Efficient Resource Allocation for Joint Operation of Large and Small-cell Heterogeneous Networks

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Abstract

This thesis investigates the downlink resource allocation problem in Orthogonal Frequency Division Multiple Access (OFDMA) Heterogeneous Networks (HetNets) consisting of macro-cells and small-cells sharing the same frequency band. Dense deployment of small-cells overlaid by a macro layer is considered to be one of the most promising solutions for providing hotspot coverage in future 5G networks.

The focus is to devise optimised policies for small-cells’ access to the shared spectrum, in terms of their transmissions, in order to maximise small-cell served users sum data rate while ensuring that certain level of quality of service (QoS) for the macro-cell users in the vicinity of small-cells is provided. We obtain the optimal solution to the resource allocation problem by employing the well-known Dual Lagrangian method. The formulated resource allocation problem is decomposed into $N$ sub-problem at each Resource Block (RB). The optimal transmit power and RB allocation for each small-cell is obtained by updating the dual variables based on sub-gradient method. Furthermore, a low complexity heuristic solution based on binary integer linear programming is proposed for practical systems, and its performance is analysed in comparison with Reuse-1 and orthogonal frequency reuse cases.

Alongside considering the data channel protection for macro-cell served users in the vicinity of small-cells, we also cater for control channel constraints. Since the control channel holds key information to decode data channel information, and if control channel is lost the data channel performance will be severely affected. We formulate the joint control and data channel resource allocation problem in HetNets. The solution to the complex problem is addressed by two low complexity heuristic solutions. The proposed interference aware heuristic solution is based on a progressive iterative approach which has significantly lower complexity compared to the optimal case.

Whilst the aim is to maximise the net data-rate performance of the small-cells, we also address the energy efficiency issues in dense small-cell networks. We formulate the optimisation problem to minimise the small-cells’ energy consumption by making use of sleep-mode capabilities. The solution to the problem is provided by another heuristic algorithm which addresses the interference problem as well as the energy consumption minimisation. The interference minimisation phase is updated on a shorter intervals, whereas sleep mode phase takes place on larger time scales, considering the wake-up delays associate with practical networks. The potential energy saving gains are extensively examined by hypothetically making use of call data records from City of Milan. This real data helps highlight the potential of energy savings by making use of small-cells’ sleep-mode capabilities along with our proposed algorithm.

Key words: 5G, Energy Efficiency, Heterogeneous Networks, Inter-cell Interference, Resource Allocation, Small-cells.

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# Nomenclature

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<th>Description</th>
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<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
</tr>
<tr>
<td>5G</td>
<td>5th Generation</td>
</tr>
<tr>
<td>ABSF</td>
<td>Almost Blank Subframe</td>
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<tr>
<td>AMC</td>
<td>Adaptive Modulation and Coding</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>CA</td>
<td>Carrier Aggregation</td>
</tr>
<tr>
<td>CC</td>
<td>Component Carriers</td>
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<tr>
<td>CCE</td>
<td>Control Channel Element</td>
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<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
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<td>CDR</td>
<td>Call Data Record</td>
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<tr>
<td>CFI</td>
<td>Control Format Indicator</td>
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<tr>
<td>CQI</td>
<td>Channel Quality Information</td>
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<tr>
<td>CRS</td>
<td>Control Reference Signal</td>
</tr>
<tr>
<td>CSG</td>
<td>Closed Subscriber Group</td>
</tr>
<tr>
<td>ECG</td>
<td>Energy Consumption Gain</td>
</tr>
<tr>
<td>ECR</td>
<td>Energy Consumption Ratio</td>
</tr>
<tr>
<td>EE</td>
<td>Energy Efficiency</td>
</tr>
<tr>
<td>EFFR</td>
<td>Enhanced Fractional Frequency Reuse</td>
</tr>
<tr>
<td>eICIC</td>
<td>Enhanced Inter-cell Interference Coordination</td>
</tr>
<tr>
<td>ERG</td>
<td>Energy Reduction Gain</td>
</tr>
<tr>
<td>ESRA</td>
<td>Efficient Suboptimal RB Allocation</td>
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<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>FFR</td>
<td>Fractional Frequency Reuse</td>
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<tr>
<td>FPC</td>
<td>Fractional Power Control</td>
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<tr>
<td>HetNet</td>
<td>Heterogeneous Network</td>
</tr>
<tr>
<td>HII</td>
<td>High Interference Indicator</td>
</tr>
<tr>
<td>ICI</td>
<td>Inter-Cell Interference</td>
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<td>ICIC</td>
<td>Inter-Cell Interference Coordination</td>
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<td>ID</td>
<td>Identity</td>
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<tr>
<td>IFR</td>
<td>Incremental Frequency Reuse</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>---------</td>
<td>--------------------------------------------------</td>
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<tr>
<td>IoT</td>
<td>Interference over Thermal</td>
</tr>
<tr>
<td>ITA</td>
<td>Interference Tolerance Aware</td>
</tr>
<tr>
<td>KKT</td>
<td>Karush-Kuhn-Tucker</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>LTE-A</td>
<td>Long Term Evolution Advanced</td>
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<tr>
<td>MAC</td>
<td>Medium Access Control</td>
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<tr>
<td>MCS</td>
<td>Modulation and Coding Scheme</td>
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<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>MINP</td>
<td>Mixed Integer Non-linear Programming</td>
</tr>
<tr>
<td>MUE</td>
<td>Macro-cell user</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
</tr>
<tr>
<td>ORA</td>
<td>Optimal Resource Allocation</td>
</tr>
<tr>
<td>OSG</td>
<td>Open Subscriber Group</td>
</tr>
<tr>
<td>PCFICH</td>
<td>Physical Control Format Indicator Channel</td>
</tr>
<tr>
<td>PCI</td>
<td>Physical Cell ID</td>
</tr>
<tr>
<td>PDCCH</td>
<td>Physical Downlink Control Channel</td>
</tr>
<tr>
<td>PDSCH</td>
<td>Physical Downlink Shared Channel</td>
</tr>
<tr>
<td>PFR</td>
<td>Partial Frequency Reuse</td>
</tr>
<tr>
<td>PHICH</td>
<td>Physical Hybrid-ARQ Indicator Channel</td>
</tr>
<tr>
<td>POI</td>
<td>Point of Interest</td>
</tr>
<tr>
<td>PRB</td>
<td>Physical Resource Block</td>
</tr>
<tr>
<td>QoE</td>
<td>Quality of Experience</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase-Shift Keying</td>
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<tr>
<td>RA</td>
<td>Resource Allocation</td>
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<tr>
<td>RB</td>
<td>Resource Block</td>
</tr>
<tr>
<td>RE</td>
<td>Resource Element</td>
</tr>
<tr>
<td>REG</td>
<td>Resource Element Group</td>
</tr>
<tr>
<td>REM</td>
<td>Radio Environment Maps</td>
</tr>
<tr>
<td>RSRP</td>
<td>Reference Symbol Received Power</td>
</tr>
<tr>
<td>RSRQ</td>
<td>Reference Signal Received Quality</td>
</tr>
<tr>
<td>SC</td>
<td>Small-Cell</td>
</tr>
<tr>
<td>SE</td>
<td>Spectral Efficiency</td>
</tr>
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<td>SFFFR</td>
<td>Soft Fractional Frequency Reuse</td>
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<tr>
<td>SFR</td>
<td>Soft Frequency Reuse</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference and Noise Ratio (SINR)</td>
</tr>
<tr>
<td>SRM</td>
<td>Small-cell Rate Maximisation</td>
</tr>
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<td>SUE</td>
<td>Small-cell User</td>
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<tr>
<td>TB</td>
<td>Transport Block</td>
</tr>
<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
</tr>
<tr>
<td>ULRP</td>
<td>Uplink Reception Power</td>
</tr>
<tr>
<td>VoLTE</td>
<td>Voice over LTE</td>
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</table>
Superscripts/Subscripts

