

**Energy-Efficient Cooperative Resource  
Allocation for OFDMA**

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PhD

**2017**

# **Energy-Efficient Cooperative Resource Allocation for OFDMA**

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A Thesis submitted in partial fulfillment of the requirements of

Kingston University for the award of

Doctor of Philosophy (PhD)

**2017**

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## **Abstract**

Energy is increasingly becoming an exclusive commodity in next generation wireless communications systems, where even in legacy systems, the mobile operators' operational expenditure is largely attributed to the energy bill. However, as the amount of mobile traffic is expected to double over the next decade as we enter the Next Generation communications era, the need to address energy efficient protocols will be a priority. Therefore, we will need to revisit the design of the mobile network in order to adopt a proactive stance towards reducing the energy consumption of the network.

Future emerging communication paradigms will evolve towards Next Generation mobile networks, that will not only consider a new air interface for high broadband connectivity, but will also integrate legacy communications (LTE/LTE-A, IEEE 802.11x, among others) networks to provide a ubiquitous communication platform, and one that can host a multitude of rich services and applications. In this context, one can say that the radio access network will predominantly be OFDMA based, providing the impetus for further research studies on how this technology can be further optimized towards energy efficiency. In fact, advanced approaches towards both energy and spectral efficient design will still dominate the research agenda. Taking a step towards this direction, LTE/LTE-A (Long Term Evolution-Advanced) have already investigated cooperative paradigms such as SON (self-Organizing Networks), Network Sharing, and CoMP (Coordinated Multipoint) transmission. Although these technologies have provided promising results, some are still in their infancy and lack an interdisciplinary design approach limiting their potential gain.

In this thesis, we aim to advance these future emerging paradigms from a resource allocation perspective on two accounts. In the first scenario, we address the challenge of load balancing (LB) in OFDMA networks, that is employed to redistribute the traffic load in the network to effectively use spectral resources throughout the day. We aim to reengineer the load-balancing (LB) approach through interdisciplinary design to develop an integrated energy efficient solution based on SON and network sharing, what we refer to as SO-LB (Self-Organizing Load balancing). Obtained simulation results show that by employing SO-LB algorithm in a shared network, it is possible to achieve up to 15–20% savings in energy consumption when compared to LTE-A non-shared networks. The second approach considers CoMP transmission, that is currently used to enhance cell coverage and capacity at the cell edge. Legacy approaches mainly consider fundamental scheduling policies towards assigning users for CoMP transmission. We build on these scheduling approaches towards a cross-layer design that provide enhanced resource utilization, fairness, and energy saving whilst maintaining low complexity, in particular for broadband applications.

## **Acknowledgement**

First and foremost, I would like to thank my supervisors, Dr. Christos Politis and Dr. Jonathan Rodriguez Gonzalez, without whom this work would not be possible.

I would also like to thank not only the supervisors that have contributed towards this thesis with their vast insights and countless supervision, but also the Instituto de Telecomunicações (IT)–Aveiro, Portugal that co-hosted my research. Moreover, I would like to thank my colleagues at the 4TELL research group at IT that have provided their valuable know-how. In particular, I would like to thank Shahid Mumtaz and Kazi Huq for their assistance towards the system level simulation methodologies, and their V2V communications expertise. I would also like to acknowledge the ITEA 2 SITAC project with grant reference number 11020, that also supported by research and University of Kingston which granted me with an accelerator bursary.

Finally, I would like to dedicate this thesis to my family members and friends, both present and absent due to the course of life, for all the patience, encouragement and support throughout this journey and life.

*In the memory of my father, Armino da Luz Monteiro, a reference  
telecommunications technician and manager, from his country, in his era*

# Table of Content

<b>Abstract</b> .....	<b>iv</b>
<b>Acknowledgement</b> .....	<b>vi</b>
<b>Table of Content</b> .....	<b>viii</b>
<b>List of Figures</b> .....	<b>xi</b>
<b>List of Abbreviations</b> .....	<b>xiii</b>
<b>1. Introduction</b> .....	<b>1</b>
1.1. <i>Scope</i> .....	1
1.2. <i>Motivation</i> .....	2
1.3. <i>Thesis Organization</i> .....	6
1.4. <i>Research Contributions</i> .....	7
<b>2. Survey on Resource Allocation for Cooperative OFDMA based Systems</b> .....	<b>12</b>
2.1. <i>Introduction</i> .....	13
2.2. <i>Cooperative Strategies for Energy Saving</i> .....	14
2.2.1.1 SON .....	15
2.2.1.2 CoMP.....	17
2.2.1.3 Network Sharing .....	18
Architecture Levels of Network Sharing.....	19
3GPP Network Sharing Proposed Functionality Overview-Use Cases.....	21
2.2.1.4 Relay Aided Networks.....	25
2.3. <i>Scenario Definition for OFDMA</i> .....	26
2.3.1.1 OFDM Fundamentals .....	26
2.3.1.2 OFDMA LTE Frame Structure .....	28
2.3.1.3 LTE Resource Block and Theoretical Throughput Computation .....	29
2.4. <i>Resource Allocation in OFDMA Systems</i> .....	31
2.4.1.1 Resource Allocation .....	31
2.4.1.2 Load Balancing .....	33
2.4.1.3 Scheduling Polices.....	33
Round Robin .....	34
Maximum C/I.....	35
Proportional Fair .....	35
Exponential (EXP) .....	36
Delay Bound QoS Based Schedulers.....	37
QoS based Schedulers .....	38
Energy-Efficient Management Schedulers .....	39
2.5. <i>Energy Efficiency for OFDMA Systems</i> .....	39



2.6.	<i>Summary</i> .....	41
<b>3.</b>	<b>Dynamic Resource Allocation for OFDMA</b> .....	<b>42</b>
3.1.	<i>Introduction</i> .....	43
3.2.	<i>System model</i> .....	44
3.2.1.1	Link Adaptation .....	45
3.2.1.2	Scheduler .....	46
3.2.1.3	Hybrid Automated Repeat Request H-ARQ .....	47
3.3.	<i>System simulation and simulator features</i> .....	48
3.3.1.1	Simulator features .....	49
3.3.1.2	Blocks developed for the purpose of this thesis .....	50
3.4.	<i>Simulator Description</i> .....	53
3.4.1.1	General view of System Level Simulation Model.....	53
3.4.1.2	Requirements for System Level Simulation Modeling.....	54
3.4.1.3	Link Layer Modelling .....	58
3.4.1.4	Evaluation and Metrics .....	64
3.5.	<i>Validation Results</i> .....	69
3.5.1.1	Reference Simulation Scenario .....	69
3.5.1.2	Results.....	72
3.6.	<i>Summary</i> .....	76
<b>4.</b>	<b>Energy-Efficient Load balanced Self-Organizing Network sharing</b> .....	<b>77</b>
4.1.	<i>Chapter Organization</i> .....	78
4.2.	<i>Self-Organized Load Balancing</i> .....	78
4.2.1.1	Scenario Definition .....	78
4.2.1.2	Beyond the State-of-the-Art .....	80
4.2.1.3	Load Balancing Algorithm .....	81
4.2.1.4	Self-Organizing Algorithm .....	83
4.3.	<i>Simulation Model and Results</i> .....	86
4.3.1.1	Relays' Optimal Position .....	88
4.3.1.2	Network Sharing .....	89
4.3.1.3	Self-Organized LB.....	90
4.3.1.4	Energy Efficiency .....	92
4.4.	<i>Summary</i> .....	94
<b>5.</b>	<b>Energy Efficient Cooperative Scheduling for Coordinated-Multipoint in OFDMA</b> .....	<b>95</b>
5.1.	<i>Introduction</i> .....	96
5.2.	<i>System Modelling</i> .....	97
5.2.1.1	Coordinated Multi-Point .....	97
5.2.1.2	Manhattan Scenario .....	98
5.3.	<i>3D Video Transmission and User Resource Allocation Algorithm</i> .....	99
5.3.1.1	3D Video Transmission .....	100
5.3.1.2	Cross-layer control signals for Video Transmission .....	102

5.3.1.3	Problem Formulation .....	103
5.3.1.4	Proposed Scheme .....	104
5.3.1.5	Complexity Analysis and Reduced-Complexity Algorithm .....	107
5.4.	<i>Simulation Results</i> .....	107
5.5.	<i>Summary</i> .....	112
<b>6.</b>	<b>Conclusions and future Work</b> .....	<b>113</b>
6.1.	<i>Main Conclusions</i> .....	113
6.2.	<i>Future Work</i> .....	115
<b>Annex 1 -</b>	<b>System simulation description</b> .....	<b>117</b>
	<i>Requirements for System Level Simulation Modeling</i> .....	117
	<i>Simulation Execution Flow and Methodology for Evaluating Scheduling</i> .....	118
	<i>Packet/Data Decoding Process</i> .....	122
	<i>Complexity and Time Resolution</i> .....	124
	<i>Network Scenario and Layout</i> .....	124
	<i>Propagation Channels Models</i> .....	126
	Path-Loss Model .....	127
	Shadowing (Slow Fading) Model.....	128
	Fast Fading Model.....	129
	<i>Signal to Interference plus Noise Ratio (SINR) Modelling</i> .....	131
	<i>Traffic Models</i> .....	136
	<i>Simulation flow</i> .....	137
<b>Annex 2 –</b>	<b>Network sharing methodologies</b> .....	<b>139</b>
<b>7.</b>	<b>References</b> .....	<b>142</b>

## List of Figures

Figure 2.1: General illustration of wireless network architecture and different degrees of network sharing [30].....	20
Figure 2.2: Full-sharing/roaming based Network sharing.....	21
Figure 2.3: Data Symbol Structure and creation of cyclic prefix.....	27
Figure 2.4: LTE Specification (FDD Frame structure).....	28
Figure 2.5: LTE Specification (TDD Frame structure).....	29
Figure 2.6: Resource block in the LTE frame structure.....	30
Figure 3.1: MAC layer architecture of the LTE system.....	45
Figure 3.2: Conventional Wireless Cellular System with multiple cells, with independent resource management.....	51
Figure 3.3: SON based resource management Cellular System.....	52
Figure 3.4: Hexagonal distributed deployment vs Manhattan network deployment with joint processing areas.....	53
Figure 3.5: Wireless Cellular System with multiple cells.....	54
Figure 3.6: Modeling of Wireless communication System.....	55
Figure 3.7: Modeling of Wireless communication System.....	56
Figure 3.8: Wireless system level simulation.....	59
Figure 3.9: Interface between system level and Link level.....	60
Figure 3.10: Overview of Link to System Level Interface.....	63
Figure 3.11: Traffic metrics interdependence.....	68
Figure 3.12: Simulation scenario with cells deployment.....	71
Figure 3.13: Spectral Efficiency vs Number of users per cell.....	73
Figure 3.14: System Throughput vs distance to cell site.....	74
Figure 3.15: Average SINR vs cell radius.....	75
Figure 3.16: CDF of Effective SINR.....	75
Figure 4.1: Self-organizing load balancing scenario.....	79
Figure 4.2: Flow chart illustration of the iterative optimization processing of SON module.....	87
Figure 4.3: Optimal fixed relay position.....	89
Figure 4.4: Total cell load versus average throughput of op-1 cell-edge users.....	90
Figure 4.5: CDF of cell load.....	92
Figure 4.6: Energy efficiency versus cell radius.....	93
Figure 4.7: Tx power versus cell throughput.....	94
Figure 5.1: Coordinated Multi-Point (CoMP).....	97
Figure 5.2: Cross-Layer Block Diagram [97].....	99
Figure 5.3: Frame of CoMP with user allocation with resources (right).....	104
Figure 5.4: Flow chart illustration of the proposed CoMP algorithm, both parameters setting, and resource allocation process.....	107
Figure 5.5: Comparison of Frame Error Rate.....	109
Figure 5.6: Throughput fairness of different scheduling algorithm.....	110
Figure 5.7: Energy Efficiency results.....	112
Figure A.1: Modeling of Wireless communication System.....	118
Figure A.2: BLER vs. SNR plot for different modulation and coding profile on Veh A.....	123
Figure A.3: Modeling of Wireless communication System.....	124
Figure A.4: Network layout deployment.....	125
Figure A.5: Antenna pattern for 3 sectors.....	125
Figure A.6: Simulation Flowchart.....	138



## List of Abbreviations

3GPP	Third Generation Partnership Project
4G	Fourth Generation of Mobile Communications Networks
5G	Fifth Generation of Mobile Communications Networks
AMC	Adaptive Modulation and Coding
BER	Bit Error Rate
BLER	Block Error Rate
BS	Based Station
C/I	Carrier- to- Interference
CAPEX	Capital Expenditure
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CO <sub>2</sub>	Carbon dioxide
CQI	Channel Quality Indicator
CN	Core Network
CR	Cognitive Radio
CU	Cognitive User
DF	Decode-and-Forward
EE	Energy Efficient
eNodeB	E-UTRAN Node B

EPC	Evolved Packet Core
ETSI	European Telecommunication Standard Institute
EU	Europe Union
e-UTRAN	Enhanced UTRAN
FDD	Frequency Division Duplex
FEC	Forward Error Correction
FER	Frame Error Rate
FRS	Fixed Relay Station
GSM	Global System for Mobile Communication
H-ARQ	Hybrid Automated Repeat Request
HSPA	High Speed Packet Access
ICT	Information and Communication Technology
ITU	International Telecommunication Union
LB	Load Balancing
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
M-LWDF	Modified Largest Weighted Delay First
MAC	Medium Access Control
Max C/I	Maximum Signal to Noise Plus Interference
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output

NGNM	Next Generation Mobile Networks
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
PHY	Physical Layer
PRB	Physical Resource Block
PU	Primary User
QAM	Quaternary Amplitude Modulation
QoS	Quality of Service
RA	Rate Adaptation
RAN	Radio Access Network
RB	Resource Block
RNC	Radio Network Controller
RR	Round Robin
RRM	Radio Resource Management
SE	Spectrum Efficiency
SINR	Signal to Interference Plus Noise Ratio
SISO	Single Input Single Output
SM	Spatial Multiplexing
SO-LB	Self-Organized Load Balancing
SON	Self-Organized Network

TDD	Time Division Duplex
TTI	Transmission Time Interval
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UTRAN	Universal Terrestrial Radio Access Network
WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Networks



# 1. Introduction

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This introductory chapter presents the scope and direction of the work, the motivations for the research work done, research contributions and the structure of the presented thesis.

## *1.1. Scope*

The evolution towards Next Generation is considered to be the convergence of internet services with existing mobile networking standards leading to the commonly used term “mobile internet” over heterogeneous networks, with very high connectivity speeds. In addition, green communications seem to play a pivotal role in this evolutionary path with key mobile stakeholders driving momentum towards a greener society through cost-effective design approaches. In fact it is becoming increasingly clear from new emerging services and technological trends that **energy and cost per bit reduction, service ubiquity, and high speed connectivity are becoming desirable traits for next generation networks.**

Providing a step towards this vision, cooperative technologies are widely accepted as the vehicle for ubiquitous Next Generation services providing cost-effective high speed communications. In this context, technologies such as network sharing, SON, and CoMP are promising approaches that have been implemented in legacy and future emerging technologies such as LTE/LTE-A.

In the network sharing paradigm, effective management of the resulting network becomes a crucial factor for the business success, and it is much more complex since it includes joint planning of the coverage front print, configuration of the network parameters, among other factors. For these complex shared networks certain techniques, such as Self-Organized Network (SON), are capable of providing cost-effective network management. CoMP is another example of cooperation where base stations pertaining to a collaborative cluster coordinate in order to maximise the coverage/capacity at the cell edge. CoMP has been introduced as a key feature in LTE-A, and also referred to as joint transmission, and exploits the inherent channel diversity in order to maximise the channel transmission quality. However, both these schemes still offer significant research challenges in terms of energy efficient design.

This research thesis, entitled “Energy-Efficient Cooperative Resource Allocation for OFDMA” tackles the dynamic management of radio resources for OFDMA based systems, that is the prominent radio access technologies for the next generation mobile networks, with focus on the energy saving aspect. In particular, the scope of this thesis will target how to extend resource allocation for SO (Self-Organized)-shared networks and CoMP transmission approaches, towards more energy efficient approaches, that can have viable applications in Next Generation networks.

## ***1.2. Motivation***

The increasing demand in data and voice services alone is not the only cause for concern: energy management and conservation is now at the forefront of the

European political agenda. The vision of Europe 2020 is to become a smart, sustainable and inclusive economy, and as part of these priorities the EU has set forth the 20:20:20 targets where greenhouse gas emissions and overall energy consumption should be reduced by 20%, whilst energy generation from renewable resources should be increased by that same amount [1].

In fact, Information and Communication Technology (ICT) accounts for 2% of the global CO<sub>2</sub> emissions in today's energy conscious society [2], [3]. A medium sized cellular network uses as much energy as 170,000 homes, and generally the cost of powering the existing BSs accounts for an overwhelming 50% of a service provider's overall expenses [4]. Therefore it is clear that new solutions are required whereby operators can accommodate this additional traffic volume whilst reducing their investment in new infrastructures, and besides that significantly reduce their energy bill. Moreover, the EU political agenda in unison with the expected growth in mobile data has identified reduction of the cost (i.e., energy) per bit as a stringent design requirement for mobile networks of the future. Network sharing is one of the most attractive solutions for cost reduction, in which operators cooperate with each other by sharing infrastructure, operational functions and even risk in a bid to reduce the capital and operational expenditure of the network. Network sharing claims to achieve up to 65% saving in both roll-out capital expenditure (CAPEX) and network operations-plus-maintenance expenditure (OPEX) [5]. As a result, regulators all over the world are now encouraging this approach, although some restrictions are kept in place in order to avoid monopolies.

Network sharing has already been implemented in various countries, such as India, UK and USA [6]. However, and despite the recent efforts, the current state-of-the-art on network sharing is still in its infancy. In practice, the widely implemented network sharing is currently deployed in a very simple form of so-called passive sharing (e.g., sharing the towers). The other kind of sharing is called active and/or roaming-based sharing. The latter type of sharing can provide more significant energy and cost saving that needs to be further investigated to support seamless and dynamic sharing. A precise definition and further discussion on the different kinds of sharing will be provided in section 2. In addition, the lack of clear cooperation strategies can hinder even passive network sharing among competing operators. Therefore, demonstration of proper network sharing business models which can provide incentives to the stakeholders is needed.

Once a sharing agreement is made among network operators, effective management of the resulting network becomes a crucial factor to secure the business success, and this can be challenging since it includes joint planning of the coverage front print, configuration of the network parameters, among other parameters. For complex shared networks, promising techniques - such as SON - are capable of providing cost-effective network management.

Self-organized Networks (SON) represent a continuation of the natural evolution of wireless networks, where automated processes are extending their scope from just frequency planning to overall network resource management. The automated process of self-healing and self-optimizing of the shared network is crucial for success of the cooperation process.

In this future emerging communication arena, one can say that the radio access network will continue to include strong component OFDMA based, providing the impetus for further research studies on how this technology can be further optimized towards energy efficiency. Taking a step towards this direction, LTE/LTE-A (Long Term Evolution-Advanced) have already investigated cooperative paradigms such as SON (self-Organizing Networks), Network Sharing, and CoMP (Coordinated Multipoint) transmission. Although these technologies have provided promising results, some are still in their infancy and lack an interdisciplinary design approach limiting their potential gain.

In this thesis, we aim to advance these future emerging paradigms from a resource allocation perspective on two accounts. In the first scenario, we address the challenge of load balancing (LB) in OFDMA networks, that is employed to redistribute the traffic load in the network to effectively use spectral resources throughout the day. We aim to reengineer the load-balancing (LB) approach through interdisciplinary design to develop an integrated energy efficient solution based on SON and network sharing, what we refer to as SO-LB (Self-Organizing Load balancing). The second approach considers CoMP transmission, that is currently used to enhance cell coverage and capacity at the cell edge. Legacy approaches mainly consider fundamental scheduling policies towards assigning users for CoMP transmission. We build on these scheduling approaches towards a cross-layer design that provide enhanced resource utilization and fairness, whilst maintaining low complexity, in particular for broadband applications.

### ***1.3. Thesis Organization***

The work presented in this thesis is organized as follows. In chapter 2, an overview background of the technologies covered by this work is presented, in particular addressing the intersection between energy saving strategies and next generation smart cooperative networks; we further include in the analysis smart self-organized networks that is an example of cooperation between network service providers to reduce operation and capital expenditure, namely promote spectral efficiency of scarce spectral resources whilst reducing the energy bill. In chapter 3. we detail the principles of Radio Resource Management (RRM) for OFDM based systems, in the backdrop of the anticipated scenarios and OFDM transmission architecture. A reference system model is also given that we use to attain baseline results for our dynamic resource allocation schemes in LTE-A, using an in-house system level simulator. This will be used as point of reference to compare results for the subsequent innovative algorithms developed hereafter. In chapter 4. we highlight the first main research contribution pertaining to energy efficient load balancing for self-organized shared networks - a novel framework for minimizing energy cost per bit-based in OFDMA systems. In chapter 5, a second research contribution is proposed that explores coordinated multipoint antenna techniques as a starting point, and proposes a new radio resource management approach to improve cell coverage and the capacity at the cell edge. Chapter 6. concludes this thesis and gives guidelines for future works.

#### ***1.4. Research Contributions***

This work intends to be a contribution to the framework of energy efficient radio resource management for OFDMA based networks exploiting cooperative technology paradigms; in this context we propose the following contributions:

- **Chapter 3** provides a baseline performance evaluation for radio resource management approaches in OFDMA systems, using LTE (4G) as a specific use-case. In the first instance, we describe the PHY and MAC layer functional architecture, including the OFDMA frame structure based on LTE. Following this, common resource management methods are outlined with typical qualitative performance parameters described. Finally, benchmarks results are collected for typical mobile operating environment using an in-house combined dynamic snapshot system level simulator, which are then used as a basis for comparing subsequent results.
- In **Chapter 4** we propose an energy-efficient load balancing algorithm for self-organized shared LTE-A networks. Energy being perceived as an expensive commodity in legacy and future emerging networks, techniques are required that can take a step towards reducing the energy consumption whilst still promoting spectral efficiency. Taking a step towards this direction, Network Sharing and SON technologies are promising solutions being addressed by the LTE/LTE-A standard. These are a type of cooperative approaches, that allow sub-units to exchange information, or share resources so as to enhance the global system performance; more than what can be achieved in the absence of cooperation. However, we investigate the resource allocation component, and specifically tackle the load balancing challenge. We go beyond legacy approaches, by

investigating a novel framework that is able to provide energy efficient load balancing as part of an integrated solution based on network sharing and SON.

- In **Chapter 5**, the Coordinated Multipoint (CoMP) technique is explored which is an example of a cooperative strategy to enhance coverage and capacity at the cell edge. One of the problem facing mobile communication systems are low service quality at the cell edge, due to the high inter-cell interference which is often present due to the lack of coordination between base stations in the global network. This effect, is even more pronounced, when there is a need to support demanding multimedia based services. Therefore, CoMP is an attractive technique that can alleviate somewhat the interference at the cell edge by using the subset of neighbouring base stations as a means to complement data transmission, rather than acting as a source of interference. However, CoMP relies on a robust scheduling approach that has been given little attention for supporting broadband service and energy saving. To solve these challenge issues, we propose a resource allocation algorithm for distributed broadband wireless OFDMA systems to support 3D video streaming service based on using the CoMP technique. The results show that efficient usage of CoMP adopting an interdisciplinary design approach can provide significant advantages over conventional deployments, with significant capability to support multimedia users at the cell edge.

### ***Publications***

On these topics, this research had led to the following published scientific works and contributions:



**V. Monteiro, S. Mumtaz, J. Rodriguez and C. Politis, Link Layer Modelling for Energy Efficient Performance Evaluation in Wireless Cellular Networks , Chapter in, *Green Communication for 4G Wireless Systems*, Shahid Mumtaz, Jonathan Rodriguez , River Publishers 2013**

Contribution: Presents the system modelling and link layer analysis of a wireless OFDMA communication system, including link adaptation methodologies, H-ARQ schemes and the link level interface model. **This scientific work complements existing approaches with an energy efficiency analysis and modelling approach.**

**V. Monteiro, S. Mumtaz, A. Nascimento, J. Rodriguez and C. Politis, System Level Evaluation Methodology for Energy Saving , Chapter in, *Green Communication for 4G Wireless Systems*, Shahid Mumtaz, Jonathan Rodriguez , River Publishers 2013**

Contribution: System level evaluation approach is presented, taking into account the advantage of multi-user diversity for energy efficient protocol/algorithm enhancement

**V. Monteiro, K. Huq, S. Mumtaz, C. Politis, J. Rodriguez, Energy efficient load balancing for future self-organized shared networks , *Springer Telecommunication Systems*, November , 2014**

Contribution: **SO-LB algorithm for minimizing energy cost per bit for OFDMA based networks.** The energy consumption of the network is analysed in the context of network sharing and SON enabling technology. This represents a key scientific outcome from this thesis, and is presented in chapter 4.

**V. Monteiro, K. Huq, S.M. Mumtaz, H.M. Marques , J. Rodriguez , 3D Video Streaming Transmission over OFDMA-based Systems , *IEEE International Conf. on Image Processing - ICIP*, Paris , France , October 2014**

Contribution: **Energy efficient scheduling for CoMP transmission in LTE, and in particular provides a design blueprint for advanced scheduling using positioning information to support multimedia services respectively.** This work is the second key scientific outcome presented in chapter 5.

In addition, others research works have been published during the research activities of the PhD program presented in this thesis, to complement the main publications listed above. These are the following:

*Publication list as 1<sup>st</sup> author (Conferences)*

V. Monteiro, T. Ramrekha, D. Yang, J. Rodriguez and S. Mumtaz, C. Politis, “**An Energy Efficient Proposal in Shared Relay-Based LTE Network**”, Tenth International Symposium on Wireless Communication Systems 2013, IEEE ISWCS 2013

V. Monteiro, S. Mumtaz, J. Rodriguez, C. Verikoukis, A. Radwan and C. Politis, “**Energy Efficient Relay-aided Shared LTE Network Using CoMP and LB**”, Future Network and Mobile Summit 2013, IEEE FUNEMS 2013

V. Monteiro, S. Mumtaz, and J. Rodriguez, “**Energy Efficient Load Balancing in Self Organized Shared Network**”, International Conference on Telecommunications and Multimedia (TEMU), 2012

V. Monteiro, S. Mumtaz, and J. Rodriguez, **Positioning for performance enhancement in shared LTE and HSPA networks**, International Conference on

Telecommunications and Multimedia (TEMU), 2012

V. Monteiro and J. Rodriguez, **Location-based Vertical Handovers for Heterogeneous Wireless Systems**, IEEE MOBIMEDIA, Lisbon 2010

*Publication as 2<sup>nd</sup> author (Journals)*

Shahid Mumtaz, Du Yang, Valdemar Monteiro, Christos Politis and Jonathan Rodriguez, “**Self organized energy efficient position aided relays in LTEA**”, Elsevier, Journal Physical Communication, 2012

Shahid Mumtaz, Du Yang, Valdemar Monteiro and Jonathan Rodriguez , “**Self-Organization Aided Network Sharing in LTEA**”, GREEN-ICT, *Journal of Green Engineering*, 2(3), pp. 215-232. ISSN (print) 1904-4720

*Publication as 2<sup>nd</sup> author (Conferences)*

Christos Thomos, Tasos Dagiuklas, Ilias Politis, Stavros A. Kotsopoulos, Shahid Mumtaz, Valdemar Monteiro, Jonathan Rodriguez, **Cross-Layer Architecture for 3D Video Streaming**, 2nd ROMEO Workshop, <http://www.ict-romeo.eu/Workshop2.html>;

## **2. Survey on Resource Allocation for Cooperative OFDMA based Systems**

---

In this chapter we provide a survey on resource allocation for OFDMA based systems, with particular emphasis on energy efficient resource allocation methods. In the first section we present the rationale and requirements for energy based resource allocation strategies in future wireless communication systems. In section 2.2. the cooperation is investigated as a promising technology paradigm to provide energy saving in ICT and, particularly, for mobile cellular communication systems. In particular, we focus on SON, CoMP and network sharing as concrete examples of cooperation, and their application towards legacy systems. In section 2.3. we present the fundamentals of the OFDM technique, including the frame structure based on the LTE standard that is used later to define the transport channel size. In section 2.4. the MAC architecture is presented, that provides a logical blueprint for the RRM approach in Long Term Evolution (LTE) systems. Given the RRM layout, the common scheduling used for system throughput optimization and QoS provisioning approaches are discussed. In section 2.5. we discuss the energy saving methods proposed for the LTE-A standard, the cellular system that precedes the future Next Generation mobile wireless communication systems. We finalize this chapter with a summary.

## **2.1. Introduction**

The introduction of new types of mobile devices coupled with the emergence of sophisticated broadband services, has generated an exponential growth in network traffic. New applications and services are requiring higher speeds. The current cellular system is steadily been pushed to the operating limit providing the motivation for optimizing legacy networks, as well as providing the trigger for investigating new air interfaces that have the capability to deliver higher speeds.; indeed the future is heading towards an integrated solution. Mobile standards is migrating further towards Next Generation, which is foreseen as “Mobile Internet” over Heterogeneous Networks, providing the means to provide personalized and high speed connectivity; expanding the availability of a true broadband connection beyond the home and the office space.

Alongside the availability of rich service requirements, Next Generation systems will also need to be energy compliant, both from the end-user and operator perspective. The future will envisage not only mobile users, but billions of connected devices to the internet (Internet of Things) requiring additional headroom in network capacity, and energy efficient operation that legacy wireless networks cannot deliver.

In this context, small cells are becoming a prominent solution for energy efficient and high speed wireless internet connectivity, as part of an integrated solution that includes both macro and small cell tiers. A HetNet (Heterogeneous Network) consist of macrocells as well as low power nodes, such as femtocells, remote radio heads

(RRUs), picocells and relay nodes. The goal of using low power nodes is to enhance coverage and throughput, thus increasing spectral efficiency by the spatial reuse of spectrum.

Cooperation is foreseen to be pivotal technology in Next Generation, as a means of promoting energy saving in handset devices and on the network side. In fact, cooperation allows the network to become both user and network centric where mobile devices also become part of the network resources, to be utilised towards improving the communication experience or effectiveness. The motivation for cooperation is clear, when the sum of the interacting entities provide a clear and concrete gain, in contrast to individual and isolated behaviour. There are many examples of cooperation that have shown promising results in future emerging mobile networks, and in particular we focus on SON, CoMP Network Sharing, and relaying as prime examples that will figure within our research scenarios, and provide a platform for the proposed innovative algorithms/protocols to be addressed. Thereafter, we will discuss resource allocation for OFDMA systems, and in particular analyse load balancing and scheduling policies as part of an integrated dynamic resource allocation architecture. Finally, this chapter discusses the need for energy efficient design with a review on existing approaches.

## ***2.2. Cooperative Strategies for Energy Saving***

Cooperation is perceived as a vehicle for system entities to collaborate, by exchanging information and beyond that sharing resources towards enhancing or optimizing a global cost function. In legacy mobile systems, cooperation is limited

and has shown partial gain. However, with the onset of smart ecosystems, where mobile systems have inherent architectures to support better information exchange and system visibility, the benefits of cooperation are coming to light and is proving to be a viable technology as we enter the Next Generation era.

Cooperation has broad applicability that can be widely be adapted throughout all layers of the network protocol stack, from the physical layer up to the application layer [7].

The most natural and traditional form of cooperative communications is based on the multi-hop packet forwarding, initially applied in wireless ad hoc networks where wireless nodes are involved in the cooperation without having support from any pre-established infrastructure.

Spatial diversity has also been exploited to improve spectral efficiency of the wireless channel through distributed space-time multiplexing techniques [8] and coordinated multipoint [9], [10]. However, in this section we focus on cooperative techniques for physical and network layers, suitable for improving the energy efficiency of multi-mode mobile terminals.

### ***2.2.1.1 SON***

The appearance of SON [11] algorithms represents a continuation of the natural evolution of wireless networks, where automated processes are extending their scope from just frequency planning to overall network resource management. The rationale for SON automation can be grouped into two broad categories:

1. Usual manual processes that are automated primarily in order to limit the manual intervention in some network operations with the objective of operational and/or deployment savings. Automating repetitive processes clearly saves time and reduces effort. Auto-configuration and self-configuration fall into this category.
2. Processes that are too complex for manual intervention, because they require automation or because they are too fast, too granular (per-user, per application, per-flow, as a function of time or loading), and/or too complex for manual intervention. Measurements collected automatically from multiple sources (e.g., from individual network elements, user devices, and on an end-to-end basis from advanced monitoring tools) will provide accurate near to real-time and real-time data up on which these algorithms can operate thus providing performance, quality, and/or operational benefits.

There is currently a SON group for LTE/LTE-A networks setup by 3GPP [12]. Many other organizations or projects such as Next Generation Mobile Networks (NGMN) [13], European Commission FP7 (Seventh Framework Program) E3 and FP7 SOCRATES projects [14] [15] have worked on key technologies of SON. A work in the scope of FP7 FLAVIA considering network virtualization was published in [16]. This work also includes an overview of 3GPP on the business models. At the same time that SON seems to gain importance in the network automation process, other technologies are appearing and their practical implementation can only be possible through these automation aspects. These are the case of opportunistic radio [17] and the device-to-device communication [18] proposed in the LTE 3GPP. The current



SON research work, however, had been focused on non-shared cellular networks. In this work we consider SON in shared cellular system.

### ***2.2.1.2 CoMP***

For improving capacity, especially for cell edge multimedia users, in the framework of 3GPP, many solutions are proposed for LTE to cope with Inter-cell Interference (ICI) and achieve overall increased cell edge throughput. Relay and Coordinated multipoint (CoMP) are examples of solutions proposed by 3GPP for the LTE-Advanced standard. Although CoMP has added advantages over Relay technologies, as CoMP uses coordination in transmission and reception of signals among different base stations, which helps to further reduce ICI [19]. CoMP transmission and reception techniques utilize multiple transmit and receive antennas from multiple antenna site locations, which may or may not belong to the same physical cell, to enhance the received signal quality as well as decrease the received spatial interference [9]. Using CoMP the cell average and cell edge throughput are boosted, unlike with Relay, which only increases the cell edge throughput. CoMP has already been adopted and standardized by 3GPP in release-11 [10]. In a conventional cellular architecture, a unique base station (BS) is located in the center of a cell to attend to all user requests. Therefore, cell coverage needs to be kept small so that users near the edge of cell can experience high-data rates. This leads to an increased number of BSs and thus higher system costs. Coordinated Multi-Point (CoMP) has been proposed as a promising solution to this problem [20]. In CoMP, multiple antennas distributed over a large area are connected to a central unit (CU) via fiber, coax cable or microwave link. This architecture allows reduction of the access distance to the user, thereby improving capacity, coverage, and power consumption [21], [22].

