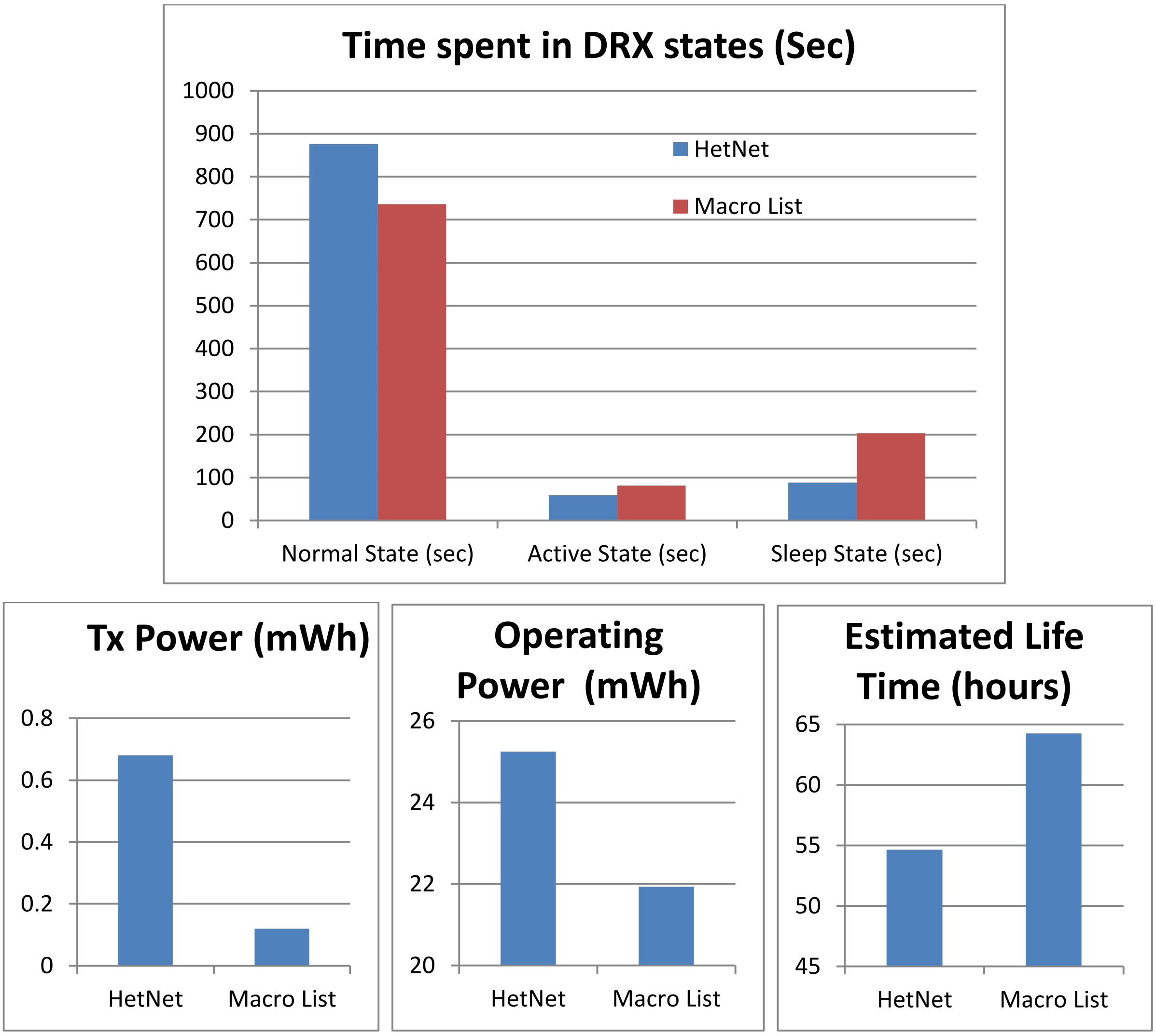

Fig. 5-26 Power statistics comparison between the two scenarios in high speed mobility

Fig. 5-26 shows the time spent in normal, active and sleep states. In the HetNet scenario, the UE has to keep taking measurements to find the most suitable neighbouring cell. Due to its fast mobility, the UE has to perform the measurements more frequently in order to be able to discover and connect to new cells quickly. These continuous measurements have a negative impact on the DRX cycles because they continuously interrupt the sleeping period and always trigger inactivity of the DRX. In the Macro-list scenario, the measurements are made less frequently because the UE is forced to connect to the Macrocells only, which has a positive impact on the DRX sleep period. According to the figure, the sleep period is almost double the period of the HetNet scenario which gives more life to the UE's battery as less power is spent on operating and on transmission.

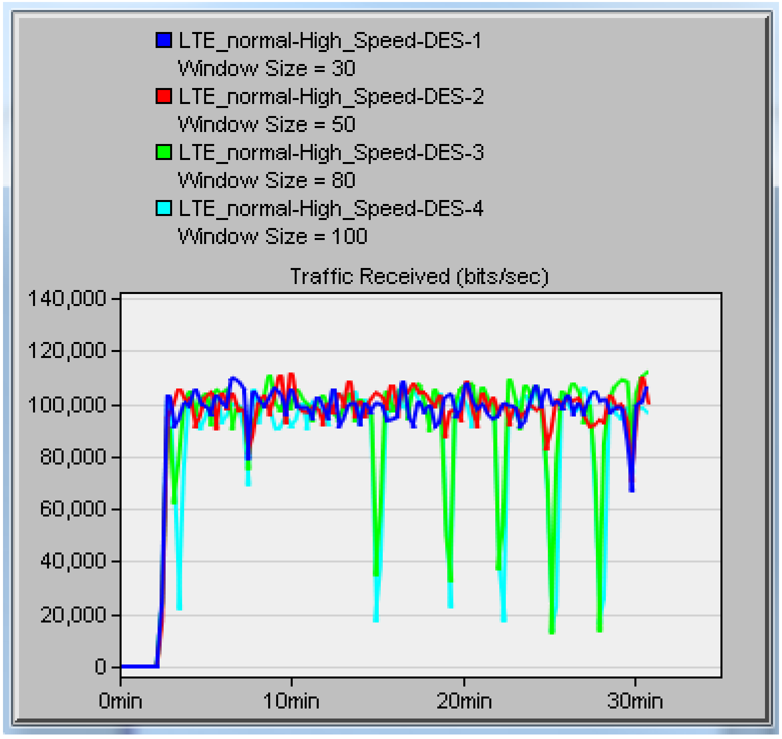

Fig. 5-27 DL received traffic for different measurement window sizes.

Effects of window measurements appear clearly on the received throughput at higher speeds. At the cell edge, the effects are remarkable due to the weak signal with low SINR received from both the serving and the neighbouring cell. Link adaptation at high speed has a negative impact on the received traffic if the UE performs measurement with a longer window size. Due to the high speed of the UE, the measured signal strength and quality will become old values because of sudden channel variation, measurement errors and reporting delays. At low speeds, the measurement window has no effects on the transmission because the channel is not quickly changing around the UE. It is very useful in this case to change the link adaptation parameters and have a new CQI report for a few frames to avoid degradation in throughput and poor performance.

Fig. 5-27 shows the effects of the measurement window size on the received throughput (downlink). In the figure, the traffic received is plotted against the simulation time (30 mins) to show the sudden changes in the traffic received. When the UE reports old CQI values to the serving cell, the cell responds with the corresponding MCS on the preferred subband. The cell's response will no longer be suitable for the new channel conditions. This causes a decrease in the throughput, especially at the cell edge.

Fig. 5-28 shows the effects of reporting delays associated with different measurement window sizes. The figure shows that the delays increase with the increase in window size when the UE is at the cell edge, whereas the delays become more stable when the UE moves towards the cell centre, due to an improvement in the signal strength and quality. These delays are the result of errors and HARQ retransmissions because of a miss-match between the UE and the serving cell. When the cell increases the MCS because the UE has a poor signal, this causes packet drops and retransmissions. In the figure, at each certain distance a scenario is simulated with the range of the measurement window value increasing from 10 ms to 120 ms.