0       Index for macro-cell
Avail   Available
c       Referring to control channel
c       Binary Multiplier for control channel reliability
c-sum   Submission for control channel
c-max   Maximum for control channel
d       Referring to data channel
d-sum   Submission for data channel
d-max   Maximum for data channel
i       Index for small-cells
k       User index
m       Cell index
max     Maximum
n       RB index
sum     Submission
Thres   Threshold
total   Total
req     Required
u       Macro-cell served user index

Symbols

B       Bandwidth
BLER    Block error rate
BR      Theoretical bit rate for a specific MCS value
C0      Binary congestion indicator at macro-cell
Δ       Slope of load dependent power consumption
e_r     Efficiency of MCS
g       Dual Function
γ       Signal to interference and noise ratio
Γ       Channel gain
H       Profit Matrix
L       Lagrangian Function
λ       First Lagrange Multiplier
μ       Second Lagrange Multiplier
N_0     Noise Power Spectral Density
ω       Interference from a single small-cell to MUE
Ω       Sum Interference from all neighbouring small-cells to MUE
φ       Binary small-cell muting variable
p       Transmit Power
P       Power
ψ       Binary cell state variable
r       MCS value
Nomenclature

\[ R \quad \text{Theocratic data rate} \]
\[ \dot{R} \quad \text{Instantaneous Throughput} \]
\[ \sigma \quad \text{Shadow fading co-efficient} \]

Sets

\[ \mathcal{K} \quad \text{Set of all users in the network} \]
\[ \mathcal{K}_0 \quad \text{Set of users in Macro-cell} \]
\[ \mathcal{K}_m \quad \text{Set of users in cell m} \]
\[ \mathcal{M} \quad \text{Set of all cells} \]
\[ \mathcal{T} \quad \text{Set of all REs} \]
\[ \mathcal{T}_n \quad \text{Set of control channel REs associated to RB n} \]
\[ \mathcal{T}_v \quad \text{Set of REs in a RB} \]

Units

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>bits/Joule</td>
<td>Energy Efficiency</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>dBm</td>
<td>Decibel relative to one milliwatt</td>
</tr>
<tr>
<td>GHz</td>
<td>Gigahertz</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>Km</td>
<td>Kilometer</td>
</tr>
<tr>
<td>m</td>
<td>Meter</td>
</tr>
<tr>
<td>MHz</td>
<td>Megahertz</td>
</tr>
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<td>W</td>
<td>Watt</td>
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Chapter 1

Introduction

In the last decade, technologies have rapidly developed towards providing better, faster and reliable communications amongst people and devices. The use of internet in our daily life has taken a big leap from being a luxury to a necessity. Along side that, the use of traditional desktop devices has evolved to the use of portable and hand-held devices. These changes in user behaviour and level of device mobility has led to a surge in telephony and internet activity on the go. Previously, mobile telephony and fixed line internet services had separate revenue markets and distinct business plans, however, recently the market has more or less unfolded to unified Quality of Experience (QoE) based service to the end user. This continuing growth in demand for better wireless broadband experience is forcing the industry to look ahead at how the current networks can be readied to fulfil the future demands.

1.1 Scope and Challenges

Future 5th generation (5G) networks are expected to be capable of providing significantly high capacity, compared to the previous generations of mobile communication systems to meet increase demand [1] [2]. In the interest of handling high data rate demands and providing a complete service structure to end users, mobile operators have invested into various solutions. Similarly the research community have also proposed several techniques to handle Hot-spots. Deployment of heterogeneous Networks (HetNets), comprising of large cells and densely deployed small-cells, is suggested as a promising solution for future 5G networks [3]. Dense deployment of small-cells overlaid within the area of larger macro-cells has the potential to provide higher spectral
efficiency, as compared to WiFi offloading and Massive Multiple-Input Multiple-Output (MIMO) systems [4].

The joint operation of small and large cells brings a number of fundamental challenges the need to be addressed. Small-cells can either be operated in a separate licensed frequency band to that of the macro-cell, or in a license free band like in case of WiFi access points. However since small-cells are deployed not only at subscriber’s premises but also at public places, and as part of the operators network they need to be operated over licensed frequency bands.

In case of small-cell operation in a licensed frequency band, and considering the expected highly dense deployment, such a deployment would be in-feasible due to high cost of limited frequency resources. Operational costs force the operators to share the same frequency band amongst large and smaller cells at the price of interference related issues. There have been several smart frequency sharing techniques discussed in [2.1.1], to address inter-site interference to an extent. Nevertheless, as the density of small-cells increases, these solutions fail to provide reliable interference avoidance.

Some of the major challenges in regards to the joint operation of large and small-cells are listed below:

- One of the major issue due to the coexistence of small-cells and large-cells is due to the presence of a macro-cell served user in the vicinity of a small-cell. In such a scenario macro-cell user faces severe interference from the nearby small-cells, which leads to a significant drop in macro-cell users performance. The signal to interference and noise ratio (SINR) of the macro-cell user drops such that the data rate targets are not met, hence the minimum requirements for certain data services could not be achieved. Interference caused by large-cell to smaller-cells is not considered critical as there are fewer users served by small-cells as compared to large-cells, and small-cell served users are anyway allocated with more bandwidth resources.

- Alongside the data channel of the macro-cell served user, the control channel is also severely affected. The important aspect to note is that the design of control channel in Orthogonal Frequency Division Multiple Access (OFDMA) based systems is not as flexible as the data channel. Secondly the reliability of the control channel has direct impact on the measured performance of the data channel, as information in the control channel serves to be a key to unlock information residing inside the data channel. If the control channel information
can not be decoded at the receiver, the data channel associated with that specific control channel shall also be lost.

- Deployment of small-cells leads to increase in the overall energy consumption, which can be in general justified due to the significant impact on network capacity. However, the service demand is not uniform throughout the day; thus, most of the small-cells are underutilised while consuming substantial amount of energy. This leads to poor energy efficiency of these devices in off-peak hours of the day [5].

1.2 Objectives and Contributions

This thesis investigates the self organisation issues in joint operation of small and large cell OFDMA systems. The major objectives of this research work are as follows:

- The first objective of the thesis is to evaluate the performance degradation in the data channel of the macro-cell served users while small-cells transmit on the same shared bandwidth resource. Furthermore, to design a low complexity algorithm which optimises the small-cell for maximum gain in the network.

- The second objective of the thesis is to analyse the control channel performance degradation of macro-cell served users in the presence of co-channel small-cells and how the control channel performance affects the data channel. Moreover, to propose a practical resource allocation scheme to address the interference related issues in control channel.

- Finally the last objective of the thesis is to assess the energy saving potentials in large and small-cells network, and propose a sleep mode algorithm to minimise the energy consumption of the network.

In accordance with the objectives of the thesis, our contributions in context of OFDMA small-cells operation with umbrella macro-cells have been summarized as follows:

- First, this study intends to evaluate the existing literature on interference management in homogeneous and heterogeneous networks and identifies the gaps in the literature. The performance of the macro-cell users is assessed in case of Reuse-1 and FFR conventional schemes. The problem of co-channel interference in HetNet scenario is formulated in-line with the existing literature to represent
the problem of interference caused by small-cell transmissions to macro-cell served users’ data channel. A complete optimal solution is derived with the help of Dual Lagrangian method to eliminate the data channel interference.