### ***2.2.1.3 Network Sharing***

Network sharing has already been implemented in various countries, such as India, UK and USA [6]. However, and despite the recent efforts, the current state-of-the-art on network sharing is still in its infancy [23]. In practice, the widely implemented network sharing is currently deployed in a very simple form of so-called passive sharing (e.g., sharing the towers). The other kind of sharing is called active and/or roaming-based sharing. The latter type of sharing can provide more significant energy and cost saving that needs to be further investigated to support seamless and dynamic sharing. A precise definition and further discussion on the different kinds of sharing will be provided in further in this section. In addition, and from a business point of view, the lack of clear cooperation strategies can hinder even passive network sharing among competing operators. Therefore, demonstration of proper network sharing business models is needed which can provide incentives to the stakeholders. Hence, there is a need for further research to address all aspects of network sharing to achieve its full potential in energy per bit reduction.

Once a sharing agreement is made among network operators, effective management of the resulting network becomes a crucial factor for the business success, and it is much more complex since it includes joint planning of the front print, configuration of the network parameters, etc. For the complex shared networks certain techniques - such as SON - are capable of providing cost-effective network management. This section provides a highlight of aspects that should be addressed in order to build and incentivize the appearance of business models, which can be drawn to fit the network sharing approaches proposed within the scope of this thesis.

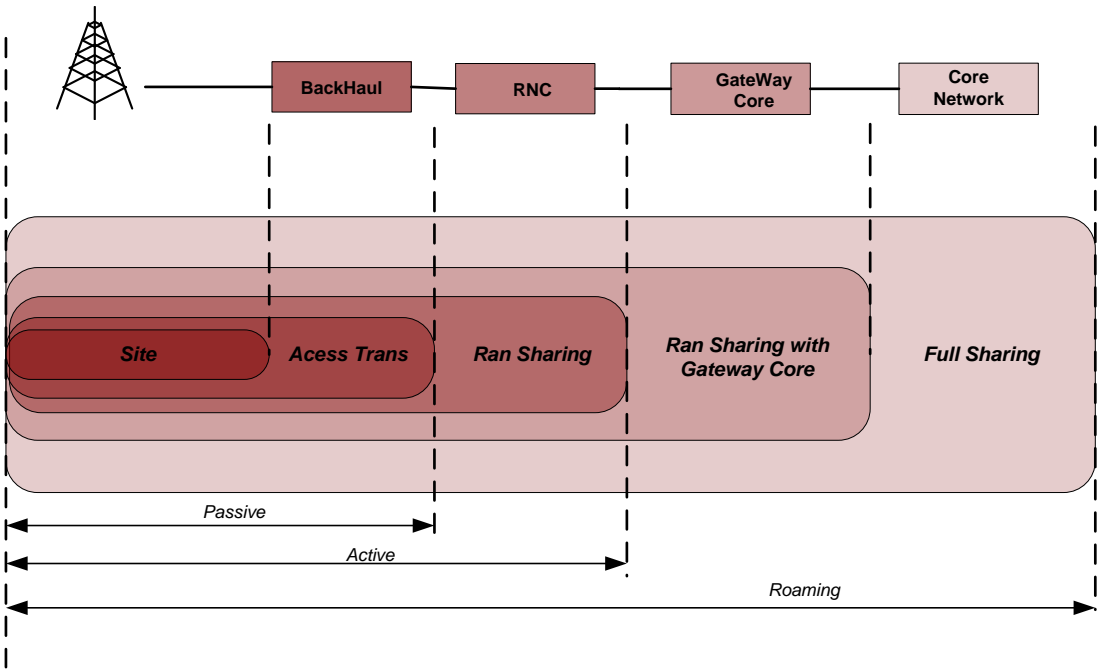
### *Architecture Levels of Network Sharing*

From the technical perspective, several architecture-level approaches have been proposed by vendors such as Ericsson [24] and Nokia [25]), as well as the EU competition Directorate [26]. Although the proposed approaches from different organizations are not identical, they can be generally categorized into three clusters:

- Passive network sharing—occurs when operators share network assets that are not considered to be an “active” part of providing services, such as the cell sites and civil engineering elements (towers, shelters, air conditioning and cooling systems, AC and DC power supply, diesel generators).
- Active network sharing—where operators share BS elements like the radio frequency (RF) chains, antennas or even radio network controllers (RNC).
- Roaming-based network sharing—where one operator relies on another operator’s coverage on a permanent basis, meaning, while the service is maintained by one operator in a certain area, the RAN coverage in it is provided by another operator.

Figure 2.1 illustrates a general architecture of a wireless system and different network sharing approaches. In general, the more network assets and operational functions are shared, the more cost savings are obtained, accompanied by the loss of control of the entire network [27]. For example, in a full sharing case (active and/or roaming-based), operator A relies on operator B’s network assets and operation functions to provide service to customers in operator B’s coverage area. This example is depicted in the Figure 2.2. In this case, both investment and operational cost are shared between operator A and B, while operator A has no control of the

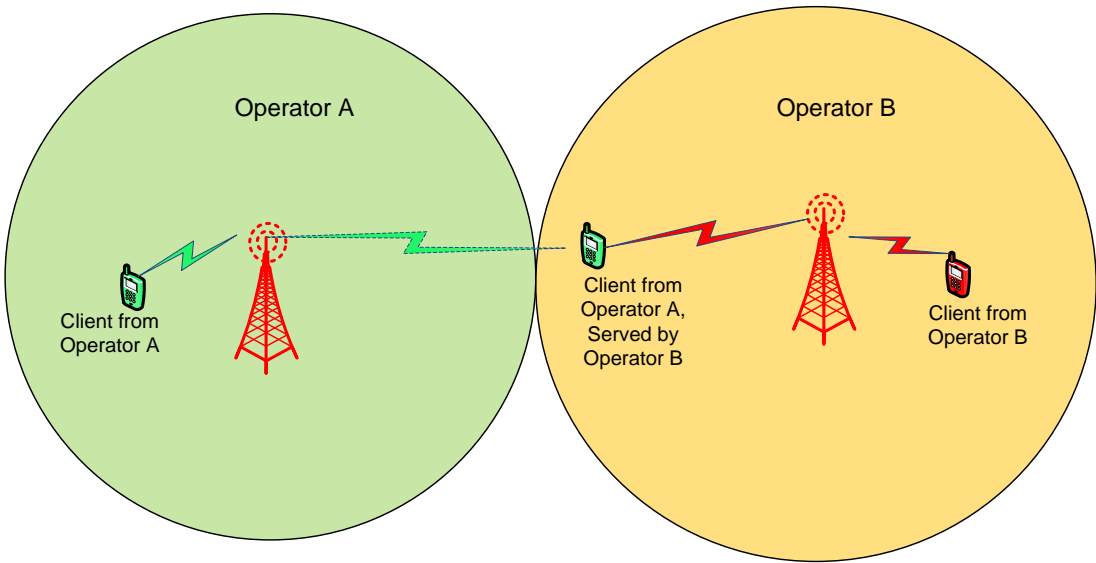
service quality at all. We will analyze use cases proposed by 3GPP for network sharing further in this section. In [28] the energy consumption of a multi-operator mobile network is optimized selecting active base stations in the low-traffic period. [29] extends this by proposing a game theoretic strategy using cost-based functions for the energy consumption optimization.



**Figure 2.1: General illustration of wireless network architecture and different degrees of network sharing [30]**

Apart from these architecture-level studies, research works considering lower-layer technologies [24] such as medium access control (MAC)/physical (PHY) layer in network sharing are very limited. From the business perspective, analysis results from both academia and industry have demonstrated the benefits of network sharing in terms of meeting the increasing data demand and reducing the network cost [30]. Moreover, network sharing will probably further break down the value chain, cultivate new businesses specialized in a certain area such as building towers, and

create mobile virtual network operators who own no other physical assets except their home location register and billing system. In addition, the adoption of the aforementioned technical approaches depends on the business situation. For example, a high-degree network sharing would not be successful if two operators cannot agree on the technology updating plan because of different business strategies. 3GPP network sharing model is described next.



**Figure 2.2: Full-sharing/roaming based Network sharing**

***3GPP Network Sharing Proposed Functionality Overview-Use Cases***

3GPP has already proposed a set of use cases for network sharing that aims to identify potential requirements, considerations and deployment scenarios that operators as well as users need to fulfil for a successful shared network. Five use cases were proposed in release 11 [31], while thirteen more detailed use cases were presented in [32]. Each scenario or use case is based on the factors that can influence the arrangements for network sharing, including business, technical, network deployment or regulatory conditions. The main entities in the proposed use cases are

defined as hosting radio access network (RAN) provider - the operator that owns the RAN in a physical region - and participating operator, the operator that uses the facilities/services given by the hosting operator in that region. The complete set of 3GPP use cases is still under work but the following were identified in release 12 [32] and are summarized below (Set of use cases for network sharing proposed by the 3GPP [32]).

**Use case 1** is called RAN sharing monitoring, and demonstrates the case where the participating operator wants to obtain the same operating and maintenance (O&M) status information from a hosting RAN as from an unshared E-UTRAN. It also shows that a hosting operator wants to restrict the participating operator from accessing certain O&M status information from a hosting RAN for business, operational or technical reasons

**Use case 2** envisages the minimization of drive testing (MDT), and describes the generation and retrieval of MDT data by a hosting RAN provider to the user equipments (UEs) connected via the network. In this case, the hosting RAN does not have an adjunct core network, therefore does not provide any other service other than RAN connectivity.

**Use case 3** is the case regarding RAN sharing granularity where the allocation granularity of a shared network can be at the sector level, as for example in a sector that covers a political border (one country to other) that needs to be shared, while the sectors covering a local country must not be shared.

**Use case 4** presents a scenario where participating operators have variable RAN resource usage, enabling the Hosting RAN Provider to apply different charge based on the resource usage, and so maximizing the revenue

**Use case 5** is divided in two types (use case 5a and 5b) for the cases of asymmetric RAN resource allocation. In use case 5a, with full or nearly-full capacity, RAN resources are shared among two participating operators, in a manner proportional to their financial interest in the Hosting RAN. In use case 5b, the asymmetric RAN resource allocation is performed in a static way scenario. In this case, RAN resources owned and operated in a joint venture are shared among two RAN Sharing Partners proportional to their interest in the joint ventures tactically.

**Use case 6** called Dynamic RAN Sharing Enhancements, is the case where the Participating Operator may require different network capacities in different periods of time, of the day or the week. The Participating Operator might request a portion of the shared RAN to meet the expected variation in network usage.

**Use case 7** called On-demand Automated Capacity Brokering, is the case where the Hosting RAN Provider shares some designated portion of its RAN capacity with other Participating Operators by automatic means. The designated portion of the shareable RAN resources is supposed to support by demand the additional capacity by Participating Operators.

**Use case 8** named Participating Operator managing allocated resources, is the case where selective O&M access is provided to the Participating Operator to perform O&M tasks. The access allowed by the Participating Operator to the shared RAN O&M elements will be based on the Hosting RAN Provider O&M access policies.

**Use case 9** -Load balancing in shared RAN- describes the case of a coverage area that is shared by multiple operators. The agreed shares are predefined among these operators. In this case Load balancing between these cells needs to take the network sharing ratio per operator into account.

**Use case 10** is named RAN Sharing Charging Event Triggering. This use case designates the situation where two or more RAN operators that might have complete or partial overlapping coverage; the example can be the case that one operator only cover areas where additional capacity might be required. The Hosting Provider shares its RAN capacity (in the areas where the additional capacity is required) with Participating Operators, which can include the overlapped area.

**Use case 11** - identified as RAN Sharing Charging Reconciliation - presents the case of a Hosting RAN provider sharing its RAN capacity with one or more Participating Operators. The Hosting RAN provider will have to verify independently of the usage of the RAN, and then generate wholesale charges for each of the Participating Operators proportionately, for the usage of the shared RAN.

**Use case 12** describes the situation that occurs when a UE is moving towards a shared RAN, which is shared by its Home operator as well as other operators, the UE shall be able to select its home service provider based on the operator guidance to get better user experience.

**Use case 13** showcases the scenario where Public Warning System is part of the shared RAN, and includes a broadcast capability where all UEs in the RAN coverage area designated by the warning message will receive the warning message to alert the users of an urgent public safety condition.



3GPP has also defined a network sharing architecture as part of the details of these use cases in order to allow different core networks (CN) operators to connect to a shared RAN [33]. In this approach, operators can share both network elements and radio resources. The two possible architectural approaches are the Gateway CN and Multi-operator CN, both described in detail in Appendix 2. Our work follows the 3GPP proposed approach on network sharing, and is based on the combination of Use Case 9 and Use Case 10 mentioned above.

#### ***2.2.1.4 Relay Aided Networks***

Relays are one of the methods which can solve the above-mentioned problems in the conventional cellular system (low signal-to-noise-ratio (SNR) at the cell edge, fairness, and coverage holes that exist due to shadowing and non-line-of-sight (NLOS) connections).

A general description of relaying function was first proposed in the [34] by its Radio Access Network Working Group1 (RAN/WG1), which is responsible for the specifications of the physical layer of radio interface covering both FDD and TDD modes. Two types of Relays (RN) have been defined in 3GPP LTE-A standards, Type-I and Type-II, and non-transparency and transparency [35]. Specifically, a Type-I (or non-transparency) RN can help a remote MS, which is located far away from an BS, to access the BS. In this case, the Type-I RN needs to transmit the common reference signal and the control information for the BS, and its main objective is to extend signal and service coverage. Type-I RNs mainly perform IP packet forwarding in the network layer (layer 3) and can make some contributions to the overall system capacity by enabling communication services and data

transmissions for remote MS. On the other hand, a Type-II (or transparency) RN can help a local MS, which is located within the coverage of a BS and has a direct communication link with the BS, to improve its service quality and link capacity. So a Type-II RN does not transmit the common reference signal or the control information, and its main objective is to increase the overall system capacity by achieving multipath diversity and transmission gains for local UE units.

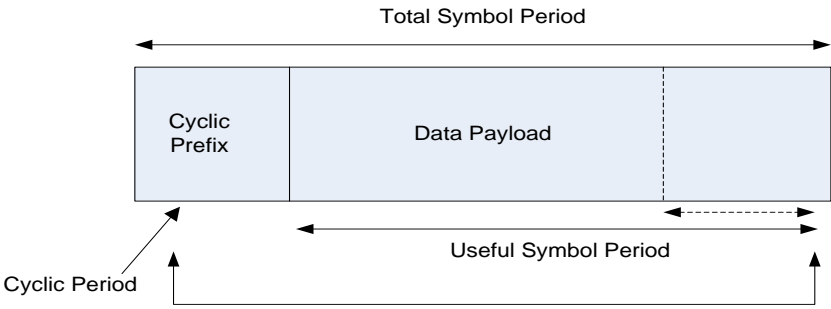
From the network architecture perspective, in order to achieve seamless coverage and higher data rate, Fixed Relay Stations (FRS) [38]-[40] have been considered as a promising candidate technology in LTE-Advanced and IEEE 802.16j/m. However, traditional load balancing schemes for FRS based cellular networks [41]-[43] only consider standalone policies. Most of these standalone mechanisms take a centralized controlled approach for selecting load balancing partners. Only few works have considered FRS networks with self-organization functionality.

### ***2.3. Scenario Definition for OFDMA***

#### ***2.3.1.1 OFDM Fundamentals***

The LTE PHY layer uses OFDM technology, which can be considered as an efficient and low-cost scheme for broadband data transmission in environments involving NLOS or multipath radio. OFDM is a spectrally efficient version of multicarrier modulation (MCM) where the sub-carriers are selected in a way that they are all orthogonal to one another over the symbol duration, thus avoiding the need to have non-overlapping subcarrier channels to eliminate inter-carrier interference (ICI). In fact, it is relatively easy to implement OFDM modulators/demodulators in discrete

time using Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) chips, respectively. The main advantage of the OFDM comes from the fact that it is very efficient in eliminating signal distortion that appears from the delay spread that arises from multipath propagation. The stream of data in OFDM is divided among orthogonal sub-carriers, which results in an increase of the symbol time interval, and which makes it more immune to Inter-Symbol-Interference (ISI). ISI, in addition, can be completely eliminated with the insertion of guard intervals between OFDM symbols, selected to be larger than the expected multipath delay spread [44]. This guard interval is called Cyclic Prefix (CP) in OFDM. The ISI can be completely eliminated if the CP is longer than the channel delay spread. The CP is a repetition of the last samples of the OFDM symbol that is appended to the beginning of the data payload. This mechanism makes the channel circular and enables the use of simple Maximum Ratio Combiners (MRC) as decoders in the receiver, instead of complex multi-user decoders such as the ones used in CDMA for example. Figure 2.3 illustrates the creation of the CP.

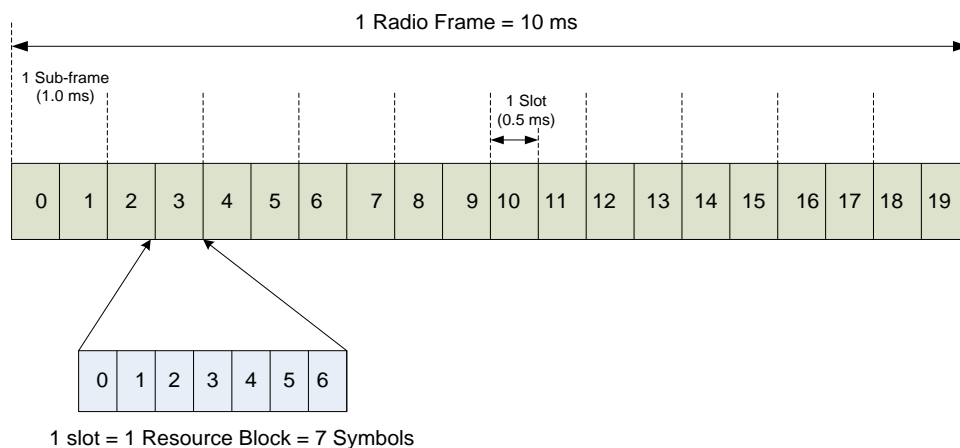


**Figure 2.3: Data Symbol Structure and creation of cyclic prefix**

### 2.3.1.2 OFDMA LTE Frame Structure

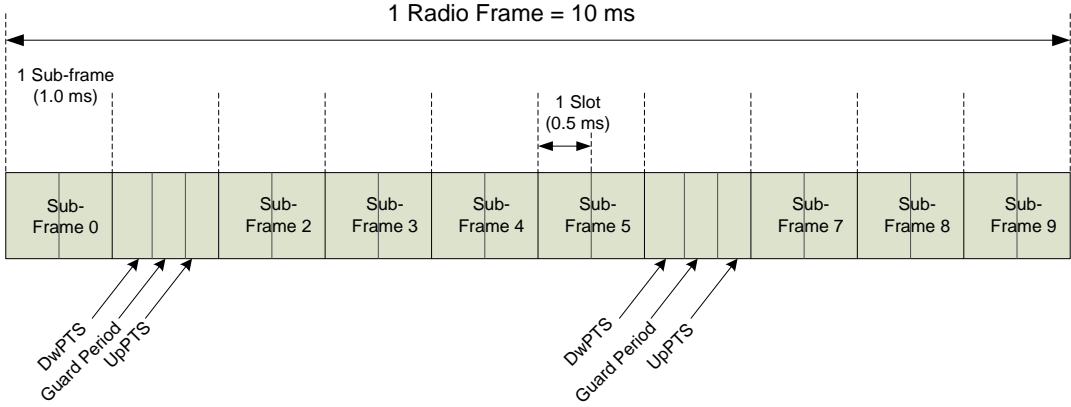
LTE system can support both Time-Division Duplex (TDD) or Frequency-Division Duplex (FDD) modes. For the downlink, the OFDMA is used. For uplink, due to power consumption problem and high peak to average power ratio of OFDM, Single Carrier Frequency Division Multiple Access the division multicarrier (SC-FDMA) is used.

The generic frame structure for both the downlink and uplink is proposed to be the same. The frame is composed of several blocks, each block being a group of assigned sub-carriers. This Physical Resource Block (PRB) is the basic unit of data to be allocated for transmission to each of the multiple users. In LTE the data is transmitted in form of 10ms duration frame. The FDD frame is further divided into 10 sub-frames of 1ms duration, which is also the TTI assigned to transmission in the LTE. Each sub-frame is divided into two time slots of 0.5ms. Figure 2.4 and Figure 2.5 present the LTE FDD and TDD frames structure respectively.



**Figure 2.4: LTE Specification (FDD Frame structure)**

In TDD, there are two special sub-frames, which are the sub-frame 2 and sub-frame 6. Sub-frame 0 and sub-frame 5 and DwPTS (Downlink Pilot Time Slot) are always reserved for Downlink. UpPTS (UpLink Pilot Time Slot) is reserved for Uplink.



**Figure 2.5: LTE Specification (TDD Frame structure)**

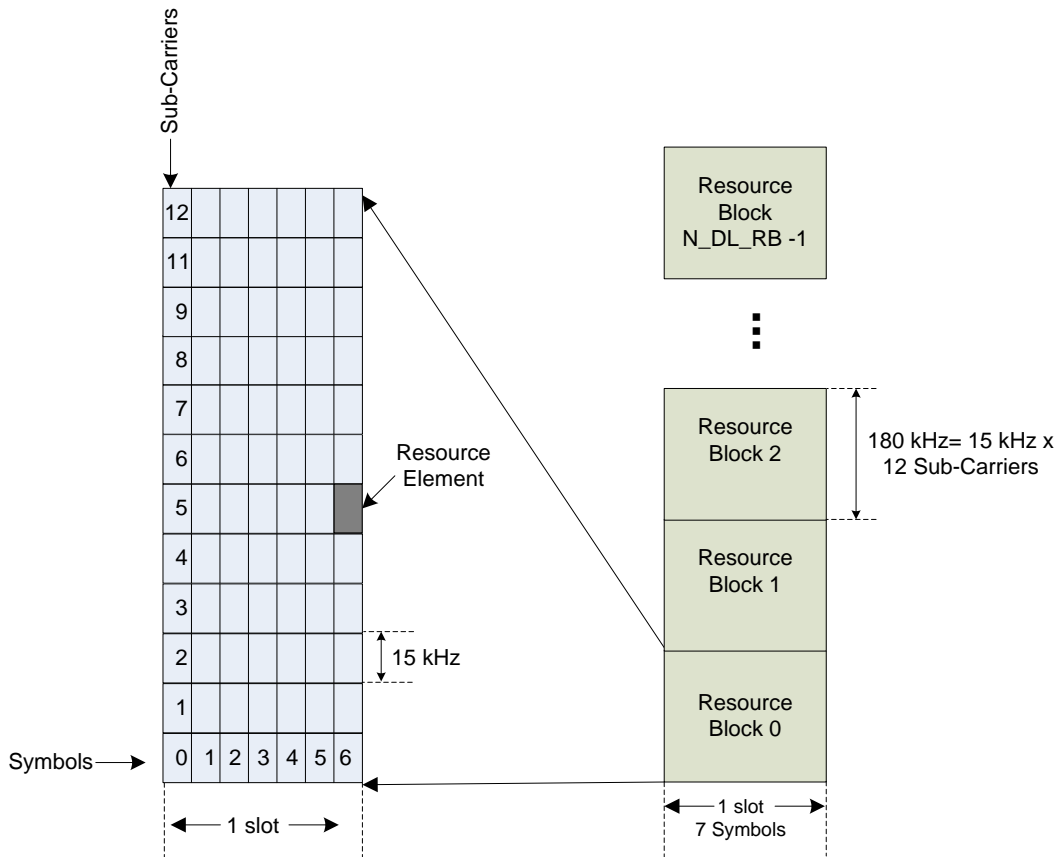
As stated above, the basic unit of data to be allocated for transmission to each of the multiple user is the Physical Resource Block (PRB). A PRB in the LTE that occupies the 0.5ms time slot presented in Figure 2.6, consists of 12 sub-carriers spaced by 15 kHz having total bandwidth of 180 kHz, and containing 7 OFDM symbols.

The number of resource blocks available for OFDMA multi-user sharing, depends on the bandwidth, since LTE supports multiple bandwidth, from 1.25 MHz to 20 MHz.

**2.3.1.3 LTE Resource Block and Theoretical Throughput Computation**

In the previous section, we presented the LTE OFDMA frame structure and the basic resources that can be allocated to multi access users. In this section we describe the methodology for calculating the data transmission throughput that can be achieved. We will consider in this calculation the adaptive modulation and channel coding rate that will in each case depend on the channel state conditions. For modulation, we

consider QPSK, 16QAM and 64QAM. For the channel coding rate we consider coding rates of 1/2 and 3/4. The theoretical throughput is given by the following equation:



**Figure 2.6: Resource block in the LTE frame structure**

$$Th_{Block} = \frac{nSubCar \times bps(modulation) \times cr \times OFDM\_Sym \times nSlots(subFrame)}{subFrameDuration} \quad (1)$$

Where  $nSubCar$  is the number of subcarriers per OFDM symbol,  $bps(modulation)$  is the number of information bit per modulation scheme,  $cr$  is the channel coding rate,  $OFDM\_Sym$  is the number of OFDM symbols per resource block,  $nSlots(subFrame)$  is the number of time slots per TTI, that is equal to the sub-frame duration.

For the specific example of 64QAM modulation and channel coding rate of 3/4, for 1ms TTI (blocks are allocated to user each sub-frame of 1ms), the throughput of a user that is allocated a block in each 1ms and the peak rate for the case of the 10MHz bandwidth (which corresponds on the 50 PRB available) are presented below

$$Th_{Block} = 12 \times \log_2(64) \times \left(\frac{3}{4}\right) \times 7 \times 2 = 756kbps \quad (2)$$

$$Peak_{Rate} = 50 \times 12 \times \log_2(64) \times \left(\frac{3}{4}\right) \times 7 \times 2 = 37.8 Mbps \quad (3)$$

Table 2.1 presents example of respective block size and peak bit rate that can be achieved using 6 different Modulation and Coding Schemes (MCS)

**Table 2.1 LTE block sizes and respective bit rates associated to different Modulation and Coding Schemes**

<i>MCS</i>	<i>Modulation, Code Rate</i>	<i>Transport Block size (bits)</i>	<i>R(CQI) [Mbps]</i>
MCS 1	QPSK, 1/2	4200	4.82
MCS 2	QPSK, 3/4	6300	6.3
MCS 3	16-QAM, 1/2	16800	16.8
MCS 4	16-QAM, 3/4	25200	25.2
MCS 5	64-QAM, 1/2	25200	25.2
MCS 6	64-QAM, 3/4	37800	37.8

## 2.4. Resource Allocation in OFDMA Systems

### 2.4.1.1 Resource Allocation

The layered architecture based on the OSI has been proposed and served well in wired networks. For wireless networks, stricter methodologies that can predict and follow radio channel variations should be used in order to match application requirements more coherently to the available channel capacity, which is now a function of time. 3G and 4G legacy radio incorporate advanced techniques such as

multiple antennas (MIMO), advanced processing techniques associated to interference cancellation, channel estimation and multi-user detection and Orthogonal Frequency Division Multiplexing (OFDM) are all used to cope with the adversity of the mobile radio channel, and provide a means to enhance the available capacity of radio link.

Making efficient use of radio resources is a challenging task for 3G/4G wireless communication systems as the scarcity of radio resources, diverse QoS requirements and wireless channel conditions pose difficulties to the design of the scheduling and radio resource management [45]-[47]. Generally, depending on the type of multiple access scheme implemented in the air interface, resources are defined in time, frequency and space domains. These resources are allocated to users, across different sessions (connections or service flows) in order to ensure that requested QoS parameters, such as delay, packet loss rate, minimum guaranteed throughput and maximum sustained throughput, are provided to each session.

Radio Resource Management, a functionality within the MAC layer, has the main role of managing the underlying radio resources to provide joint support for bursty data traffic applications, as well as to ensure that the spectral resources are exploited effectively. There are several examples of resource management, however, in this thesis we are preliminary concerned with load balancing and dynamic resource allocation. The former provides resource management across different cells, whilst the latter can be considered per cell.



#### ***2.4.1.2 Load Balancing***

Load Balancing (LB) aims at making efficient use of the limited spectrum to deal with unequal loads in order to improve network reliability by reducing the congestion probability in hot spot areas of cellular networks [48]. Load balancing is one of the key use cases in SON [15]. Four standalone load balance policies (transmit power adjustment, antenna parameters adjustment, cell reselection, and handover parameters adjustment) are proposed in [36] and [37]. Load based handover and cell reselection optimization are also proposed by 3GPP [13] and NGMN [15]. However, these research works mainly focus on identifying technical requirements and relevant load balancing policies and there have been only few publications with simulation results [38]. From the network architecture point of view, in order to achieve seamless coverage and higher data rate, Fixed Relay Stations (FRS) [38]-[40] have been considered as a promising candidate technology in LTE-A and IEEE 802.16j/m. However, traditional load balancing schemes for FRS based cellular networks [41]-[43] only consider standalone policy. Most of these standalone mechanisms take centrally controlled approach for selecting load balancing partners. Only a few schemes of FRS networks have the self-organization functionality. However, all of the above mentioned schemes for SO-LB or FRS are mainly focused on “non-shared network” cellular systems.

#### ***2.4.1.3 Scheduling Policies***

How to efficiently use the radio resources is still one of the most challenging tasks facing future Next Generation networks; since the lack of radio resources, multiple end-user QoS requirements and the aggressive wireless channel conditions pose

difficulties on “who should transmit and when”. Typically, the packet scheduler [45], [46] is responsible for managing these decisions. In fact, the design of scheduling algorithms for mobile wireless communications systems is constrained by the intrinsic characteristics of the mobile wireless channel. The random and time variant behavior of the wireless signal is dependent on the receiver location and the users’ mobility across the cell.

The schedulers in the wireless systems should be designed in order to both be reactive to changes in the channel and to follow traffic data delay constraint requirements, in order to maintain the requested QoS of users and their applications. Since the data packets at the queue are associated to a specific service id and respective QoS requirements, the scheduler should determine a suitable packet transmission order among users’, that exploits the instantaneous channel characteristics as well as the traffic type. At each Transmission Time Interval (TTI), the scheduler provides transmission opportunities to eligible users based on the Channel Quality Indicator (CQI) reported from each user on a frame-by-frame basis and QoS level; based on this criteria, the scheduler will re-compute the users’ access priority at every frame period. In the next section, common scheduling methods are presented.

### ***Round Robin***

The most simple and fair scheduling method usually used in wired system is the Round Robin (RR). In this scheme, the users are served in a cyclic order, ignoring the channel quality conditions. The limitation of this method is that it hardly makes an efficient use of radio resources in terms of overall performance.

### ***Maximum C/I***

The most common packed scheduler in the wireless cellular system is the Maximum C/I (Max C/I) scheduler. The Max C/I scheduler selects in every TTI the mobile user with the best instantaneous signal quality. This method has the advantage to potentiate the cell throughput maximization [49]. On other hand, this comes at the cost the fairness, since users experiencing worst propagation conditions, hardly get served by the system resources; Due to the high variance of the radio channel as a result of the fast fading characteristic, the users with initial worst radio conditions can still access the channel.

### ***Proportional Fair***

The proportional fair (PF) algorithm introduces fairness in the scheduling process while still taking advantage of the best channel conditions of each user. This method was introduced in [50], and it serves the user with the largest relative channel quality, based on [51]:

$$P_i = \frac{R_i(t)}{\lambda_i(t)} \quad i = 1, \dots, N \quad (4)$$

where the priority  $P_i(t)$  of the user  $i$ , is given by the instantaneous bit rate according to the channel condition  $R_i(t)$  over its average throughput  $\lambda_i(t)$ . As can be seen, this method intends to prioritize users with favorable instantaneous radio channel conditions relative to their average channel condition. The optimization in this method is linked to the averaging window, which should be related to the channel

fast fading and user service characteristics. In fact, the optimization process leads to the priority based schedulers presented next.

### ***Exponential (EXP)***

The exponential (EXP) scheduler [52] is a variation of the PF scheduler that also tries to explicitly equalize the latencies of all users when their differences become large. At frame period  $n$  the algorithm selects for transmission the user satisfying the condition given equation.

$$j = \arg \max_{i \in \{1, \dots, K\}} \left( a_i \frac{r_i(n)}{r_i(n)} \exp \left( \frac{l_i(n) - \overline{l(n)}}{1 + \sqrt{\overline{l(n)}}} \right) \right) \quad (5)$$

Where:

- $\overline{l(n)} = \frac{1}{K} \sum_{i=1}^K l_i(n)$  is the average of the head of line packet delays observed by all  $K$  users in the system at frame period  $n$ .
- $a_i$  is the so-called service specific user weight. It is used in the support of multi-service provisioning, by assigning different weights to users based on QoS requirements.

The EXP rule tries to equalize the weighted delays  $a_i w_i(n)$  of all queues when their differences are large:

- If one of the queues would have a larger weighted delay than the others by more than order  $\sqrt{aW}$ , then the exponential term becomes very large and overrides channel considerations (as long as its channel can support a non-zero rate), hence leading to that queue getting priority.
- For small weighed delay differences (less than order  $\sqrt{aW}$ ), the exponential term is close to 1 and the policy becomes the proportionally fair rule.

The term  $\overline{aW}$  in the exponent can be dropped without changing the rule as it is common for all the queues and the factor 1 in the denominator of the exponential is present simply to prevent the exponent from blowing up when the weighted delays are small.