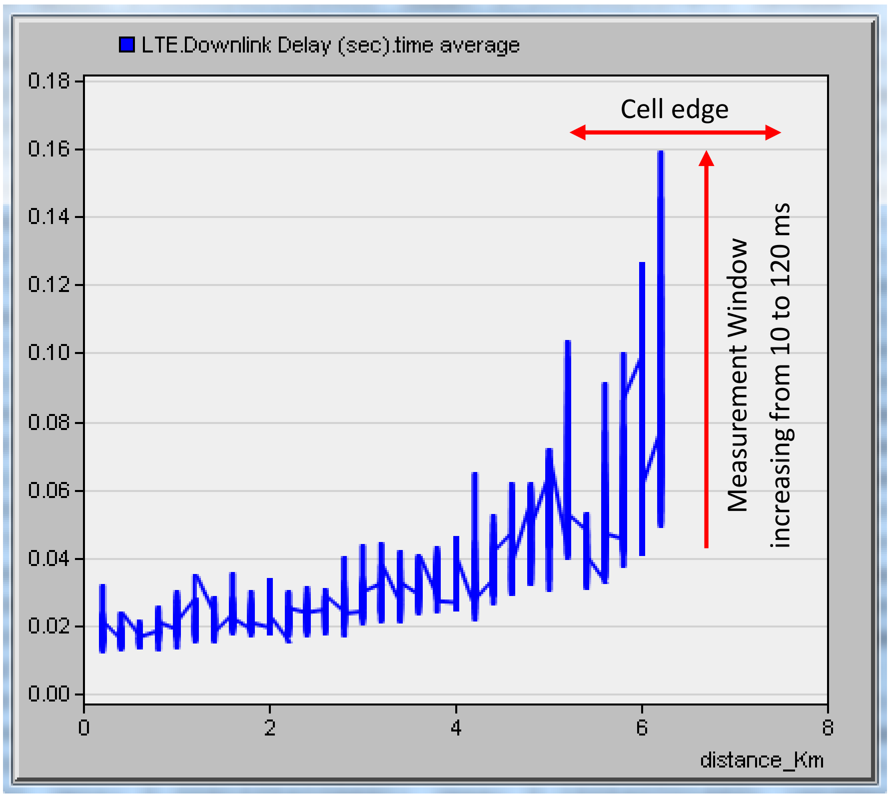

Fig. 5-28 Reporting delays for different measurement window sizes

The second scenario considers the low mobility state. In this scenario, due to the low speed of the UE, the Macrocell has enough time to guide the UE in order to enhance the system's performance. The proposed method (called HetNet-Guided-UE) in this case aims to improve the cell search and selection during mobility. In low speed mobility the UE has enough time to find the best cell. Normally the UE doesn't know whether a neighbouring cell is small or large. The objective is to find a method that will make sure that the UE does not start a cell search and connect to a small cell until it is close enough to it, so that it saves time and power spent on measuring the surrounding environment. The UE spends a considerable amount of its battery energy on performing measurements to find the small cells. The power consumption is higher when the small cells are operating on different carrier frequencies of the UE. Discovery of the small cells could take a longer time if they operate in an On/Off mode.

Here the consideration is that the Macrocell has X2 interfaces with the small cells under its coverage. When the UE starts approaching a small cell, the Macrocell will trigger measurement reporting to the UE and the UE starts to generate reports to perform handover. If the Macrocell has information about the small cell band, this will improve the cell search and measurement significantly.

In dense small cell deployment, one issue to be considered is the fluctuating interference originating from the small cells because of their high dynamic traffic; as a result the reported feedback from the UEs may not be accurate and may also have an adverse impact on interference estimation. Network guidance helps to reduce the effects of the dynamic traffic nature of the small cell. This helps to reduce the RS and control signals transmitted by the small cells and reduces the interference resulting from them. If the small cell has a low number of UEs, the Macrocell may not guide the UE to that small cell and this cell could be turned off to save energy in an On/Off mechanism.

An improvement in the reception of the received traffic will be reflected in a smaller number of drops in the received traffic. Fig. 5-29 shows a comparison between the two scenarios, Normal HetNet and Guided HetNet. The figure shows that the UE is generally connected to the same eNBs (Macro and Pico) in the two cases during mobility. In the second case the UE will receive a command from the Macrocell about the candidate small cell, instead of performing measurements of all the eNBs' received signals. In Fig. 5-30 a comparison is shown between the simulated events for the two states (Normal HetNet and Guided UE HetNet). In the second case there are fewer events executed during the simulation; this is due to the fact that the UE has performed less measurements and signal processing when it is guided by the Macrocell to the smaller cells.

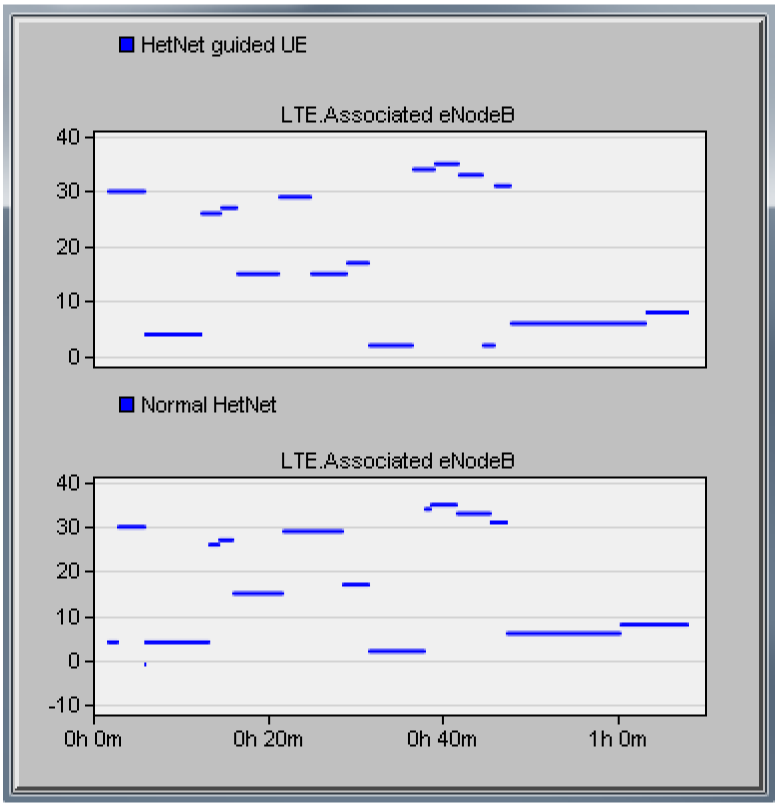

Fig. 5-29 Associated eNBs IDs

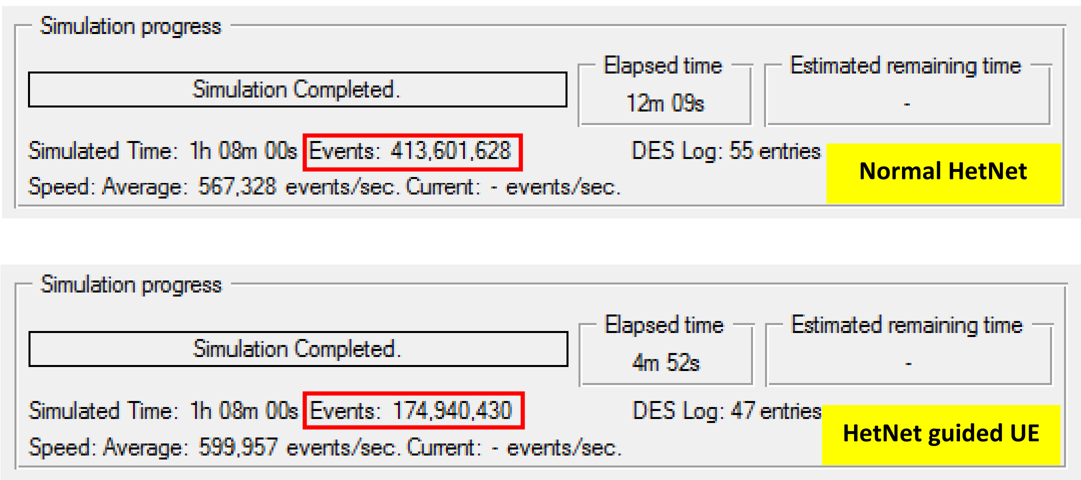

Fig. 5-30 Number of generated events in low speed mobility

In this scenario the improvements will appear more on the battery's saved power, than on the amount of traffic received (Fig. 5-31). The figure shows that in both simulated scenarios the traffic received is the same with some exceptions.