- Alongside the optimal solution, a heuristic solution based on binary integer linear programming is proposed to reduce the computational complexity relative to the optimal solution with similar performance. The performance is also compared for both the solutions with the conventional schemes. Moreover, the feasibility of the proposed solution is also analysed to be implemented in a practical Long-term Evolution (LTE) network.

- Next, the issue of control channel interference is addressed by reformulating the previous data-channel-only problem into joint control and data channel problem. It is important to reformulate the problem while considering the control channel as the constraints of both the channels are different. The new problem is mathematically formulated and further solved based on two heuristic solutions. A progressive step wise iterative procedure is incorporated to solve the control channel problem for real-time systems. Alongside comparing the results with conventional frequency reuse systems, the computational complexity is also compared amongst the proposed solutions.

- The aspect of energy consumption in small-cell networks is also considered in this thesis, the original data channel interference management problem is reformulated to include the aspect of energy savings for off-peak hours of the day. The proposed energy efficient heuristic algorithm manages to save a significant amount of energy under various deterministically tested load conditions.

- Finally, real Call Data Records (CDR) form City of Milan are used to evaluate the energy saving potentials of the proposed energy efficient algorithm discussed in the previous bullet point. The calling and internet activity data is hypothetically normalised on same units and set in case of macro and small cells. The activity levels are fed into the simulator to generate user load accordingly. It is identified that up to 8 times energy savings are possible in a real urban city topology.

Research work carried out during the course of this PhD has resulted in the publications listed below. Published material which has been added in this thesis is indicated in Section 1.3.
1.2. Objectives and Contributions

Journals


Book Chapter


Conferences


1.3 Thesis Organisation

The content of this thesis is structured as follows:

Chapter 2 provides a background on interference management in homogeneous and heterogeneous networks discussing the categories and relative literature in each category. Further the chapter also introduces energy efficient resource allocation and sleep mode techniques in small-cell networks. An introduction to LTE frame structure and most important control channels is also presented in this chapter. Some of the contents of this chapter are published in J.5.
Chapter 3 introduces the most relevant literature on data channel interference management in macro and small-cell heterogeneous networks alongside the mathematical modelling for interference tolerance allowance for macro-cell served users. The problem of inter-tier interference caused by small-cell transmissions to the data channel of the macro-cell served users is mathematically formulated and the Dual Lagrangian and sub-gradient method based optimal solution is derived in detail. Considering the discussed computational complexity of the optimal solution, a binary linear integer programming based solution is also presented. The results for the two proposed schemes are compared with Reuse-1 and Fractional Frequency Reuse (FFR) schemes. A discussion on feasibility of our proposed methodology in LTE systems is also presented. This work has been published in J.1.

Chapter 4 presents the work on control and data channel resource allocation in heterogeneous networks. This work is an extension to the previous chapter. In this chapter the importance of control channel is considered and based on that the user signal strength modelling is presented for both control and data channels. Although some of the mathematical equations are similar to that as in case of data channel in Chapter 3, but since the control channel has different constraints so it is important to introduce different notions for control and data channels. The problem is formulated considering joint constraints for data and control channels. Two heuristic solutions are presented to solve the problem, carefully considering the time complexity for a practical system. This research work is published as part of C.6 and J.2.

Chapter 5 brings forward the idea of energy savings based on the work done in Chapter 3. The objective of the work in Chapter 3 was to maximise the sum data rate performance of the small-cells. In this chapter the objective is modified to maximisation of energy efficiency by making use of sleep-mode capabilities in small-cells. The mathematical problem is formulated and solved based on a heuristic algorithm. Simulation results are presented initially based on a deterministic scenario with variable load conditions. In order to demonstrate the scale of energy savings from under-utilised cells on a metropolitan city level, real data from a telecom operator is used. Detail analysis on daily and weekly activity levels is presented in the same macro and small-cell scenario. First part of this work is published in C.7, and the later half is under review in J.4.

Chapter 6 concludes the thesis with key results and contributions, providing a holistic overview of the author’s achievements while highlighting remaining challenges and
shortcomings. It also discusses future research directions and highlights potential applications that could benefit from this study.
Chapter 2

Background and State of the Art

This chapter provides a comprehensive overview of the existing literature related to small-cells’ operation. Three main topics are covered in this chapter, interference and resource management in small-cells, Energy Efficiency (EE) aspects in small-cells and some general discussion introducing literature regarding deployment, backhauling and access modes in small-cell networks.

2.1 Interference and Resource Management in Cellular Networks

Macro and small-cell HetNets can be operational either with dedicated channel assignment or co-channel assignment. Dedicated channel assigned macro and small cell HetNets operate in different frequency bands. In other words the operators licensed chunk of frequency band is further divided in two or more parts to distinct the frequency allocation for overlayed small cells. Such a scheme is fairly easy to implement with fewer complexities, but is indeed a waste of resource, resulting in a reduced network capacity.

In order to fully utilise the resources, co-channel frequency assignment scheme is used. In simple words both the macro and small cells operate in the same frequency band fully utilising the network resources. This utilisation of complete spectrum chunk brings in complexity to the system. The main challenge to address here is the interference amongst these heterogeneous cells. This problem becomes more severe in the presence of Closed Subscriber Group (CSG) small-cells, limiting the access of the macro cell to
its users. In the following subsections the state of the art interference management techniques for the macro and small-cell HetNets, focusing more towards OFDMA systems will be discussed in detail.

2.1. Interference and Resource Management in Cellular Networks

2.1.1 Inter-cell Interference Coordination

Inter-cell interference coordination (ICIC) schemes are focused to mainly minimise interference in homogeneous macro cells only environment. Interference can be categorised into two major types, Intra-cell interference and Inter-cell interference (ICI). Intra-cell interference is eliminated by the use of OFDMA which consists of distinct sub-carriers. Whereas Inter-cell interference is a topic of major concern in the communications community [6–9]. Inter-cell interference can be mitigated by major three type of techniques, Interference Cancellation, Interference Randomization and Interference Avoidance.

Interference cancellation is defined as the regeneration of the interference signals and subsequently subtracting them from the desired signal. It is based on the receiver processing e.g scrambling/interleaving aiming to whiten the inter-cell interference. Such a process is highly complex and requires very frequent exchange of information to maximise gains.

Interference randomization or frequency hopping is known as the averaging of the interference across the data blocks or the whole frequency band, making interference appear as background noise. Though such a process makes interference appear as White Gaussian Noise but does not reduce interference, hence there are no substantial performance gains.

Interference avoidance as obvious from the name, are the techniques for the reuse of the frequency spectrum in such a manner that there is no or minimum interference in the system. The are two major categories of interference avoidance techniques, Frequency Reuse based schemes and Cell Coordination based schemes.

2.1.1.1 Frequency Reuse Based Schemes

Frequency reuse based schemes are considered to be relatively easy to implement since there is no frequent exchange of information required amongst the transmission nodes. However, these techniques also have a drawback of being non adaptive to dynamic
Figure 2.1: Categories of ICIC techniques
conditions in the network. They are usually pre-set at the time of deployment and operate likewise. Frequency reuse based schemes are further categorised as Conventional Frequency Reuse and Fractional Frequency Reuse (FFR).