### ***Delay Bound QoS Based Schedulers***

Based on the application QoS requirements, especially in delay sensitive services, the schedulers should not only take into account the channel characteristics, mainly in the case of bottlenecks of wireless communication, but should also take into account the delay constraints of the users' application. In fact, for many applications (especially for real-time or near-real-time based applications) after a certain delay, the packet is no longer useful and should be discarded. There are several proposals for schedulers that try to cope with these constraints: Priority scheduler [53] or Modified Largest Weighted Delay First (M-LWDF) [54] are such examples. [53] tries to prioritize packets based on maximum delay and channel state, using actual information. The M-LWDF [54] intends to guarantee a percentage value of discarded packets within a given maximum delay bound, which means that the probability must be below a given threshold, which in this case depends on the type of service. The M-LWDF scheduling method selects the user  $k$  based on the following equation.

$$k(n) = \arg \max_{i \in \{1, \dots, K\}} (\gamma_i W_i(n) r_i(n)) \quad (6)$$

Where:

- $W_i(n)$  is the delay of the head of line packet on the queue of user  $i$ .
- $r_i(n)$  is the channel capacity from user  $i$ .

- $\gamma_i$  is an arbitrary positive constant.

Variants of these method can be achieved by replacing the delay  $W_i(n)$  with queue length  $Q_i(n)$  (in bits), or averaging the delay value over packets in the queue. The arbitrary constant  $\gamma_i$  enables the control of packet delay distributions for different users or services.

### ***QoE based Schedulers***

Quality-of-Experience (QoE) schedulers are new approach on the inter-layer resource management, where in opposite to QoS schedulers, makes use of the user experience feedback mainly in the multimedia services such as VoIP or video, as feedback mechanism to make the scheduling decision. This new paradigm is also called interlayer scheduling. Few works have been dedicated to QoE scheduling. In [55] the user experience is considered while using the multimedia services such as VoIP, by jointly considering the user QoE and available wireless radio resources in the LTE-A network. The work proposed a new queue management technique based on QoE metrics where also real-time feedback of UEs were used to make the scheduling decision. In [56] QoE perception is used on 3D video, where reconstruction problem that occurs at the receiver affects QoE. In this work in discussed how real-time quality evaluation methodologies can be used to overcome these effects. In [57], is proposed a HTTP progressive video downloading in OFDMA systems where an estimation of the amount of video data stored in the player buffer is used as the main criterion for resource assignment to avoid of playback interruptions, with improvements on the video pauses.

### ***Energy-Efficient Management Schedulers***

Conventional wireless networks have been emphasizing mainly aspects of ubiquitous access, large system capacity and spectral efficiency (SE), while aspects as energy efficiency were not the main concern. New trends are envisaging the inclusion of energy efficiency in the joint design across all system levels and protocol stacks. Concerning energy-efficiency (EE), some of the scheduling schemes have been proposed in the literature in recent years, devising innovative energy-harvesting, dynamic power-saving and cross-layer energy-aware designs to resolve energy efficiency issues. In [58] and fundamental trade-off between EE and SE in downlink orthogonal frequency division multiple access (OFDMA) networks is addressed, including the impact of channel power gain and circuit power on the EE-SE relation. Based on the EE-SE relation, a low-complexity but near-optimal resource allocation algorithm for practical application of the EE-SE trade-off. In [59] a low complexity EE uplink scheduling for the OFDMA considering time-averaged bits-per-Joule metrics in opposite of using more complex iterative approach. In [60], resource allocation is based a non-convex optimization problem for maximizing the energy efficiency of data transmission, taking into account the minimum required system data rate. Despite of significant work carried-out in this field, most of the work had being focus on cellular systems, without taking account cooperation strategies.

#### ***2.5. Energy Efficiency for OFDMA Systems***

Few works have been done on energy saving methods in LTE-A, and their focus has mainly been on BS planning. [61] shows the possibility of energy saving by planning

the switching-on and off of BS, by using simple simulations. Authors in [62] studied the BS switching strategy using a simplified analysis and have shown simulation results for several switching-off BSs. In [63] the research work has been extended to the overlay network environment with the proposal of BS switching strategies based on the utility balance of two networks. In [64], BS switching algorithms are presented, to illustrate the relationship between energy saving by BS switching-off and outage probability. [65] gives a pre-defined BS sleep scheme according to a deterministic variation of traffic pattern over time. [61] is dedicated to WLAN systems with APs, powered by green energy, for optional coverage extension, which is different from our scenario that is about standard BSs under low traffic condition. [66] considers BS energy saving as a dynamic BS planning problem. For dynamic resource control with respect to the spatial-time traffic variation, one could refer to load balancing schemes (see for example [67] and [68]). Notice that the object of load balancing is to evenly distribute traffic among BSs, while energy saving on BS aims to concentrate traffic to a subset of the BSs. [69] and [70] analyze the sensor networks coverage problem with energy constraints, and turning off certain sensors periodically is adopted as a way to save energy. There are few other works, e.g., [61]-[75] that evaluate the gains due to relay deployments in cellular systems. The main focus of these is towards energy saving from the user's perspective. In this thesis, we shift views and consider the energy saving from the operators' view, and in particular address the challenge of energy efficient resource allocation for cooperative strategies.



## **2.6. Summary**

In this chapter, a literature review on resource allocation for cooperative 3G and 4G legacy networks , cooperation being considered as a vehicle for potentially increasing the energy efficiency and reducing the cost per bit in modern mobile communication systems. These strategies included network sharing, CoMP , and SON all of which are considered in our research scenarios to be addressed in chapter 4 and 5We conclude this chapter with a review of energy saving methods in LTE-A, and describe the limitations with the current attempts towards with energy saving in legacy networks..

### 3. Dynamic Resource Allocation for OFDMA

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#### **Abstract**

In this chapter we describe dynamic radio resource management for wireless systems, and in particular develop the logical architecture for OFDMA type systems. This includes an integrated solution that includes the allocation policy, scheduling, link adaptation and H-ARQ. Each of these work in synergy to provide packet error control as well dictating how the users are allocated the available radio resources. Moreover, the OFDMA frame structure is elaborated based on the LTE/LTE-A standard, and subsequently a work flow is defined to indicate how users are scheduled, allocated resources and transmitted over the air interface. Experimentation is needed in order to provide performance guideline in this highly complex multi-parameter environment mobile operating environment. Therefore, we provide the fundamentals on system level modeling and build our model of the proposed simulation scenario, that includes the link level interface. The models are complemented by baseline results representing DRA performance in OFDMA systems.

### **3.1. Introduction**

A hierarchical protocol reference model constituting structured layers was the typical approach towards protocol design, intended initially for fixed wired networks. However, this was based on the notion of minor dependencies between different layers of the protocol stack that resulted in little influence on the design of the individual protocol. However, with the advent of wireless connectivity, the underlying channel was seen as an aggressive medium – in contrast to the fixed wired fixed channel - for the transmission of the information [76], [77]. Path loss attenuation, multipath propagation resulting from reflections and diffractions, and shadowing resulting from surrounding buildings and other dense object area, all contribute to significant challenges in terms of QoS provisioning over the wireless link. This means that the underlying channel can be viewed as a radio resource with a variable capacity, where strict layered scheduling approaches fails to harness fully the available radio spectrum. Moreover, the need to support services with different QoS profiles, provided the impetus to revisit the channel to examine how we can adapt it to maximize the transmission efficiency.

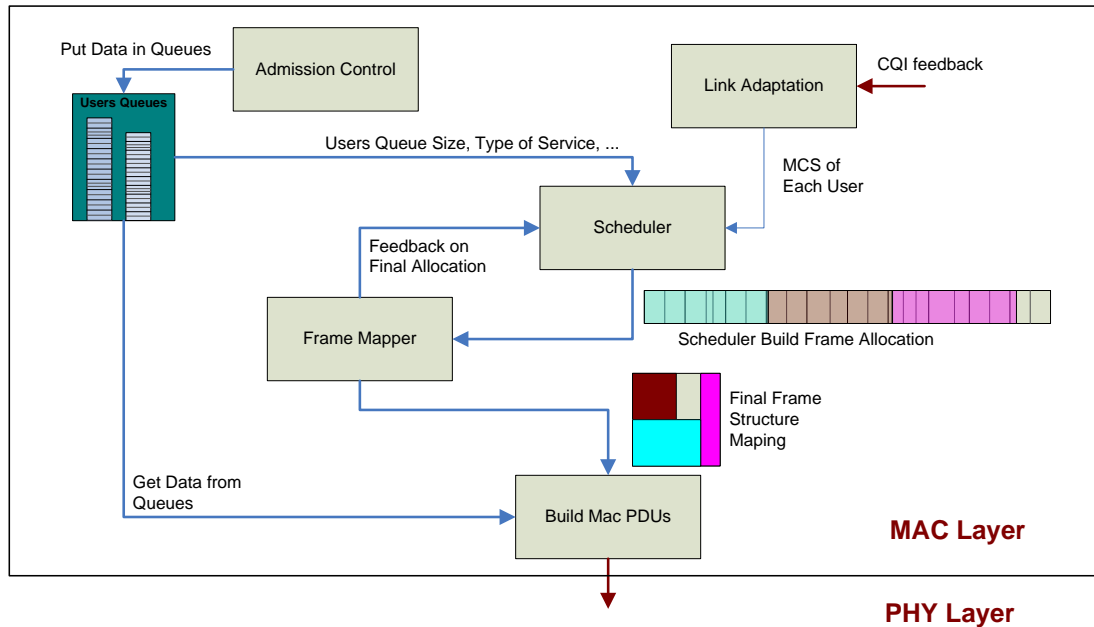
Next generation mobile systems will be more complex systems, that are dynamic in nature creating dependencies between components. In this context, an interdisciplinary design approach is required that can capture the dynamic of the system. Legacy scheduling approach should be redesigned to assign user apriority where the available and variable channel capacity is taken into account in order to increase the spectral efficiency. This approach is pivotal in the design of the Dynamic

Resource allocation approach, that plays a major role in the way we can exploit the channel resources effectively.

This chapter details the principles and performance of RRM for OFDMA based systems, which is the radio access protocol for the 4G networks and beyond, and is organized as follows: in section 3.2. we describe the baseline system model that includes the dynamic resource management component; section 3.4. describes the system simulation methodology for practical experimentation; section 3.5. showcases the baseline performance for DRA schemes based on LTE, and in section 3.6. we summarize this chapter.

### **3.2. *System model***

LTE standard as an evolution of the UMTS was designed and developed for the delivery of broadband applications in all packet data traffic basis. The MAC layer, in particular, has inherent flexibility designed to support both burst data traffic applications that requires high peak rate demands and as well as streaming or delay sensitive applications. The fine granularity of the resource block described in the previous section, and associated flexibility that can be provided by the MAC layer for the resource allocation makes the LTE OFDMA system able to respond to the user's bandwidth needs, and to reduce the latency incurred in handling user's bandwidth requests. Based on scheduling decisions, efficient DRA schemes makes it possible to send data through the air-interface under stringent QoS requirements for each type of service flow, whilst using radio resources efficiency. Figure 3.1 presents the LTE MAC layer structure.



**Figure 3.1: MAC layer architecture of the LTE system.**

### 3.2.1.1 Link Adaptation

The role of link adaptation is to enable the system to effectively exploit the available radio resources, whilst realizing the QoS required for the transmission of the data streams. The link adaptation is an adaptive modification of the burst profile, in terms of modulation and channel coding types, that take place in the physical link to adapt the traffic to the instantaneous radio channel condition.

Adaptive Modulation and Coding (AMC) is performed for the radio link adaptation before each packet data transmission, to follow the fast variation characteristic of the wireless medium. Unlike circuit switch based cellular systems, like GSM, packet switched wireless systems tends to adapt and maximize the bandwidth utilization by exploiting different channel coding rates and modulation. LTE supports a variety of MCS schemes for data transmission, each depending on the CQI feedback given by the mobile station on the PUSCH channel. On the downlink, the base station selects

the MCS according to the CSI, and this selection can be performed on a burst-by-burst basis per link. On the uplink the base station estimates the channel quality based on the received signal. The MCS used is the one which maximizes the throughput while keeping the estimated Block Error Rate (BLER) lower than the pre-defined threshold. This threshold depends on the type of service.

AMC increases significantly the overall system capacity since it allows real-time trade-off between throughput and robustness on each link. The modulation and coding schemes supported by LTE in downlink are QPSK, 16 QAM and 64 QAM. In uplink the same modulation schemes are proposed, but only one PRB is allowed. Forward Error Correction (FEC) using turbo coding is mandatory.

### ***3.2.1.2 Scheduler***

The scheduler is the main entity in the MAC layer and responsible for the efficient use of Dynamic Resource Allocation. Making efficient use of radio resources is a challenging task for 3G and 4G legacy mobile communication systems as the scarcity of radio resources, diverse QoS requirements and wireless channel conditions pose difficulties to the design of the scheduling and radio resource management [45], [46], [47].

As described in chapter 2. the design of the scheduling algorithms for wireless networks is shaped by the intrinsic characteristics of the mobile radio channel. Fast fading and slow fading shadowing, as well as path-loss, result in a time-varying wireless link, both in time and space. This random behavior of the signal impinging on the receiver is also location dependent and is influenced by the user's mobility across the cell.

The scheduler, together with the DRA, Connection Admission Controller (CAC), Congestion Controller (CC) and the Link Adaptation (LA) modules, compose the RRM, and the functional behavior of these modules depend on the scheduling policies implemented. The main function of the scheduler is to intelligently allocate radio resources to achieve high system performance in terms of efficiency and fairness in radio resource allocation. Scheduling decisions are based on a plethora of information, such as: number of active sessions, QoS constraints, link state and the state of the queues with new packets and with packets in retransmission. A well designed scheduler should be able to provide the following features: efficient radio link utilization, fairness among users, low Complexity and provide as much scalability as possible, and a wither requirement for 4G+, efficient energy consumption.

### ***3.2.1.3 Hybrid Automated Repeat Request H-ARQ***

Hybrid Automated Repeat Request (H-ARQ) is a combination of Automated Repeat Request (ARQ) with FEC at the physical layer, and it provides improved link performance over traditional ARQ, at the cost of implementation complexity. Retransmission is requested with H-ARQ, if a block is received in error, meaning that the decoder was unable to correctly decode the received block. In this case, the received retransmitted coded block will be combined with the previously detected coded blocks, and feedback to the input of the FEC decoder. The probability of success in the decoding of the data block is increased by combining the different replicas of the block. Two types of HARQ can be implemented: Chase Combining, or Type One H-ARQ and Incremental Redundancy, called Type II H-ARQ. This former relates to Type I H-HARQ.

To further improve the reliability of retransmission, LTE type II H-ARQ, which is also called incremental redundancy. Here, unlike in type I H-ARQ, each (re)transmission is coded differently to gain improved performance. Typically, the code rate is effectively decreased on every retransmission. That is, additional parity bits are sent in every iteration, equivalent to coding across retransmissions.

LTE standard supports this by combining an N-channel stop and wait ARQ along with a variety of supported FEC codes. Doing multiple parallel channels of H-ARQ at a time can improve the throughput, since when one H-ARQ process is waiting for an acknowledgment, another process can use the channel to send some more data. LTE supports up to 8 parallel H-ARQ process. LTE supports signaling mechanisms to allow asynchronous operation of H-ARQ and supports a dedicated acknowledgment channel in the uplink for ACK/NACK signaling. Asynchronous operations allow variable delay between retransmissions, which provides greater flexibility for the scheduler. In our work, Type I H-ARQ was employed.

### ***3.3. System simulation and simulator features***

The optimization of cellular networks can be performed on many different levels and for a large number of different aspects. This includes static optimizations during the network planning process, as well as highly dynamic optimization during network operation. The latter, the process being increasingly automated through SON. Here, we investigate DRA performance and optimization at the planning stage by using system level simulations, since we are interested in the overall performance of the



network, following the typical KPI conditions, namely the supported average data rate of users in a certain area, network QoS, among others.

In order to reduce the complexity, usually it is advantageous to decouple simulators working at different levels of abstraction. In this case, appropriate interfaces are required between the simulators, namely, system level simulators and link level simulators. Some problems, however, may require the combination of different simulation levels in one simulator. The specific case of interfacing the system level simulation with link level is evaluated in the section 3.4.1.3.

In this section we describe the methodology for system level simulation incorporating DRA metrics. We focus on OFDMA cellular and typical environments namely urban, including accurate radio channel and interference modeling.

### ***3.3.1.1 Simulator features***

The complexity of existing and future cellular mobile networks makes their optimization and performance evaluation a challenging task. Although many aspects of the cellular networks can be evaluated analytically, the use of testbeds or computer simulations are often the only way to be able to acquire performance results closer to real scenarios. In many cases, especially in the design phase of new standards or for dynamic algorithms optimization phase, computer simulations are a commonly applied method, since it provides an easier implementation and maintenance solution, when compared to testbeds.

Based on this purpose, a collaborative work resulted in an in-house system level simulator for cellular systems that was designed and implemented initially to obtain

performance results closer to real scenario of one of the access technologies candidates of what was supposed to be the 4G of mobile communication systems, based on Multi-Carrier Code Division Multiple Access (MC-CDMA) [78]. The design was proposed to be modular to facilitate both collaborative work and also adaptive to different cellular data packet standards and requirements. This modular PHY-MAC based dynamic system simulator has evolved since then for UMTS HSPA [53] [79] and lately to LTE standard. Since relevant standardization bodies and industry consortia have specified reference scenarios, model parameterizations, and metrics, they are used in order to allow a comparison of simulation results generated by different research groups. These simulation specifications can be found in [80] for the 3GPP and in [81] for the Next Generation Mobile Networks (NGMN) Alliance.

A part of the fact that is an in-house simulator tool, with inherent flexibility and support to the authors, this simulation tool is fully developed in C++, under Linux operating system, in opposite for example to other simulators based in other platforms [82], which makes it suitable for heavy and complex processing requirements of the multi-cell, multi-user MAC algorithms of dynamic cellular systems.

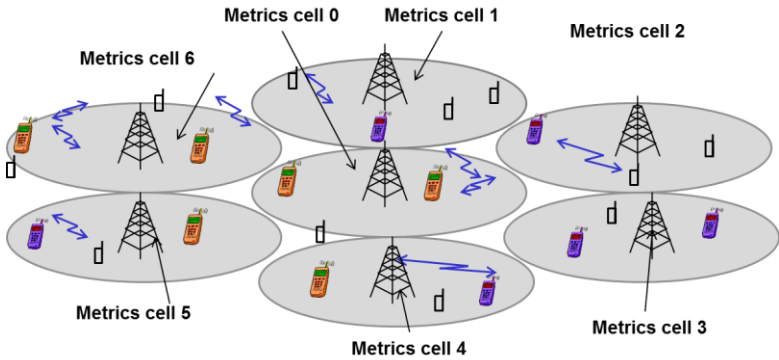
### ***3.3.1.2 Blocks developed for the purpose of this thesis***

This chapter describes methodology used for system level simulator used in this work. The methodology focuses on OFDMA cellular and typical environments namely urban, including accurate radio channel and interference modeling.

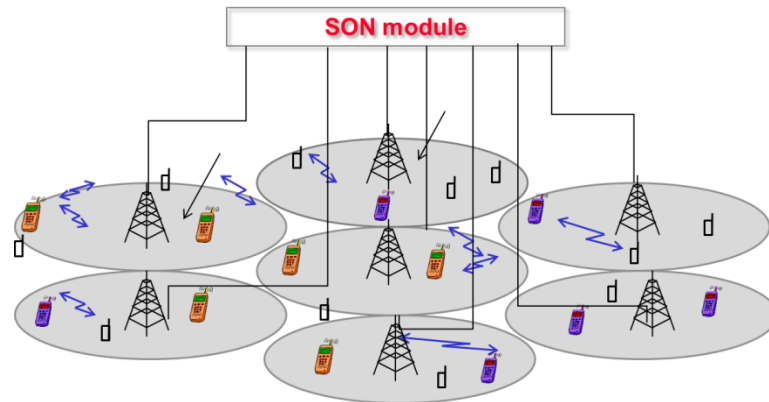
A part of the detailed description of the simulator and its features, in this section we indicate particular extra modules that were developed and included in the simulator described in this chapter, for the sole purpose of the work presented in this thesis.

***SON module***

The multiple cells approach is shown in Figure 3.5, where in each cell there is one base station and a random number of mobiles, randomly located inside each cell. In the conventional cellular system, each cell independently manages its resources through MAC, as described in the section Figure 3.1. For SON based implementation, a centralized approach is need in order an cells independent entity be able to manage cells resources, or at least collect information and give to the cell management directives. For this purpose a SON module was implemented in the simulator and interacts with all cells. The two approaches, with independent cell resource managements and SON based resource management are presented in Figure 3.2 and Figure 3.3 respectively. SON based management is carried-out in the chapter 4.



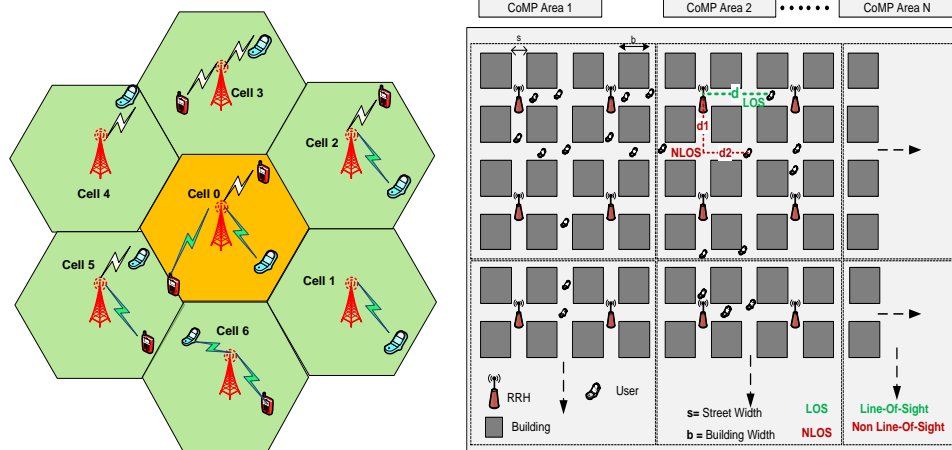
**Figure 3.2: Conventional Wireless Cellular System with multiple cells, with independent resource management.**



**Figure 3.3: SON based resource management Cellular System.**

***Manhattan Scenario for Coordinated Multi-Point***

As described, the simulator was designed for cellular systems and all deployment follows the cellular model of Figure 3.5, a new deployment was proposed and implemented for CoMP studies of chapter 5. based on Manhattan model. Manhattan Model [83] is proposed in [84] for broadband systems and is an attractive scenario for deployment of the CoMP in a dense urban environment, where fiber has already been deployed and can be reused to transport the radio signals to/from the RAUs, or can be economically deployed. Furthermore, end users will be mainly in line-of-sight conditions or near line-of-sight with the antenna. This Manhattan deployment consists of a rectangular regular grid of RAUs. This rectangular grid follows the regular street structure of a city with buildings, streets, and blocks of the same size. The RAUs are considered to be deployed at optimal positions on the streets (see Fig. 2).

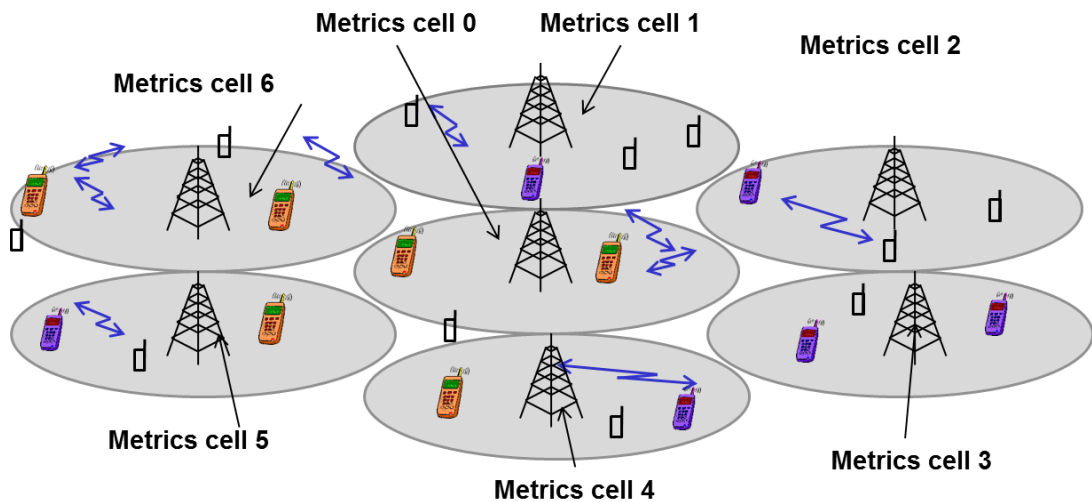


**Figure 3.4: Hexagonal distributed deployment vs Manhattan network deployment with joint processing areas.**

### 3.4. Simulator Description

#### 3.4.1.1 General view of System Level Simulation Model

A system with multiple cells is shown in Figure 3.5, where in each cell there is one base station and a random number of mobiles, randomly located inside each cell. Mobiles access the network through the Base station (BS's). A comprehensive system level tool is needed to evaluate the performance of this type of systems that should capture every aspect of the real cellular environment. This kind of tool is called a System Level Simulator (SLS).



**Figure 3.5: Wireless Cellular System with multiple cells.**

### ***3.4.1.2 Requirements for System Level Simulation Modeling***

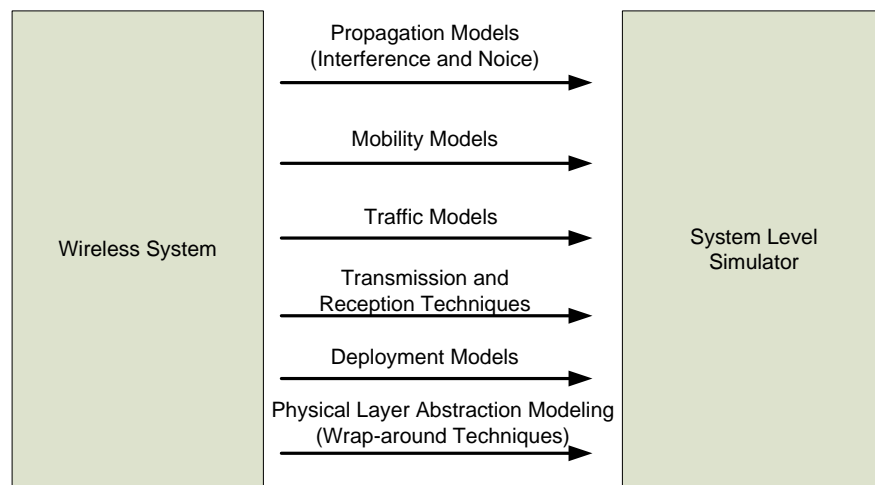
Implementation of a system level tool requires complex modeling of the real environment. As shown in Figure 3.6, several aspects need accurate modeling. The minimum modeling of wireless systems should involve three aspects:

- Users dynamic behavior, namely user mobility;
- Traffic characteristics for the applications considered;
- Radio aspects involved in the transmission of the signals from users to destination.

Taking a deeper insight into the characteristics of the simulation environment, we need to capture certain traits which pertain to real-life instances in cellular networks, Therefore, when considering the user's behavior, as their position can be random, there is the need for a deployment model. Secondly, as they are mobile, there is the need for a mobility model related to each scenario or environment. Thirdly, as the user use wireless communication protocols to transport applications or services there

is the need for a model of the data traffic. Finally, the information is sent by a radio waveform modulated by a channel, thus creating the need to model the impact of the channel on the signal quality requiring appropriate propagation models. Therefore, the main modeling requirements for the SLS, as shown in Figure 3.6, are:

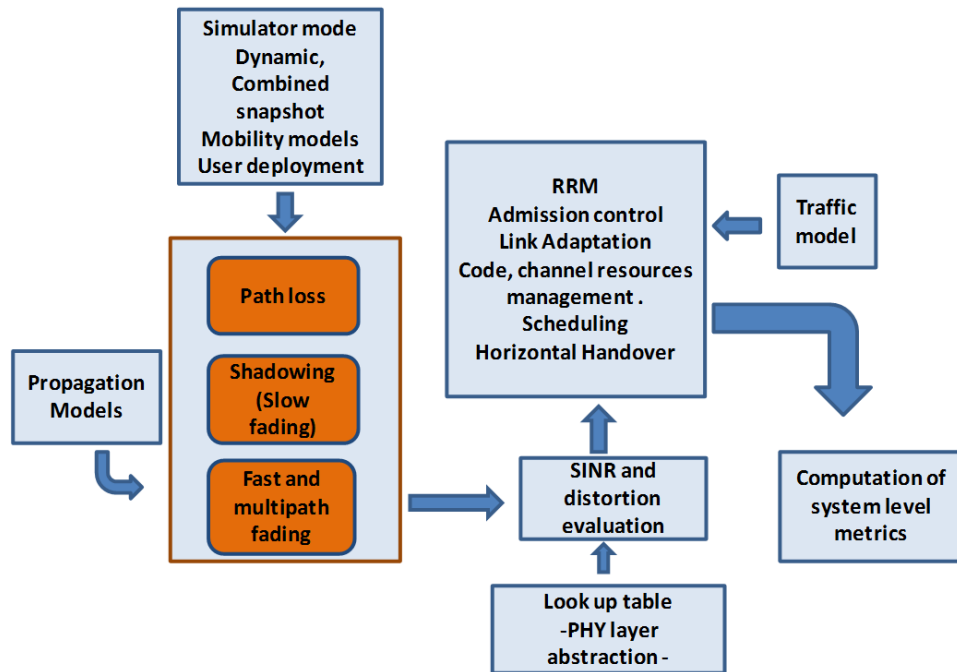
- Deployment Modeling;
- Mobility Modeling;
- Traffic Modeling;
- Radio Channel Propagation Modeling;
- Transmission/reception techniques.



**Figure 3.6: Modeling of Wireless communication System**

The methodology followed in the system level simulations depends on a diverse set of settings regarding: type of wireless system simulated; air interface technology; simulation complexity and time resolution; interface with other layers of the protocol

stack, such as the physical layer and/or network layer; channel and interference modeling and application traffic models. In particular, these are elaborated further:



**Figure 3.7: Modeling of Wireless communication System**

### Network Scenario

- This is related to the particular environment considered in the simulations: urban, rural, vehicular or indoor. Each has a specific user mobility pattern.

### Network Layout

- Amount of tiers and number of base stations simulated. This is crucial for the amount of interference considered.
- Type of cells in each site/base station: one omnidirectional cell or three, six sectored cells for example.



- Number of mobile stations and their distribution over the network coverage area.

### **Radio Resource Management**

- Power control.
- User mobility and handover.
- Definition of the radio resources according to the type of air interface and the medium access layer.

### **Physical Layer Modeling and Abstraction**

- Definition of the metrics used to map the physical layer performance to higher layers of the protocol stack.
- Type of interface used in the interaction between system and physical layers.

### **Propagation and channel modeling**

- Path loss propagation.
- Slow fading (shadowing) propagation.
- Fast fading channel modeling.

### **Interference modeling**

- Intra-cell and inter-cell and inter-system interference.

### **Implemented radio access system**

- Multiple access to radio resources, circuit switch/packet switch,

### **Traffic models for application services**

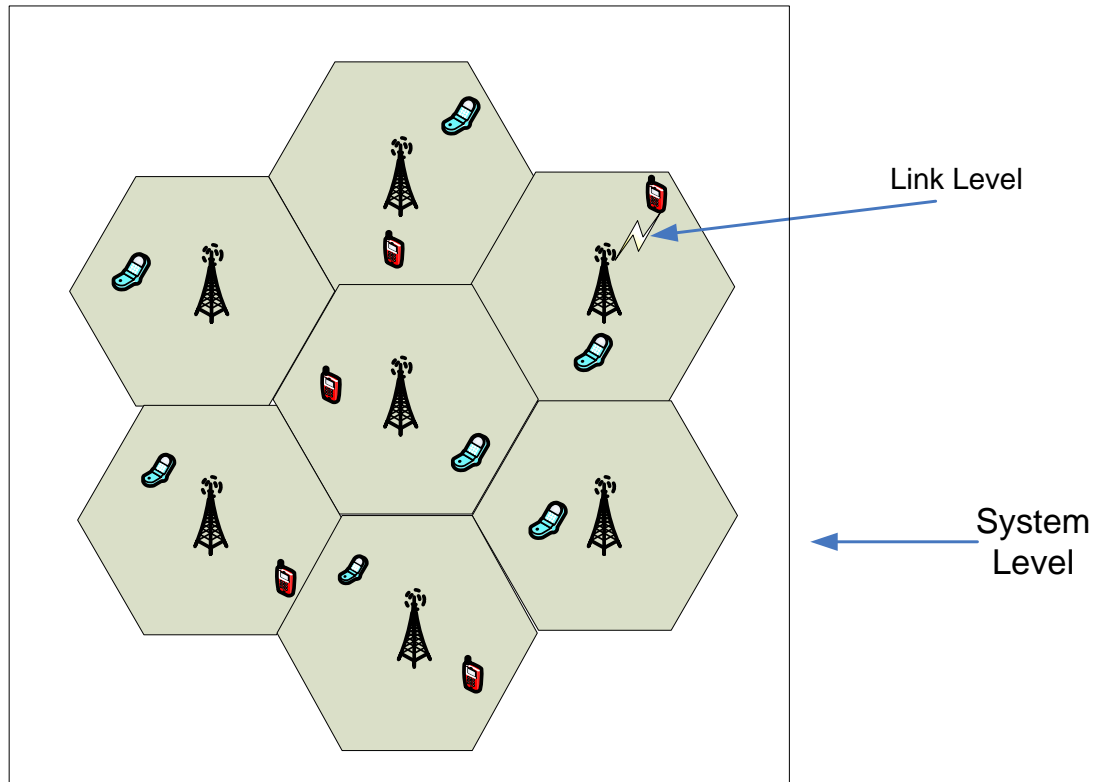
- Choice of traffic models: emulation by using pre-defined traffic models or use of real traces from real networks.

### **Performance metrics**

- Metrics for network evaluation performance.
- Metrics for user satisfaction evaluation.