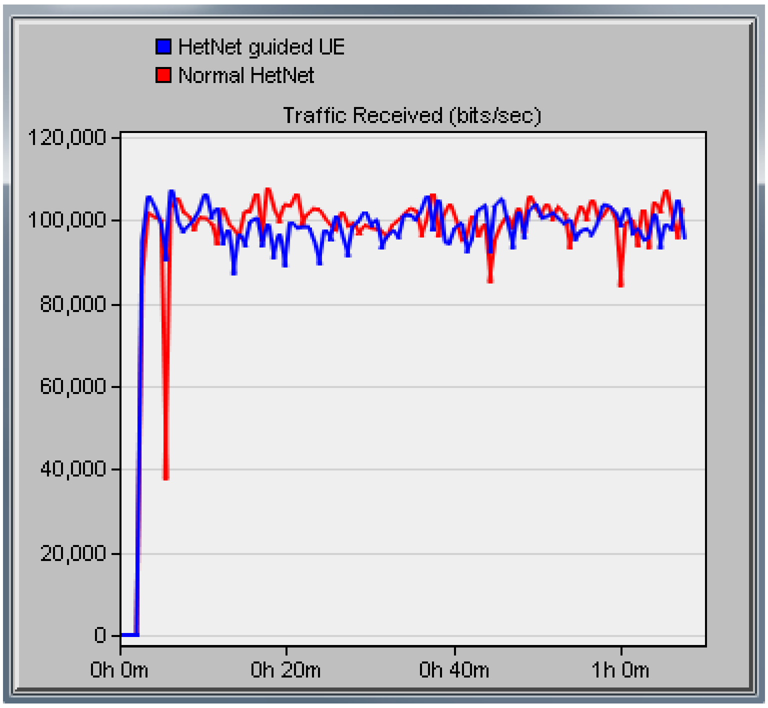

Fig. 5-31 DL received traffic

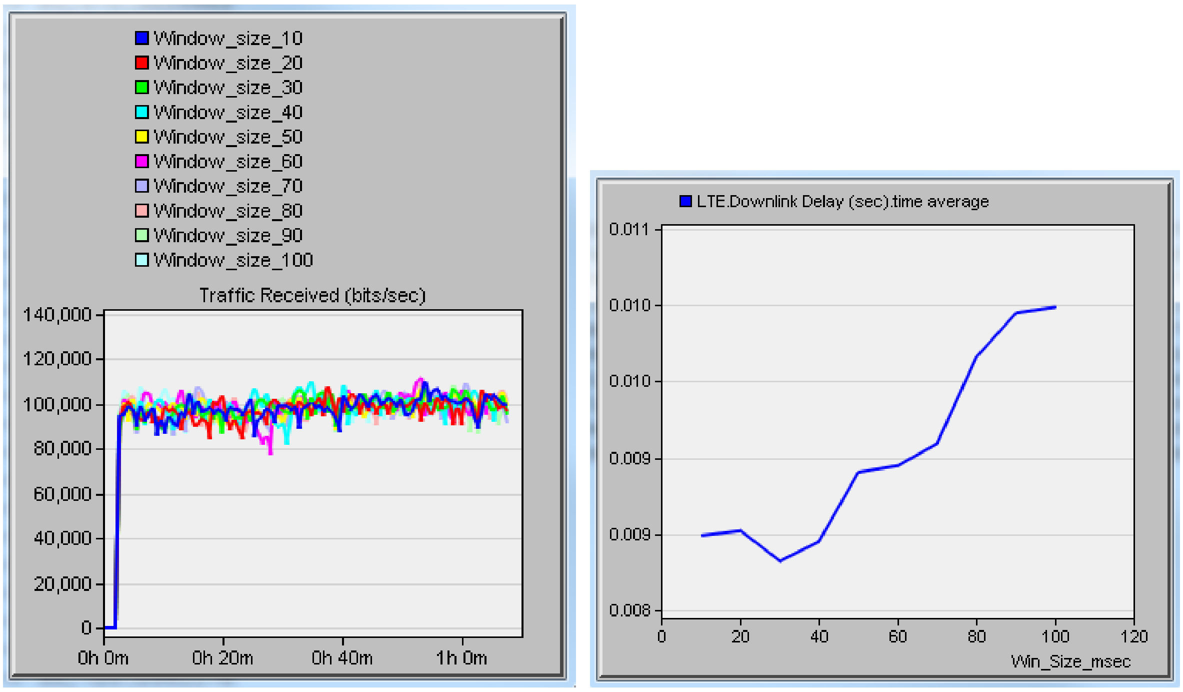

Fig. 5-32 DL delays and received traffic for different measurement window sizes

Fig. 5-32 shows that window measurement size does not have a considerable effect on the received traffic at low speed mobility. This is due to the fact that the UE has enough time to perform measurements and report the result during the same link condition, without any introduced delays or aging in the reported value. On the other hand, the window sizes range from 10 to 100 ms and the corresponding downlink delays are 2ms between the shortest window and the longest window size.

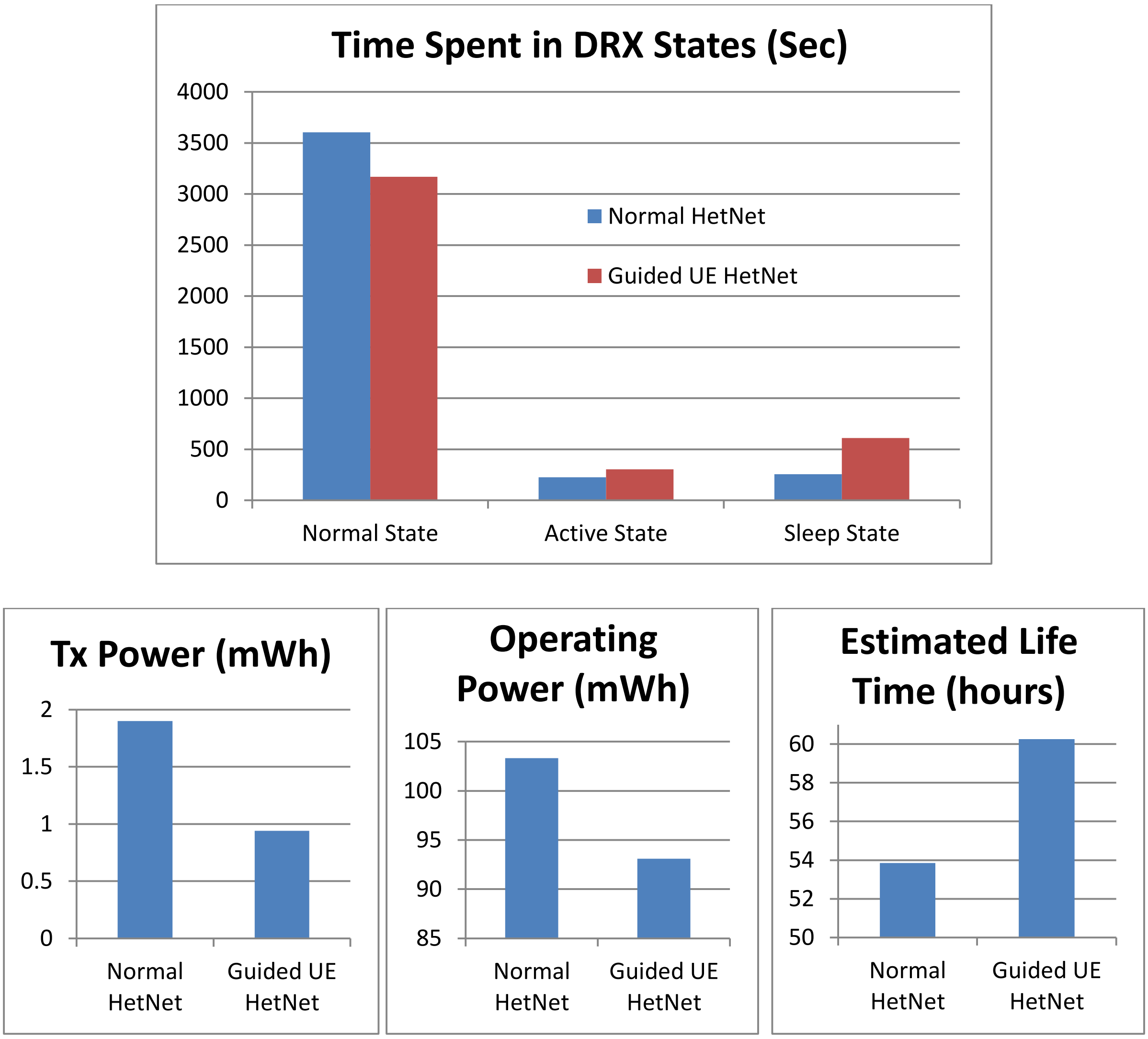

Fig. 5-33 Power statistics comparison between the two scenarios in low speed mobility

As mentioned earlier, optimised cell search has a positive impact on power consumption, as the UE saves a considerable amount of power spent on radio measurement. The sleep period in the proposed scenario (the Guided UE HetNet) is almost double the period in the Normal HetNet scenario (Fig. 5-33). The difference in operating power is (103.5 – 93) = 10.5 mWh.

Fig. 5-34 shows the number of measurement GAP triggers during the simulation time (1 hour) according to the process model shown in Fig. 5-17.

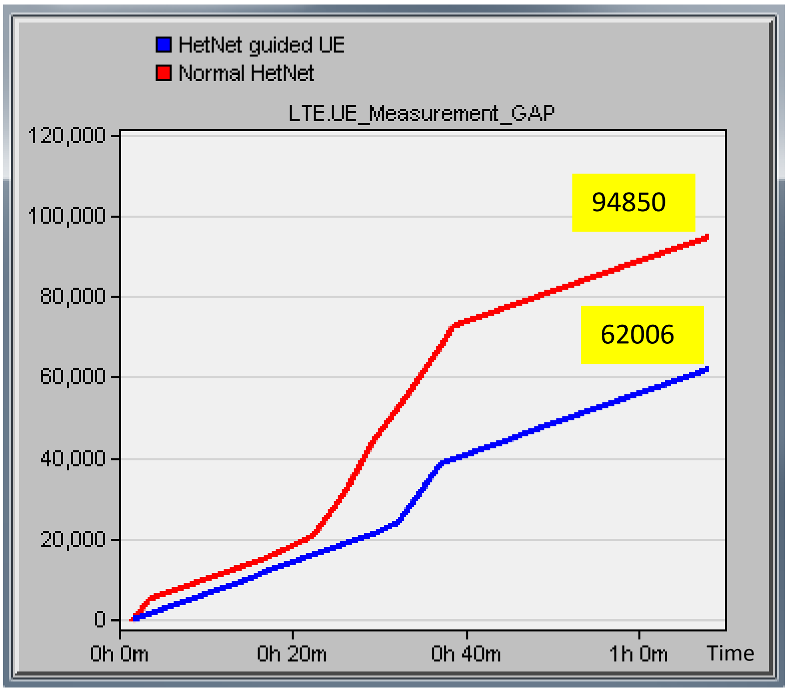

Fig. 5-34 The cumulative number of measurement GAP triggers

The measurement GAP is 6ms long [21] and the power consumption of the device, as defined in our model in the active mode, is 0.1 W. Thus the power consumed on measurement is in the range of $1.667e^{-4}$ mWh. The decrease in the number of measurement events is approximately 94850 - 62006 = 32844 events between the two scenarios.