**Conventional Frequency Reuse**  The simplest frequency reuse is the reuse of factor one, widely known as frequency Reuse-1 scheme. In such a scheme all the sectors or cells use the same frequency band with no power limitations, resulting in maximum throughput. However, with reuse 1, very high inter-cell interference is experienced by the cell edge users. To overcome this high interference present due to the Reuse-1 schemes, another scheme was presented with a reuse factor of 3. In this scheme, the total bandwidth is divided into three portions and these portions are used by adjacent sectors to reduce the interference. Frequency Reuse-3 can be considered as one of the most simplest form of static interference coordination, but such coordination degrades the throughput up to one third since the total bandwidth gets statically divided. Figure 2.2 gives a graphical explanation of these frequency reuse schemes.

![Figure 2.2: Frequency Reuse 1 and Reuse 3](image-url)
Fractional Frequency Reuse  Ahead from the traditional frequency reuse schemes, FFR schemes are more sophisticated and beneficial in terms of providing better coverage to cell edge users. The basic idea behind FFR is the division of the available frequency and power resources into major and minor group. These groups are used to serve cell-edge users and cell-centre users respectively. There are two basic types of FFR schemes, Partial Frequency Reuse (PFR) and Soft Frequency Reuse (SFR).

PFR is also termed as full isolation frequency reuse, since the cell-edges are fully isolated from adjacent cell interference. In this scheme portions of frequency are restricted to be used in certain geographical portions of a cell. An application could be in a tri-sector cell, one portion of the frequency band can be used with low power for centre users, whereas the remaining portion of frequency can be further distributed amongst adjacent sectors to serve cell-edge users with higher power.

SFR can be considered as a scheme hybrid of PFR and frequency Reuse-1. SFR makes use of Reuse-1 for the centre users with low transmit power, whereas each adjacent sector transmits at higher power in a certain frequency portions. As a result of this smart frequency allocation, the utilisation of the frequency is increased as compared to PFR and the interference is the system is also relatively lower, as compared to Reuse-1 scheme. Figure 2.3 gives a graphical explanation of these fractional frequency reuse schemes. There are several variants of Fractional Frequency reuse, mostly based on PFR and SFR. Some well known schemes are as Soft Fractional Frequency Reuse (SFFR), Incremental Frequency Reuse (IFR) and Enhanced Fractional Frequency Reuse (EFFR).

2.1.1.2 Cell Coordination Based Schemes

To overcome the static behaviour of the above mentioned frequency/power allocation schemes and make the networks dynamic to traffic requirements, coordination amongst the transmission sites has been discussed as a possible solution. Cell coordination can be made possible at different levels within the network. A central entity depending on the level or coordination makes decisions for the allocation of resources, minimising the overall interference in the network. Cell coordination based schemes can be further categorised as Centralised, Semi-Distributed and Distributed.

A centralised cell coordination scheme is based on the idea of controlling the frequency allocation of all the cells in the network by a central entity. This central entity receives, hold and processes all the information to make decision on the resource allocation amongst the cells. The aim is usually to do smart frequency and power allocation to
minimise the interference in the network as well as to balance the load conditions across the cells in the network.

A semi-distributed coordination is neither completely central nor distributed. In fact, it is a form of coordination amongst a group of transmission cells, governed by different central entities within every sub-coordination group. Similar to the centralised schemes, the central entity responds back to the individual cells regarding their frequency allocation policy. The central entities across sub-coordination groups may as well share information. Such a scheme is more feasible for networks with large densities of clustered cells to reduce the delays and signalling within the network.

The signalling load within the network is further minimised by adapting distributed or de-centralised schemes. The prime difference from centralised and semi-distributed schemes is that there is no central entity required for distributed schemes to function. The cells within the network coordinate amongst each other and optimise their resources without the presence of the central controller, following a specific network policy individually. Distributed schemes are further categorised into Coordinated-Distributed schemes and Autonomous-Distributed scheme. As obvious from the name, a Coordinated-Distributed scheme is where the cells interact over a common interface.
for the exchange of information and optimise their performance and resources based on a greedy approach. In an Autonomous-Distributed scheme there is no exchange of information amongst the nodes, hence completely illuminating the coordination signalling load due no information exchange. Each node self organises itself based on the network policies or in a more advanced scheme, based on sensing nearby interference and users. However, such a scheme requires processing and sensing capabilities at each cell.

### 2.1.2 Enhanced Inter-cell Interference Coordination

Since most of the aforementioned interference avoidance techniques were more focused towards interference minimisation in larger homogeneous size cells, the rapid increase in the deployment of heterogeneous networks brought forward the need for Enhanced Inter-cell Interference Coordination (eICIC) techniques. These techniques are proposed with keeping a non-homogeneous network topology into consideration. Apart for data channel protection, eICIC also focus on the protection of control channels. Figure 2.4, shows the main types of eICIC techniques along with subcategories. eICIC techniques are mainly categories into Time Domain, Frequency Domain and Power Control techniques.

#### 2.1.2.1 Time Domain Techniques

Time domain techniques are focused to mitigate interference to victim users (users which face severe interference from cells in the vicinity) from a dominant interferer by restricting time domain resources. Generally in an OFDMA mobile network, all the radio resource units are considered to be time aligned. If a victim user is in close proximity of a dominant interferer and transmitting in the same time domain units, it gets difficult to decode control and data channels. Subframe Alignment and OFDM symbol shift are the two major time domain eICIC techniques [10]. A summary of time domain techniques is presented in Table 2.1.

**Subframe Alignment** Subframe alignment is also known as Almost Blank Subframe (ABSF), where the control channel of the dominant interferer is muted in certain subframes. This muting in some resource blocks (RBs) for the control and data channels is further defined as No-PDCCH case. There also exists a possibility of only muting the data channels where as for control channels load control is implemented. Such a case
2.1. Interference and Resource Management in Cellular Networks

Figure 2.4: Categories of eICIC techniques
is defined as Lightly-loaded PDCCH case. In subframe alignment Control Reference Signal (CRS) interference still exists.

**OFDM Symbol Shift** As the name signifies, Orthogonal frequency division multiplexing (OFDM) symbol shifting is the shifting of the OFDM symbol boundary of the dominant interferer by a number of OFDM symbols with respect to the victim’s subframe boundary. With this technique the overlapping of the control channels of the victim and interferer is prevented, however there might be interference on the control channels of the victim from the data channels of the interferer. This interference from the data channels of the interferer can be avoid by either interferer’s data channel symbol muting (Physical Downlink Shared Channel (PDSCH) symbol muting) or consecutive subframe blanking.

PDSCH symbol muting is referred to the muting of the OFDM data symbols of the interferer which pose high interference to the control channels of the victim user. Whereas for consecutive subframe blanking, previously explained ABSF technique is applied over the interferer’s transmission to avoid overlapping of the interferer’s control channel towards the control channels of the victim. It is important to mention here that time domain eICIC techniques require strict time domain synchronisation. A time synchronisation approach is proposed in [11] to effectively apply interference mitigation techniques in HetNets. This time synchronisation is sometimes difficult to achieve in practical systems [12]. Physical Cell ID (PCI) manipulation is proposed by [13] where the small-cells sniffs the identity (ID) of the neighbouring cells and adjusts its own cell ID by adding a integer to it. This integer is generated as the result of a hash function. Since the control channel placement is mainly dependent on the PCI of the cell, so a change to the PCI by adding a specific integer shall eliminate the interference in the control region. This technique is further explained in Chapter 4.