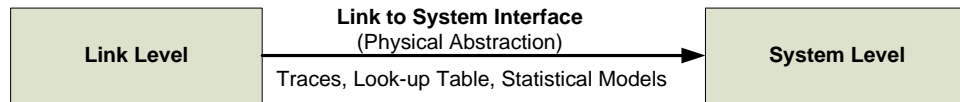
#### ***3.4.1.3 Link Layer Modelling***

A single simulator approach that constitutes the two approaches, as presented in Figure 3.8, including the multi-Link Level and radio resource management protocols would be preferred. However, the complexity of such a simulator is far too high in relation to the required simulation resolution and simulation processing times. In addition, the scope of both simulators are very distinct, i.e. a link level simulates a single link, one base station and one user whereas a system level simulator simulates multiple links as shown in Figure 3.8.



**Figure 3.8: Wireless system level simulation.**

At the link level [85] the granularity is in the order of the BER, which for CDMA/WCDMA system, it can be as low as nanoseconds according to the respective chip rate. While at the network level, it is at the packet level and radio blocks durations, as presented in section 2.3. , which is typically several orders of magnitude higher than the BER. Due to these computational complexities, it is not possible to simulate an entire network in one System level Simulator. Therefore, separate link and system level simulations are required with an appropriate methodology to pass the results from the link level to the system level. This is the so-called Link-to-System (L2S) interface as shown in Figure 3.9. In practice, this interface is realized through a set of mapping tables known as Look up Tables (LUT). These mapping tables are constructed at the link level and they represent a tabulated BER or FER function as a function instantaneous system level SINR.



**Figure 3.9: Interface between system level and Link level.**

The performance evaluation of a practical system by means of simulations has to consider the overall system layers of the whole communication protocol stack: physical layer, link layer (both Logical Link Control – LLC and Medium Access Control – MAC) and upper layers (network, application and transport layers).

Simulations carried out on the radio link level are performed for a point-to-point link between the base and mobile stations, either in a SISO or MIMO propagation channel. The whole transmission chain is simulated at the granularity of the bit level. It includes all modules responsible for the transmission and reception of the signal to either end of the link. The ultimate goal is the generation of a set of curves illustrating the variation of the Bit Error Rate (BER), Block Error Rate (BLER) or Symbol Error Rate (SER) with the Signal to Noise Ratio at the bit level:  $E_b/N_0$ .

At the system level, simulations are conducted for a group of base stations, in a typical hexagonal cellular layout, which transmit (downlink connection) and receive (uplink connection) to/from a group of mobile stations attached to its area of coverage (cell). At this level simulations, are conducted in a point-to-multi-point configuration, where a group of mobile stations are attached to each cell in the network and the ultimate goal is the generation of a set of metrics, which reflects the performance of the network in terms of: achieved user and cell throughput, packet drop ratio, average packet delay, etc.

Both layers perform simulations under different time-scales: physical layer simulations are performed at the bit level and system level simulations are performed at the frame interval, or transmission time interval. Therefore, there is a need to adopt a simple model that would be accurate enough to capture the signal statistics and impact on performance metrics, whilst still maintaining the simulation time frame within an acceptable limit.

For this reason, system performance evaluation is based on a separation among the different layers functionalities:

- On the one hand system level performance evaluations do not consider the steps performed on the physical layer for the transmission of each bit of information between both ends of the communication link. System Link level RRM algorithms performing at the frame interval level of granularity consider the physical layer as a “black box”, interacting with it by means of well-defined interfaces.
- On the other hand, physical layer simulations are unaware of the algorithms performed on higher layers for RRM, such as Dynamic Channel Allocation (DCA), Power Control, Handover, Connection Admission Control (CAC) and Scheduling.

This separation among layers implies the definition of interfaces which must be properly designed in order to, as accurately as possible, integrate the impact of the physical layer on the system level. This strategy results in an implicit trade-off between simulation time and accuracy.

The performance of the physical layer is modeled by means of Look-Up Tables (LUT) in which the behavior of the radio link is encapsulated. An example of a metric that could be used in the performance abstraction of the physical layer is the variation of the Frame Error Rate (FER) with the Signal-to-Interference plus Noise Ratio (SINR), averaged over many channel realizations for the specific channel model used.

According to the simulated scenario two types of interfaces can be defined in the physical layer abstraction for system level simulations [86], [87]:

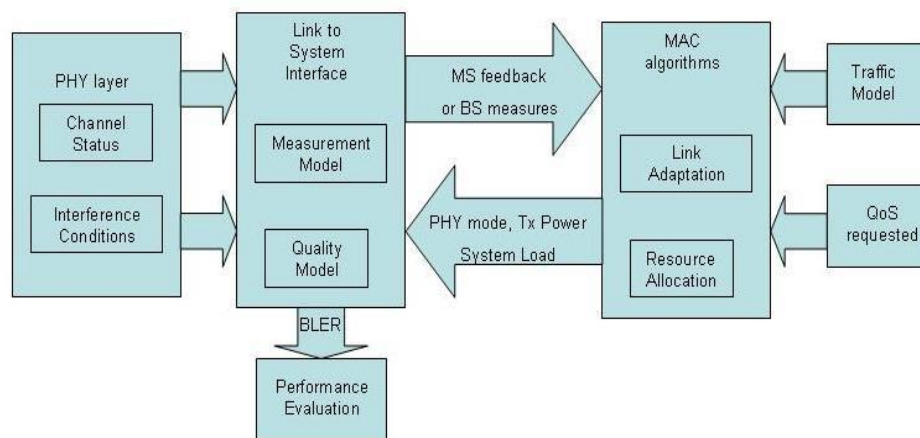
**Average Value Interface** – this type of interface reflects the radio link quality for a long time interval. This scenario is typical for mobile speeds corresponding to values of the coherence time smaller than the duration of a single transmission time interval, making it unrealistic to assume the channel constant along one or two radio frames. Only statistical channel behavior is assumed as channel state value is averaged over time. The average value interface is not accurate if there are fast changes in the interference due to, e.g., high bit rate packet users.

**Actual Value Interface** – this type of interface reflects the instantaneous value of the radio link. It is suitable for scenarios of low mobility, resulting in a slow fading channel profile.

Figure 3.10 illustrates the processing blocks involved in system level simulations and their dependencies.

These blocks reflect the functionalities implemented in both PHY (left) and MAC (right) layers. It can be observed that:

- The performance of the physical layer, as modeled by the Link to System Interface Module (LSIM), depends on both the channel quality and the interference conditions, and is reflected in the computation of the SINR metric. The SINR depends on the position of each mobile on the network (geometric factor) and on the traffic load due to the total amount of active mobiles in the system.



**Figure 3.10: Overview of Link to System Level Interface**

On the System Level, the MAC sub-layer schedules the amount of resources required by each service flow. Its performance depends on the Quality and Measurement Models used. The Quality model is responsible for the estimation of the link performance based on the resource allocation. Link quality estimation is performed by means of the Packet Error Rate (PER) or the BLER, and these metrics are the outputs of the Look-Up Tables (LUT). The Measurement Model is the block responsible for the computation of the quality metric used by MAC algorithms such as: channel-dependent scheduling and resource allocation, power control and link adaptation.

For proof of concept we selected 6 transmission modes of the LTE, among the 15 possible, which includes different modulation and coding schemes which will serve the purpose of the proof of concepts carried-out on the work of this thesis.

**Table 3.1 LTE Transport Block size and Bit rate associated to MCS**

MCS (Mode)	Modulation, Code Rate	Transport Block size (bits)	R(CQI) [Mbps]
MCS 1	QPSK, $\frac{1}{2}$	4200	4.82
MCS 2	QPSK, $\frac{3}{4}$	6300	6.3
MCS 3	16-QAM, $\frac{1}{2}$	16800	16.8
MCS 4	16-QAM, $\frac{3}{4}$	25200	25.2
MCS 5	64-QAM, $\frac{1}{2}$	25200	25.2
MCS 6	64-QAM, $\frac{3}{4}$	37800	37.8

#### **3.4.1.4 Evaluation and Metrics**

In order to evaluate the performance of any system and/or respective resource management algorithms, evaluation outputs metrics and statistics are needed. To evaluate the performance of DRA based algorithms, a number of statistics are collected for the computation of the performance metrics in the SLS. In this section we overview relevant performance metrics, which are available in the literature and discuss their merits and limitations. The performance can be evaluated from a user's perspective in terms of QoS provisioning, or from the overall system basis.

On a user or service perspective, the different metrics can be grouped in objective performance metrics and subjective metrics. Objective metrics are referred to as Grade of Service or QoS. These metrics comprise all data that can be measured directly, such as packet delay and jitter, throughput, packet loss. Subjective metrics



are always specific to a particular application or service. For some applications, it is possible to infer a subjective performance metric from measured objective metrics, such as for speech. However, most applications, like for example video applications, require extensive test trials with test users.

The evaluation from a system perspective, most of the important metrics are related to air interface usage efficiency, spectral efficiency, both at cell center and at the cell edge. When multiplied by the available bandwidth, the spectral efficiency results in the aggregate cell sector throughput and the cell edge throughput, respectively. Along with the Throughput distribution across the cell, the study of SIR or SINR is important since it is directly relate to the maximum achievable spectral efficiency (and Throughput) defined by the Shannon–Hartley theorem. One approach used to evaluate the SINR and Throughput distribution across the cell, is by measuring the cumulative distribution function (CDF) of all mobile terminals in a cell sector, which effectively shows how often a particular throughput result can be expected [81].

In the following section we will present and describe some metrics that are used in the system level performance. Although a general and broad view of existing and possible metrics is used in the system level performance evaluation, in this study the evaluation results were made for cell and the overall system point-of-view.

In the execution of each transmission time interval a number of statistics are collected for the computation of metrics used in the evaluation of the system level performance. These performance statistics are generated as outputs from the system level simulations and are used in the performance evaluation of the defined scenarios

and proposed algorithms. The following parameters are used as inputs for the computation of the performance metrics:

- Simulation time per run:  $T_{sim}$ .
- Number of simulation runs:  $D$ .
- Total number of cells being simulated:  $N_{cells}$ .
- Total number of users in cells of interest (cells being simulated):  $N_{users}$ .
- Number of packet calls for user  $u$ :  $P_u$ .
- Number of packets in  $i_{th}$  packet call of user  $u$ :  $q_{i,u}$ .

### **Spectral Efficiency (bps/Hz)**

This is the ratio of correctly transmitted bits over the radio resources to the total amount of available bandwidth. The average cell spectral efficiency is defined as in equation (6).

$$SE = \frac{R}{BW_{eff}} \quad (7)$$

Where  $R$  is the aggregate cell throughput,  $BW_{eff}$  is the effective channel bandwidth, defined as  $BW_{eff} = BW * TR$ , where  $BW$  is the used channel bandwidth and  $TR$  is the time ratio of the link. For example for TDD with DL: UL=2:1,  $TR = 2/3$  for DL and  $1/3$  for UL.

### **Average Service Throughput per-Cell**

The average service throughput per cell is defined as the sum of the total amount of bits successfully received by all active users in the system, divided by the product of the number of cells simulated and the simulation duration.

$$R_{service}^{DL(UL)} = \frac{\sum_{u=1}^{N_k^{usersDL(UL)}} \sum_{i=1}^{p_{u,k}^{DL(UL)}} \sum_{j=1}^{q_{i,u,k}^{DL(UL)}} b_{j,i,u}}{N_{cells} T_{Sim}} \quad (8)$$

Where  $N_k^{usersDL(UL)}$  is the number of users transmitting in DL(UL) in the  $k_{th}$  cell,  $p_{u,k}^{DL(UL)}$  is the number of packet calls for user  $u$  in cell  $k$ ,  $q_{i,u,k}^{DL(UL)}$  is the number of packets for the  $i_{th}$  packet call for user  $u$  in cell  $k$  and  $b_{j,i,u}$  is the number of bits received with success in the  $j_{th}$  packet of packet call  $i$  for user  $u$  in cell  $k$ .

### Offered Cell Load (kbps/cell) (3GPP Definition)

This metric is used in the evaluation of the data load (in kbps) withdrawn from the base station's buffers for transmission, i.e., the influence of the channel in the transmission of the data is not being considered.

$$R_{OL3GPP}^{DL(UL)} = \frac{b_{Sent}^{DL(UL)}}{N_{Cells} T_{Sim}} \quad (9)$$

Where  $b_{Sent}^{DL(UL)}$  is the total amount of data bits that have been withdrawn from the base station's queues and sent over the air interface for DL(UL) connection, for all mobile stations being simulated over the whole simulation run.

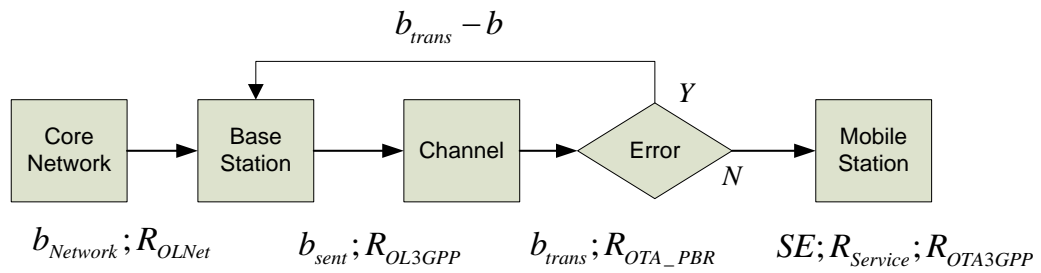
### Offered Cell Load (kbps/cell) (Network Definition)

This metric measures the offered load from the core network to the base station for all mobile stations being simulated in the system over the whole simulation run.

$$R_{OLNetwork}^{DL(UL)} = \frac{b_{Network}^{DL(UL)}}{N_{Cells} T_{Sim}} \quad (10)$$

Where  $b_{Network}^{DL(UL)}$  is the total amount of data bits that have arrived to the base station's queues from the core network over the whole simulation run.

Figure 3.11 illustrates the relation among these different metrics and figures.



**Figure 3.11: Traffic metrics interdependence**

### Use Average Packet Delay

The average packet delay is defined as the average interval between packets originated at the source station (mobile or base station) and received at the destination station (base or mobile station) in a system for a given packet call duration. The average packet delay for user  $u$  is given by equation (10).

$$D_u^{avg,DL(UL)} = \frac{\sum_{i=1}^{P_u} \sum_{j=1}^{q_{i,u}} (T_{j,i,u}^{dep,DL(UL)} - T_{j,i,u}^{arr,DL(UL)})}{\sum_{i=1}^{P_u} q_{i,u}} \quad (11)$$

More detail of the system simulation implementation is presented in the Annex 1.

### 3.5. Validation Results

#### 3.5.1.1 Reference Simulation Scenario

Main simulation parameters are mentioned in Table 3.2. LTE hexagonal cells deployment is considered, which considers a layout of 3 tiers consisting of 19 cells, depicted in Figure 3.12. All the simulation results are collected from the central cell, with the other cells serving as interferers.

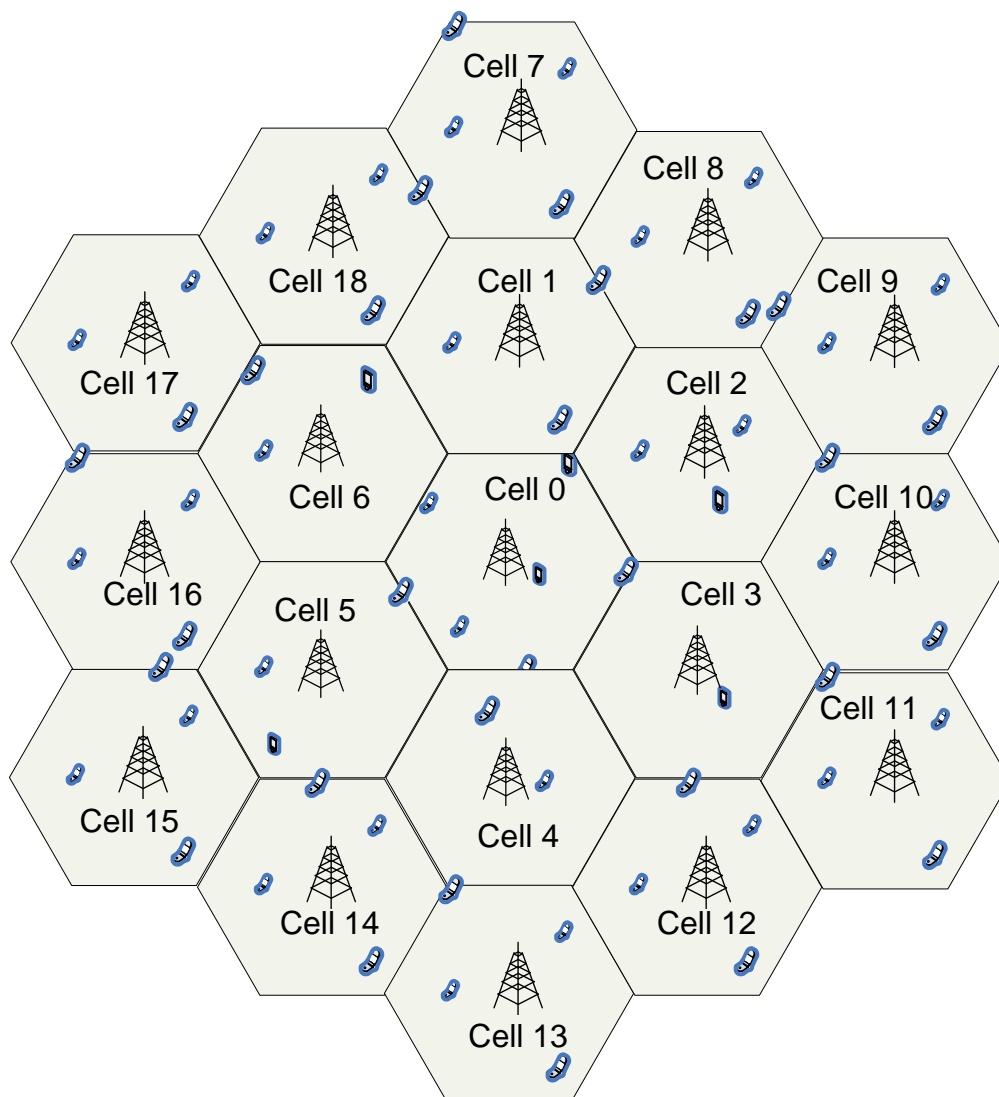
The simulator includes several propagation and traffic models, and the channel losses are computed by the simulator (both slow and fast fading), ensuring thereby accuracy in the system level parameters computed.

**Table 3.2 LTE simulation parameters**

<b>LTE Simulations Parameter</b>	
Download Transmission Technique	OFDMA
Uplink Transmission Technique	SC-FDMA
Duplex Method	FDD & TDD
Channel Bandwidth[MHz]	1.4 , 3 , 5 , 10 , 15 , 20
Number of Resource Blocks	6 , 15, 25, 50, 75 , 100
Subcarrier spacing	15Khz
Frame Size	10ms with 10 sub-frame
Scheduling Speed	Every sub-frame (1ms)
Modulation	QPSK,16QAM,64 QAM
Coding	Turbo code (1/2, 2/3...)
Diversity	SISO (MIMO possible up to 2×4 (TD & SM))

Link Adaptation	EESM with 3 HARQ process
Scheduler	Round Robin, MAX C/I, Proportional fairness
Traffic	Mix/Full Queue (NGMN specification)
Channel Modelling	Path Loss, Shadowing &Fast fading (SISO&MIMO)
Deployment	Hexagonal
Cell Size	2200m

The radio resource management block comprises algorithms for the call admission control (to regulate the operation of the network), link adaptation (to select the appropriate parameters in function of the current radio conditions) and the scheduler that decides how to allocate the appropriate radio resource to the users, which settings for the cell and operator selections, based on the service type, the amount of data, the current load in the cell, among others. The interference block (SINR) determines the average interference power received by central base station, i.e. inter-cell interference.



**Figure 3.12: Simulation scenario with cells deployment**

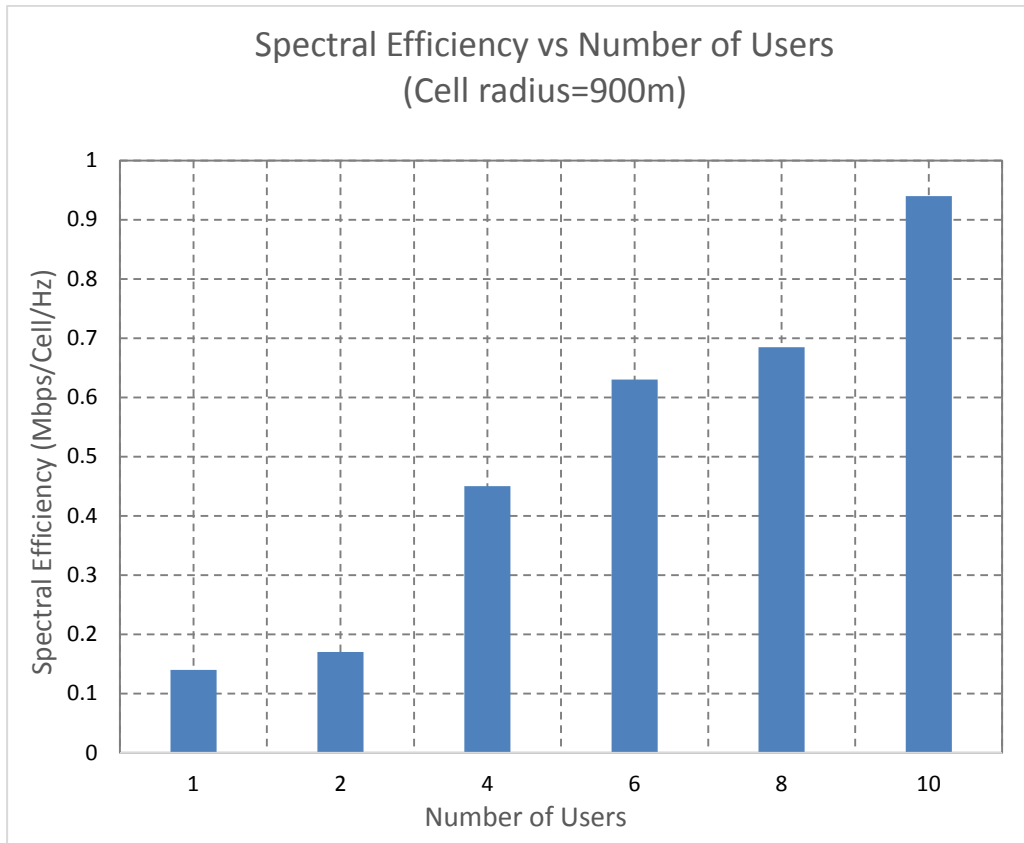
The arrival process of the users is generated by the scheduler mechanism, according to a Poisson arrival process. Data is allocated by each MS in units of RB (Resource Block). RB, as described in section 2.3. spans 12 consecutive sub-carriers at a sub-carrier spacing of 15 kHz, and 7 consecutive symbols over a slot duration of 0.5 ms. A RB thus has 84 resource elements (12 sub-carriers x 7 symbols) which corresponds to one slot in the time domain and 180 kHz (12 sub-carriers x 15 kHz spacing) in the frequency domain. The number of available physical RBs depends on the

transmission bandwidth and the size of RB is the same for all bandwidths. The number of available RBs in the frequency domain can range from 6 (for the transmission bandwidth of 1.4 MHz) to 100 (for the transmission bandwidth of 20 MHz). For this simulation we are considering the usage of 10MHz bandwidth, thus 50 resource blocks are available to be shared among users in each 1ms sub-frame.

### ***3.5.1.2 Results***

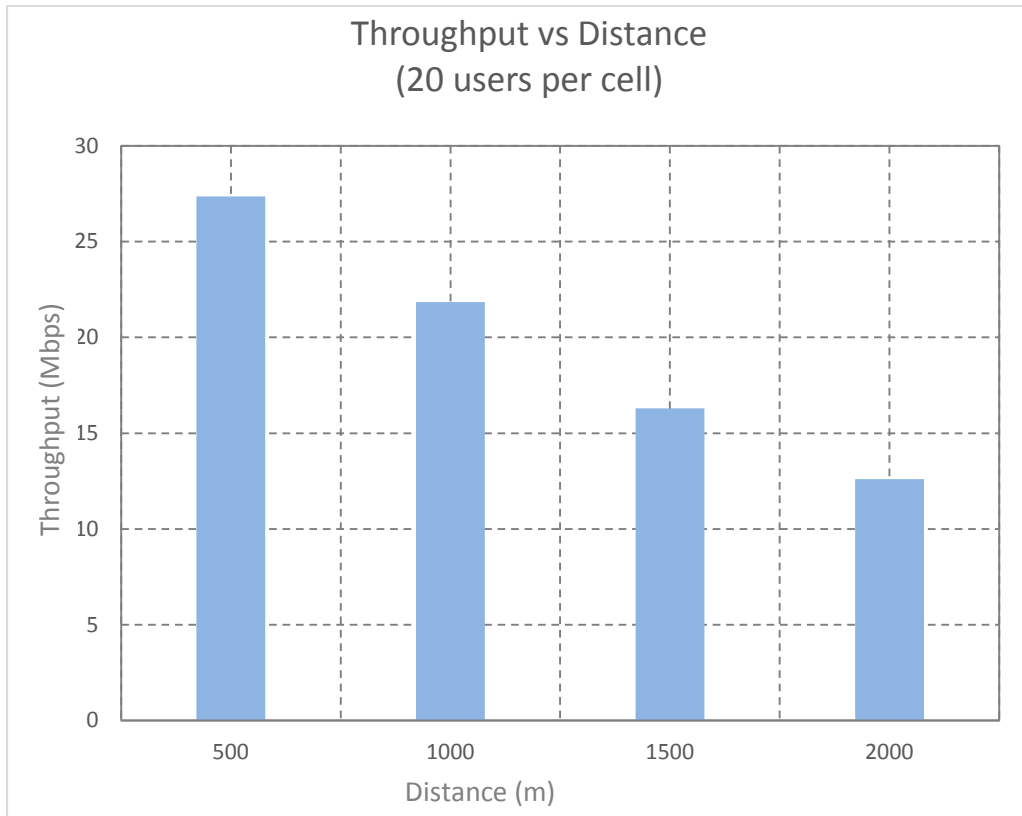
In this simulation, we collect reference simulation results with the DRA schemes described in section 3.2. of this chapter and using the Max C/I scheduling algorithm described in section 2.4.1.3. All UEs receive signals from the BS. In this case the interference comes from the other 18 BSs. Figure 3.13 provides the spectral efficiency of the system with different number of users in the cell. The purpose is to analyze how DRA in OFDMA system can exploit multi-user diversity to increase system efficiency. One can see the spectral efficiency of 0.17 bps/Hz/Cell when there is only one user is in the cell, against 0.94 bps/Cell/Hz when 10 users are in the cell. In fact, when more users are randomly spread in the cell, the DRA can take advantage of opportunistic channel quality to improve the system efficiency of the air interface.





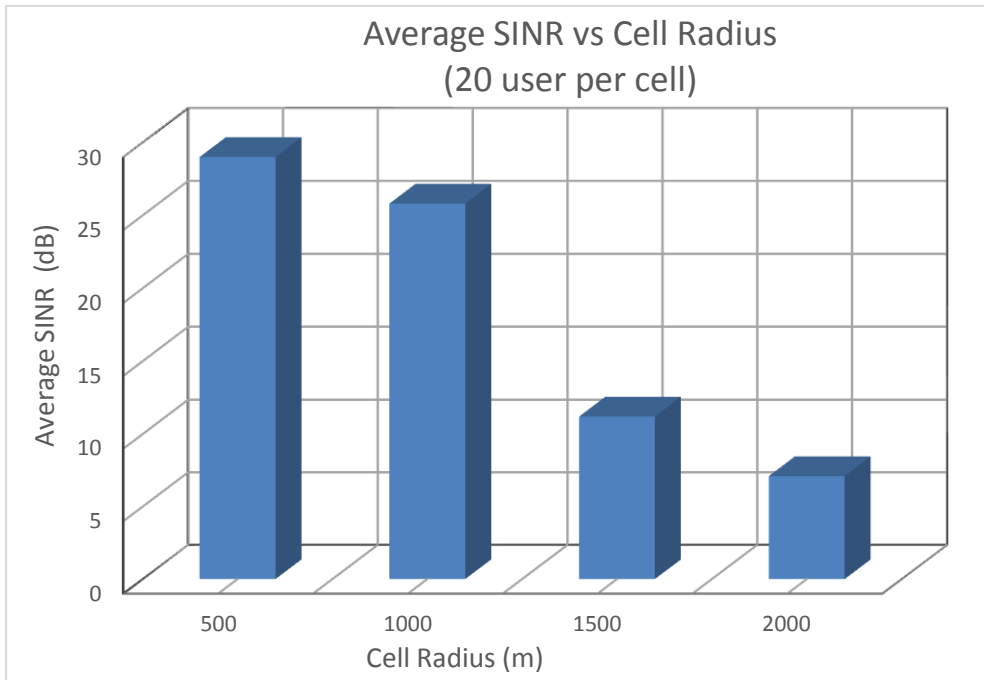
**Figure 3.13: Spectral Efficiency vs Number of users per cell**

Figure 3.14 shows simulation results of average user throughput versus distance from the centre of cell. It achieves a throughput of around 27 Mbps for users close to the centre, against 7 Mbps for users closer to the cell boundary (2000 m from the cell).

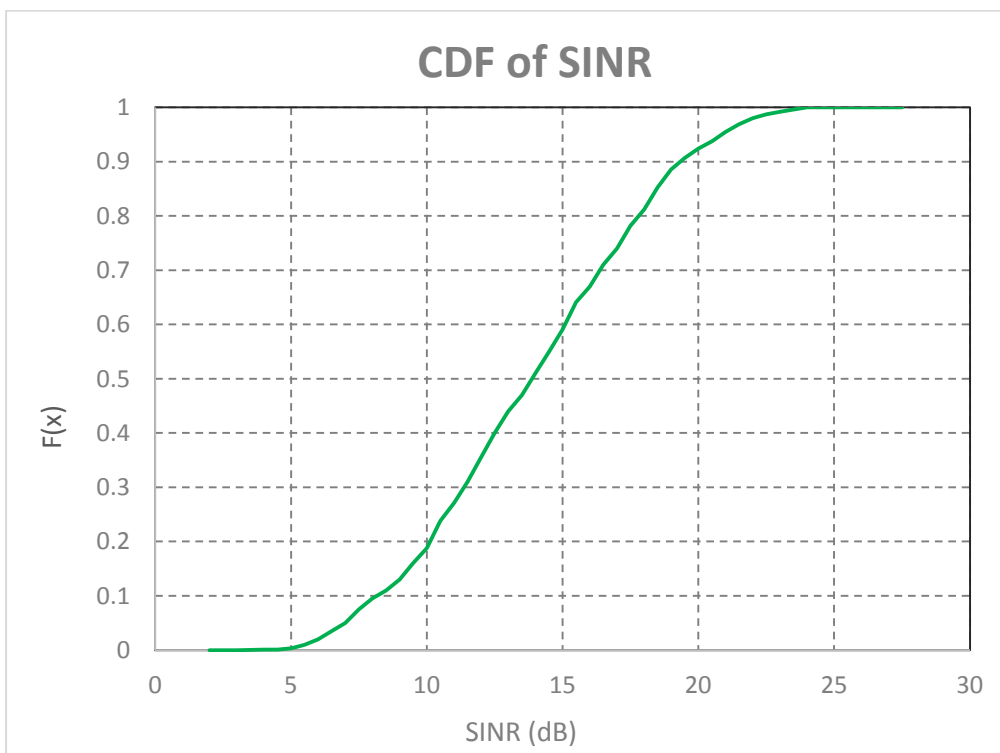


**Figure 3.14: System Throughput vs distance to cell site**

Figure 3.15 and Figure 3.16 show the average SINR values versus distance from the cell and the CDF of this SINR respectively. With these figures, one can assess the expected performance in the cell area. Depending on the expected required performance or traffic demand, the network operator - or owner - can improve the performance in certain areas, for example by resorting to MIMO schemes.



**Figure 3.15: Average SINR vs cell radius**



**Figure 3.16: CDF of Effective SINR**

### **3.6. Summary**

This chapter describes in detail the Dynamic Resource Allocation for OFDMA based cellular systems. We start by describing the scenario for OFDMA based systems, including the fundamentals of OFDM modulation, definition of the OFDMA frame and resource block, and the minimum resource that is shared and transmitted among mobile users. The MAC architecture of the OFDMA system model is elaborated and in particular the DRA process in each frame period is described. Moreover, we explain the simulation methodology for System Level Simulations in wireless and cellular networks, and slowly build a simulation model of our baseline scenario with performance metrics. This chapter also describes in detail all the execution flow in each frame period for the DRA protocol, between the base and the mobile stations, that defines how a packet is queued, assigned a priority and scheduled for transmission, including error control and link adaptation. Benchmark results are obtained and presented for typical DRA strategies that will be used as baseline for subsequent results emanating from chapter 4 and 5.

## **4. Energy-Efficient Load balanced Self-Organizing Network sharing**

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In this chapter we focus on the energy efficiency requirements of future mobile cellular networks and propose an energy-efficient load balancing algorithm for a self-organized shared LTE-A network. Given the baseline approaches described in chapter 2, we define a cooperative networking environment based on network sharing and SO. The network sharing in this context provides the platform for offloading users between network operators without additional investment in infrastructure. This scenario is complemented by SO, that until now is still in its infancy and employed to overcome manual procedures with regards to installing and configuring new networking elements. Here we extend SO towards resource management allowing the system to fully benefit from network sharing in a dynamic way. Load-balancing is a typical approach for redistributing users among the available cells, however we aim to extend current load balancing approaches to work not only in synergy with SO and network sharing, but to be energy efficient. We propose a so called energy efficient SO-LB approach for network shared networks. The load balancing approach exploits the notion of utility functions, to define a suitability objective function, where users are allocated the best available network/cell based on the service requirement (QoS profile) and the energy cost. The scenario is modelled and validated using a system level simulator.