The accompanied decrease in the operating power is 5.5 mWh which means that approximately 48% of the saved energy (saved: 10.5 mWh) in the second scenario is saved due to the reduction in the measurement GAP events (Fig. 5-35).

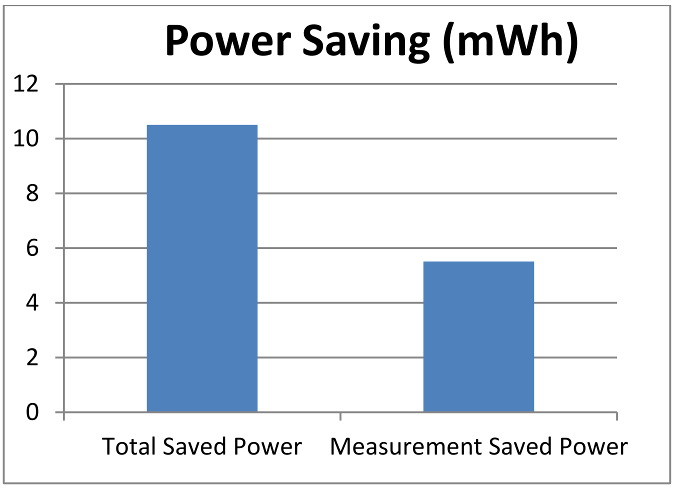

Fig. 5-35 Power saving statistics in low speed mobility

The third scenario is the medium speed mobility level. Here in is this section, the aim is to make the best use of the offloading to small cells at the same time so that the majority of the handovers should go to the Picocells. One of the main causes of radio link failures is performing the handover at the wrong times (early or late handover triggers). The network must have a fast dynamic response to decide to hand over to Picocell or Macrocell or to ignore handover for certain period. To create a dynamic response, the parameters must depend on the UE's position in the Macrocell, especially at the cell edge where the performance undergoes degradation. There have been X2 interface interconnections among cells of different sizes in the same area which gives more flexibility to find the optimum threshold (and thus the optimum time) for successful handover between cells. In addition, they reduce the overhead accompanied with the wireless interface for acquiring cell information.

When the UE leaves the small cell and fails to hand over to a Macrocell, it spends some time disconnected until the received signal meets the required level. Cell selection depends on the received RSRP level of the cell and failures occurs due to early handover from the small cell to the Macrocell. The following scenario represents one of the worst cases that occur during mobility. The UE is set to move randomly and the resulting path is shown in Fig. 5-36, this path is at the cell edge and traverses through multiple Macrocells and other small cells.

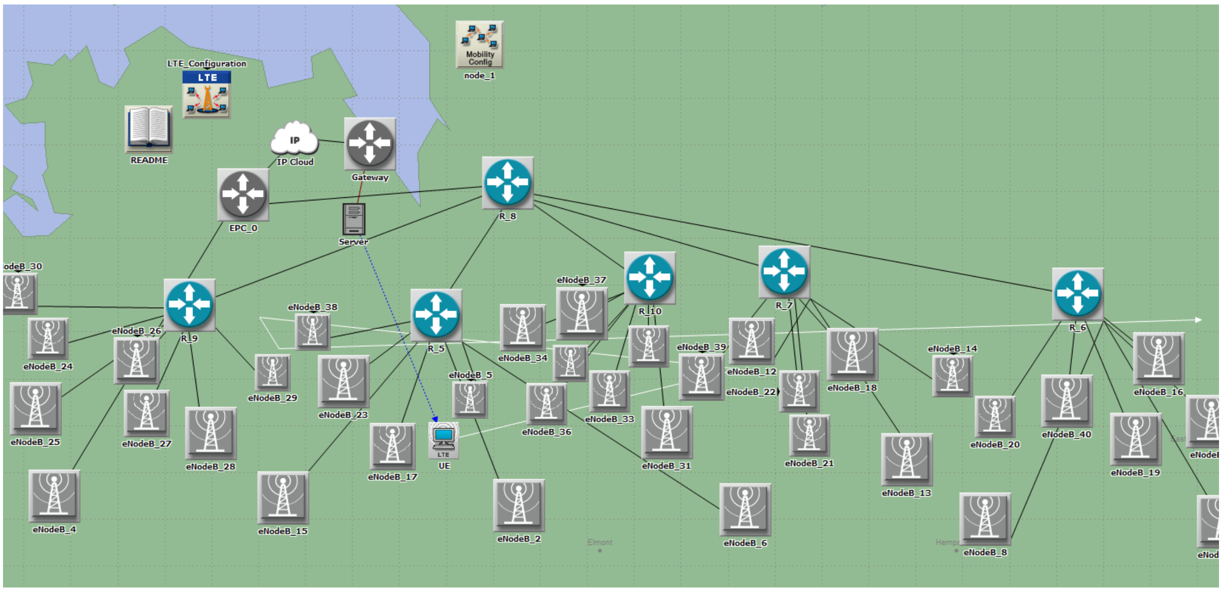

Fig. 5-36 The simulated scenario of medium speed mobility

To avoid early handover and radio link failures from the small cells, some offset is added to the small cell handover trigger threshold (we do not add or relay on cell range expansion to avoid any confusion due to interference). In this procedure the UE must be insured that it hears the suitable cell on the downlink. Handover is triggered when the measured RSRP of the serving cell becomes lower than that of the neighbouring cell. The small cell will not start the handover procedure until the handover criteria meets the Macrocell selection threshold which is the required minimum received RSRP and corresponds to the broadcasted value of the Qrxlevmin or more. This value could be obtained directly by the small cell through X2 negotiation or through decoding the Macrocell's downlink signal [36]. If the handover is triggered and the UE transmits a satisfying measurement report to the small cell, it will not trigger the handover until the reported value matches the stored value of the accepted RSRP by the Macrocell. When the UE achieves this, the handover will be secured and completed successfully

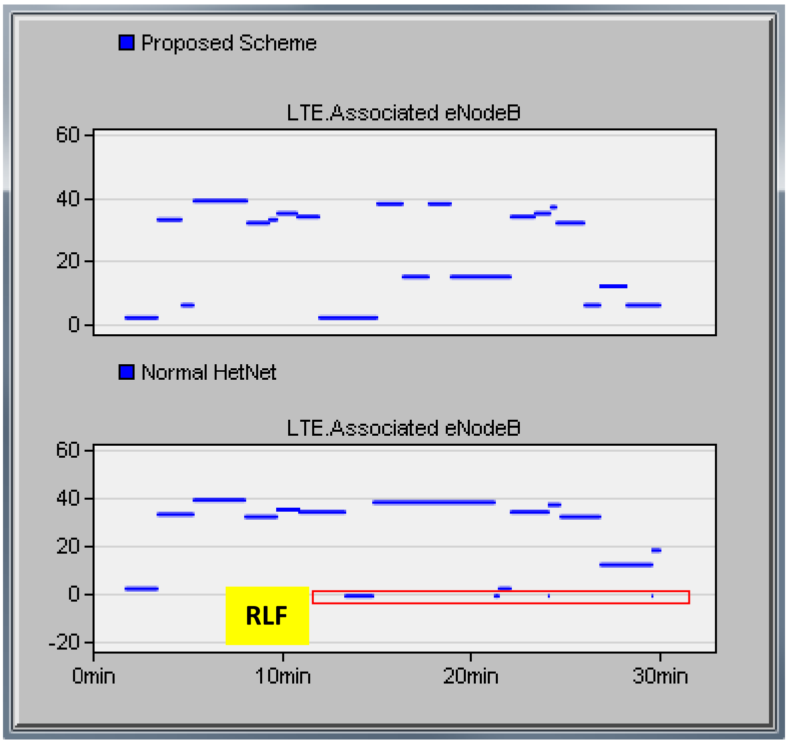

Fig. 5-37 Associated eNBs IDs and RLF in medium speed mobility

Fig. 5-37 shows improvements in the radio link failure rates between the normal HetNet scenario and the proposed scheme for medium mobility level. The decrease in radio link failures improves the traffic received by the UE. The proposed scheme in Fig. 5-38 shows improvement in the received traffic; other remaining effects on the received traffic are due to the window measurement effects.