### 2.1.2.2 Power Control Techniques

Power control is one of the most fundamental technique to overcome the interference by limiting the transmit power of the interferer or increasing the transmit power of the source. Power control is usually used with spectrum management techniques to overcome the affects of interference in the system. A number of author have proposed their ideas for power control in heterogeneous environments. Power control techniques are one of the most widely discussed techniques in the 3rd Generation Partnership Project (3GPP) community. The basic concept is the reduction in the transmit power
Table 2.1: Summary of time domain eICIC techniques

<table>
<thead>
<tr>
<th>Sub-frame alignment</th>
<th>MUE</th>
<th>SUE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control CH</td>
<td>Data Ch</td>
</tr>
<tr>
<td>No PDCCH</td>
<td>Interference from SCs CRS</td>
<td>Interference from SCs CRS</td>
</tr>
<tr>
<td>Lightly loaded PDCCH</td>
<td>Interference from SCs CRS and control CH</td>
<td>No transmission with load control</td>
</tr>
<tr>
<td>OFDM symbol shift</td>
<td>PDSCH symbol muting</td>
<td>No interference</td>
</tr>
<tr>
<td></td>
<td>Consecutive sub-frame blanking</td>
<td>Interference from SCs CRS and control CH</td>
</tr>
</tbody>
</table>

of the interfere to reduce the interfere to the nearby victim UE. Following four power control techniques are standardised in 3GPP specifications, which can also be used in conjunction with other eICIC techniques. Details of the following techniques can be found in [14].

- Strongest macro-cell received power
- Pathloss between small-cell and macro-cell user.
- Objective SINR of macro-cell user
- Objective SINR of small-cell user

Two power control schemes are presented for small-cells in [15], the author provides a centralised network guided framework for macro and small-cell power control. In the first approach a minimum Quality of Service (QoS) target for small-cell users is guided by the network to the small-cells, the small-cells adjust their transmit powers to meet the minimum target. In the second approach, interference reports are updated by the macro-cell served users to their serving macro-cells, these macro-cells further relay this information along with the interfering small-cells identity to the central entity. The central entity guides the small-cells to adjust their powers. The work in this thesis makes use of this concept while presenting the proposed solutions.

A similar, but radio environment maps (REM) based power control scheme is presented in [16]. This work makes use of a database present at the central entity, which contains and updates user/cell locations and the interference experienced by the users. This central entity guides the small-cells with the maximum allowable power limit to avoid interference to nearby macro-cell. The database holds different levels of network information including the environmental conditions, path-loss, shadowing and geographical
data. The small-cells on detection of a victim user, adjust their transmit power on the basis of the estimated received SINR to the macro-cell user. However, the small-cells do not completely compromise on the performance of their users to protect the victim user, and at-least transmit at the minimum defined power level.

An open loop Fractional Power Control (FPC) is presented by [17], along with a resource allocation algorithm emphasising the need of applying spectrum management along with power control mechanisms. Another well known power control optimization technique is the use of Q-learning algorithm, [18] presents a distributed Q-learning algorithm for power control, where macro-cell users report interfering small-cells’ identity to their serving macro-cell. The macro-cells further guide the small-cells with the victim user’s resource allocation bitmap. A learning loop is created which analyses every action and determines if the action resulted in a interference reward or a penalty.

An interesting ideas regarding the trade-off between macro-cell and small-cells’ performance is presented in [19]. The authors assigns a weightage to the transmit power of the marco and small-cells. Increasing the or decreasing a single control parameter assigns higher/low priority to macro or small-cell users’ performance. Authors in [20] bring forward an autonomous way for small-cells to detect existence of a victim macro-cell served user by measuring the Uplink Reception Power (ULRP), if the ULRP of a user is more than a certain threshold then the small-cell acknowledges the presence of a victim users and acts accordingly to adjust its transmit power. However, the macro-cell attached users who are in idle mode would not be detected by such a scheme. [21] sheds light on the idle mode macro-cell users facing interference from small-cells, such users are unable to communicate to macro node as well as to the small-cells, in this case the author proposes a self power control for small-cells to sense and degrade their Tx power to accommodate victim users.

As mentioned previously, data region is not the only part affected by interference resulting in throughput degradation, in fact the control region is more sensitive to interference, [22] proposed to limit power and frequency resources at control region from the small-cells and provide extra resources in this region to macro-cells, this improves the macrocell users’ outage probability. In [13] a similar idea is presented for control channel, along with the use of spectrum management techniques to improve the interference in the control region. The approach is discussed further details in chapter 4.

Power control based on the distance of the small-cell to the macro-cell has also been discussed by some researchers, [23] suggests to increase the small-cell coverage area with respect to the distance from the macro-cell, authors claim that this approach
would require lesser number of small-cells resulting the same performance. Similar [24] provides the upper and lower bounds for the transmit power of small-cells for a reliable downlink coverage, authors suggest that the location of the cells or the distance can be either pre calibrated or could be based on Global Positioning System (GPS) data.

A timer based power control mechanism is presented in [25]. According to the approach if a macro-cell user faces interference from a small-cell, it reports this to its respective macro-cell, which sends an interference alert message back to the user. The user further forward this message to the small-cell. This alert message would force the small-cell to reduce its transmit power for a certain time and further if another interference message is received. If not further alert messages are received the small-cell increases its transmit power back to the default value.

2.1.2.3 Frequency Domain Techniques

Frequency domain techniques are also known as reduced bandwidth schemes, these schemes are very similar to the previously discussed ICIC techniques, but consider HetNet operation for interference avoidance in data as well as control channels. Interference can be avoided amongst neighbouring nodes by static demarcation of available bandwidth, which indeed is spectrally inefficient. Such a concept of dividing resources amongst macro and small-cells with a common shared frequency band, is presented in [26]. This concept is illustrated in 2.5. Sharing of bandwidth amongst the macro and small-cells has also been studied as a business case in [27]. Their work revolves around the idea leasing macro-cell spectrum to the small-cells, and in return the the small-cells serve macro-cell users to off-load larger cells. Along side that, [28] suggest operators can have mutual agreements to serve affected victim users within each others networks.

Centralised frequency partitioning In a typical centralised frequency partitioning approach the small-cells measuring reference signals, cell identities from neighbouring small-cells and users, and report this information to a central entity. Users also report their channel conditions to the central entity. These reports are updated every specific time frequency or at certain load condition thresholds. The central entity process this data and further guides the cells with the optimal resource allocation.

Adjacency graph based studies have been widely discussed in literature for the joint operation of macro and small-cells, avoid interference amongst them. Use of Graph
A coloring method is proposed by [29,30] where graph coloring tries to find the minimum number of colors to connect the adjacent vertices, or in case of small-cells, the minimum number of RBs or frequency channels to avoid interference between adjacent transmit nodes. A detailed analysis of graph coloring methods is presented in [31–33].
On the basis of these graphs, the central entity guides the small-cells with their respective allocated transmission patterns. Another variant of this mechanism is the central entity providing knowledge of the transmission patterns of the neighbours to small-cells, the small cells monitor the neighbouring cells and adjust their transmissions accordingly [34].

**Distributed dynamic frequency partitioning** Use of jamming graphs is also a popular approach. Based on the locally collected information within small-cells, jamming graphs are created. Each neighbouring node in the graph represents an active cell and an edge represents jamming conditions. This approach is usually used to combat intra-tier interference amongst dense clusters of small-cells. Further to the determination of jamming conditions, small-cells communicate over a common backhaul link to negotiate their transmit patterns to minimise interference amongst themselves [34].