## **4.1. Chapter Organization**

In this chapter we analyze the energy efficiency requirements of future mobile cellular networks and propose an energy-efficient load balancing algorithm for a self-organized shared LTE-A network, given the baseline approaches described in chapter 3. We define a cooperative networking environment, bringing together the notions of Relay Nodes, Network Sharing, Load Balancing, Self-Organization and energy efficiency in synergy to provide a new approach toward load balancing and enhancing spectral efficiency.

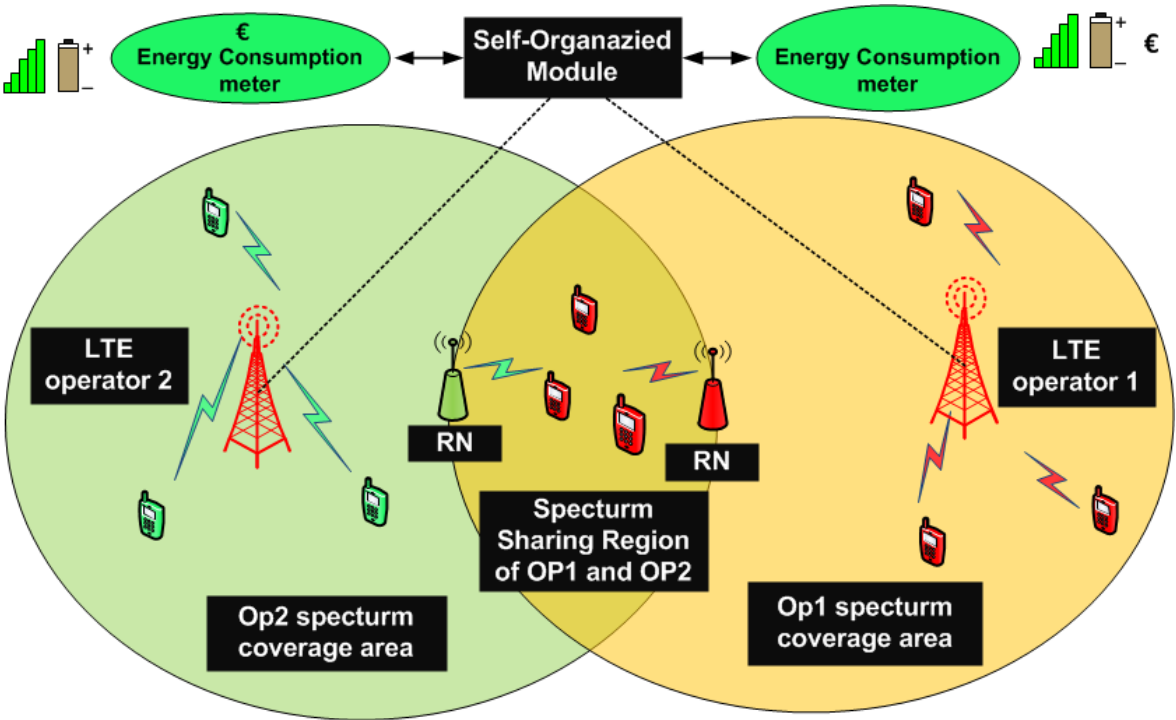
The rest of the chapter is organized as follows: Section 4.2. presents the novel SO-LB framework in a shared network, while section 4.3. showcases the simulation model and results, followed by summary in section 4.4.

## **4.2. Self-Organized Load Balancing**

### **4.2.1.1 Scenario Definition**

A relay-aided shared network composed by two LTE systems belonging to two operators—LTE operator1 (*op1*) and LTE operator2 (*op2*) is depicted in Figure 4.1. The coverage area of *op1* is represented by orange color, and the coverage area of *op2* is represented by green color. The dark green-orange color represents a crossed area covered by both operators. Each operator has its own BS (eNB) as well as RNs. BSs are located at the center of coverage area, while RNs are installed at pre-optimized location having Line-of-Sight connection to their associated BS. MUs are randomly distributed over the entire area. With a service-level agreement between

*op1* and *op2*, the MUs are allowed to communicate with any RN and any BS regardless of the associated operators. The RNs are allowed to communicate with any MU, but only with the BS belonging to their same operator. The BSs can communicate with each other via the backhaul link, and they are controlled by a remote entity called “RAN sharing”.



**Figure 4.1: Self-organizing load balancing scenario**

Only down-link data traffic is considered in this work, and the buffer-size at BSs and RNs for each MU is assumed to be infinite. We assume that the operators use different frequency bands. The transmit power of a RN is 10 % of the transmit power of a BS. For an LTE system, the basic unit of data transmission in every frame is a resource block (RB), composed by OFDM sub-carriers. The resource block size in bits, the modulation used and respective achievable bit rate used by our LTE system

level simulator is presented in the Table 3.1, in section 3.4.1.3. The communication to the MU belonging to any operator can be made in two different ways:

1. With a direct link from a BS belonging to *op1* or *op2*;
2. Via a RN belonging to *op1* or *op2*;

#### ***4.2.1.2 Beyond the State-of-the-Art***

Compared to the current state of the art, in this chapter we propose a novel framework for energy-efficient load balancing algorithm in self-organized shared network. We consider energy efficiency according to operators' point of view. In this chapter we bring the novelty by considering a new complex scenario that combines the aforementioned four techniques, namely, network sharing, self-optimization, load balancing and energy efficiency. More explicitly, relay node (RN) and LTE technologies are employed. The proposed method is based on two assumptions.

1. Firstly, the service area is jointly covered by two different network operators having service level agreement, so that their subscribers are free to communicate with both of them through Load Balancing algorithm. For the 3GPP network sharing point-of-view, this can be a situation close to the use case 9 described in section 2.2.1.3, where both involved operators play the role of Hosting RAN Provider, and Participating Operator in a complementary region, as depicted in the Figure 4.1.
2. Secondly, a centralized SON algorithm is proposed for optimizing the mobile users (MUs) communication mode with the purpose of minimizing the energy consumption per bit. The MUs are allowed to communicate in different manners, including directly to their closest cell, or via a RN content.



#### 4.2.1.3 Load Balancing Algorithm

A Load balancing algorithm is centrally controlled by the SON module, which will be discussed at a later stage. Studies show that concave and convex functions are the most suitable types of functions when bounded and limited parameters are evaluated. This is the case of scheduling delay bounded packets [88], [89]. Based on these principles, an empirical algorithm for energy consumption optimization and load balancing among the two LTE operators is proposed for the incoming calls. The idea behind the algorithm is to select the suitable operator  $S_{opi}$  to serve the new incoming user call based either on load or energy efficiency constraints of both operators. Load balancing based suitability or energy efficiency based suitability condition will be used, depending on the critical load condition  $L_{th}$  achieved by any of the operators.  $S_{opi}$  is expressed by the following equation

$$S_{opi} = \begin{cases} S_{L,opi} & \text{if } L_{opi} \geq L_{Th} \\ S_{EE,opi} & \text{if } L_{opi} < L_{Th} \end{cases}, \forall i = 1, \dots, O \quad (12)$$

where  $S_{L,opi}$  is the suitability when operators load  $L_{opi}$  are in load critical conditions,  $L_{opi} \geq L_{th}$ , and  $S_{EE,opi}$  is the suitability based on energy efficiency, when operators are in under load condition,  $L_{opi} < L_{th}$ .  $O$  is the number of available operators covering the area of the user in current time, which in our case is two.

For load critical conditions the following empirical convex algorithm is proposed to balance the load among the two operators:

$$S_{L,opi} = \arg \max_{opi=1:O} \left( \frac{1 - L_{opi,n,m}}{1 - L_{Th}} \right)^2 \quad \text{if } L_{opi} \geq L_{Th}, \forall i = 1, \dots, O \quad (13)$$

The load  $L_{opi,n,m}$  is a normalized Load value according to the LTE system capacity in terms of available resources (see chapter 3. and Table 3.1), when the operator  $opi$  is communicating to the new mobile user  $n$  using mode  $m$  (Table 3.1).

The normalized load estimation in any cell of the operator  $opi$ , is obtained as the ratio between the active load in the cell and the overall cell capacity as described by the following equation:

$$L_{Normalized} = \frac{L_{active}}{L_{capacity}} \quad (14)$$

where  $L_{active}$  is the active load in the cell and can be directly obtained by the sum of average service rate associated to each user, while  $L_{capacity}$  is the actual capacity of cell taking into account the radio propagation conditions of each active user (for example fading model parameters in Table 4.1).

- Suitability for Energy Efficiency

The other suitability condition in equation (12) is based on energy constraint, when cells of each operators are not load critical condition, then the SON can optimized the energy consumption. The energy saving problem is to select the suitable operator that minimize the energy consumption of the BSs, either transmitting directly using the eNB or through the relay. The suitability for Energy Efficiency is formalized as follow

$$S_{EE,opi} = \arg \min_{opi=1..O} \left( E_{opi,n} = \frac{P_{tx}}{R_{n,m,SINR}} \right), L_{opi} < L_{Th}, \forall i = 1, \dots, O \quad (15)$$

where  $E_{opi,n}$  is the energy consumption per bit, as given in the equation (18) bellow, when operator  $opi$  communicating to the mobile  $n$ ,  $P_{tx}$  is total the transmitted power (both using eNodeB link or RN link).  $R_{n,m,SINR}$ , is the effective data rate of user  $n$ , using mode  $m$ , and experiencing  $SINR$  signal to noise plus interference ratio, as given in equation (20) bellow. The equivalent mode transmission  $m$ , as given in Table 3.1. The transmission power  $P_{tx}$  is given by the following equation (16),

$$P_{tx} = P_{BS} + x_r(t)P_r \quad (16)$$

which is the sum of the transmit power of the BS,  $P_{BS}$  and of the relay,  $P_R$ , where  $x_r(t)$  is equal 1 if relay is used for transmission, or equal to 0 if the communication through direct from the base station.

#### ***4.2.1.4 Self-Organizing Algorithm***

In this subsection, we define the following parameters related to the self-organizing algorithm.

- Coverage Area of each Operator

We assume that the coverage area has a hexagonal shape  $r_{opi}$ , and the symbol  $r_{opi}$  represents the edge length of the hexagonal area covered by  $operator\_i$ . As a result,

the area covered by  $operator\_i$  is calculated as  $\varphi(op_i) = \frac{3\sqrt{3}}{2}r_{opi}^2$ . Moreover, the

length of the hexagon changes depend on the transmission power  $P$ . The position of the Fixed Relay Station (FRS) depends upon the transmission power of the base station, and the optimal positioning of relays is found through simulations (Sect. 0). FRS are deployed at the distance of 2/3 radius from the base station.

- Operators sharing area

This metric represents the ratio of the sharing area between  $operator\_i$  and other operators which is expressed in the following:

$$SA_{op_i} = \frac{\sum_{j=1, j \neq i}^O \phi(op_i, op_j)}{\phi(op_i)} \quad (17)$$

where  $\phi(op_i, op_j)$  is the area of the region shared between  $op_i$  and  $op_j$ . The symbol  $SA_{op_i}$  represents the sharing ratio. A large  $SA$  means large sharing area. Index  $j$  is the operator index;  $O$  is total number of operators, and  $\phi(op_i) = \frac{3\sqrt{3}}{2} r_{op_i}^2$  is the area value of the region covered by  $operator\_i$ .

- Energy

Energy expenditure of each operator in sharing region is measured in Joule/Bit

$$E : \frac{Power}{Data\ rate} : \frac{Watt}{bit/second} : \frac{Watt \times second}{bit} : \frac{Joule}{bit} \quad (18)$$

- Reference signal received power (RSRP)

We consider that the transmit power of the BS in  $operator\_i\ cell_i$  is measured in  $P_i$  (dBm) at the antenna, the path-loss from this BS to a user MU  $n$  equal to  $\Gamma_{i,n}^p$  (dBm), the corresponding shadow fading  $\Gamma_{i,n}^s$  (dBm) has a log-normal distribution with standard deviation of 3 dB, and the fast fading is represented as  $\Gamma_{i,n}^f$  (dBm). The RSRP in dBm between this user and the BS in cell $i$  is formulated as

$$RSRP_{i,n} = P_i - \Gamma_{i,n}^p - \Gamma_{i,n}^s - \Gamma_{i,n}^f \quad (19)$$

• *Signal-to-interference-and-noise ratio (SINR)*

Supposing that the user  $n$  is connected to the BS in  $cell_i$ , and receives interference from other cells, and then SINR is formulated as

$$SINR_n = \frac{RSRP_{i,n} (mW)}{\sum_{j \neq i}^O RSPR_{j,n} (mW) + N_0 (mW)}, \quad (20)$$

where all values are converted from dBm into mW,  $O$  is the total number of cells, and  $N_0$  the symbol represents the noise power.

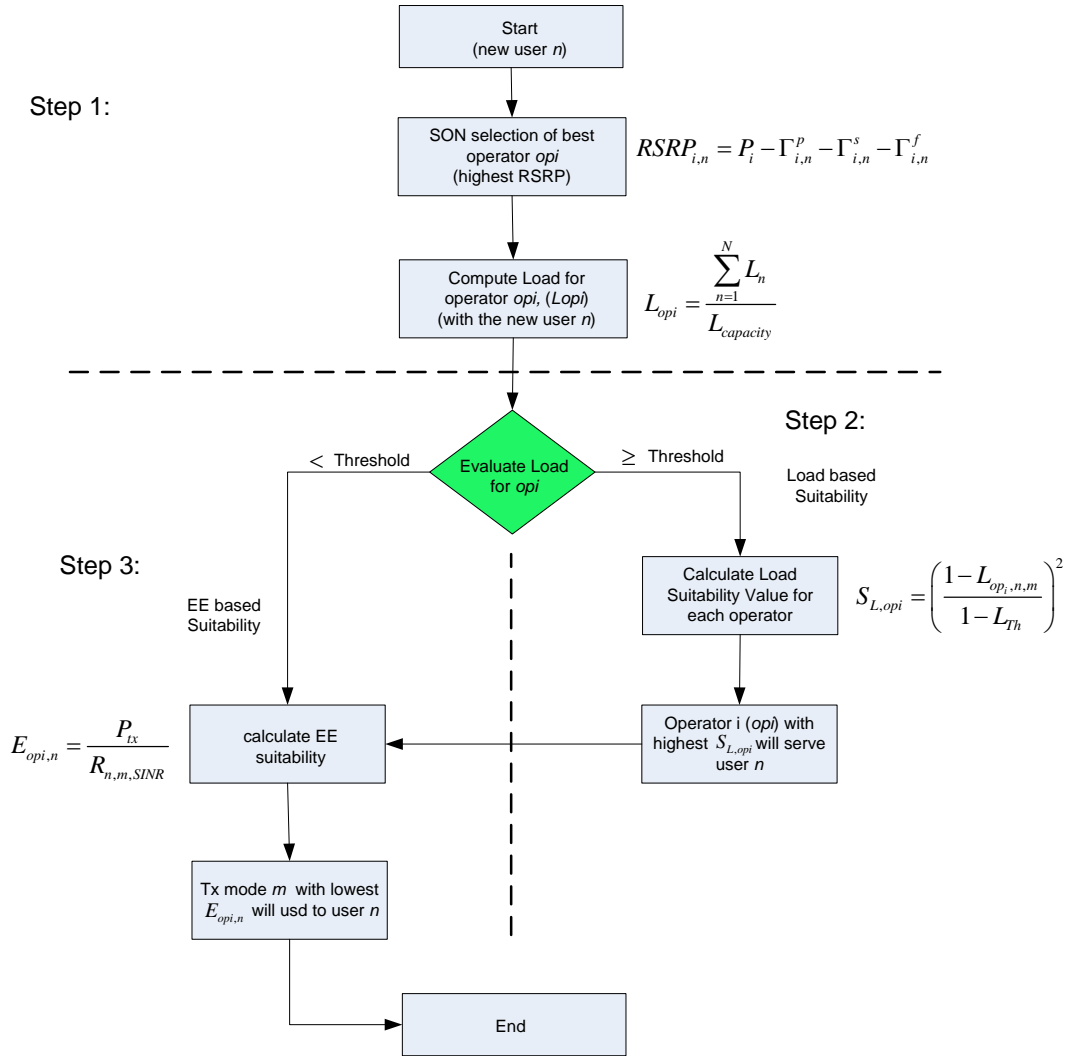
The selection of serving operator is based on the reference signal received power (RSRP) of MU, which comprises an offset that can be positive or negative. This RSRP value is calculated at the SON module by exploiting all feedback information including the current loading value and the current channel conditions. However, if the RSRP has the same strength for both operators, a subscriber of  $op1$  prefers to connect to BS/RN belonging to this  $op1$ , since an operator intends to use its own resources as much as possible rather considering the extra cost introduced by using the resources of other operators. For the sake of simplicity, we only consider a scenario where  $op1$  is overloaded and some of its subscribers located at the crossed region can be transferred to  $op2$  by the load balancing algorithm. This scenario is represented in Figure 4.1. However, all the calculation made for this scenario is also valid for the symmetric scenario of overloaded  $op2$ . Referring to the network sharing categories described in section 2.2.1.3, the scenario we considered is an active RAN

sharing. Moreover, the two operators could either further share or not their MSC, core network, etc., or not depending on their policies. Particularly, we are only taking into account in the proposed algorithm, the Radio Access Network.

### **4.3. *Simulation Model and Results***

We consider a LTE-A cellular system consisting of 19 cells. All the simulation results are collected from the central cell, with the other cells serving as interferers. The system level simulator (SLS) interfaces with the link level simulator through look up tables (LUTs), which are input to the simulator, described in section 3.4.

Simulation parameters are summarized in Table 4.1 and the self-organization module operation is illustrated in Figure 4.2. The self-organization module takes as input parameter the RSRPs and SINRs from users' feedback, as well as the current traffic load from the BS counter.



**Figure 4.2: Flow chart illustration of the iterative optimization processing of SON module**

**Table 4.1: Simulation parameters**

Parameters	Downlink LTE-A (FDD) System
Carrier frequency $f_c$	Operator_1: 2GHz Operator_2: 1.9GHz
Bandwidth	10MHz
Fast fading model	Rayleigh fading using Pedestrian B model (6 taps, SISO) Urban
Number of Cells	Hexagonal grid
Number of Users	100 per cell

User speed	3 & 30 km/h
Users Power	23dBm
BS transmit power	43dBm
Inter-site distance	500m
Time transmission interval ( $T_{ii}$ )	1 ms (sub-frame)
Number of Resource Block	50 RB in each slot, 7 symbol, number of subcarriers per RB=12, total subcarrier=600
Link Adaptation	EESM( Exp Effective SINR Mapping)
Traffic model	Mix Traffic Option (VoIP & NRTV), Cell Arrival Rate: 10 user/cell/Sec
Radio Resource Management	RR, PF, Max C/I
Number of MCS	12 (from QPSK 113 to 64-QAM 3/4)

For the SO-LB scheme we are proposing in this chapter, we will analyze the performance based on network parameters that this scheme is intended to enhance, such as overall system throughput, load balancing in each operator, and the energy efficiency.

#### ***4.3.1.1 Relays' Optimal Position***

Figure 4.3 shows the average SNR value with respect to the fixed relay positions in the cells. The relays are placed on the segment between the overlapping regions of the cells. Here the fixed relay position is indicated by a parameter  $m$  showing how far away the relay is from the BS. Note that relays are included in all cells.

$$m = \frac{a}{R} ,$$

where  $a$  is the distance from the BS to the relay, and  $R$  is the distance from the BS to one corner of the cell. Results show that the best range for the relay position is 0.7 to



0.8 away from the BS (related to the cell radius), when the transmit power of the BS is 43 dBm. FRS uses 10 % of the transmission power of a BS. In fact, we have concluded that the position of relays is highly dependent of both transmit power of BS and cell radius.

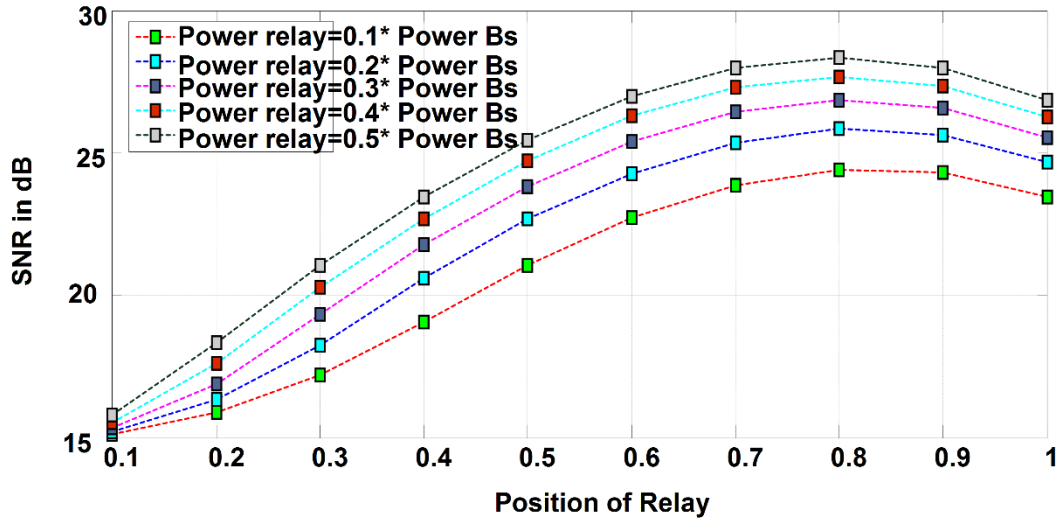


Figure 4.3: Optimal fixed relay position

#### 4.3.1.2 Network Sharing

Figure 4.4 shows the simulation results of average cell-edge user throughput versus the entire cell load. Traffic load and sharing region of each operator are calculated according to Equations (2) and (3) of this chapter.

A user is defined as cell-edge user if the distance between the user and its serving BS is larger than  $2/3$  of the radius of the cell [90]. The Proportional fair scheduling described in section 2.4.1.3 is employed. It is demonstrated that the achievable average throughput of cell-edge users with network sharing is significantly higher than the throughput without sharing strategies.

For instance, cell-edge average user throughput gain in non-sharing scheme is 33% on cell load of 12Mb/s, while in multi-operator sharing scheme the average user throughput is increased approximately by about 22% on same cell load. This is because, being aided by network sharing, the cell edge users become able to communicate with a closer BS. As a result, the channel quality as well as the achievable throughput experienced by the cell-edge user is improved.

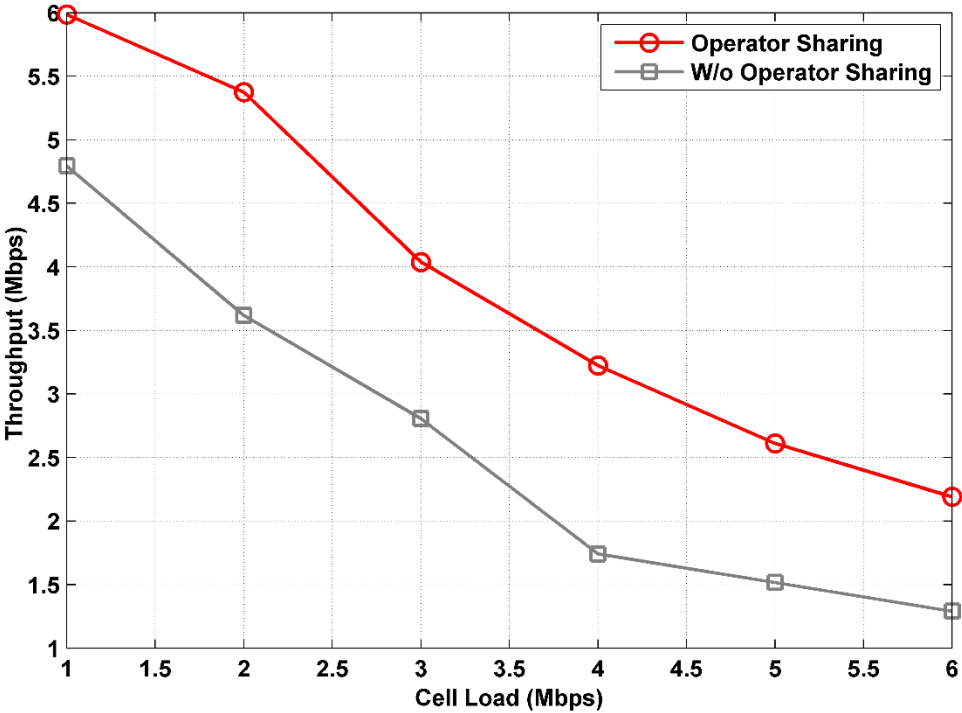


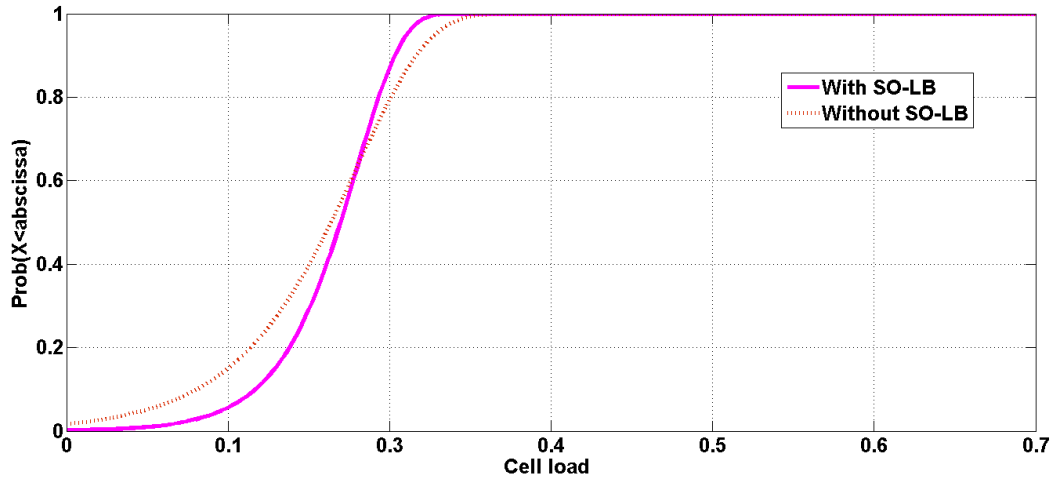
Figure 4.4: Total cell load versus average throughput of op-1 cell-edge users

4.3.1.3 Self-Organized LB

As illustrated in Figure 4.2, the self-organization module takes as input parameters the RSRPs and SINRs from users’ feedback, as well as the current traffic load from the BS counter. The module adjusts the load between operators according to these parameters in order to maximize the SINR values of the active users. For example, in a situation like the one shown in Figure 4.1, the demanded traffic load can increase

for *operator\_1*, and can get over the maximum affordable traffic load. In this case, the users who are under the coverage of *operator\_1* cannot be served in a “traditional” way because of traffic overloading. The SON module detects this situation by observing a high ratio of admission denies in *operator\_1*.

As a consequence, the SON module triggers the load balancing algorithm (section 4.2.1.3) and transfers users to the shared region with the help of the relay. More explicitly, the BS of *operator\_1* hands over its cell-edge users from *operator\_2* to the shared region, where *operator\_2* is available to serve these users by the Self-Organized Load Balancing Algorithm. For simulation purposes, fixed numbers of users are deployed in each operator to see the performance of the SON module. Figure 4.5 shows the CDF of cell load aggregated over all operators’ cells and over the whole simulation, for the case of a mean offered load of 2.5 Mbps/cell. As expected, SO-LB results in a narrower CDF (i.e. load is distributed more evenly) but a higher mean load. The mean load is increased because LB causes some cell-edge users to handover earlier with the support of Relay, resulting in worse radio conditions in the cell, and hence worse average radio conditions over the whole network. This worse average radio condition does not decrease overall throughput because the more even distribution of users between cells sustains the throughput.



**Figure 4.5: CDF of cell load**

#### ***4.3.1.4 Energy Efficiency***

Energy efficiency (EE) is simply defined as the ratio of the capacity to the rate of signal power, i.e. the number of bits that can be transmitted per unit energy of energy consumed. Figure 4.6 represents the average optimum cell energy efficiency as function of the cell radius for different perspective of network sharing. The EE is monotonically decreasing as cell radius increases for whole range of radius axis in the plot. Mobile users are randomly distributed over each operator's site. When the cell radius is smaller, the network sharing provides much more gain in EE compared to bigger cell radius as shown in Figure 4.6; that also clearly shows that network sharing achieves significant energy efficiency over non sharing network.

Figure 4.7 shows the average cell throughput with the total transmit power, where the maximum allowable transmit power is 40W as given in the 3GPP LTE downlink specification. From what is observed in the figure, we can see that the operator sharing method can sustain more than 100Mbps average cell throughput with 1W and we can deduce that the operator sharing can save the transmit power about 10W more

than the w/o operator sharing mode while sustaining the same cell throughput. For example, to achieve average cell throughput 125 Mbps our architecture consumes 10 W whereas the w/o operator sharing method consumes 20 W.

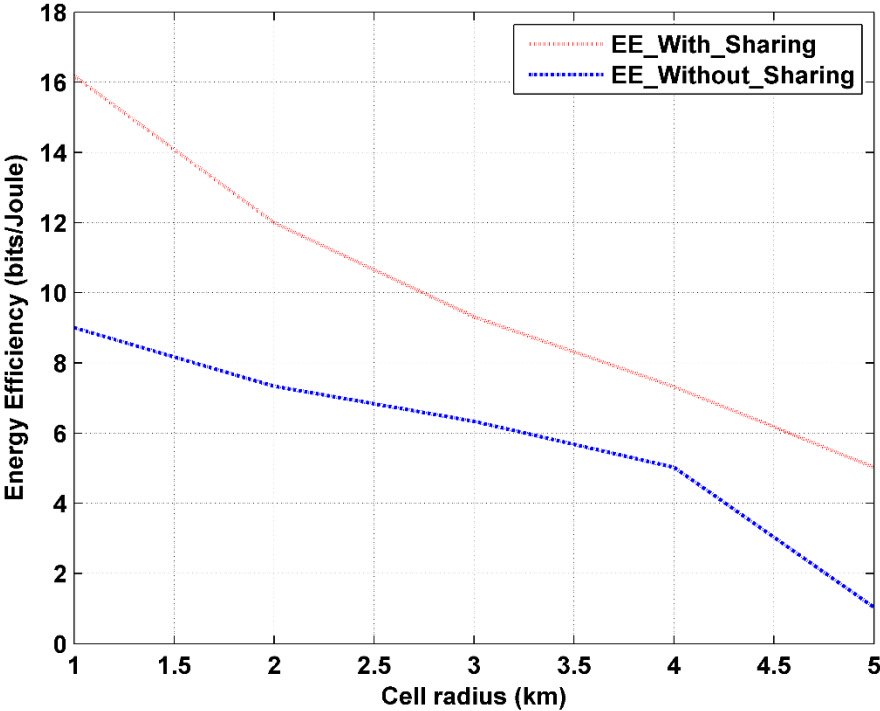
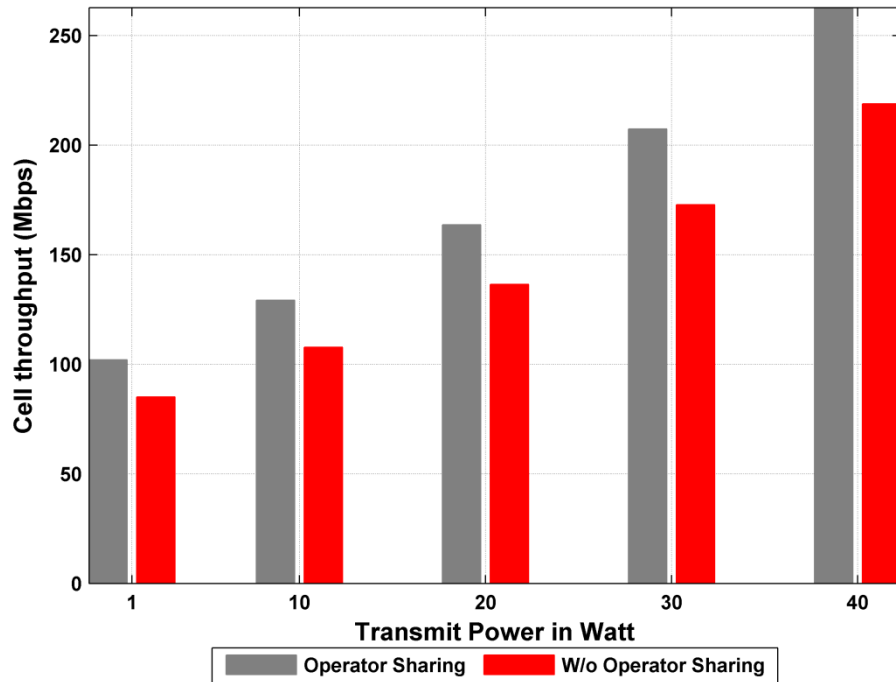


Figure 4.6: Energy efficiency versus cell radius



**Figure 4.7: Tx power versus cell throughput**

#### **4.4. Summary**

In this chapter we present a novel framework for energy efficient resource management in OFDMA systems. We presented an energy efficient load balancing approach, that works in synergy with SO and network sharing as an integrated solution. The results presented in this chapter demonstrate that the proposed design is able to optimize the wireless network utility and enhance the energy efficiency perspective. In particular, the proposed algorithm is able to reduce the energy consumption by up to 15–20 % assisted by SON technology. The results also suggest that significant gain in call blocking and cell edge users' throughput can be achieved in a shared network, with the help of relays.

## 5. Energy Efficient Cooperative Scheduling for Coordinated-Multipoint in OFDMA

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In this chapter Coordinated Multipoint technique is used for Radio Resource Management to improve communication efficiency in OFDMA networks. Coordinated Multipoint systems (CoMP) is a recent addition to the LTE-A 3GPP standard that has shown promising results in terms of capacity and coverage improvement, particularly for users at the cell edge. However, much work is still required towards developing energy efficient CoMP, particular in dense urban scenarios and for supporting high speed data connectivity. Therefore, in this chapter we address user scheduling and resource allocation algorithm for distributed broadband wireless systems based on OFDMA (orthogonal frequency division multiple access) for multimedia services, where the 3D video streaming service is used as an example case. The study considers a *Manhattan* network which is one of the most promising scenarios for CoMP. The algorithm combines the concepts of maximum carrier-to-interference scheduling and antenna selection to increase throughput and ensure zero intra-cell interference. Consequent antenna selection to mitigate the interference leads to a deliberate on-off on the transmission points, with consequent improvement in the energy efficiency. The results show that the use of CoMP improve energy efficiency and can provide significant advantages over conventional deployments for the delay and quality sensitive multimedia services.