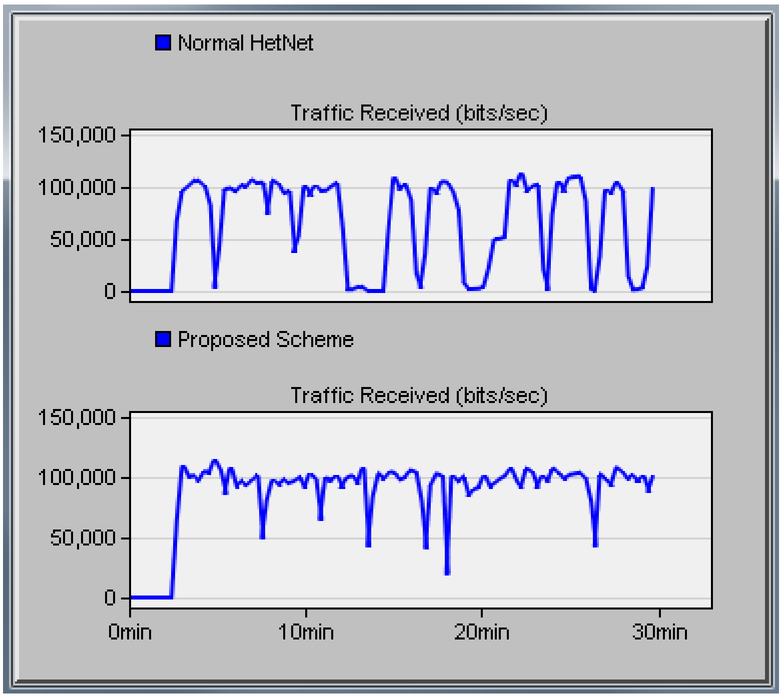

Fig. 5-38 DL received traffic in medium speed mobility

In order to verify the effects of the measurement window size, the average of the received traffic against the window size from 20 to 100 (ms) is plotted. Fig. 5-39 shows, with some exceptions, improvements in the received traffic.

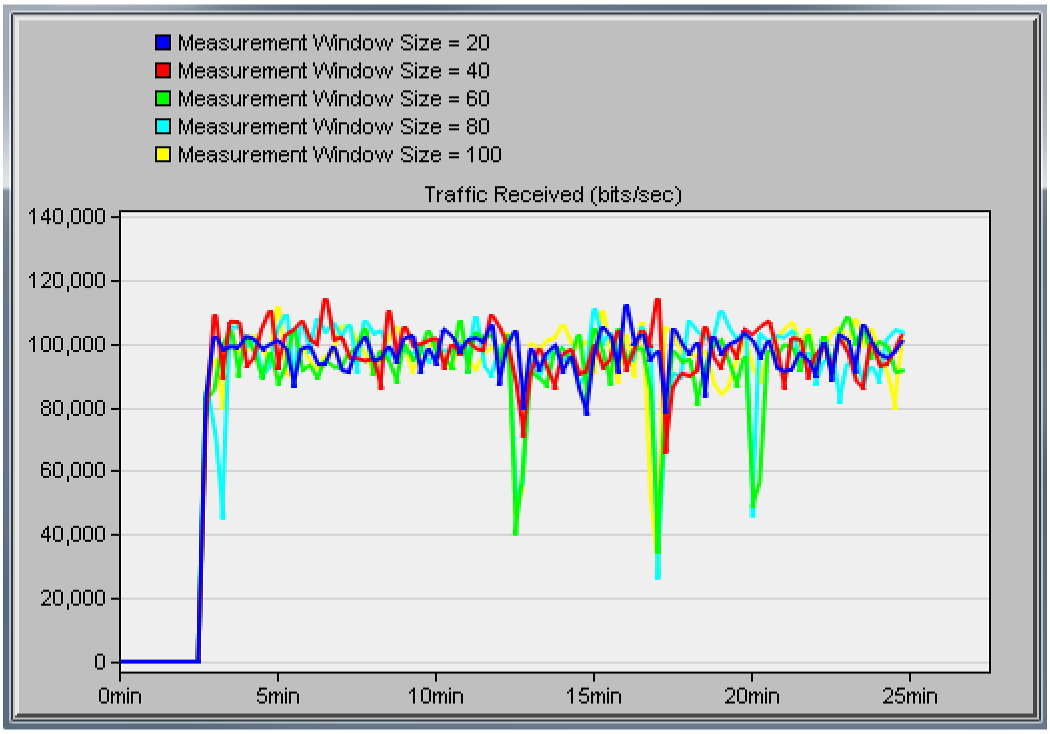

Fig. 5-39 DL received traffic in medium speed mobility

In the figure, due to the repetition of the cell edge scenario each time the UE leaves the small cell and connects to the Macrocell, short window measurements show better performance. Improvements start to appear with smaller window sizes due to lower HARQ delays and due to the fact that CQI values are reported more frequently.

When the UE is camped on a small cell, it is enough to employ a short measurement window to measure the radio condition. Because the small cell has a small coverage with good RSRP signal strength, the UE will request higher CQI and MCS. If this happens at the Macrocell edge (Picocell is at the Macrocell edge) and the UE starts to move to the small cell edge, there will be a significant difference between the received RSRP of the two cells (Fig. 5-40). If the UE does not perform fast measurements to find out the suitable CQI value and hence MCS value for the Macrocell, this will adversely impact on the received traffic due to the weak signal of the Macrocell and its low SINR at the cell edge. The UE has to leave the small cell with short measurement window when connecting to the Macrocell. If the small cell is located close to the centre of Macrocell, the Macrocell signal will be good enough and the measurement window size does not have a significant impact. As the speed increases, the effects will be more significant.

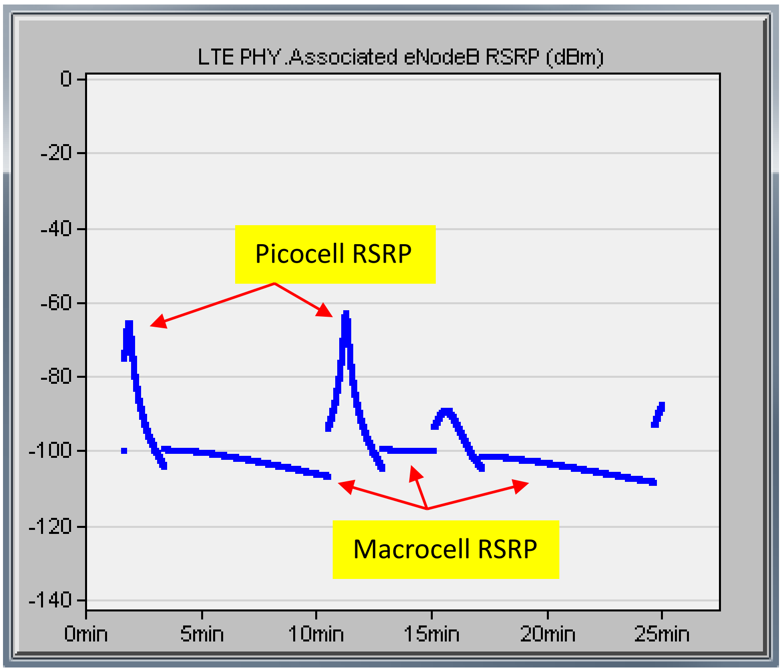

Fig. 5-40 Picocell and Macrocell RSRP

5.6 Summary

In conclusion to this work, handover and link adaptation performance was presented during mobility in heterogeneous networks. The handover process combines many processes together to provide seamless movement of the UE between cells. Mobility in a wireless network has an impact on the handover process and may cause radio link failure and delays. Another issue which is considered is the effects of mobility on the link quality during connection and data transmission. Mobility causes an increase in the effect of the channel coherence time. In HetNet it was shown that it is not efficient to keep the same parameters with different mobility levels. Furthermore it was shown that the network can control the process seamlessly and show better performance and adapt different parameters efficiently.

Measurements during mobility are very important for the UE in order to keep the connection at the desired level. The proposed methods imply more cooperation and network monitoring in a quick manner to avoid radio link failure and to be able to keep pace with the varying channel conditions. Due to different mobility levels, the serving cell is programed to have higher activity levels regarding mobility and handover such as guiding the UE to the small cells under its coverage and issuing the measurement periods at the cell edge where the coverage is weak and there is high potential interference.

Small cells have improved the network performance without needing to change the standard; when the UE passes through a large number of different cells, this mobility requires an increase in activity levels in processes such as cell search and re-selection, measurement reports, link monitoring and signal processing. When optimising the UE's mobility, results show improvements in the system's performance at the cell edge and near the cell centre. Improvements included the consumed power from the UE's battery, throughput instant degradation and handover delays. According to the results, the drop in the throughput at some places, when the UE is handed over from the small cell to the Macrocell, could be recovered by making the handover faster and more successful, in addition to avoiding delays when performing measurements for link adaptation at the cell edge. This also has a positive impact on retransmissions.