**Victim User Detection** Determination of a victim user can take place at a macro-cell or at a small-cell on the basis of the user feedback to its serving cell. This information can be exchanged amongst the nodes over the common interface. Victim user detection can also take place locally at a small-cell by detecting uplink transmissions from the victim user. In such a case the victim user would be closer to the small-cell as compared to the macro-cell, as a result the uplink transmission would be at high power. This high high power transmissions from the user and lower path loss between the user and small-cell makes the detection process promising. Another approach for localised victim user detection is based on interference over thermal (IoT). High IoT in a certain portion of the band indicates the presence of a victim user being served. Along with this, properties of the uplink reference signals could also be used to detect victim users [34]. Furthermore, a combination of IoT approach and can be used along with reference signal detection. In this approach, initially the IoT is monitored, if the IoT is below a certain threshold the small-cell can transmit over the complete spectrum. If the IoT exceeds the threshold then reference signal detection is triggered, if the victim user is detected the small-cell shall restrict its transmission in certain subframes.

It is important to mention here, that the above mentioned victim user detection approaches shall not be successful to detect idle mode users since neither they send back measurement reports in idle mode nor there are any transmission in uplink. So the above mentioned detections are not feasible. In this case the best option shall be the use of time/frequency based partitioning and keeping the idle users over the dedicated
2.2 Energy Efficient Techniques for HetNets

2.2.1 Sleep Modes

A macro or small-cell experiences variable load conditions during different times of the day, along side they could also be in different states. Load on the cell mainly affects the total transmission energy consumption, where as the states of the node determine its circuit energy consumption. Other than the fully operation states a macro/small-cell can be put to idle or sleep mode, where most of the modules are turned off. Switching the cell to sleep mode significantly reduces the energy consumption. Cells can also be put to complete shut-down mode, eliminating both the transmission as well as circuit energy consumption. However, waking up a cell for these states is also a important topic of research, as different levels of sleep add significant wakeup delay and complexity to the network. In this subsection we will discuss various existing sleep mode techniques.

The simplest sleep mode technique is where the transmission sites are put to sleep mode based on a pre-set timer. This timer is manually configured for a statistical traffic cycle, usually during few hours of night when user traffic is very low. In such a case the load...
or coverage of the cell in sleep mode is allocated to the neighbours [41]. A drawback of such a scheme is very obvious that since the sleep mode cycle is static and only based on historical traffic statistics, in event of unusual activity the system performance might degrade or need to be manually reconfigured. In case of small-cells such unusual traffic patterns may occur relatively frequent and would proof to be difficult to reconfigure the timer.

To overcome this limitation various dynamic sleep mode techniques have been proposed in literature, one of the most notable scheme includes the addition of a sniffer or a small radio module to the small-cells. The sniffer is equipped with a reverse paging function listening to data requirement activity from the user which wakes up the sleeping cell, once the call ends the node goes back in sleep mode [42]. The wakeup function of the cell can be categorised into three types; cell controlled, core network controlled and user controlled [43].

Node controlled techniques, as the name signifies is when the small-cell performs pilot signal sensing for user activity, while the user is attached and is being served by an umbrella macro-cell. As the user is detected in the vicinity with the help of pilot signal sensing, the small-cell wakes up and a hand-over to the small-cell could be initiated to improve the performance of the user. This techniques require an addition smart user sensing controller at the small cell [44]. While this technique is very effective, it does also have a drawback of small-cell being unnecessary activate due to the non-subscriber activity in the area.

Network controlled technique overcome this issue since the sleep/wakeup messages are sent to cells over the backhaul common interface [43, 45, 46]. It is evident that this scheme requires a control interface between the cells the core network. Researchers in [47, 48] present a macro-cell controlled sleep/wake cycle for small-cells, making use of the continuous time Markov decision process. A state is attached to each action and corresponding transition probabilities and rewards. The process monitors the current state of the network and takes a set of potential actions. Cost attached to each action is a function of increasing energy and decreasing QoS. Authors also suggest the use localisation information of user by GPS information forwarded to the small-cell over common backhaul link.

The third wakeup technique; user controlled mode is where the user periodically sends wakeup beacon messages to small-cells in the nearby area [43, 45]. This scheme can be very energy efficient for the perspective of the small-cells, however this is not the case for the users as they might end up transmitting several wakeup messages while there
are no small-cells to cater the request.

Adaptive traffic conditions based techniques have also been discussed in literature. A scheme based on the idea of altering cells’ transmit power while the network load reaches certain pre-set thresholds is proposed in [49]. Similarly, [50] proposes sleep mode switching of cells based on predefined load conditions.

Sleep/wakeup decision making capabilities can be added to cells. Low activity cells can cooperate with neighbours to take over their users. If the acceptor cells current load is below a certain threshold, it accepts the off-loading request and the subject cell goes into sleep mode [51, 52]. The author also proposes a macro-cell cooperation scenario where operators with mutual agreements operating in same area with lower traffic requirements, shut down there nodes and redistribute traffic [53]. Hardware based individual component wise small-cell power consumption model along with the power consumption of additional sleep mode controller’s power consumption is discussed in [54].

Since is evident that serving users with small-cells as compared to macro-cells is defiantly beneficial from energy efficiency point of view [55]. However, considering the high density future deployments of small-cells, it should be noted that if the small-cells are considered energy efficient only if they remain sufficiently utilised [56]. Generally a typical residential small-cell can support up to eight users, however, as the number of users increase in a small-cell the resources get divided and affect the net throughput of each user. On the other hand, it is suggested that increasing number of user in a small cell does not significantly affect the energy consumption of the cell. To maximise the energy efficiency along with satisfying the user demands, it is important to optimise the macro and small-cell deployment/activation [57].

2.2.1.1 Energy Efficient Resource Management

Macro-cell offloading to small-cells has been proved to be very energy efficient [51–53]. Highly loaded macro-cells consume high amounts of energy, which can be reduced by smartly deployment/activating small cells. Aforementioned wakeup techniques could be use to activate sleeping small-cells. Keeping the smalls cells active all times of the day does not proved to be energy efficient, researchers in [58, 59] claim that dense deployment of small cells is only efficient in high data demand scenarios.

It is also important to consider a balance between the energy efficiency and capacity of the network, authors in [60] introduce a frequency access ratio for small-cells.
2.3. Small-cell Access Groups and Deployment

Optimising the ratio for different network load conditions results in maximum energy efficiency.

For an energy efficient system maximum data rate should be achieved with minimum energy consumption, it is claimed that infinite bandwidth would achieve maximum energy efficiency gains. However, in practice the network’s frequency resources are limited and the entire system bandwidth cannot be allocated to a single user. Hence, frequency domain resource allocation remains critical in determining the overall network energy efficiency. It is also pointed out that in a circuit power dominate regimes, usually for short range communication, maximising the energy efficiency is equivalent to maximizing the spectral efficiency. In other word, maximum data should be transferred at maximum transmit power and as soon as the data transfer task is complete, the transmission cell should be put to sleep mode. However this does not holds valid for transmit power dominate regimes. The case gets further complex in an interference dominate regime where ON-OFF approach is considered optimal [61]. In the downlink case this ON-OFF approach could be applied to resource block restrictions for small-cells to avoid interference. Based on this ON/OFF approach, [62] develop an energy efficiency maximisation problem where interference sources are identified from reference signals.