## **5.1. Introduction**

The focus of this chapter is on the downlink CoMP transmission chain, and investigates how the scheduling approach can be reengineered to support multimedia services, where the 3D multi-view media and service is used as an example of application; since uplink CoMP technologies tend to have less standardization impact, as receiver processing at the network side can be performed in an almost transparent way when compared to the user equipment (UE) [9]. The proposed algorithm combines the concepts of maximum carrier-to-interference (Max C/I) scheduling and antenna selection diversity. It also shows a considerable improvement of fairness using the Gini coefficient [91], [92] as compared to conventional systems with MaxCI scheduling. The use of the Gini fairness index, as an inequality measure of resource sharing, has been borrowed from the literature of economics and indicates that a much more equal access is granted to the users, is a new approach to fairness studies of OFDMA system [93].

The remainder of the chapter is organized as follows: in Section 5.2. the system model is described, in particular the Manhattan scenario [83], [84] and the propagation models. Section 5.3. illustrates the proposed cross-layer design, in particular the resource scheduling algorithm applied to the 3D video services. In Section 5.4. , the proposed technique is validated on a system level simulator and results are presented. A summary of the chapter is made in Section 5.5.



## 5.2. System Modelling

### 5.2.1.1 Coordinated Multi-Point

The Coordinated Multi-Point (CoMP), depicted in Figure 5.1, consists of a set of Remote Radio Heads (RRH) connected (via fiber) to a central unit (CU) where a joint processing is performed. Inside one CU there are several joint processing units (JPU), each one processing several RRHs. The main virtues of CoMP are: simplified BSs (RRHs), lower maintenance costs, re-configurability and upgradeability. CoMP extends the cell concept in cellular systems by allowing multiple RRHs to form a dynamic cell (called here joint processing area or CoMP area). It brings flexibility to setup a cell, which consists of two options: multiple RRHs as branches of a virtual MIMO system in a single cell, or multiple RRHs forming multiple overlapped cells in which some RRHs serve multiple cells.

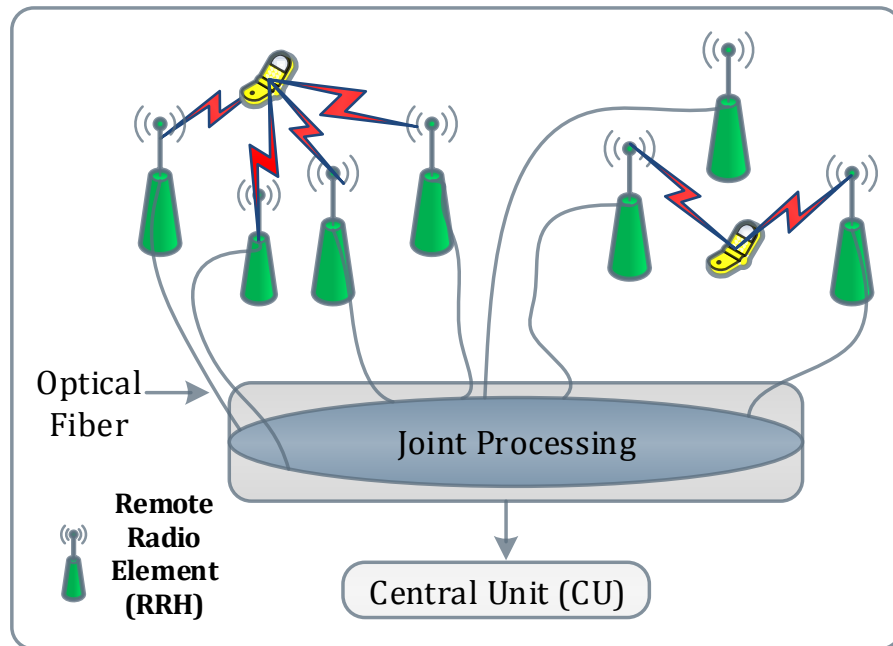


Figure 5.1: Coordinated Multi-Point (CoMP)

### *5.2.1.2 Manhattan Scenario*

Manhattan Model is proposed in [83] for broadband systems. The Manhattan model is an attractive scenario for deployment of the CoMP in a dense urban environment, where fiber has already been deployed and can be reused to transport the radio signals to/from the RRHs, or can be economically deployed. Furthermore, end users will be mainly in line-of-sight conditions or near line-of-sight with the antenna. This Manhattan deployment consists of a rectangular regular grid of RRHs. This rectangular grid follows the regular street structure of a city with buildings, streets, and blocks of the same size. The RRHs are considered to be deployed at optimal positions on the streets.

For purposes of the CoMP system, the CoMP area is defined as the group of RRHs that are jointly processed at the CU. Within this CoMP area, a user can be attached to only one of the RRHs using selective antenna algorithms, or to more than one of the antennas using MIMO and other spatial diversity schemes. For example, a Manhattan deployment configuration with 4 RRHs or nodes per processing area and frequency reuse factor 1. The RRHs are considered to be located at the main street-crossing with four RRHs in a cell. The side-length of a building block ( $b$ ) and the street width ( $s$ ) are set to be  $b=200$  meters and  $s=50$  meters, respectively. So, the CoMP-cell covers 16 building blocks and cell coverage is about  $1000 \times 1000$  square meters.

The propagation model proposed in [94] is considered, where the path-loss, shadow and multipath models for the urban micro-cell environment (Manhattan B1 model) are adopted.

### 5.3. 3D Video Transmission and User Resource Allocation Algorithm

In this section the definition of the necessary cross-layer information exchanged through a signaling mechanism among the components of the considered system architecture is presented. Multimedia based services is having an important impact in the 4G and beyond networks, where 3D applications are emerging. 3D video transmission for the LTE network is analyzed in [95], and general QoE on 3D streaming is evaluated in [96]. However due to interferences, cell edge users still suffer from bandwidth and spectral efficiency limitations when compared with users closer to cell site. In this chapter the CoMP is used in order to improve capacity for quality sensitive applications, such as 3D video, where particular features are analyzed.

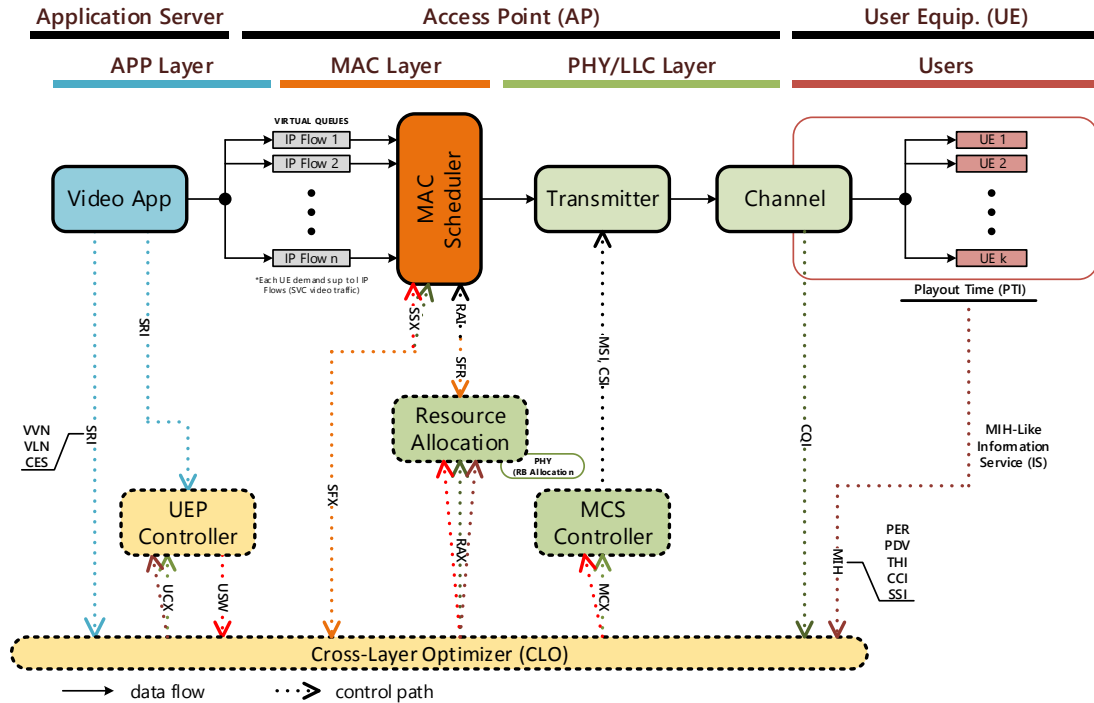


Figure 5.2: Cross-Layer Block Diagram [97].

The cross-layer architecture which is described in this section, is a result of collaborative work in the scope of the ROMEO project with University of Patras [97]. The architecture is presented in Figure 5.2, including the control signals for cross-layer communication. Multiple colors indicate the dependence of control information, coming out of the Cross-Layer Optimizer (CLO).

In fact, the objective is to combine the informations of the upper layer video application with the CoMP (suitable antenna/radio head and frequency resources) to maintain the QoS of the 3D video during the scheduling period.

#### ***5.3.1.1 3D Video Transmission***

The video content generated in the application layer (APP) Layer by the 3D video application can be encoded using two different approaches. In the first approach each View ( e.g. Base and Non-Base View in the case of a stereoscopic 3D video) can be encoded independently using Scalable Video Coding (SVC) encoding. Scalable video coding (SVC) [98] [99] decomposes the video stream into multiple video layers which are classified as base layer (BL), that provides a basic video quality and can be decoded alone without the need of delivering and decoding the rest of the video layers, and enhancement layer(s) (EL), that are additional video layers which help to gradually increase the quality of the decoded representation of the video. Scalability is very useful for service continuity under bandwidth varying networks by adapting the quality of the streamed video without the need of re-encoding the video source. In the case of multi-view video applications the total data rate per user is considered to be equal to the sum of the bit rate of each layer (BL+EL1+EL2...) multiplied by the number of views  $V$ , e.g.  $V=2V = 2$  for stereoscopic 3D video.

A second approach - Multiple Description Coding (MDC) video coding - is also considered. This approach aims primarily at error resiliency rather than the SVC's stream adaptability. MDC technique fragments a single media stream and creates several independent sub-streams that are referred to as Descriptions. Descriptions contribute to one or more characteristics of the reconstructed video, such as temporal or spatial resolution frequency content or PSNR (Peak Signal-to-Noise Ratio). The advantage of MDC is that all Descriptions are self-contained and can be decoded without the need of decoding other Descriptions, unlike SVC. In order to decode the media stream, any Description can be used; however, the quality improves with the number of Descriptions received in parallel. Since there is no priority between each Description, an arbitrary subset of Descriptions can be decoded, thus achieving bit rate adaptation but also consolidating error-resilience over unreliable channels with unavoidable packet loss and congestion. Accordingly, for MDC video coding, the selected Views can be encoded using two different Descriptions, namely MDC1 and MDC2 that represent even and odd information lines, respectively for the Color and Depth channels. A layer coding mechanism like SVC can be used after data partitioning, to generate a BL and ELs for the descriptions, e.g. MDC1B, MDC1E and MDC2B, MDC2E.

UEP controller is a mechanism that enables Unequal Error Protection (UEP) scheme for the transmission of the video content. UEP processing can lead to better performance for the perceived video quality in erroneous environments, by protecting in a different manner, parts of video data that have different level of importance, without increasing the size of the overall data. A coding scheme that uses UEP means that parts of the bit-stream that are more susceptible to errors causing disturbances

are provided with more protection (i.e. a lower code rate) and vice versa. UEP methods are usually combined with FEC techniques. Using UEP techniques and prioritization of layers, the layered structure of a scalable video stream and different priorities among the layers could be supported for the cross-layer design.

### ***5.3.1.2 Cross-layer control signals for Video Transmission***

Considering the interaction with the application layer, SRI (Source Related Information) control signal is generated by the video application at the APP Layer. It can be exploited directly by the UEP Controller and contains information that can be utilized for improving the QoS (or QoE). This information consists of information about the sensitivity of source bits to channel errors (CES), information about the number of Layers per View (VLN) of the SVC encoded video and information about the number of Views (VVN) in a multi-view media application.

USW (UEP Strategy and Weights Information) control signal is used by the UEP Controller which determines the strategy to be followed by producing weights that determine UEP budget per layer (BL or EL) and per View. UEP controller gives priority in the protection of the most important information of the traffic by taking as input the number of layers of SVC video and determines the policy that will be followed according to the weights that determine UEP budget per Layer and View.

Considering the Resource Allocation (RA) component and its interaction with the Scheduler, control signals RAI (RA Information to Scheduler) and SFR (Scheduler Feedback to RA Unit) are necessary. Scheduling could be based on two different optimization strategies. The first one, considers the need for high-quality stereoscopic 3D video and the second one is based on the maximization of the number of Views,

without regard to the video quality. Since priority is primarily given to those nodes that have the best conditions, the Scheduler also should follow a fairness strategy for nodes that have bad conditions for a sufficiently long period and thus are poorly served. When the conditions of these nodes improve then they should get an extra priority, considering a kind of credit of resources [100].

Finally, for the Cross-Layer Optimizer (CLO) unit, necessary control signals are considered to be UCX (UEP Signal from CLO) that controls the operation of UEP Controller and is mainly affected by the CQI and User Equipment (UE) info, MCX (MCS Signal from CLO) that controls the operation of MCS Controller mainly being influenced by the CQI and USW Info, SSX (Scheduler Feedback signal from CLO) which controls the operation of the Scheduler and is mainly affected by USW and CQI signals, SFX is the Scheduler Unit feedback control signal to CLO, and, RAX (RA Info from CLO) controls the operation of the RA Unit and is mainly influenced by USW, CQI and UE info.

The component of the interaction with application layer can be analyzed with more detail in the following references [97] [101]. In the CoMP implementation, simulation and performance evaluation, the KPIs used are presented in the section 5.4.

### ***5.3.1.3 Problem Formulation***

This subsection describes a user scheduling and resource allocation algorithm for CoMP considering OFDMA technology, taking into account the video content of upper layer [102]-[103] . Figure 5.3 illustrates the OFDMA-based frame structure to be used. In the frame, resources are available in two domains: time (symbols) and

frequency (subcarriers, or sub-channels i.e., groups of subcarriers). The combination of one frequency and one time resource (sometimes called chunk) is the basic CoMP radio resource unit. In a CoMP cell resources are allocated within each RRH as presented in Figure 5.3 (right side). It shows each RRH has  $m$  resources in their OFDMA frame. The resource allocation and user scheduling problem consists of selecting the optimum set of users and their optimum assigned set of resources that maximizes the performance of the network. To avoid interference within a cell we assign the user to each RRH in the following way— if a resource of one RRH is occupied by a user then the same resource of the other RRHs will not be occupied by any other user.

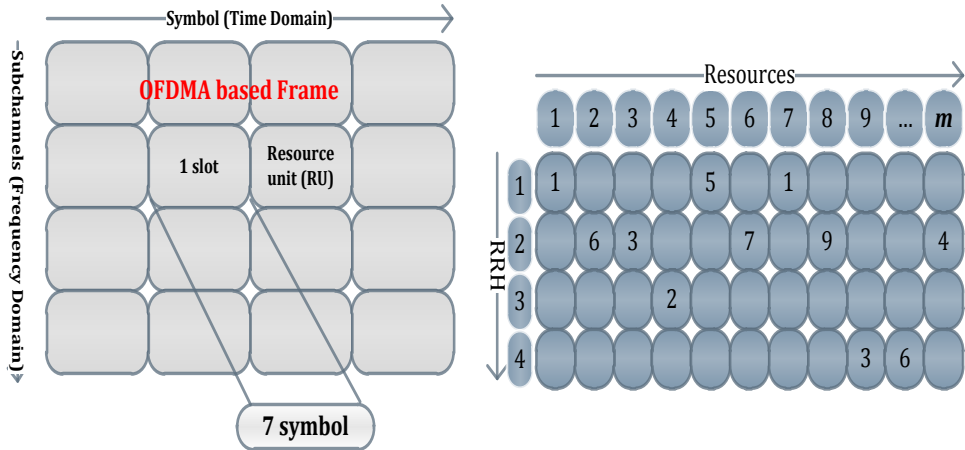


Figure 5.3: Frame of CoMP with user allocation with resources (right)

5.3.1.4 Proposed Scheme

Consider a Coordinated Multi-Point with a set  $\mathcal{A}$  of  $K$  RRHs  $\mathcal{A} = \{1, \dots, K\}$  attending a set  $\mathcal{U}$  of  $N$  user terminals  $\mathcal{U} = \{1, \dots, N\}$  over a set  $\mathcal{R}$  of  $M$  radio resources to be allocated  $\mathcal{R} = \{1, \dots, M\}$ . Assuming that user  $n$  needs  $D_n$  radio resources, and the power in each RU (Resource Unit) is the same, the algorithm aims to maximize the

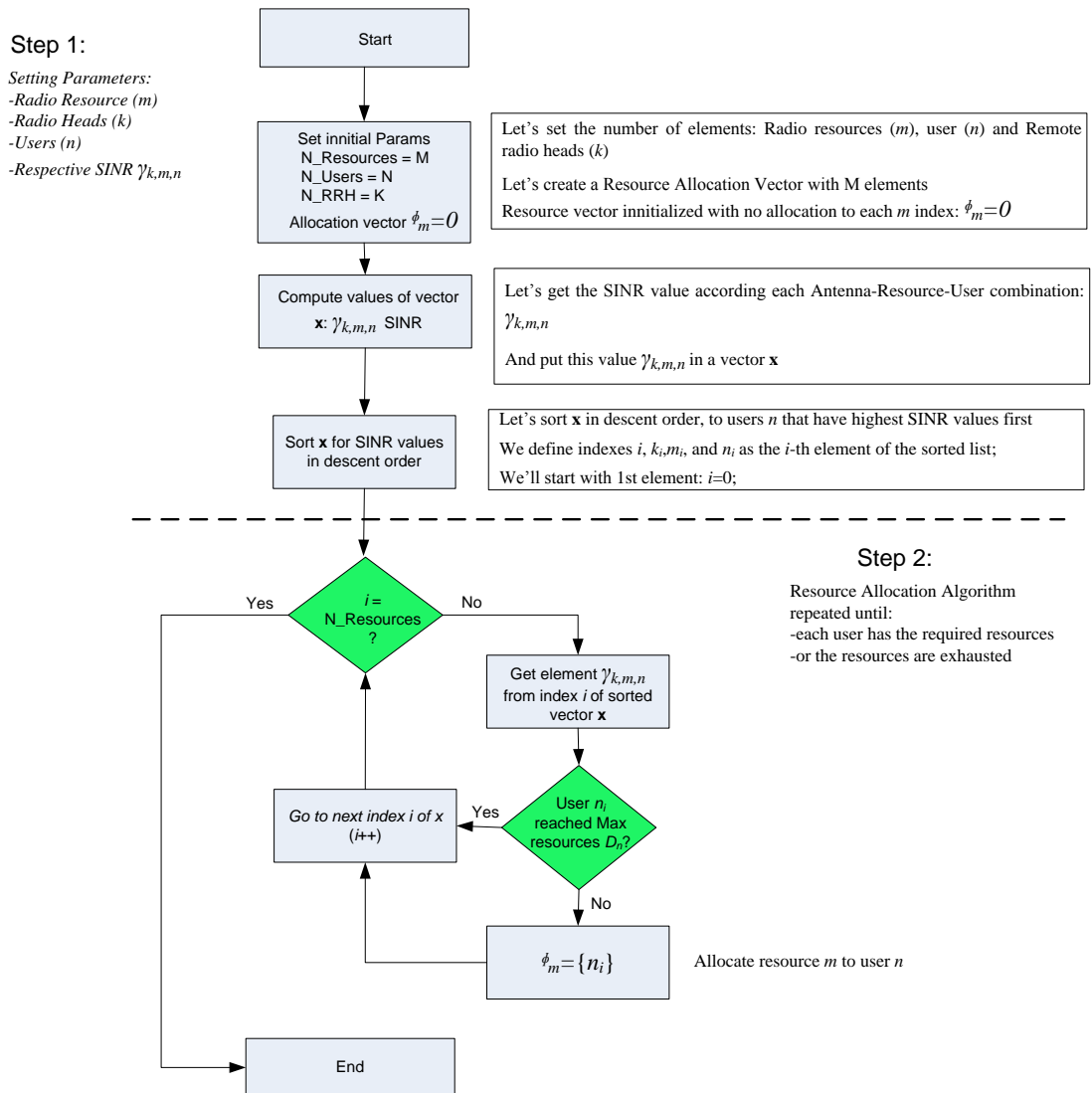


capacity by assigning resources according to the sorting of the channel gains and using the higher modulation format that guarantees a frame error rate (FER) of Figure 5.5. This allocation is also subject to the condition of non-interference shown in Figure 5.3 where only one chunk per column is allowed to be filled. This means that the algorithm will assign only one user to a single RRH in a single radio resource. The resource allocation algorithm is repeated until each user has the required resources assigned (subject to a maximum FER) or the resources are exhausted.

The proposed algorithm can be described in more detail as follows. Consider that the signal-to-interference-plus-noise ratio (SINR) of each antenna-resource-user combination is denoted by  $\gamma_{k,m,n}$ . To indicate whether a resource  $m$  is already allocated or not to a particular user we will use the set variable  $\phi_m$ , which will contain the index of the user to which resource  $m$  has been allocated.  $\phi_m$  will have a value of empty set ( $\phi_m = \emptyset$ ) if no user was allocated. To keep track of the number of resources allocated to user  $n$  we will use the variable  $d_n$ .

The first step of the algorithm consists of rearranging all the values of  $\gamma_{k,m,n}$  into a linear or vector array, which we call for simplicity  $\mathbf{x}$ . Each value  $\gamma_{k,m,n}$  corresponds to a unique value  $x_i$  in the vector  $\mathbf{x}$ . The second step is to sort the elements of vector  $\mathbf{x}$  in descending order. As the result of this sorting operation we define the indexes  $k_i, m_i$ , and  $n_i$  as the antenna, resource and user indexes of the  $i$ -th element of the sorted list, respectively. The next step is to explore all the elements of the list starting from the first element and check if the resource of that element is already allocated or not. Now if the resource  $m_i$  of the sorted list happens to be free and the number of

resources already allocated to user  $n_i$  of the list  $d_{n_i}$  is less than the maximum number of resources  $D_{n_i}$ , then the resource is allocated to user  $n_i$  of the list, while the variable  $\phi_{m_i}$  is set to  $\phi_{m_i} = \{n_i\}$  and the resources allocated to user  $n_i$  is increased by one ( $d_{n_i} = d_{n_i} + 1$ ). This scheme is repeated until we reach the end of the list or until all users have been allocated all their requested resources or until all the resources have been allocated. The proposed scheme is presented in the flowchart of Figure 5.4.



**Figure 5.4: Flow chart illustration of the proposed CoMP algorithm, both parameters setting, and resource allocation process**

### ***5.3.1.5 Complexity Analysis and Reduced-Complexity Algorithm***

The complexity of the proposed algorithm can be approximated by using the number of operations required by the sorting operation. The complexity of the sorting algorithm is bounded by the square of the number of elements used in the list. In this case the total number of elements is  $NKM$  and thus the complexity is  $(NKM)^2$ , which can be quite high. A method to reduce the complexity of the sorting operation is to sort the elements resource per resource, obtaining the best user-antenna combination per resource and then sort again these values to select the best values for each user. This technique provides exactly the same results as the original algorithm but with a complexity of  $(NK)^2 + M^2$  as compared to the original algorithm with  $(NKM)^2$ . For example, in a network with  $N=10$  users,  $K=4$  antennas and  $M=450$  resources, the complexity of original algorithm gives  $(180,00)^2=3.24e8$  while the second algorithm gives  $(40)^2+(450)^2=36,250$ , which represents a considerable reduction.

## ***5.4. Simulation Results***

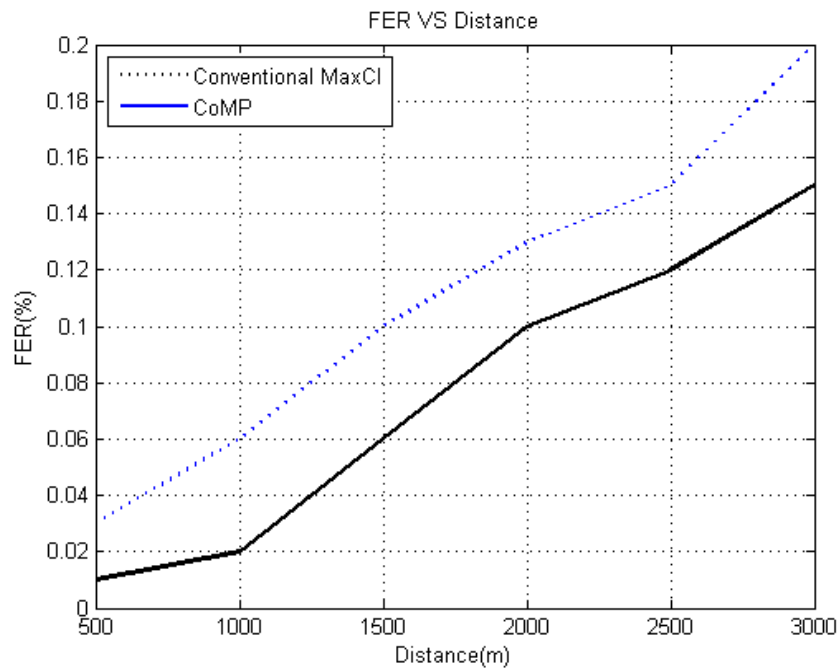
This section represents simulation results of the proposed algorithm. Monte Carlo simulation is used where the users are randomly (uniformly within the streets) distributed over the geographical area. Full-queue traffic mode is used for all the users, which means they always have information ready to be transmitted. The key parameters of the simulated system are set according to the OFDMA mode [104], which is summarized in Table 5.1.

**Table 5.1: Simulation Scenario**

Parameter Name	Value
Transmission technique	OFDMA
Frame Duration (TTI)	1 ms
Bandwidth	20 MHz
No. of PRB	100
No. of sub-carriers per sub-channel	1200
Subcarriers SNR average method	MIESM
Cell size	1000 m (500 -3000meters)
User	10...100 per cell
BS Power (Conventional)	20 Watt
RRH Power (CoMP)	5 Watt
Carrier frequency	5 GHz
Mobile terminals velocity	10 km/h
Modulation and coding rate	QPSK,16-QAM,64QAM;1/2,3/4
Traffic model	Full Queue (Continuous Data)
Channel model	WINNER B1
Antenna gain	14 dB
Duplex mode /simulation type	TDD /Downlink
Total Cells Simulated	25(two-tier interfering cells)

Video streaming service performance is evaluated in this system based on the requirements specified by the 3GPP for the LTE. 3GPP requirements for QoS Class Identifier (QCI) for different type of services are given in [105]. 3GPP standardized for upper layer point-of-view from the MAC, a packet delay of 150 ms and Packet Error Rate of  $10^{-3}$  for the live video service.

For the scheme we are proposing in this chapter, we will analyze network parameters that can affect video services such as FER, the fairness achieved on cell-boundary users, and overall energy efficiency. The first metric to be analyzed is the frame error rate (FER), which will play an important role. FER is defined as the ratio of the number of incorrect frames to the total number of frames. Comparison of FER between the distributed and the conventional systems for different sizes of the cell is presented in Figure 5.5. Due to the proposed scheduling algorithm, the FER in CoMP is less than the conventional system. Values show a reduction in the order of 30%.

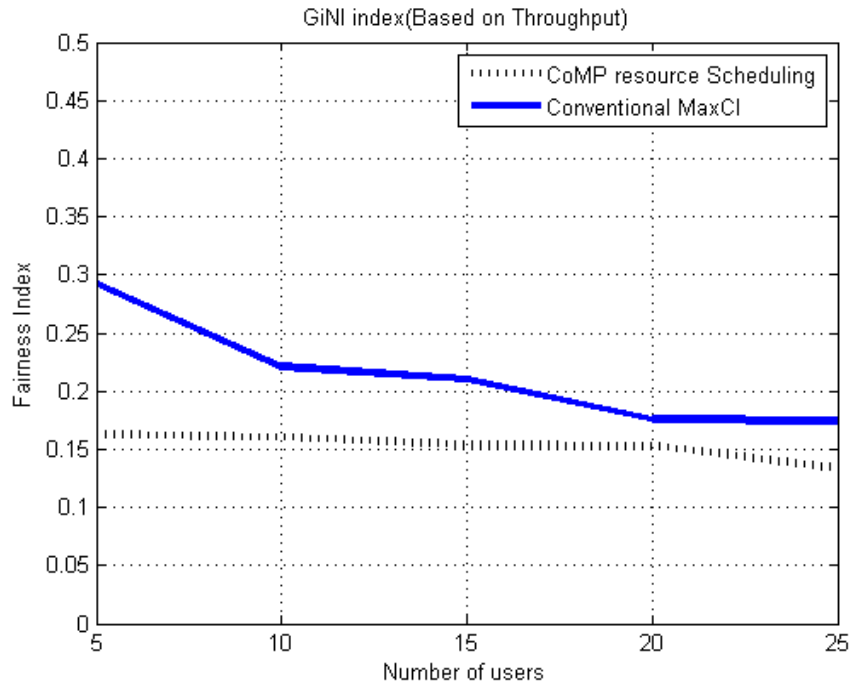


**Figure 5.5: Comparison of Frame Error Rate**

In the following analysis, we mention one fairness index (FI) termed as *GINI* coefficient [91]. *GINI* coefficient is used to measure the equality/inequality of the resources. The generic *GINI* coefficient formula is [92].

$$FI_{Gini} = \frac{\sum_{i=1}^N \sum_{j=1}^N |T_i - T_j|}{2N^2 \bar{T}} \quad (21)$$

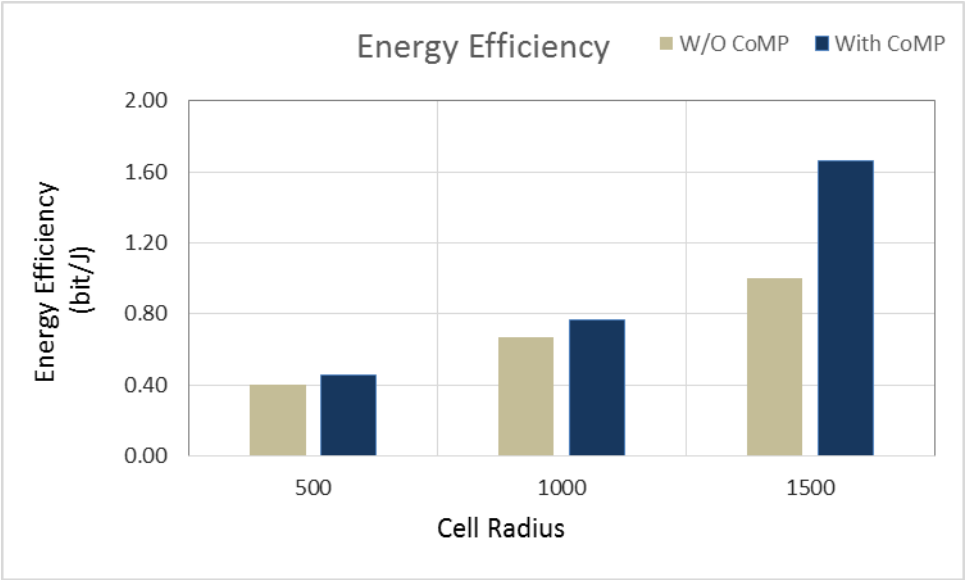
Where  $T_i$  is the observed throughput value of users  $i$ ,  $N$  is the total number of users, and  $\bar{T}$  is the average throughput of all users. The value of  $FI$  lies between 0 and 1. If the value is 0 complete fairness is achieved and 1 otherwise. For our simulation we observed service throughput of different users to measure fairness using  $GINI$  formula. In Figure 5.6, the throughput-based fairness comparison between conventional scheduling methods and the proposed scheme is shown. It can be observed that in our proposed scheme, fairness index gradually improves fairness as the number of user increases.



**Figure 5.6: Throughput fairness of different scheduling algorithm**

As anticipated in section 2.4.1.3, Max C/I scheduler in the conventional cellular system shows less fairness since it tries to allocate the resources to users with best channel condition. And also this channel-aware policy monopolizes all the resources to good-channel users that are usually located close to the base station, while cell edge users starve with low data rates. This starvation is significantly reduced by granting much more equal access to users using the proposed scheduling algorithm with RRH. The more deployed users the more it tends to be fair in terms of throughput.

In terms of energy efficiency analysis, Figure 5.7 compares the energy efficiency in terms of the cell radius with and with-out using CoMP, where the energy metric we consider is the same as presented in section 4.3.1.4 (information bit transmitted per energy unit (bit/Joule)). It can be seen, that using CoMP has inherent advantages due to the coordinated transmission approach to support users at the cell edge, that has the effect of alleviating the interference in the cellular system. . We can still see, however, that the energy consumptions increases with cell radius, which is expected.



### **Figure 5.7: Energy Efficiency results**

#### **5.5. Summary**

In this chapter, we proposed a new scheduling approach for downlink CoMP transmission in OFDMA systems designed to support 3D video services. The algorithm analyzes the characteristic of the channels from each mobile to each antenna to maximize the total system rate subject to no intra-cell interference. The use of RRH within the cell further contributes to an improved fairness in the network access among users. Simulation results demonstrate that the proposed scheme for the CoMP can achieve significant improvements over conventional cellular system in terms of throughput fairness and energy efficiency, with an energy reduction from 10% to 30%, depending on the cell distance.



## 6. Conclusions and future Work

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### 6.1. *Main Conclusions*

This work is a contribution to the framework of energy efficient radio resource management in OFDMA based systems, the radio-access network proposed for 4G and beyond. The presented work focuses on Resource Allocation algorithms in the MAC layer, including load balancing to optimize the energy cost per bit based on using LTE (4G emanating from the 3GPP standardization) as a use-case. For the design of future mobile networks it is not only important to improve the spectral efficiency (SE), but also the energy efficiency (EE) to ensure reduced cost per bit in an era where spectral resources and energy are at a premium. Consequently, it is important to find a trade-off point between these SE and EE metrics, so that the end users are served with minimum energy, while satisfying their QoS requirements.