5.7 References

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CHAPTER 6

Thesis Conclusion and Future Work

6.1 Conclusion

As mentioned in the presented chapters, the worst case scenario was shown in terms of a heavily loaded network, severe interference, and high speed mobility. Different types of applications are configured over all the simulated scenarios to bring the network performance closer to reality, and create interactions among the different systems' processes and layers. Some results are presented over a time scale to show the dynamic behaviour of the studied statistics and values; while other statistics were presented in comparisons to show the system evolution and to anticipate the optimal values and present the enhancements. OPNET software gives results close to real life because it combines multiple processes operating together such as handover, random access procedures, power saving and cell search. These processes span different layers of the LTE model starting from the physical layer to the higher layers through the MAC layer. Also the software supports the LTE MAC layer with downlink measurement support and link rate adaptation in addition to scheduling services. This made it possible to compare the proposed works with the current standard and demonstrate their contributions to the LTE system. The studied parameters are the network throughput, application performance, handover, delays and power consumption. The scenarios were simulated with parameters and configurations driven from real networks' parameters and according to the 3GPP reports and standards as shown in the provided references. The software supports the power-saving mechanism in LTE systems and it is fully modelled according to the 3GPP specifications. Thus, this gave flexibility to present, when possible, some aspects of the effects of the system and the proposed schemes on the mobile device's power consumption.

The DRX mechanism is the current mechanism for power saving in mobile devices. This approach is continuing for LTE-Advanced and efforts are being made to enhance the performance of this mechanism and to reduce the high power consumption of the wireless terminal. The currently being used algorithm saves power consumption in trade off with the delays. The aim of developing the current DRX process was to make it more adaptive and able to perform well with different bursty traffic models. If it is made possible for the device to expect or not the arrival of the packet, this improves the system performance and reduces delays. Therefore, in the first contribution, an analytical model was introduced to analyse the DRX performance in terms of power consumption and delays, then we were able to show the optimal operational point for different configurations. The proposed scheme for LTE-Advanced is the adaptive power-saving mechanism; it is based on a prediction of the system's load. The adaptive scheme continuously updates the device's settings in response to the network's activity level. The main approach of this section is to adapt the DRX parameters to improve the mobile device's performance. In this work, the impact of DRX process is analysed. Although DRX is created to save the power of the wireless terminal, the evolving technology has extended the effects of this mechanism to the whole system and application performance, when the device is set to entre sleep mode, this may interrupt other process such as handover and cell selection if the sleeping period is set for longer periods. It is vital to the efficiency of the system that the performance of adaptive DRX scheme does not undermine the activity level of the other running process. In this contribution, a centralised adaptive scheme was proposed to avoid limitations, such as overhead and the trade-off between delays and power saving, while taking into account the performance of other running processes such as HARQ, scheduling and handovers.

Future networks will be loaded with voice calls, in addition to video streaming and broadcasting. This introduces difficulties to the operator's manual cell planning and causes unexpected changes in the spectrum access. In two-tier networks a secondary system network, represented by Femtocells, coexists with a primary network, represented by the Macrocells, in an OFDM based air interface. While Femtocells are a promising technology and although these small nodes increase the system capacity and improve the link quality, however, there are many technical issues that need to be considered. One of these issues is the interference management between the Macrocell and the Femtocell in co-channel deployment. Co-channel deployment is introduced in order to have better spectrum utilisation and efficiency compared to other methods for coexistence such as spectrum portioning, where the number of supported UEs is low due to splitting the spectrum between the Femtocells and the Macrocells. This is especially so when there is a large number of deployed Femtocells within the coverage of the Macrocell. Future Femtocells will need to be equipped with some dynamic capabilities and sensing, because these devices are end-user-installed, and they also have the capability to switch on/off at any time. Therefore, in the second contribution, a method was proposed for robust sensing performed by the co-channel femtocell in order to be aware of the current and future scheduling opportunities.

The superiority of the presented scheme is that the femtocell in addition to listening to the macrocell DL to find the current scheduling and free resources, and UL sensing to discover the remote macro-users resources signal and sensing the UL signal to discover the far macro-users, it is enabled to decode the nearby macro-user UL signal to predict future scheduling opportunities depending on the link adaptation process and channel dependant scheduling in LTE. There was minor co-operation with the macrocell over the X2 interface to avoid any potential transmission delay especially when there is huge amount of data to be shared with large number of nodes.

For multi-tier heterogeneous networks, where there is a random deployment of different cell sizes, challenges appear when the mobile device has to perform handover and cell selection from overlapping network layers with different coverage distributions and cell edge performances. In this regard a mobility enhancement solution for supporting different UEs' mobility levels was proposed. Therefore, in this contribution, the mobility level is classified for signalling and data transmission according to different mobile speeds with accurate estimation and lower complexity. The cell-edge speed-dependant measurement scenarios are considered for simulation where the picocells had been distributed according to the 3GPP defined trajectories for heterogeneous networks. Also in this regard it is worth mentioning that the OPNET software supports full handover model with all the parameters required to set the new configuration in addition to supporting full link adaptation process and object-positioning procedures to estimate mobility. Mobility level is estimated depending on Geo-location techniques other than the current method which relays on the handover count. Different proposed approaches, such as guiding the mobile device through a network list or through a neighbouring-cell list, are simulated in heterogeneous deployment and attention has been focused on the network configuration and self-organised approach to find the best serving cell efficiently with lower power consumption. Also, the effects of long measurement widow on the link adaptation process at different mobility speeds were presented and the results illustrated that this issue could degrade the performance at higher speeds due to reporting delays and aging of the reported values. Therefore, these presented management schemes and self-optimising capabilities in a heterogeneous network are very effective for reducing the amount of complicated work required for system deployment and operational tasks.

6.2 Future work

For the future work in LTE systems, the focus should be on network throughput enhancement and higher data rates for 5G and onwards. Future wireless systems will be required to support and provide technical demands in the areas of higher data rates, a greater number of devices to be served, a more extended battery life, the ability to support fast applications and a reduced response time, all provided at an acceptable cost.

Dynamic spectrum implementation is an important goal to serve a large number of connected subscribers and millions of devices and sensors. In the current LTE standard, channel-dependent scheduling gives flexibility of the bandwidth, however, for future requirements the operating bandwidth may be more than the current one of 20 MHz, although this may require very complicated radio frequency systems with the introduction of the carrier aggregation techniques and MIMO antennas. The spectrum is expected to be more dynamically utilised with multiple radio technology and WiFi offloading.