2.3 Small-cell Access Groups and Deployment

2.3.1 Small-Cell Access groups

Heterogeneous operation of macro and small-cells sharing the same frequency resources, brings forward the concept of access groups as a major player effecting the performance of the network. There are generally two types of small-cell access groups, Closed Subscriber Groups (CSG) and Open Subscriber Groups (OSG). Since the primary purpose of adding small-cells to a network is to off-load the macro-cell users to small-cells, OSG small-cells serve this purpose. OSG small-cells, as the name indicates, are open to all the users in the network and usually any user which is in close vicinity of a OSG small-cell gets handovered. Such offloading of small-cells has been widely analysed as very beneficial in terms of improving the users QoE as well as energy efficiency of the network [63]. Nevertheless, CSG small-cells have also been fairly popular due their strong business model. CSG small-cells only allow access to a pre-defined list of users. Such limited access can be useful for providing premium QoE as well as
security to a limited number of users. Some operators offer CSG small-cell to residential areas and small enterprises to improve indoor coverage. Some critics suggest that operation of OSG small-cells is more cost effective as compared to CSGs [63]. CSG small-cell, although having a strong business case, pose interference issues for non-subscriber users in the vicinity of these small-cells [64]. Since CSG reuse the same frequency resources as the larger macro-cell, some macro-cell served users get trapped by the strong interference from CSG small-cells. In this thesis we look focus on safe guarding these victim users trapped in the vicinity of small-cells. This interference issue is not only limited to CSG small-cells, in certain high load conditions OSG small-cells may also pose interference issues to macro-cell served users.

2.3.2 Deployment and Backhauling

Deployment of small-cells is a major factor effecting the performance of the network. Usually in case of larger cells, it is easier to deploy the cells at optimal locations. However, this is not always the case with small-cell. Firstly, small-cells are usually deployed at selected indoor locations with high data rate demands, changing the positions of these small-cells in not always in the control of the operators. Secondly, dense deployment of small-cells makes the optimisation of deployment locations far more complex as compared to that in case of fewer large cells. Some researchers have done extensive work to find the optimal small-cell deployment in order to maintain a target user outage probability [65]. Placement of small-cells in indoor environments has also been studied. It is suggested that small-cells placed close to edges and windows of the buildings pose higher interference issue to the outer environment, as the penetration and path losses play an important role in degrading unwanted signals from small-cells to the outer environment [66]. Some researches also suggest the use of higher frequency bands for small-cells as higher frequency has higher penetrations losses [67, 68].

Small-cells are usually provided backhaul links over the usual internet connections, certain small-cells are also facilitated with dedicated backhaul links. The research community has also been widely discussing the possible backhaul options for small-cells, considering the latency and security issues. For LTE networks, a common communications link to facilitate communications amongst the cells has been made possible by the introduction of X2-interface. This X2-interface creates a tunnel to make communications possible amongst neighbouring cells within the backhaul link [69]. In the latter sections, further discussion will be presented on the use of X-2 interface in our scenarios.
2.4 LTE Basics and Control Channels

2.4.1 LTE Frame Structure

In LTE OFDMA - frequency division duplex (FDD) the whole system bandwidth is divided into RBs of 180KHz each. Each RB consists of 12 sub-carriers (15Khz each). However, a RB represents the basic OFDMA time-frequency unit. A Physical Resource Block (PRB) consists for one RB in the frequency domain and two constitutive slots in the time domain, where each slot is 0.5 msec. These two consecutive time slots make one subframe (1msec) and ten such subframes make one 10ms radio frame. Each PRB consists of 14 OFDM symbols (12 in extended mode), of which first three symbols are usually considered for common and user specific control signalling (control region is dynamic from 1 to 3 symbols). The remaining symbols constitute of the data channels. Inter-spread within these are cell specific reference symbols, which help facilitate channel estimation. The modulation and coding scheme adapted for the transmitted OFDM symbols is determined by the Adaptive Modulation and Coding module (AMC). AMC takes place at the medium access control (MAC) layer, where the logical channels from radio link control (RLC) layer are converted to physical channels. On the basis of the received signal at the user, spectral efficiency (SE) is calculated, this SE value is further converted into a CQI value ranging between 0-15. The user feedbacks this CQI value back to the serving cell, which converted this CQI value into a Modulation and Coding Scheme (MCS) value ranging from 0-32. This MCS value determines the type of modulation and coding to be used for each symbol, and further determines the transport block (TB) size. Figure 2.8 shows the SINR, CQI and MCS values for a exemplary user, moving away from the serving cell. A maximum MCS value would ideally return the maximum throughput. However, for the control channels usually the most robust modulation schemes is used to ensure reliability. The most important control channels are discussed below. LTE OFDM grid is shown in figure 2.7.

2.4.1.1 The PHICH and PCFICH

The physical hybrid-ARQ indicator channel (PHICH) contains the uplink hybrid-ARQ ACK/NACK information, indicating weather the serving cell has correctly received an uplink transmission from the user. The PHICH location in the grid is cyclically rotated dependent on the PCI of that cell. The PHICH is three times redundantly repeated in the frequency domain. It can occur on any combination of the available
OFDM symbols, however usually present in the first OFDM symbol (presence in the second and third OFDM symbol is possible under the extended PHICH configuration). However, the physical control format indicator channel (PCFICH) is always present in the first OFDM symbol only; since it contains the control format indicator (CFI) indicating the number of OFDM symbols used for transmission of downlink control channel; the reason being simple, user should be able to determine the size of the control region before decoding the remaining control information. Two bits of information is sufficient to indicate the CFI information (1, 2 or 3 OFDM symbols), however, this

Figure 2.7: LTE Resource Allocation Grid
2.4. LTE Basics and Control Channels

Figure 2.8: This figure shows the SINR to CQI and MCS conversion of a user with increasing distance from the serving cell. As the user moves away from the cell, the SINR level drops due to path loss, so does the CQI and MCS.

Vital information is made redundant by a 32 bits long corresponding codeword which amount to a code rate of 1/16. This 32 bit long information is mapped to 16 REs using quadrature phase-shift keying (QPSK) modulation. The PCFICH is transmitted in groups of four REs, distributed four times in the frequency domain to achieve frequency diversity. The PCFICH location in the grid is cyclically rotated dependent on the PCI of the cell, similar to the PHICH.

2.4.1.2 The PDCCH

The physical downlink control channel (PDCCH) contains the downlink (and uplink) scheduling grants, power control commands and the information required to decode and demodulate the OFDM symbols in the downlink (encode and modulate in the uplink). The PDCCH dedicated to a specific user may consist of 1, 2, 4, 8 control channel elements (CCEs), depending on the selected aggregation level based on the prevailing channel conditions between the serving cell and the user. Link adaptation is performed considering the vital information contained in the PDCCH, a target bit
error rate (BER) of 1% is pursued. Each CCE is made up of nine resource element
groups (REGs) and each REG consists of four consecutive resource elements (REs).
The REGs still free after placement of PHICH and PCFICH are allocated to PDCCH
after going through a inter-column permutation interleaving pattern [70].
HetNets comprising macro-cells and densely deployed small-cells are considered as a promising solution for future 5G networks [3]. It is indicated in [4] that dense deployment of small-cells \(^1\) can provide higher spectral efficiency gains, as compared to Wi-Fi offloading. However, mass deployment of small-cells overlaid within the area of larger cells raises challenges regarding their joint operation. As discussed in section 2.3.1, small-cells can usually operate in as either OSG or CSG. OSG small-cells are deployed and owned by the network operator and operate as open cells to serve macro-cell users in HotSpots or near the edges of the cells. This type of small-cells are simple to manage and have demonstrated to improve access network capacity [71]. CSG SCs are typically open only to a long term managed list of users. On the other hand, CSG SCs are easy to manage if they are operated in a separate licence free band similar to Wi-Fi. However, these small-cells, serving indoor subscribers as part of the operators network, need to be operated in a licensed band. Since the licensed spectrum resources are expensive and scarce, operators prefer to deploy these SCs under the so-called co-channel deployment, i.e. by spatially reusing the available spectrum. As a trade-off, this sharing of the frequency band amongst the macro-cell and CSG small-cells increases ICI within the network which, if left unmanaged, may significantly deteriorate overall network performance [72]. This highlights the need for introduction of efficient low-complexity radio resource management techniques which can be implemented in practical systems. In this chapter of the thesis, a system model is defined to further highlight this issue and along with that the problem is mathematically formulated for the data channel interference management.