After a general and brief introduction of the work, a literature review on resource allocation for cooperative 3G and 4G legacy networks in the terms of energy efficiency is given. This provided the context for the cooperative scenarios that were modeled in subsequent chapters. Moreover, we describe the details of an OFDMA DRA based cellular systems, using the LTE as application example. The system was modeled and implemented on a purpose made system level experimental platform, that was used to acquire benchmark results and used as baseline for subsequent

results emanating from chapter 4 and 5, which are the main research contributions to this thesis.

In the Chapter 4 we present a novel framework for energy efficiency management in future cooperative wireless cellular networks, where an energy-efficient scheduling algorithm in a self-organized shared LTE-A network is employed. The results obtained demonstrate that the combination of network sharing, Self-Organization, and Load Balancing technology are able to work in synergy to optimize the entire wireless network utilization in terms of minimizing the energy and cost per bit in inter-operator network sharing scenarios. The proposed algorithm that was designed with energy efficiency as an objective criteria has shown that the energy spent by the network can be reduced by up to 15–20 % . The results suggest that significant gain in call blocking and cell edge users' throughput can be achieved in a shared network with the help of relays.

In chapter 5, recent advanced in CoMP was used as a starting point. CoMP is a prime example of cooperation/coordination between Base Stations within a cluster of cells towards exploiting spatial diversity and thus enhancing cell edge throughput/coverage. However, the resource allocation approach towards CoMP users from an energy efficiency perspective is still a research challenge. In this context, we propose resource allocation for a downlink OFDMA-based system resulting in better resource utilization and improved fairness while maintaining simplicity and modularity, with application towards 3D video services. The algorithm analyzes the characteristic of the channels from each mobile to each antenna to maximize the total system rate subject to no intra-cell interference. The

use of RRH within the cell further contributes to an improved fairness in the network access among users. Simulation results demonstrate that the proposed scheme for the CoMP can achieve significant improvements over conventional cellular system in terms of throughput fairness and energy efficiency, with an energy reduction of up to 30%, depending on the cell distance.

## **6.2. Future Work**

There a number of possibilities where this work can be extended. The upcoming paradigm of the Internet of Things is fast approaching, that envisages billions of devices connected to the internet, the enabler for Smart “X” scenarios, such as health, security government, cities, among others. In parallel, future emerging scenarios driven by 3GPP are hinting towards Device-to-Device (D2D) communication, that are infrastructure based controlled to allow direct message delivery between terminals to support user offloading and proximity based services [106]. Vehicular communication are also be considered as a major use-case. All of these are considered different applications of the Next Generation network, thus placing stringent design requirements on the future mobile network in terms of QoS provisioning, and above all energy efficiency. Therefore, resource allocation work considered here could be extended to support these future emerging use-cases to drive the energy savings further. In fact, the author has initiated a study on the application of this work towards LTE-A to support vehicular communications based on the D2D paradigm [107]. The imposed challenges like stringent latency requirements in the vehicular communication network has been analysed and initial

results have been obtained using the LTE-A band. Further study also includes to propose a novel cognitive radio based resource allocation scheme, that would allow the cellular network to offload V2V users. This would raise new research challenges in terms of dynamic resource allocation in unlicensed bands working in synergy with LTE/LTE-A.

## **Annex 1 - System simulation description**

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### ***Requirements for System Level Simulation Modeling***

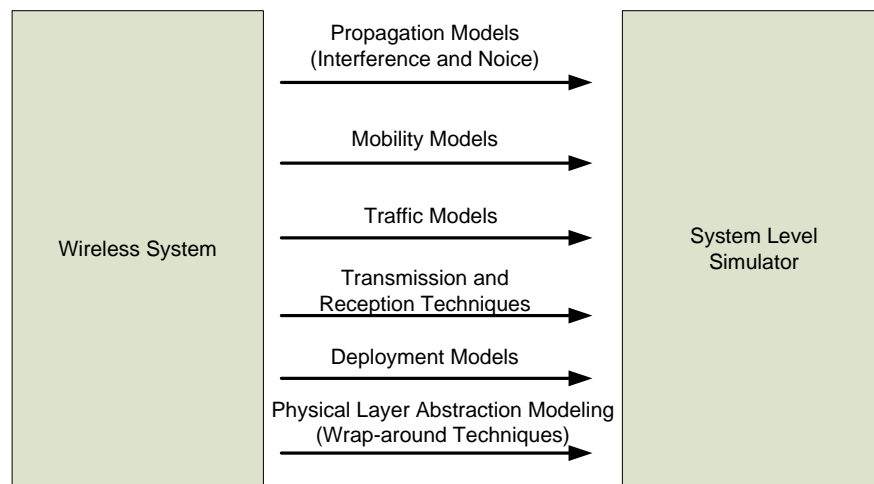
System level simulations are designed to evaluate radio resource management schemes for wireless access technologies, namely HSPA, LTE, or other that are being proposed. Implementation of a system level tool requires complex modelling of the real environment, as was shown in 3.4. , several aspects of the real environment needed accurate modelling to enable the collection of results as close possible to the real situation. The minimum modelling of wireless systems should involve three aspects:

- Users dynamic behaviour, namely user mobility;
- Traffic characteristics for the applications considered;
- Radio aspects involved in the transmission of the signals from users to destination.

Taking a deeper insight into the characteristics of simulation environment, we need to capture certain traits which pertain to real-life instances in cellular networks, Therefore, when considering the users' behaviour, as their position can be random, there is need for a deployment model. Secondly, as they are mobile, there is need for a mobility model related to each scenario or environment. Thirdly, as the user uses wireless communication protocols to transport applications or services there is need for a model of the data traffic. Finally, the information is sent by a radio waveform modulated by a channel, thus creating

the need to model the impact of the channel on the signal quality requiring appropriate propagation models. Therefore, the main modelling requirements for the SLS, as shown in Figure A.1, are:

- Deployment Modeling;
- Mobility Modeling;
- Traffic Modeling;
- Radio Channel Propagation Modeling;
- Transmission/reception techniques.



**Figure A.1: Modeling of Wireless communication System**

### *Simulation Execution Flow and Methodology for Evaluating Scheduling*

Two different types of simulations can be performed at system level: using a Combined Snapshot-Dynamic or a Dynamic mode.

- **Dynamic mode:** in this mode, the full dynamics are simulated. Mobility is enabled as mobiles travel along the network coverage area performing handovers. Mobiles

are dropped in the network in the beginning of the simulation run and remain active, however the begin time can be coincident with the beginning of the simulation run or be defined by some random distribution. Only one simulation run is performed and mobiles are removed at the end of the simulation. Statistics are collected as mobiles travel through the network coverage area. All channels components, including Path-loss, shadowing and fast fading propagation components are re-computed at every transmission time interval. The new position of the mobile station in the next transmission time interval is also computed according to the chosen mobility model. The trade-off in this mode is the inherent complexity, since all channel components are calculated in each iteration.

- **Combined snapshot-dynamic mode:** mobility and handovers are disabled in this mode and a given number of simulation runs are performed (Monte-Carlo simulation). Mobile stations are created at the beginning of each simulation run and removed at the end. However the begin time can be coincident with the beginning of the simulation run or be defined by some random distribution. In this mode, path-loss and shadowing are computed at the beginning of each simulation run and remain constant until the end of the run. Fast fading is re-computed at every transmission time interval. This mode increases the simulation speed as the different simulation runs (snapshots) can be performed in parallel. The final results should be averaged on the number of snapshots.

In both modes mobiles are randomly uniformly distributed over the hexagonal cells. Each base station can be configured with one sector (omnidirectional antenna pattern) or with three sectors/cells (directional antenna pattern).

However when evaluating MAC protocols like scheduling, the combined snapshot-dynamic mode can be a valuable method to conduct system level simulations. A meaningful number of simulation runs (snapshots) should be performed along each evaluation.

A Complementary method to reduce the complexity and thus the processing time during the simulation run is to consider mobile stations in the first tier of cells only. The neighbouring cells contribute only to interference generation. With this approach the number of mobiles are reduced as well as the number of channel calculations whilst ensuring sufficient accuracy for evaluating the impact of scheduling policies in the MAC protocols.

In this method path-loss and shadowing are computed at the beginning of each run and for each mobile-base station pair (including neighbouring cells), and are kept constant until the end of the run; whilst fast fading is executed for each transmission time interval.

The steps followed in the simulation flow for a single run of a general system level simulation tool are as follows, for both omni or sectorized base stations:

- Mobile stations are dropped independently, with uniform distribution throughout the system. Each mobile corresponds to an active user session that runs for the whole run.
- Mobiles are assigned channel models. This can be a channel mix or separate statistical realizations of a single type of channel model.
- Mobiles are assigned a traffic model and packets are generated according to the desired traffic model/service.



- Cell assignment is based on the received power at the mobile station from all potential serving cells. The cell with the best path to the mobile station, taking into account slow fading, path-loss and antenna gains, is chosen as the serving sector.
- For simulations that do not involve handover performance, evaluation of the location of each mobile station remains unchanged during a drop and the mobile's speed is used only to determine the Doppler effect of fast fading. The mobile station is assumed to remain attached to the same base station for the duration of the drop.
- For a given drop the simulation is run for the pre-defined duration and then the process is repeated with the mobile stations being dropped at new random locations.
- Performance statistics are collected for mobile stations in all cells.

Each run is made up of a number of transmission time intervals or frame periods, as each transmission time interval lasts for the period of time equal to the transmission of a single OFDM frame. Regarding execution flow, the simulator developed for B3G/4G standards LTE, WiMAX or HSPA system level simulations is basically a finite machine whose states repeat at each transmission time interval. A TTI should be equal to frame period. In our approaches the TTI for LTE is 1ms, for WiMAX is 5 ms and for HSPA is 2 ms.

For each TTI the following events are performed:

- Fast fading is computed for each mobile station in each transmission time interval. Slow fading and path loss are assumed as constant during the whole simulation run.

- Packets are withdrawn from buffers assigned to traffic models. Packets are not blocked, as the queues are assumed as infinite. Start times for each traffic type for each user should be randomized.
- Map of radio resources allocation is updated.
- Packets are scheduled with a packet scheduler using the required metric. Packet decoding errors result in packet retransmissions. In the Dynamic Resource Allocation (DRA) module a Hybrid Automatic Repeat Request (HARQ) process is modelled by explicitly rescheduling a packet as part of the current packet call and after a specified feedback delay period.
- The map of radio resources allocation is computed, according to the implemented scheduler. This is performed by the Dynamic Resource Allocation (DRA) Module.
- Packets are transmitted.

Packet quality detection is performed and feedback regarding the status of the decoding is reported back.

### ***Packet/Data Decoding Process***

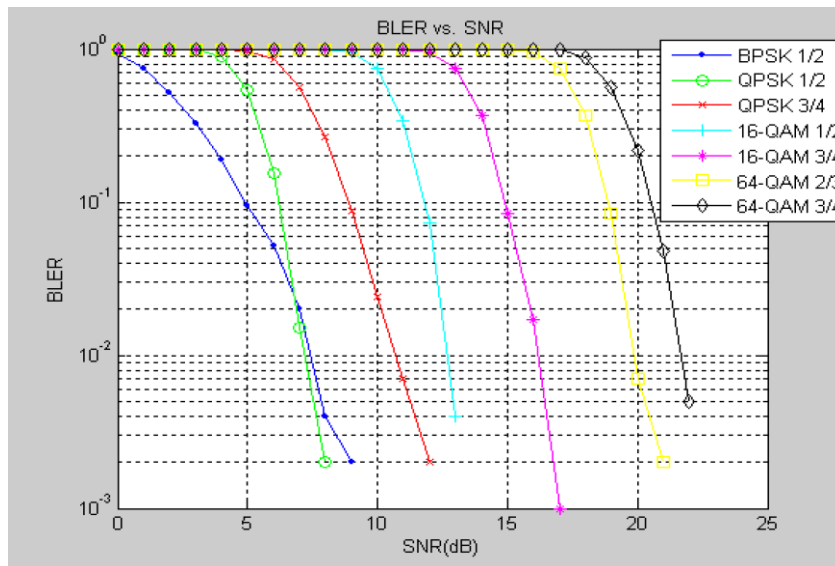
The BLER resulting from decoding the information transmitted along a single Resource Unit ( $RU$ ) is denoted by  $BLER_{RU}(SINR_{RU})$  and is obtained from the link-to-system interface between the PHY and MAC layers, using as input the Signal to Interference plus Noise Ratio,  $SINR_{RU}$ . Then a random variable, uniformly distributed between 0 and 1, is drawn. In case the random value is less than  $BLER_{RU}(SINR_{RU})$  the block is considered as erroneous and a Negative Acknowledge ( $NACK$ ) message is sent back to the base station on the

associated signalling channel. Otherwise, the block is deemed as error free and an Acknowledge (*ACK*) message is transmitted.

The success or failure in the decoding of the transmitted block of information is computed from decoding each individual resource unit into which the data block is mapped. Assuming that a total amount of  $N_{res}$  radio resources are used in the transmission and that the decoding is an independent and identically distributed random process, the *BLER* for the whole radio block is given by equation (A.1).

$$BLER_{RB} = 1 - [1 - BLER_{RU}(SINR_{RU})]^{N_{res}} \quad (A.1)$$

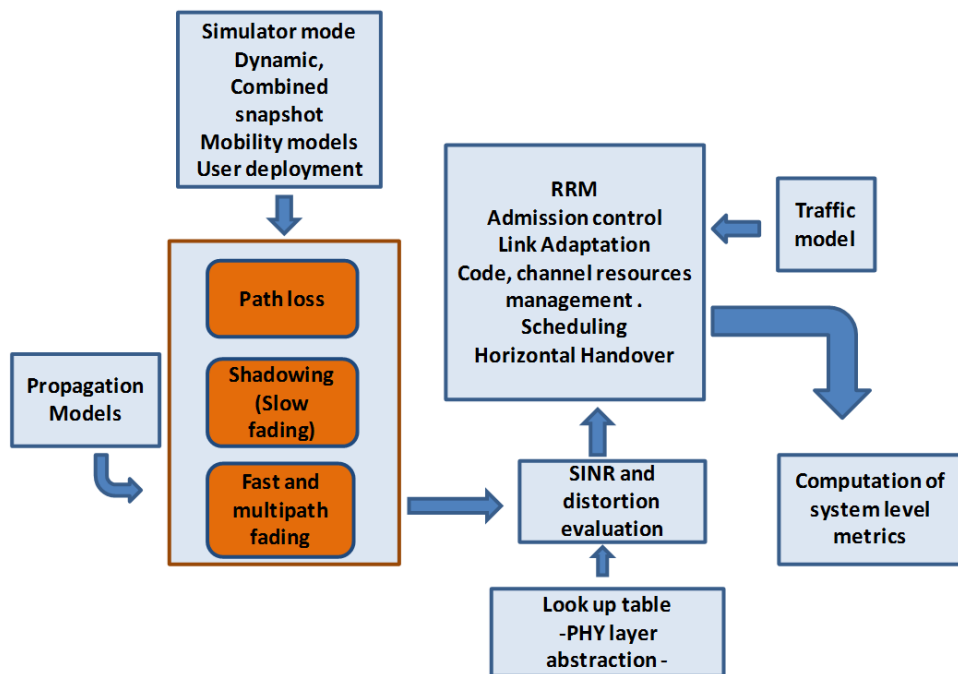
Figure A.2 presents the *BLER* curves versus *SINR*, for different modulation and coding schemes, used in the LTE simulation.



**Figure A.2: BLER vs. SNR plot for different modulation and coding profile on Veh A.**

### *Complexity and Time Resolution*

There is a trade-off between accuracy and complexity resulting in simulation execution time. The correct balance must be found for each aspect of the system to be evaluated, and in this section we will not say which is best. We will rather give the guidelines and approaches usually taken for typical cases. The main components of a complete system level simulation tool and their interconnection and flow are illustrated in Figure A.3, according to simulation procedures elaborated in [108].

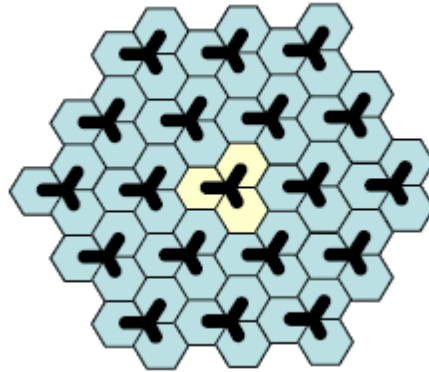


**Figure A.3: Modeling of Wireless communication System**

### *Network Scenario and Layout*

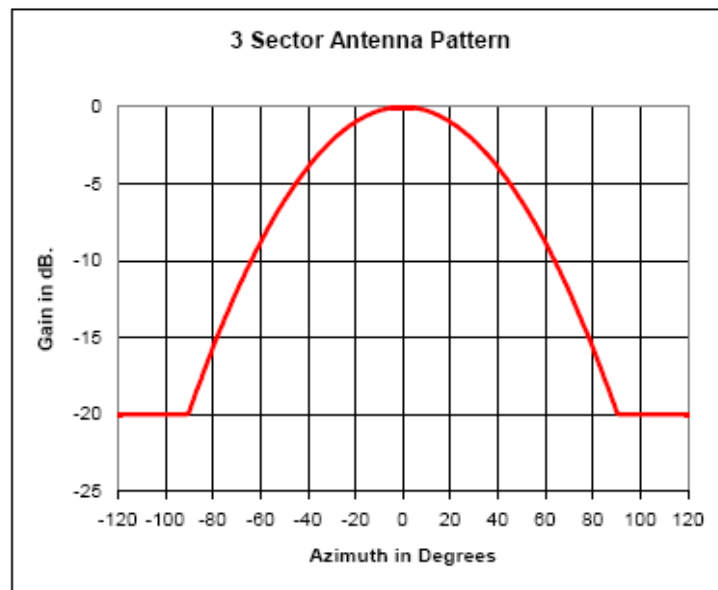
All system level simulations conducted in this work were performed assuming an urban environment scenario. The simulated network is constituted of 57 sectors (19 base stations

with 3 sectors each), composing a 3 tier hexagonal cellular network layout, as illustrated in Figure A.4.



**Figure A.4: Network layout deployment**

The antenna pattern used in each sector is plotted in Figure A.5.



**Figure A.5: Antenna pattern for 3 sectors**

The antenna pattern used for the sectored antenna deployment only considers the horizontal pattern, corresponding to a main sector of 70 degrees. According to the model

for the typical antenna pattern proposed in [109], power attenuation is computed as a function of the angle between the antenna pointing direction and the mobile to base station direction, as given by equation (A.2).

$$A(\theta) = -\min \left[ 12 \left( \frac{\theta}{\theta_{3dB}} \right), A_m \right] \quad (\text{A.2})$$

Where:

- $-180 < \theta < 180$  is the angle between the antenna's pointing direction and the mobile to base station line-of-sight direction in degrees.
- $\theta_{3dB} = 70^\circ$  is the beam width at 3dB.
- $A_m = 20$  dB is the maximum attenuation.

Two types of cell configurations can be defined for simulations: central-cell and non-central cell approach. In the central-cell approach mobiles are dropped along the coverage of the central base station and statistics are collected only for the cells of this base station. Naturally the central cell approach simulation method can be enabled only in conjunction with the combined snapshot-dynamic mode, as mobility modelling is disabled. The cells in the remaining tiers are assumed as fully loaded, i.e., transmitting with maximum power and contribute to interference only.

### ***Propagation Channels Models***

The radio propagation is divided into three distinct components, namely path loss, slow fading (shadowing) and fast fading. The decrease of the transmitted radio signal impinging on the receiver antennas is the result of their contribution. Accurate modelling of each one

of these three radio propagation components depends on the simulation scenario envisaged for the system-level simulations. Namely the simulation scenario can be described according to the following characteristics:

- Type of environments: indoor, urban, suburban and rural.
- Mobile speed: pedestrian, vehicular, train.
- Type of receiver used in the signal processing at the receiving end.
- Antenna radiation pattern.
- Antenna configuration used in the communication between the transmitter and the receiver (SISO, SIMO, MISO, MIMO). We do not consider MIMO in this work. However, more explanation in the MIMO implementation is presented in [110]
- Radio transmission parameters: carrier frequency, system bandwidth, etc.

#### Path-Loss Model

Path loss is defined as the power loss due to the propagation environment. The signal attenuation is directly proportional to a power of the distance between the transmitter and the receiver. The attenuation also depends on the carrier frequency and on the type of environment. The model used for the computation of the attenuation of the radio signal between the transmitter and the receiver is the one proposed in [109] for vehicular environments. This model is suitable for both urban and suburban scenarios, in which the buildings form a relatively homogenous clutter. According to [111] the path loss in dB is given by equation (9.3).

$$L_{[dB]} = \left[ 40 \left( 1 - 4 \times 10^{-3} \frac{\Delta h_b}{m} \right) \right] \log_{10} \left( \frac{R}{Km} \right) - 18 \log_{10} \left( \frac{\Delta h_b}{m} \right) + 21 \log_{10} \left( \frac{f}{MHz} \right) + 80dB \quad (A.3)$$

Where:

- $R$  represents the distance in kilometres between the base station and the mobile.
- $f$  is the carrier frequency.
- $\Delta h_b$  is the base station antenna height from the roof level.

Simulations were performed assuming the carrier frequency of 2 GHz. Also, it was assumed an antenna height,  $\Delta h_b$ , at the base station equal to 15 m. For this setting, the path loss in equation (A.3) results in the formula presented in equation (A.4), which is the expression used for the computation of the path loss in the simulations.

$$L_{[dB]} = 130.18 + 37.6 \log_{10} \left( \frac{R}{Km} \right) \quad (A.4)$$

#### Shadowing (Slow Fading) Model

Shadowing is the slow variation of the signal power at the receiver. It is given in dB and is modelled by a Gaussian random variable with linear autocorrelation, which is an exponential function of the de-correlation distance,  $d_{corr}$ , according to [112] and is given by equation (A.5).

$$\rho(d) = e^{-\ln(2) \frac{d}{d_{corr}}} \quad (A.5)$$

The parameter  $d_{corr}$  is the length of the de-correlation distance for which the auto-correlation of the shadowing process,  $\rho$ , is equal to 0.5.

Although Gaussian random processes can be modelled as a sum of sinusoids (SOS), conventional one-dimensional channel models (1-D) cannot capture the spatial correlation of shadowing processes. For example, when a given mobile is moving along a closed path around its base station, 1-D models cannot capture the influence of the slow shadowing, in



the variation of the signal received at the mobile station, and this affects the performance of the handover algorithm.

According to this, [113] proposes a two-dimensional (2-D) SOS-based channel model to simulate slow fading. The shadowing  $SH_{(x,y)}^j$  in dB between one mobile station at position (x,y) and base station j is the sum of two spatial functions,  $F_0$  and  $F_j$ , having a Gaussian distribution, with standard deviation mean equal to  $\sigma_{SH}$  (the shadowing standard deviation in dB) and auto-correlation given by (A.4), using the method described in [108]. It is given by equation (A.6).

$$SH_{(x,y)}^j = \sqrt{0.5x} [F_0(x, y) + F_j(x, y)] \quad (\text{A.6})$$

**Table A.1 Parameters for shadow fading model**

<i>Parameters</i>	<i>Values</i>
Log-Normal Shadowing std $\sigma_{SH}$	8dB
De-correlation length $d_{corr}$	20m

The standard deviation,  $\sigma_{SH}$ , and the de-correlation length,  $d_{corr}$ , for the urban scenario used in the system level simulations are the ones listed in table 1.

#### Fast Fading Model

The fast fading component of the signal is simulated by fast generation of independent Rayleigh faders, according to a modified Jake's model from the method proposed in [114], [115]. In order to speed-up simulations, the multi-path channel model is used for the serving cell, while a flat fading channel model (with only one tap) is assumed for

neighbouring cells. The mobile speed and carrier frequency are the parameters considered in the generation of the fading statistics. In this context a channel model corresponds to a specific number of paths, a power profile giving the relative powers of these multiple paths and Doppler frequencies to specify the fade rate.

ITU multi-path channel models for narrowband SISO are proposed in [116]. These models are based on a discrete version of the scattering function of the propagation channel and are designated as tapped delay line models. Each tap is characterized by an attenuation,  $A_i$ , a corresponding delay,  $\tau_i$ , a Doppler frequency,  $f_d$ , and a Doppler Power Spectrum (DPS),  $P_s(f_d, \tau_i)$ , at the  $i_{th}$  tap. A separate link level simulation must be performed for each specific channel model and mobile stations' velocity combination.

**Table A.2 Parameters for the different types of fast fading channel models for SISO**

<i>Channel Model</i>	<i>Multi-path Model</i>	<i>Number of Paths</i>	<i>Speed (Km/h)</i>	<i>Fadin g</i>
Model 1	Ch-100	1	30	Jakes
Model 2	Ch-100	1	120	Jakes
Model 3	Ch-104	6	30	Jakes
Model 4	Ch-104	6	120	Jakes
Model 5	Ch-102	4	3	Jakes
Model 6	Ch-103	6	3	Jakes

**Table A.3 Multi-Path Channel Models for Performance Simulation.**

<i>Channel Model</i>		<i>Path 1</i>	<i>Path 2</i>	<i>Path 3</i>	<i>Path 4</i>	<i>Path 5</i>	<i>Path 6</i>
Flat	Path Power (dB)	0	-	-	-	-	-

<i>Channel</i>		<i>Path</i>	<i>Path</i>	<i>Path 3</i>	<i>Path 4</i>	<i>Path 5</i>	<i>Path 6</i>
<i>Model</i>		<i>1</i>	<i>2</i>				
Fading							
Ch-100							
ITU Ped.	Path Power (dB)	-0.51	-	-19.71	-23.31	-	-
A Ch-		10.21					
102	Delay (ns)	0	110	190	410	-	-
ITU Ped.	Path Power (dB)	-3.92	-4.82	-8.82	-11.92	-11.72	-27.82
B	Delay (ns)	0	200	800	1200	2300	3700
Ch-103							
ITU Veh.	Path Power (dB)	-3.14	-4.14	-12.14	-13.14	-18.14	-23.14
A	Delay (ns)	0	310	710	1090	1730	2510
Ch-104							

Table A.2 and Table A.3 detail the parameters used in the definition of each type of channel model proposed by ITU [117]. The channel model assigned to a specific user remains fixed over the whole duration of a simulation run. The absolute power values are normalized so that they sum to zero dB (unit energy) for each given channel.

### ***Signal to Interference plus Noise Ratio (SINR) Modelling***

In system level simulations mobile stations are randomly dropped along the simulated coverage area. When the mobile station becomes active, its serving cell is selected according to signal strength and the mobile station camps on this cell. As mentioned in the previous sections, the signal coming from the serving cell is modeled as a frequency selective fading channel, whereas the signal coming from neighboring cells is modeled according to a flat frequency fading channel.

Assume then a given mobile station  $MS_i$  is camping in the coverage area of cell  $Cell_i$ . Assume also a SISO channel. The power received from serving base station  $BS_{serving}$  for data sub-carrier  $i, i \in [0, \dots, N_{data} - 1]$  on mobile station  $MS_i$  in the  $n$ th frame interval is given by equation (A.7).

$$P_{BS_{serving}}^{(i)}(n) = \frac{P_{data}^{(i)} |H_{BS_{serving}}^{(i)}(n)|^2 G_{BS_{serving}} G_{MS_i}}{PL_{MS_i, BS_{serving}} SH_{MS_i, BS_{serving}} L_{loss}} \quad (A.7)$$

Where:

- $|H_{BS_{serving}}^{(i)}(n)|^2$  is the instantaneous power from the serving base station  $BS_{serving}$  at the  $i_{th}$  data sub-carrier at the  $n$ th frame interval.
- $G_{MS_i}$  is the gain of the antenna at the mobile station  $MS_i$ .
- $G_{BS_{serving}}$  is the gain of the antenna at the serving base station  $BS_{serving}$ .
- $PL_{MS_i, BS_{serving}}$  is the path-loss between serving base station  $BS_{serving}$  and mobile station  $MS_i$ .
- $SH_{MS_i, BS_{serving}}$  is the shadowing loss between serving base station  $BS_{serving}$  and mobile station  $MS_i$ .
- $L_{Loss}$  encompasses the other losses in the transmission (cable losses, body loss, ...).

As sub-carriers are mutual exclusively assigned inside each cell there is no intra-cell interference. Therefore, only inter-cell interference must be considered. The interfering power arriving at mobile station  $MS_i$  from neighbouring cells is given by equation (A.8)

$$P_{Inter}^{(i)}(n) = \sum_{BS_j \in \{BS_{Inter}\}} \frac{P_{data,BS_j}^{(i)} |H_{BS_j}^{(i)}(n)|^2 G_{BS_j} G_{MS_i}}{PL_{MS_i,BS_j} SH_{MS_i,BS_j} L_{Loss}} \quad (A.8)$$

Where:

$\{B_{Inter}\}$  is the set of interfering base stations and  $BS_j \in \{B_{Inter}\}$ .

- $|H_{BS_j}^{(i)}(n)|^2$  is the instantaneous power from the interfering base station  $BS_j$  at the  $i$ th data sub-carrier at the  $n$ th frame interval.
- $G_{BS_j}$  is the gain of the antenna at the interfering base station  $BS_j$ .
- $PL_{MS_i,BS_j}$  is the path-loss between interfering base station  $BS_j$  and mobile station  $MS_i$ .
- $SH_{MS_i,BS_j}$  is the shadowing loss between interfering base station  $BS_j$  and mobile station  $MS_i$ .
- $L_{Loss}$  encompasses the other losses in the transmission (cable losses, body loss, ...).

According to equations (A.7) and (A.8), the SINR at sub-carrier  $i$  and for the  $n$ th frame interval is given by equation (A.9).

$$SINR^{(i)}(n) = \frac{P_{BS_{serving}}^{(i)}(n)}{P_{Inter}^{(i)}(n) + N_0 W_i F_{MS_i}} \quad (A.9)$$

Where:

- $N_0$  is the received noise spectral density.
- $W_i$  is the sub-carrier bandwidth.
- $F_{MS_i}$  is the noise figure at the mobile station.

The method followed in equations (A.7-A.9) for the derivation of the SINR is perfectly general. It was adapted to OFDM system level simulations in [118], [119], and adopted in the system level simulator platform for the computation of the SINR in each data sub-carrier  $k$ , as given by equation (A.10).

$$SINR^{(k)}(n) = P^{(k)}(n) \cdot \bar{G} \cdot \left( \frac{N}{N + N_p} \right) \cdot \frac{R_D}{N_{SD} / N_{ST}} \quad (A.10)$$

Where:

- $P^{(k)}(n)$  is the frequency selective fading power profile for the serving cell (propagation from interfering cells is modelled as flat fading).
- $\bar{G}$  is the Geometric Factor between the mobile station and its serving and interfering cells and is given by equation (A.11).
- $N$  is the FFT size, including pilot, data and guard sub-carriers.
- $N_p$  is the cyclic prefix length.
- $R_D$  is the percentage of maximum total available transmission power allocated to data sub-carriers.
- $N_{SD}$  is the amount of data sub-carriers per each OFDM symbol.
- $N_{ST}$  is the amount of useful (pilot plus data) sub-carriers per OFDM symbol.

The Geometric Factor is defined by equation (A.11)

$$\bar{G} = \frac{G(Cell_0, MS) \times \frac{1}{PL(Cell_0, MS) \times SH(Cell_0, MS)}}{\sum_{k=1}^N G(Cell_k, MS) \times \frac{1}{PL(Cell_k, MS) \times SH(Cell_k, MS)} + N_0 W_{F_{MS}}} \quad (A.11)$$

In equation (11)  $Cell_0$  is the serving cell and  $N$  is the total amount of interfering base stations.

Assuming that multi-path fading magnitudes and phases, respectively  $M_p(n)$  and  $\theta_p(n)$ , are constant over the frame interval for each path  $p$  of the tapped delay channel filter, the frequency-selective fading power profile for the  $k_{th}$  sub-carrier is given by equation (A.12) [118].

$$P^{(k)}(n) = \left| \sum_{p=1}^{N_{paths}} M_p A_p \exp(j\theta_p) \exp(-j2\pi f_k T_p) \right|^2 \quad (A.12)$$

Where:

- $p$  is the tap index (from 1 to 6) of the tapped delay model.
- $A_p$  is the amplitude value of the long-term average power for the  $p_{th}$  tap of the tapped delay filter.
- $T_p$  is the relative time delay of the  $p_{th}$  tap of the tapped delay filter.
- $f_k$  is the relative frequency offset of the  $k_{th}$  sub-carrier within the spectrum of the OFDM symbol.

Parameters  $A_p$  and  $T_p$  depend on the type of ITU channel used in the modeling of multi-path channel propagation.

LTE standard is an OFDM-based technology. If one designates the set of sub-carriers available for data transmission in each OFDM symbol as  $N_{data}$ , the power available at the base station for data transmission (not considering the power boost used in the

transmission of pilot sub-carriers, used in channel estimation) by  $P_{data}$ , and if one splits this power uniformly over the set of data sub-carriers, the power assigned for the transmission of data sub-carrier  $n, n \in [0, \dots, N_{data} - 1]$  is given by equation (A.13):

$$P_{data}^{(n)} = \frac{P_{data}}{N_{data}} \quad (\text{A.13})$$

### ***Traffic Models***

In the simulations widespread traffic models have been used for system validation and for characterizing typical mobile applications. The traffic models include:

- Full Queue (FQ) traffic model in which we assume that there is an infinite amount of data bits waiting in the queue of each active user in the system. That is, users are designated as backlogged. This traffic model is particularly interesting in evaluating the maximum capacity of the network.
- Voice over IP traffic model.
- Near Real Time Video with an average source bit rate of 32 kbps, 2 Mbps and 10 Mbps.
- World Wide Web (WWW) traffic model with a source bit rate of 64 kbps, 2 Mbps and 10 Mbps.
- File Transfer Protocol (FTP) traffic model with a source bits rate of 64 kbps and 384 kbps.