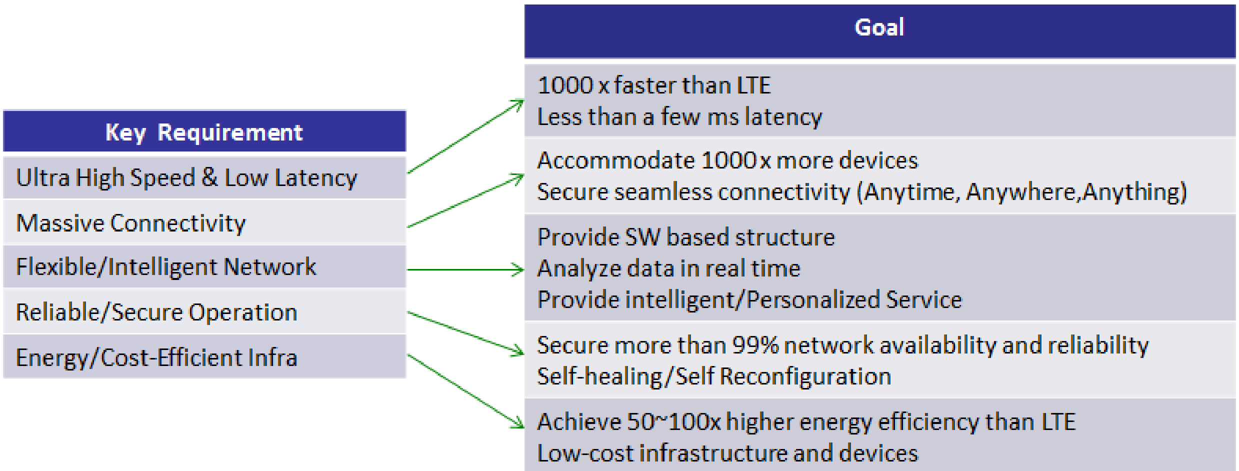


Fig. 6-1 The key requirements for 5G

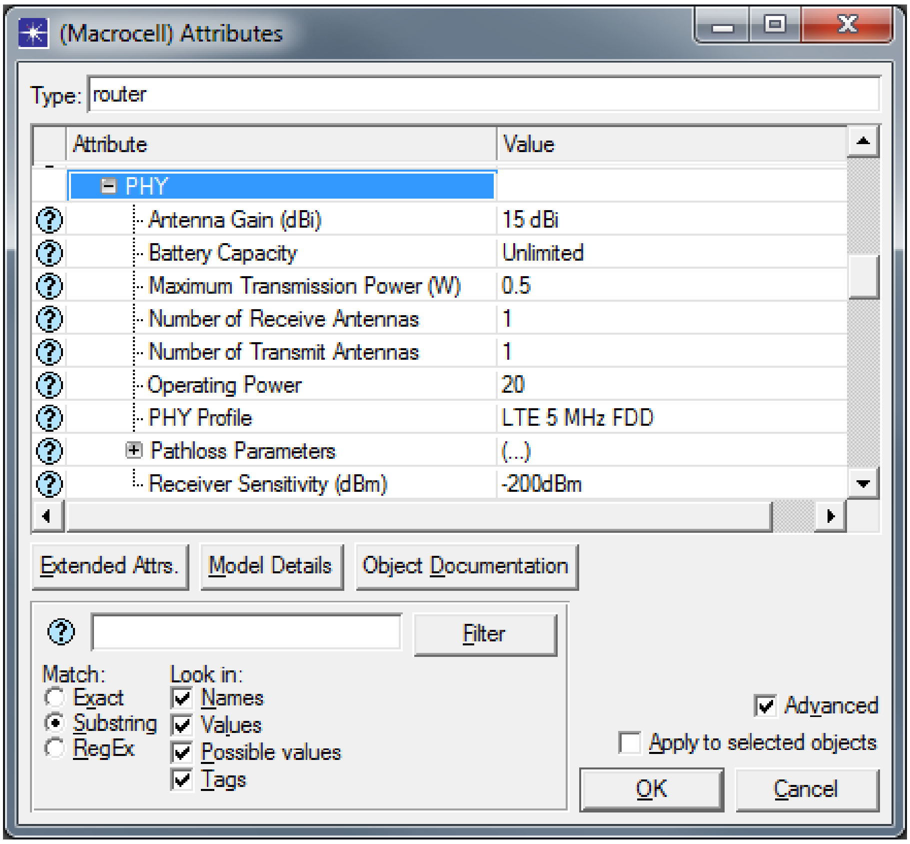
The future of LTE systems is discussed from two parallel approaches; the first one is an internal (soft) approach which considers the current system processes and the amount of generated data and the running applications, while the second one is an external (hard) approach which considers the network management and the interactions between different technologies from different vendors.

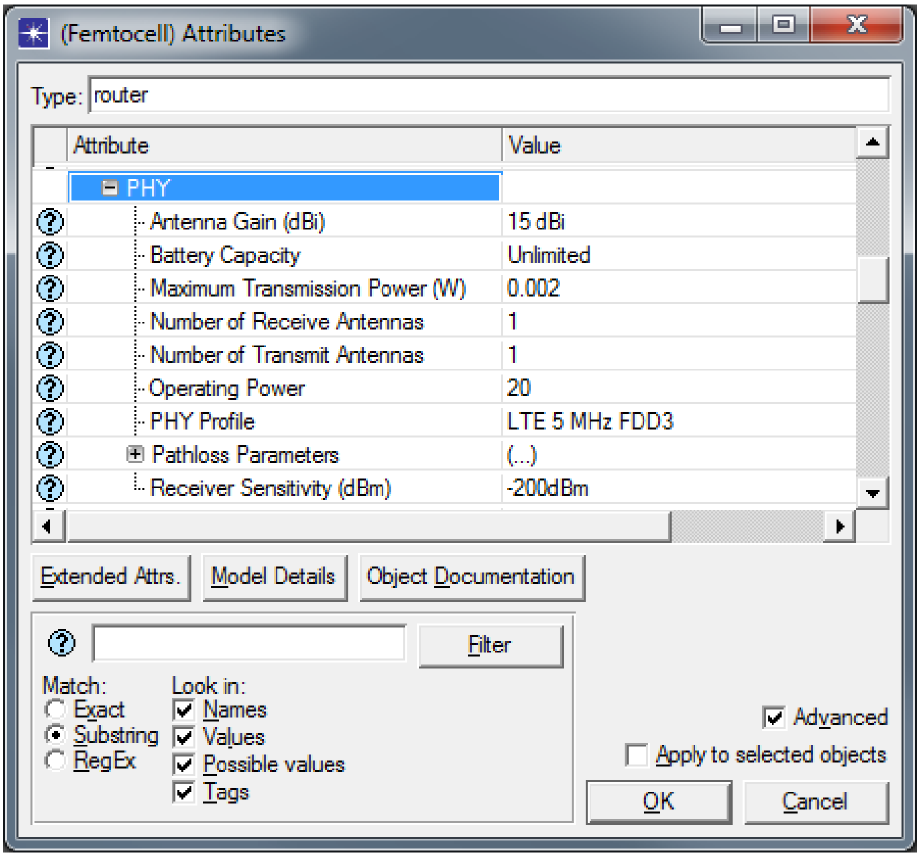
For the network data of 4G and onward, it is more beneficial to find and establish an accurate modelling for the traffic generated in wireless networks in order to optimize the system. Understanding the traffic models and the ability to anticipate the traffic behaviour for different applications has an essential role in building new algorithms for future networks so that the performance is improved and the power consumption can be estimated accurately. The mobile's battery life has to keep pace with evolution in the mobile industry and its technology. The DRX approach for power saving is expected to continue for future releases of LTE systems, with new developments to the current DRX standard. DRX is a flexible mechanism and many factors can be included to control its performance according to the UE's preferences. Regarding the network performance management, the expectation for future networks is that it will be based on adaptive approaches with smart technologies. The challenge is to increase the dynamic functionality of the next generation of wireless networks. One of the most urgent issues in wireless networks for future consideration is improving the accuracy of location services. The indoor/outdoor positioning is an important issue for supporting future technology and is also expected to play an essential role in national services such as disaster tracking in real time manner.

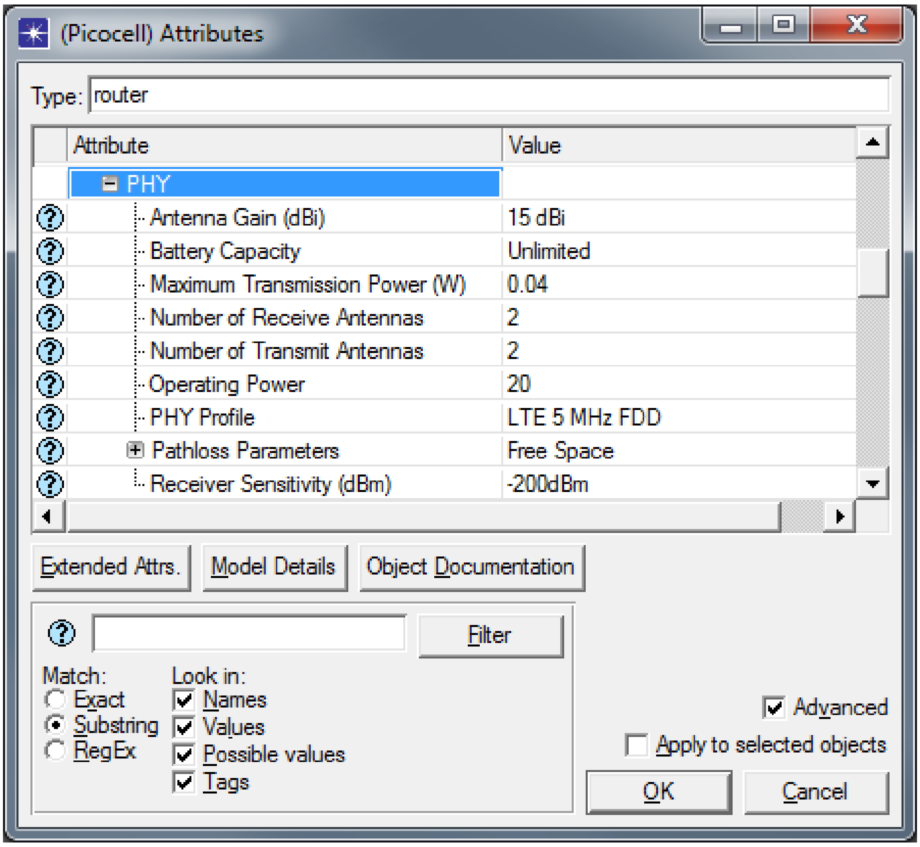
Interference cancellation approaches are expected to be more adaptive so that the system can adapt quickly and dynamically in an efficient manner. In this regards, the recommendations are focused on intelligent and fast-sensing capabilities for the deployed secondary systems, such as Femtocells operating in co-channel deployment or other systems operating in a cognitive approach together with primary systems. The more self-organizing capabilities are available, the better consistency the network can reach in improving the mobility levels in the system. For future heterogeneous networks and according to many published works, there is a need for an effective approach to identify the location of the mobile devices within the network in addition to providing the ability to distinguish between different serving cells from different RATs for fast detection.