More details on traffic models implementation can be found in [4].



### *Simulation flow*

Figure A.6 presents the flowchart of the simulation process. The simulator constitutes a number of modules, each associated to the described function in the flowchart. Cells and mobiles are created and deployed in the beginning of the simulation and the traffic of each mobile is initially random, meaning that the system is stationary in the begin of the simulation. The simulation occur during a number of cycles described in the flowchart, where each cycle is equivalent to a TTI. For the LTE, the TTI is a sub-frame period, equals to 1 ms.

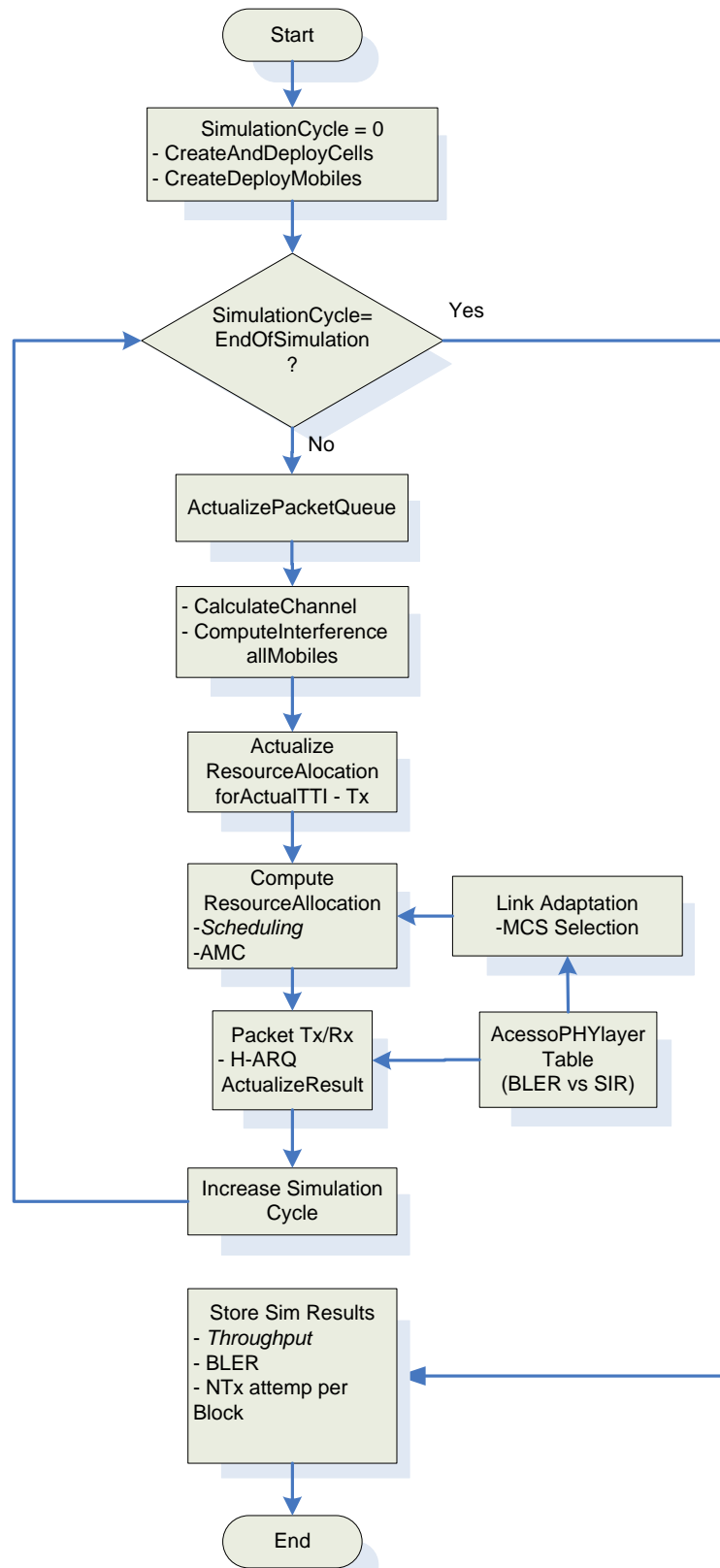
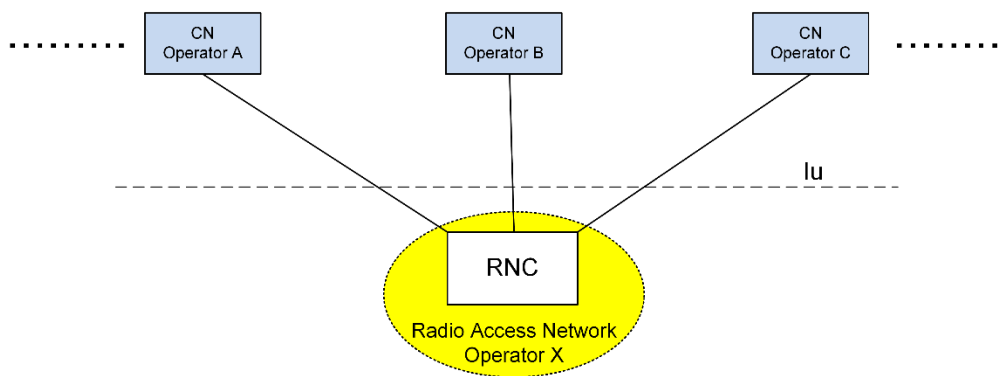


Figure A.6: Simulation Flowchart.

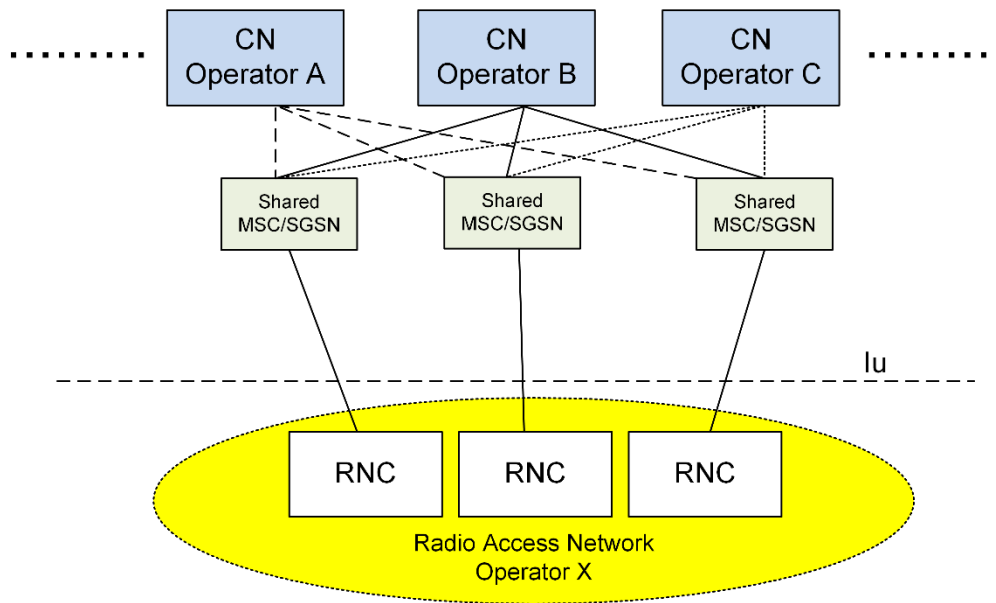
## Annex 2 – Network sharing methodologies

3GPP network sharing proposed architecture 3GPP has specified in the [33] a Network Sharing architecture in the Release 12 as shown in Figure. A.7 and Figure A.8, which allows a singular physical UTRAN deployment to be shared between multiple core network (CN) operators, each with their own separate CN infrastructure deployments. Two architectural variations of Network Sharing are defined:

- MOCN: Multiple Operator Core Network
- GWCN: Gateway Core Network



**Figure A.7: MOCN: multiple operator core network**



**Figure A.8: GWCN: gateway core network**

In both architectures, the radio access network is shared. Figure A.7 shows reference architecture for network sharing in which also MSCs and SGSNs are shared. This configuration will be referred to as a gateway core network (GWCN) configuration. The UE behaviour in both of these configurations shall be the same. No information concerning the configuration of a shared network shall be indicated to the UE. For the evolved packet system (EPS), only the PS domain of the above figures is relevant. For EUTRAN access Figs. A.7 and Fig A.8 both apply but with the Mobility Management Entity (MME) replacing the SGSN, the eNodeB replacing the RNC, and the S1, the reference point replacing the *Iu* interface (the *Iu* interface is an external interface that connects the RNC to the Core Network (CN)). For GERAN access, both GWCN and MOCN are applicable but with the BSC replacing the RNC and the A/Gb-Interfaces replacing the *Iu* interface.



## 7. References

- [1] European Commission, “Communication from the Commission- Europe 2020: A strategy for smart, sustainable and inclusive growth”, <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:2020:FIN:EN:PDF>, Brussels, 03/2010
- [2] C. Chan, A. Gyax, E. Wong, C. Leckie, A Nirmalathas, and D. Kilper, “Methodologies for Assessing the Use-Phase Power Consumption and Greenhouse Gas Emissions of Telecommunications Network Services”, *Environ. Sci. Technol.*, vol 47, pp 485–492, 2013
- [3] S. Lambert, W. Heddeghem, W. Vereecken, B. Lannoo, D. Colle, and M. Pickavet, “Worldwide electricity consumption of communication networks”, Vol. 20, No. 26, *Optics Express*, OSA, Dec. 2012
- [4] Shahid Mumtaz, Jonathan Rodriguez, “Green Communication in 4G Wireless Systems”, ISBN 978-87-92982-05-6, River Publishers, 2013
- [5] S. Zehle and G. Friend, “Network Sharing Business Plan,” <http://www.coleago.co.uk/>, July 2010
- [6] BMI-T, “Mobile Network Sharing: Benefits and Pitfalls”, <http://www.bmi-t.co.za/node/199>

- [7] S. Mumtaz, D. Yang, V. Monteiro, J. Rodriguez and C. Politis, "Green ICT: Self-Organization Aided Network Sharing in LTE-A", *Journal of Green Engineering*, 2(3):215-232, 2012
- [8] K. Liu, A.M. Sayeed, "Space-time multiplexing for multi-antenna channels", *Proceedings. 2002 IEEE International Symposium on Information Theory*, 2002
- [9] D. Lee, H. Seo, B. Clerckx, E. Hardouin, D. Mazzaresse, S. Nagata, and K. Sayana, "Coordinated multipoint transmission and reception in LTE-advanced: deployment scenarios and operational challenges," *Communications Magazine, IEEE*, vol. 50, pp. 148-155, 02/2012
- [10] 3GPP, "Technical Specification Group Radio Access Network; Coordinated multipoint operation for LTE physical layer aspects (Release 11)," TR 36.819, V11.1.0, December, 2011
- [11] H. Hu, J. Zhang, X. Zheng, Y. Yang, and P. Wu, "Self-configuration and self-optimization for LTE networks," *Communications Magazine, IEEE*, vol. 48, no. 2, pp. 94-100, 2010
- [12] BMI-T, "Mobile Network Sharing: Benefits and Pitfalls", <http://www.bmi-t.co.za/node/199>
- [13] J. Boggis, J. Castro, H. Liu, A. Minokuchi, D. Salam, P. Schwinghammer, M. Shahbaz, "Next Generation Mobile Networks Beyond HSPA & EVDO " A White Paper by the NGMN Alliance, 5 December 2006
- [14] "Use cases for self-organizing networks," D2.1, v1.0, March 2008 <http://www.fp7-socrates.eu/?q=node/1>

- [15] 3GPP TSG RAN3, R3-071438, "Load balancing SON Use case", Athens, Greece, Alcatel-Lucent, August 2007
- [16] X. Costa-Perez, J. Swetina, T. Guo and R. Mahindra, "Radio access network virtualization for future mobile carrier networks", *IEEE Communications Magazine*, Vol.51 Issue7, July 2013
- [17] Y. Zhang, C. Leung, "Cross-layer resource allocation for real-time services in OFDM-based cognitive radio systems", *Springer Telecommunication Systems Journal*, October 2009, Volume 42, Issue 1-2, pp 97-108
- [18] J. Chóliz, Á. Hernández, I. Alastruey, A. Valdovinos, "Coexistence and interworking between UMTS and UWB: a performance evaluation of a UMTS/UWB interoperability platform ", *Springer Telecommunication Systems Journal*, April 2012, Volume 49, Issue 4, pp 409-420
- [19] I. F. Akyildiz, D. M. Gutierrez-Estevez, and E. C. Reyes, "The evolution to 4G cellular systems: LTE-Advanced," *Physical Communication*, vol. 3, pp. 217-244, 2010
- [20] S. Zhou, M. Zhao, X. Xu, J. Wang and Y. Yao, "Distributed wireless communication system: a new architecture for future public wireless access," *IEEE Communications Magazine*, Vol. 41, Issue. 3, pp.108-113, March 2003
- [21] W. Choi, J. G. Andrews, "Downlink performance and capacity of distributed antenna systems in a multicell environment," *IEEE Trans. Wireless Commun.*, vol. 6, no. 1, pp. 69-73, Jan. 2007
- [22] Wei Feng; Yunzhou Li; Shidong Zhou; Jing Wang; Minghua Xia; , "Downlink Capacity of Distributed Antenna Systems in a Multi-Cell Environment," *IEEE Wireless*



Communications and Networking Conference, 2009. WCNC 2009., vol., no., pp.1-5, 5-8  
April

[23] A. Khan, W. Kellerer, K. Koza, and M. Yabusaki, “Network sharing in the next mobile network: TCO reduction, management flexibility, and operational independence,” *Communications Magazine, IEEE*, vol. 49, no. 10, pp. 134–142, 2011

[24] Ericsson, “Shared Networks An operator alternative to reduce initial investments, increase coverage and reduce Time To Market for WCDMA by.” pp. 1-9, 2003

[25] Nokia, “Network Sharing in 3G.” 2001.

[26] Northstream, “3G Rollout Status.” 2002.

[27] T. Frisanco, P. Tafertshofer, P. Lurin, and R. Ang, “Infrastructure sharing and shared operations for mobile network operators From a deployment and operations view,” in *IEEE Network Operations and Management Symposium*, 2008, pp. 129-136

[28] A. Bousia, A. Antonopoulos, L. Alonso, C. Verikoukis, ““Green” Distance-Aware Base Station Sleeping Algorithm in LTE-Advanced”, *IEEE ICC*, June 2012, Ottawa, Canada

[29] A. Bousia, E. Kartsakli, A. Antonopoulos, L. Alonso, C. Verikoukis, “Game Theoretic Approach for Switching Off Base Stations in Multi-Operator Environments”, *IEEE ICC*, June 2013, Budapest, Hungary

[30] 3GPP, Overview of 3GPP release 8 v.0.1.1, Tech. Rep., June 2001

[31] 3GPP TR 22.951, “ Service aspects and requirements for network sharing (Release 11)” V11.0.0 (2012-09)

[32] 3GPP TR 22.852 “Study on Radio Access Network (RAN) sharing enhancements”  
Release 12, V12.0.0 (2013-06).

[33] 3GPP TR 23.251 “Network sharing: architecture and functional description”  
V11.3.0 (2012).

[34] Matti Kiiski, LTE-Advanced: The Mainstream in Mobile Broadband  
Evolution;European Wireless Conference, 2010

[35] Yang Yang, Honglin Hu and Jing Xu, Guoqiang Mao; Relay Technologies for  
WiMAX and LTE-Advanced Mobile Systems; IEEE Communications Magazine,  
October 2009

[36] M. Salem, A. Adinoyi, M. Rahman, H. Yanikomeroglu, D. Falconer, Young-  
Doo Kim, “Fairness-aware Joint Routing and Scheduling in OFDMA-based Cellular  
Fixed Relay Networks,” IEEE International Conference on Communication 2009, pp. 1-  
6, June 2009

[37] C. Sunghyun, E. W. Jang, J. M. Cioffi, “Handover in multihop cellular  
networks,” IEEE Communication Magazine, vol.47, no.7, pp.64-73, July 2009

[38] R. Pabst, B. H. Walke, D. C. Schultz, P. Herhold, H. Yanikomeroglu,  
S. Mukherjee, H. Viswanathan, M. Lott, W. Zirwas, M. Dohler, H. Aghvami, D. D.  
Falconer, G. P. Fettweis, “Relay-Based Deployment Concepts for Wireless and Mobile  
Broadband Radio,” IEEE Communication Magazine, vol. 42, no. 9, pp. 80–89,  
September 2004

[39] H. Hu, H. Yanikomeroglu, D. D. Falconer, S. Periyalwar, “Range Extension  
without Capacity Penalty in Cellular Networks with Digital Fixed Relays,” IEEE  
GLOBECOM 2004, vol. 5, pp. 3053–57, November 2004.

- [40] L. Yu, C. Liu, S. Zhang, W. Zhou, “A New Load Balancing Strategy in Relay Enhanced Cellular Networks with Multiple Traffic Types”, Springer, Advances in Electric and Electronics Lecture Notes in Electrical Engineering Volume 155, 2012
- [41] J. Fan, T. Hui, Xu Haibo, W. Xijun, “A Novel Relay Based Load Balancing Scheme and Performance Analysis Using Markov Models,” IEEE Vehicular Technology Conference, pp. 1-5, April 2009.
- [42] D. C. Dimitrova, J. L. van den Berg, G. Heijenk, “Uplink packet scheduling in cellular networks with relaying—comparative study”, Springer Telecommunication Systems Journal, December 2011, Volume 48, Issue 3-4, pp 237-246
- [43] V. Venkatkumar, T. Haustein and M. Faulkner “Relaying results for indoor coverage in long-term evolution and beyond†”EUROPEAN TRANSACTIONS ON TELECOMMUNICATIONS Volume 21, Issue 8, December 2010, Pages: 770–779, Article first published online : 28 NOV 2010, DOI: 10.1002/ett.1450
- [44] Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation, WiMAX Forum
- [45] Yaxin Cao and Li, V.O.K.; “Scheduling algorithms in broadband wireless networks”, Proceedings of the IEEE, vol. 89, no. 1, Jan. 2001, PP. 76-87
- [46] H. Fattah; C. Leung; “An overview of scheduling algorithms in wireless multimedia networks”, IEEE Wireless Communications, vol. 9, no. 5, Oct. 2002, pp. 76-83
- [47] Zhu H.J.; Hafez, R.H.M.; “Scheduling schemes for multimedia service in wireless OFDM systems”, IEEE Wireless Communications, vol. 14, no. 5, Oct. 2007, pp. 99-105

- [48] K. Son, S. Member, and S. Chong, “Dynamic Association for Load Balancing and Interference Avoidance in Multi-cell Networks,” *IEEE Transactions on Wireless Communications*, vol. 8, pp. 3566–3576, 2009
- [49] Knopp, R.P.; Humblet, P.A.; “Information Capacity and Power Control in Single-Cell Multiuser Communications”, *Proceedings of the International Conference on Communications, (ICC)*, June 1995, Seattle, USA
- [50] Holtzman J.M. *CDMA Forward Link Waterfilling Power Control*. Vehicular Technology Conference, 2000. VTC 2000 Spring. Volume 3. pp. 1663-1667
- [51] Jalali A. et al. *Data Throughput of CDMA-HDR a High Efficiency-High Data Rate Personal Communication Wireless System*. Vehicular Technology Conference, 2000. VTC 2000 Spring. Volume 3. pp. 1854-1858
- [52] Sanjav S.; Alexander L.S.; “Scheduling Algorithms for a Mixture of Real-Time and Non-Real-Time Data In HDR”, *Proceedings of International Teletraffic Congress (ITC)*, 2001
- [53] V. Monteiro, J. Rodriguez, and A. Gameiro, “Dynamic Packet Scheduling for HSDPA Systems”, *WWRF Meeting, Paris, Dec. 2005*
- [54] Andrews, M.; Kumaran, K.; Ramanan, K.; Stolyar A.; Whiting, P. Vijayakumar, R. “Providing quality of service over a shared wireless link”, *IEEE Comm. Magazine*, vol. 39, no. 2, Feb. 2001, pp. 150-154
- [55] M. Mushtaq, B. Augustin, A. Mellouk, “QoE-based LTE downlink scheduler for VoIP”, *IEEE Wireless Communications and Networking Conference (WCNC)*, 2014
- [56] C. Hewage, and M. Martini, “Quality of experience for 3D video streaming”, *IEEE Communications Magazine*, 2013

- [57] J. Navarro-Ortiz, P. Ameigeiras, J. Soler, J. Hernando, Q. Tarrero, R. Perez, “A QoS-Aware Scheduler for HTTP Progressive Video in OFDMA Systems” IEEE Communications Letters, Vol. 17, Issue 4, 2013
- [58] C. Xiong, G. Y. Li, S. Zhang, Y. Chen, and S. Xu, “Energy- and Spectral-Efficiency Tradeoff in Downlink OFDMA Networks”, IEEE Transactions on Wireless Communications, vol. 10, no. 11, pp. 3874–3886, November 2011.
- [59] G. Miao, N. Himayat, G. Li, S. Talwar, “Low-Complexity Energy-Efficient Scheduling for Uplink OFDMA”, IEEE Transactions on Communications, Vol. 60, Issue 1, January 2012
- [60] D. Kwan Ng, E. Lo, R. Schober, “Energy-efficient resource allocation in multiuser OFDM systems with wireless information and power transfer”, IEEE Wireless Communications and Networking Conference (WCNC), 2013
- [61] M. A. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, “Optimal energy savings in cellular access networks, ” in Proc. of IEEE ICC Workshop, Dresden, Germany, Jun. 18, 2009, pp. 1–5
- [62] M. A. Marsan and M. Meo, “Energy efficient management of two cellular access networks,” in Proc. of ACM SIGMETRICS workshop, Seattle, WA, Jun. 15, 2009, pp. 1–5
- [63] S. Zhou, J. Gong, Z. Yang, Z. Niu, and P. Yang, “Green mobile access network with dynamic base station energy saving,” in Proc. of ACM MobiCom, Beijing, China, Sep. 20-25, 2009, pp. 1–3
- [64] M. A. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo. “Optimal energy savings in cellular access networks. ”Proc. IEEE ICC'09 Workshop, GreenComm, June 2009

- [65] T. D. Todd, A. A. Sayegh, M. N. Smadi, and D. Zhao. "The need for access point power saving in solar powered WLAN mesh networks". *IEEE Network*,22(3):4 10, May 2008
- [66] R. Mathar and M. Schmeink. "Optimal base station positioning and channel assignment for 3G mobile networks by integer programming. " *Annals of Operation Research*, 104:225236, 2001
- [67] A. Sang, X. Wang, M. Madhian, and R. D. Gitlin. "Coordinated load balancing, hando@/cell-site selection and scheduling in multi-cell packet data systems. " *Proc. MobiCom'04*, pages 302,314, Sept. 2004
- [68] Y. Bejerano and S. J. Han. "Cell breathing technique for load balancing in wireless LANs." *IEEE Trans. Mob. Compt.*, 8(6):735,749, June 2009
- [69] M. Cardei, M. T. Thai, and Y. Li. "Energy-efficient target coverage in wireless sensor network. " *Proc. Infocom'05* May 2005
- [70] W. Dargie, X. Chao, M. K. Denko, "Modelling the energy cost of a fully operational wireless sensor network ", *Springer Telecommunication Systems Journal*, June 2010, Volume 44, Issue 1-2, pp 3-15
- [71] H. Viswanathan and S. Mukherjee, "Performance of cellular networks with relays and centralized scheduling," *IEEE Trans. Wireless Commun.*,vol. 4, pp. 2318–2328, Sept 2005
- [72] M. Saito, S. Haraguchi, M. Okada, "Dual-Hop Non-regenerative OFDM Relay Systems with Chunk-Based Power Allocation," in *Springer Wireless Personal Communications*, May 2012, Volume 64, Issue 1, pp 51-64

- [73] S. H. Seo, J. S. Song, "An energy-efficient interface selection for multi-mode terminals by utilizing out-of-band paging channels," Springer Telecommunication Systems journal, October 2009, Volume 42, Issue 1-2, pp 151-161
- [74] T. A. Ramrekha, V. N. Talooki, J. Rodriguez, C. Politis, "Energy efficient and Scalable Routing Protocol for Extreme Emergency Ad Hoc Communications", Mobile Advances: Applications and Energy-Efficient Technologies, Springer, Volume 17, Issue 2, April 2012
- [75] F. Saghezchi, M. Alam, A. Radwan, J. Rodriguez, "Cooperative Strategies for Power Saving in Multi-standard Wireless Devices" in book: The Future Internet, edited by A. Galis, A. Gavras, Lecture Notes in Computer Science, Springer, Volume 7858, 2013, pp 284-296
- [76] Rappaport, T.; "Wireless Communications – Principles and Practice", Prentice-Hall, 2<sup>o</sup> edition
- [77] Goldsmith, A.J.; Varaiya, P.P.; "Capacity of fading channels with channel side information", IEEE Transactions on Information Theory, Nov. 1997, vol. 43, no. 6, pp. 1986-1992
- [78] Dinh Thuy Phan Huy, Jonathan Rodriguez, Atilio Gameiro, Rahim Tafazolli, "Dynamic Resource Allocation for Beyond 3G Cellular Networks". Wireless Personal Communications, Volume 43, Issue 4, pp 1727–1740, Springer, December 2007,
- [79] 3GPP TR 25.922 V7.1.0. Radio resource management strategies (Release 7). (Annex J) 3rd Generation Partnership Project, March 2006

- [80] 29 30 31 3GPP TS 25.814. Physical layer aspects for evolved Universal Terrestrial Radio Access (UTRA) (Release 7). 3rd Generation Partnership Project, June 2006
- [81] NGMN performance evaluation methodology. Version 1.2, Next Generation Mobile Networks Alliance, June 2007
- [82] Vienna LTE-A Simulators, <https://www.nt.tuwien.ac.at/research/mobile-communications/vienna-lte-a-simulators/>
- [83] P. Jesus et al., “Key Scenarios and Implications for WINNER II,” IST-4-027756 WINNER II D6.11.2 version 1.0, September 2006, publicly available at <https://www.ist-winner.org>
- [84] FUTON (Fibre optic networks for distributed and extendible heterogeneous radio architectures and service provisioning),” Description of Work(DoW) , [www.ict-futon.eu](http://www.ict-futon.eu).
- [85] V. Monteiro, S. Mumtaz, J. Rodriguez and C. Politis, Link Layer Modelling for Energy Efficient Performance Evaluation in Wireless Cellular Networks , Chapter in, *Green Communication for 4G Wireless Systems*, Shahid Mumtaz, Jonathan Rodriguez , River Publishers 2013
- [86] Hamalainen, S.; Slanina P.; Hartman, M.; Lappetelainen, A.; Holma, H.; Salonaho, O.; “A novel interface between link and system level simulations”, Proceedings of ACTS Summit 1997, Oct. 1997
- [87] Brueninghaus, K.; Astély, D.; Saltzer, T.; Visuri, S.; Alexiou, A.; Karger, S.; Seraji, G.; “Link performance models for level simulations of broadband radio access systems”, Proceedings IEE International Symposium on Personal, Indoor and Mobile Radio Communications, March, 2005



- [88] Patrick Hosein “On the optimal scheduling of uplink resources in OFDMA-based wireless networks”, in Proc. of EW 2006 - 12th European Wireless Conference, Athens, Greece, Apr. 2006.
- [89] 3GPP 25.214, “Physical layer procedures (FDD) (Release 9)” 3GPP TS 25.214 V9.3.0, 2010 -09
- [90] J Cho and Z. J. Haas, “On the Throughput Enhancement of the Downstream Channel in Cellular Radio Networks Through Multihop Relaying ” IEEE Journal on Selected Areas in Communications, vol. 22, no. 7, september 2004
- [91] F. A. Cowell, Measuring inequality: techniques for the social sciences, John Wiley & Sons, New York, 1977
- [92] Hongyuan Shi; Sethu, H.; , "Greedy fair queueing: a goal-oriented strategy for fair real-time packet scheduling," 24th IEEE Real-Time Systems Symposium, 2003. RTSS 2003., vol., no., pp. 345- 356, 3-5 Dec.2003
- [93] M. Mehrjoo, M. Awad, M. Dianati, and X. Shen, "Design of Fair Weights for Heterogeneous Traffic Scheduling in Multichannel Wireless Networks," IEEE Transactions on Communications, Vol. 58, no. 10, October 2010
- [94] IST-4-027756 WINNER deliverable D1.1.2 . Final link level and system level channel models. <https://www.ist-winner.org/>
- [95] M. Nasralla, O. Ognenoski, and M. Martini, “Bandwidth scalability and efficient 2D and 3D video transmission over LTE networks”, IEEE International Conference on Communications; 9 - 13 June 2013, Budapest, Hungary.
- [96] C. Hewage, and M. Martini, “Quality of experience for 3D video streaming”, IEEE Communications Magazine, 51(5), ISSN (print) 0163-6804

- [97] C. Thomos, T. Dagiuklas, I. Politis, S. A. Kotsopoulos, S. Mumtaz, V. Monteiro, J. Rodriguez “Cross-Layer Architecture for 3D Video Streaming” 2nd ROMEIO Workshop, Istanbul Jul. 2013.
- [98] Schwarz H., Marpe D., and Wiegand T., “Overview of the scalable video coding extension of the H.264/AVC standard,” *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 17, no. 9, pp. 1103–1120, Sept. 2007
- [99] H. Saki, M.G. Martini, M. Shikh-Bahaei, “Multi-user scalable video transmission over cognitive radio networks,” 2015 IEEE International Conference on Communications (ICC), 8-12 June 2015
- [100] “Evolved universal terrestrial radio access (e-utra); physical channels and modulation, (release 10),” 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; 3GPP TS 36.211 V10.3.0 (2011-09).
- [101] V. Monteiro, K. Huq, S.M. Mumtaz, H.M. Marques, J. Rodriguez, , 3D Video Streaming Transmission over OFDMA-based Systems , *IEEE International Conf. on Image Processing - ICIP*, Paris , France , Vol. 0 , pp. 0 - 0 , October 2014
- [102] Srivastava, V.; Motani, M.; “Cross-Layer Design: A Survey and the Road Ahead”, *IEEE Communications Magazine*, Dec. 2005, vol. 43, no. 12, pp. 112-119
- [103] Lyo H., Ci S., Wu D., Wu J. and Tang H., "Quality-Driven Cross-Layer Optimized Video Delivery over LTE, " *IEEE Communications Magazine*, vol. 48, No. 2, pp. 102-109, Feb. 2010
- [104] 3GPP TR 25.996 V6.1.0, "Spatial channel model for Multiple Input Multiple Output (MIMO) simulations," Sept. 2003

- [105] 3GPP TS 23.203 V10.6.0, "3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Policy and charging control architecture (Release 10)," Mar. 2012
- [106] Shahid Mumtaz, Kazi M.S Huq, and Jonathan Rodriguez, "LTE-A D2D Communication: A 5G paradigm", *IEEE wireless Communication Magazine*, OCT, 2014
- [107] S. Mumtaz, K. Huq, J. Rodriguez, V.M. Monteiro, C.P. Politis , *Cognitive Vehicular Communication for 5G* , *IEEE Communications Magazine*, Vol. 45 , No. 34 , pp. 2 - 3 , July 2015
- [108] WiMAX Forum, WiMAX System Evaluation Methodology V2.1, July 2008
- [109] Universal Mobile Telecommunications System (UMTS) ETSI. Selection procedures for the choice of the radio transmission technologies of the UMTS. Technical Report (UMTS 30.03 version 3.2.0), TR 101 112 v3.2.0, April 1998
- [110] V. Monteiro, S. Mumtaz, A. Nascimento, J. Rodriguez and C. Politis, System Level Evaluation Methodology for Energy Saving , Chapter in, *Green Communication for 4G Wireless Systems*, Shahid Mumtaz, Jonathan Rodriguez , River Publishers 2013
- [111] O. Arnold et al. Power consumption modeling of different base station types in heterogeneous cellular networks, in *Proceedings of Future Network and Mobile Summit*, June 2010.
- [112] M. Gudmundson, "Correlation model for shadow fading in mobile radio systems", *Electronics Letters*, vol. 27, no. 4, pp. 2145–2146, November 1991
- [113] Xiadong Cai, B. Georgios, and G. Giannakis, "A two-dimensional channel simulation

model for shadowing processes”, IEEE Transactions on Vehicular Technology, vol. 52, no. 6, pp. 498–523, November 2003

[114] W. C. Jakes, *Microwave Mobile Communications*, Wiley, New York, 1974

[115] Yunxin Li and Xiaojing Huang, “The generation of independent Rayleigh faders”, in Proceedings of the IEEE International Conference on Communications (ICC 2000), vol. 1, pp. 18–22, June 2000

[116] ITU, “Guidelines for evaluation of radio transmission technologies for IMT-2000”. Technical Report, Recommendations ITU-R, M.1225, 1997.

[117] J. Medbo, H. Anderson, P. Schramm, and H. Asplund, “Channel models for hipernlan/2 in different indoor scenarios.”, Technical report, COST259 TD(98), Bradford, UK, April 1998

[118] F 3GPP, Feasibility study for OFDM for UTRAN enhancement. Technical report, 3GPP,TR, 25.892, V1.1.0., 2004

[119] F. Wang, A. Ghosh, R. Love, K. Stewart, R. Ratasuk, R. Bachu, Y. Sun, and Q. Zhao, “IEEE 802.16e system performance: analysis and simulations”, in Proceedings of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2005), vol. 2, pp. 900–904, 2005

[120] V.M. Monteiro, K. Huq, S.M. Mumtaz, C.P. Politis, J. Rodriguez, Energy efficient load balancing for future self-organized shared networks, *Springer Telecommunication Systems*, Vol. DOI 10.1007, No. s11235-014-9888-1, pp. 0 - 0, November, 2014

[121] V. Monteiro, S.Mumtaz, J. Rodriguez, C. Politis, Positioning for performance enhancement in shared LTE and HSPA networks, *IEEE International Conference on*

*Telecommunications and Multimedia (TEMU)*, 2012, Chania, Greece, Vol. 0 , pp. 169 -  
174, July 2012