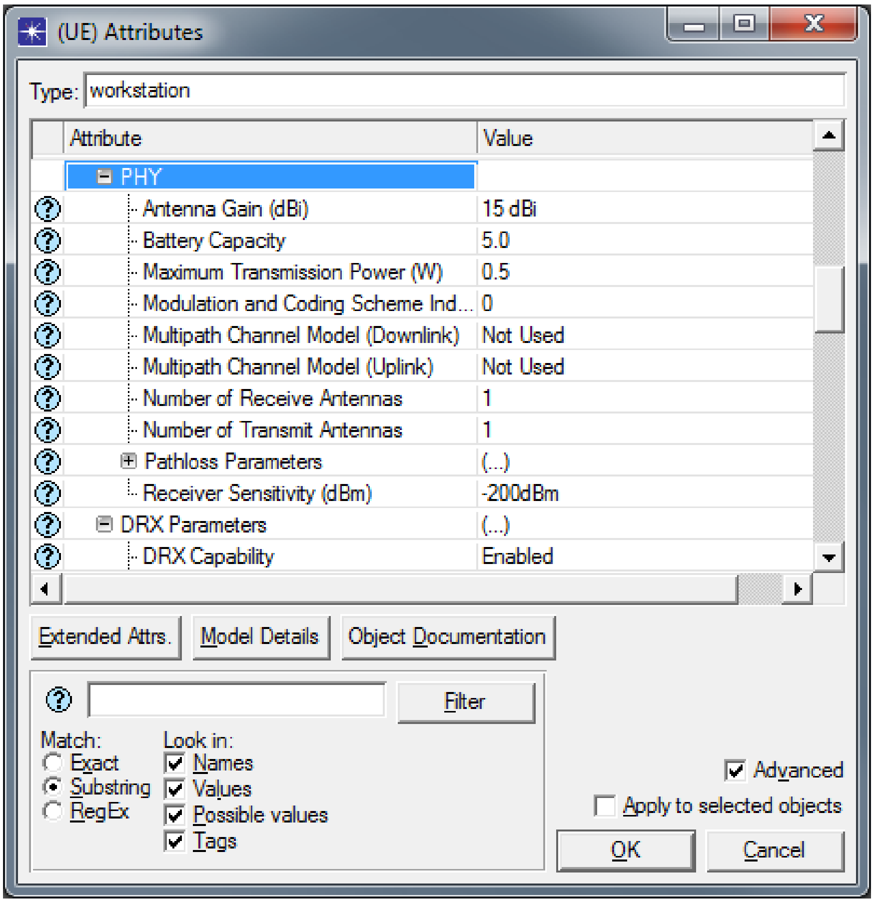
APPENDIX

A. Node's parameters

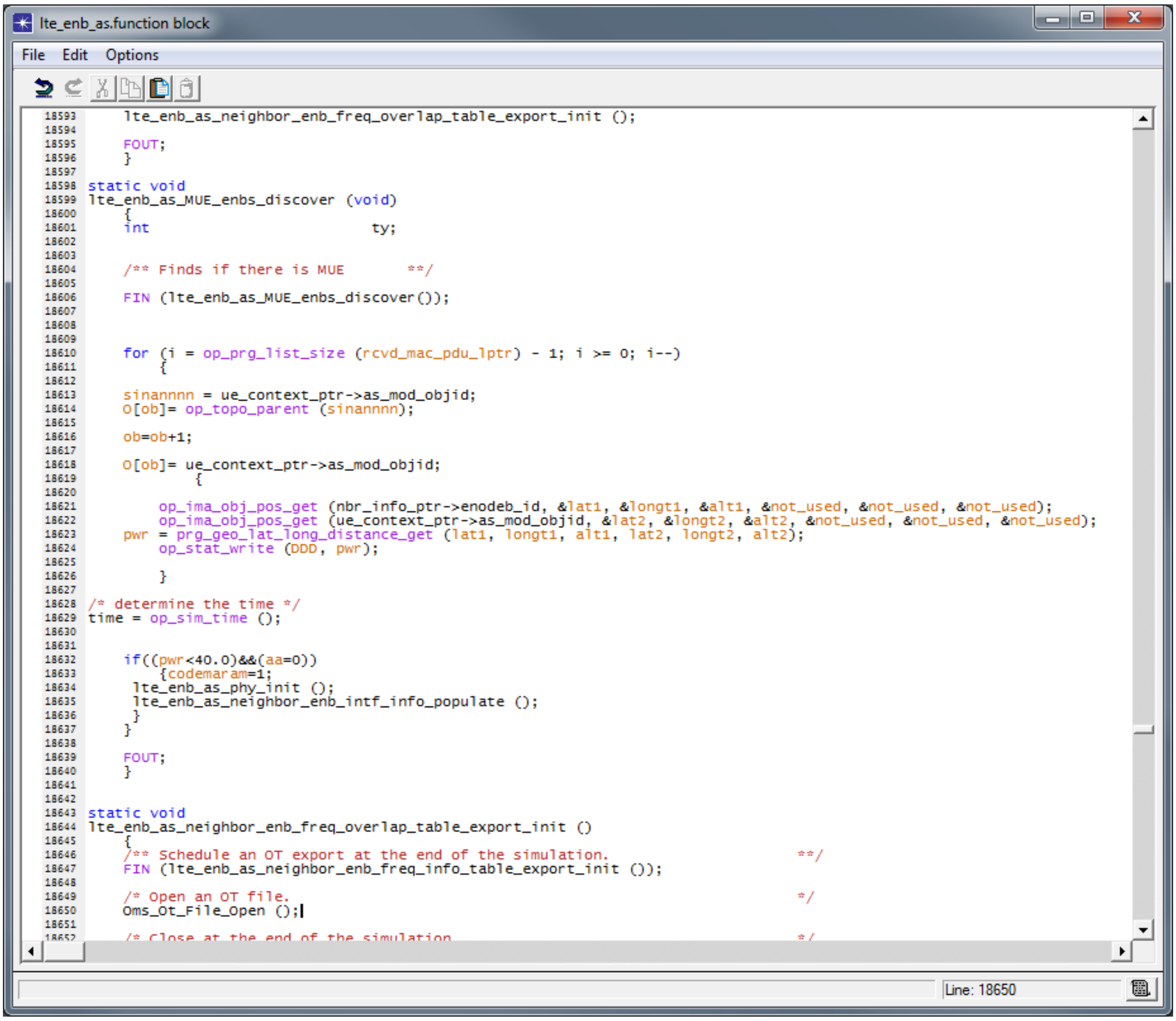





(Picocell) Attributes
Type: router
Attribute
Value
PHY
Antenna Gain (dBi)
15 dBi
Battery Capacity
Unlimited
Maximum Transmission Power (W)
0.04
Number of Receive Antennas
2
Number of Transmit Antennas
2
Operating Power
20
PHY Profile
LTE 5 MHz FDD
Pathloss Parameters
Free Space
Receiver Sensitivity (dBm)
-200dBm
Extended Attrs.
Model Details
Object Documentation
Filter
Match:
Exact
Substring
RegEx
Look in:
Names
Values
Possible values
Tags
Advanced
Apply to selected objects
OK
Cancel


(UE) Attributes
Type: workstation
Attribute
Value
PHY
Antenna Gain (dBi)
15 dBi
Battery Capacity
5.0
Maximum Transmission Power (W)
0.5
Modulation and Coding Scheme Ind...
0
Multipath Channel Model (Downlink)
Not Used
Multipath Channel Model (Uplink)
Not Used
Number of Receive Antennas
1
Number of Transmit Antennas
1
Pathloss Parameters
(...)
Receiver Sensitivity (dBm)
-200dBm
DRX Parameters
(...)
DRX Capability
Enabled
Extended Attrs.
Model Details
Object Documentation
Filter
Match:
Exact
Substring
RegEx
Look in:
Names
Values
Possible values
Tags
Advanced
Apply to selected objects
OK
Cancel

B. Distance & Time function




```
    lte_enb_as_neighbor_enb_freq_overlap_table_export_init ();

    FOUT;
    }

static void
lte_enb_as_MUE_enbs_discover (void)
    {
    int                             ty;


    /** Finds if there is MUE       **/

    FIN (lte_enb_as_MUE_enbs_discover());



    for (i = op_prg_list_size (rcvd_mac_pdu_lptr) - 1; i >= 0; i--)
        {

    sinannnn = ue_context_ptr->as_mod_objid;
    O[ob]= op_topo_parent (sinannnn);

    ob=ob+1;

    O[ob]= ue_context_ptr->as_mod_objid;
            {

        op_ima_obj_pos_get (nbr_info_ptr->enodeb_id, &lat1, &longt1, &alt1, &not_used, &not_used, &not_used);
        op_ima_obj_pos_get (ue_context_ptr->as_mod_objid, &lat2, &longt2, &alt2, &not_used, &not_used, &not_used);
    pwr = prg_geo_lat_long_distance_get (lat1, longt1, alt1, lat2, longt2, alt2);
        op_stat_write (DDD, pwr);

        }

/* determine the time */
time = op_sim_time ();


    if((pwr<40.0)&&(aa=0))
        {codemaram=1;
     lte_enb_as_phy_init ();
     lte_enb_as_neighbor_enb_intf_info_populate ();
     }
    }

    FOUT;
    }


static void
lte_enb_as_neighbor_enb_freq_overlap_table_export_init ()
    {
    /** Schedule an OT export at the end of the simulation.                 **/
    FIN (lte_enb_as_neighbor_enb_freq_info_table_export_init ());

    /* Open an OT file.                                                    */
    Oms_Ot_File_Open ();

    /* Close at the end of the simulation                                  */
```