\(^1\)We interchangeably use the terms small-cell and SC in this thesis.
ICI problem has been widely discussed in literature, with focus initially targeted at homogeneous\(^2\) macro-cell scenarios. The simplest downlink frequency allocation technique is to share the whole available frequency band amongst multiple transmission nodes. This so-called Reuse-1 technique has the highest spectrum usage but also results in severe ICI experienced amongst the neighbouring cells. To reduce ICI, FFR schemes were initially introduced [73]. However FFR schemes reduce the spectrum usage and are mostly preplanned in nature, prohibiting adaptive frequency allocation to system dynamics. More recently, Dynamic Fractional Frequency Reuse (D-FFR) techniques have been introduced. In [74], a central broker is considered which constantly updates users into groups, based on their signal strength. These groups are assigned sub-carriers which are further used to serve the users in each group. This scheme employs low spatial reuse, hence reducing the overall throughput of the network. In [75], a dynamic graph based FFR scheme is discussed where neighbouring macro-cells are assigned orthogonal chunks of spectrum based on the load on each cell. This approach results in a greedy and low spatial reuse, especially when heavily loaded cells require high number of Resource Blocks (RBs). Another approach for dynamic FFR is discussed in [76], where each cell aims to minimise its transmit power on each RB. This leads to each cell utilising only the RBs with best channel quality (least interference) to serve its users. A similar approach is shown in [77], whereas neighbouring nodes notify each other about their RB usage, so that they avoid assigning high transmission power in those RBs. A two step solution approach is proposed in this work: Dynamic Frequency Planning (DFP) takes places in the first step to distribute chunks of frequency bands to the participant sharing macro-cells; at the next step, a resource allocation (RA) algorithm is proposed to take place within each macro-cell. Furthermore, the authors in [78] and [79] apply the aforementioned concept of minimising transmission power and discuss the use of interference tolerance estimation for performing resource allocation in homogeneous macro and small-cell deployments, respectively.

The aforementioned techniques, being only designed for homogeneous scenarios, cannot perfectly fit to networks with underlaid macro-cells and overlaid densely deployed small-cells; the reason is that the dominant interferers for a user in the homogeneous scenario are limited and usually not as strong as in the dense HetNet scenario. Thus, focusing on the HetNet scenario and on the small-cell to small-cell interference, [80]

\(^2\)By homogeneous networks, we indicate the networks with same size and same access technology cells.
suggests that small-cells should serve their users on RBs with the least measured pilot signal strength from neighbouring small-cells (hence the least small-cell to small-cell interference). Similarly, [81] proposes a technique where small-cells assign the top best RBs to their users and adjust their transmit power subject to small-cell served user’s QoS constraints.

Although small-cell to small-cell interference is a notable aspect in HetNet scenarios, the degradation of performance for macro-cell served users due to interference caused from small-cells to macro-cell users will be more critical than in case of small-cell users; since there are fewer users served by small-cells as compared to macro-cells, small-cell served users are anyway allocated with more bandwidth resources. Thus, regarding the interference from small-cell to macro-cell users, [82] presents a bandwidth partitioning amongst macro-cells and small-cells, where small-cells are not allowed to transmit in the bandwidth assigned to a macro-cell, hence, reducing the spatial reuse. In [83], authors elaborate on the presence of CSG small-cells further elevating the issue of ICI as compared to public small-cells and discuss the use of shared, separate and partially shared bandwidth for this case. Furthermore [84] suggests the use of higher level modulation and coding schemes for indoor small-cells as their users generally realise good signal strengths. In [85], a scheme is proposed which zones small-cell served users for either link adoption or requirement of orthogonal sub-bands and a central entity assigns the users with separate sub-bands from a pool. Finally, in [86], a mathematical framework is presented to minimise the interference from small-cells to macro-cells. Small-cells are allowed to transmit on certain RBs based on the calculated distance between the small-cells and neighbouring macro-cells. However, for enhanced performance small-cell muting decisions should be more adaptive to the system dynamics and consider the presence of macro-cell served users in the vicinity of small-cells. To the best of our knowledge there is no such analysis in literature based on the idea of interference estimation, caused by small-cells to macro-cell users. This is a notable shortcoming, as macro victim users trapped in the vicinity of CSG small-cells suffer from severe interference [83].

3.2 System Model

We consider a system of $M + 1$ cells, comprising one macro-cell (identified as cell 0) and $M$ small-cells within the macro-cell area. The set of small-cells is defined as $\mathcal{M} = \{1, \ldots, M\}$. We assume that there are $K$ active users in the system. We consider
3.2. System Model for Data Channel Resource Allocation

Figure 3.1: Example of dynamic small-cell resource allocation for victim macro-user protection. Small-cell node A may use the full available resources while the transmission for small-cell node B is restricted in order to protect macro-cell user B, which is in its vicinity at that specific time instance.

that each user can have only one serving node, but each cell can support multiple users; thus, $K \triangleq |K| = |K_0 \cup K_1 \cdots \cup K_M|$, where $K$ denotes the set of all users in the system and $K_m$ denotes the set of users served by node in cell $m$.

Following the binary RB allocation nature of the OFDMA systems the total system bandwidth is divided in $N$ RBs and each RB can be allocated to only one user in each cell. Macro-cell node can allocate all the available RBs to its associated macro-users (MUE). Moreover, macro-cell users are assumed to have minimum data rate requirements.

On the other hand, small-cell nodes reuse the same resources to serve their small-cells users (SUE) based on a resource allocation policy. We consider a central entity residing at the macro-cell node which is able to collect relevant information to make resource allocation decisions and guide small-cells on the resource allocation policy to be adopted. Such a policy shall be considered semi-distributed in nature where several central entities residing at umbrella macro-cells guide under-laying small-cells.

We define binary indicator variables $\phi_{k,m,n} \in \{0, 1\}$, where $\phi_{k,m,n} = 1$ when small-cell $m$ serves its $k^{th}$ assigned user in the $n^{th}$ RB; otherwise, the RB allocation parameters take the zero value. Thus, we can define the vector containing all RB allocation parameters $\phi = [\phi_{1,1,1} \cdots \phi_{K_M,M,N}]$, which characterizes the small-cells RB allocation policy. Moreover, transmit power of the $m^{th}$ small-cell in the $n^{th}$ RB is denoted by
3.2. System Model for Data Channel Resource Allocation

$p_{m,n} \leq P_{\text{max}}$, where $P_{\text{max}}$ is the maximum allowed transmission power of any small-cell. Vector $\mathbf{p} = [p_{1,1} \ldots p_{M,N}]$ characterizes the small-cells’ power allocation policy.

### 3.2.1 User SINR and Rate Modelling

The SINR of MUE or SUE users can be modelled as follows. Using index 0 as macro-cell identification, the SINR of the $u^{th}$ MUE at RB $n$ can be given by:

$$
\gamma_{u,0,n} = \frac{p_{0,n} \Gamma_{0,u,0,n}}{\sum_{m=1}^{M} \left( \sum_{k \in \mathcal{K}_m} \phi_{k,m,n} \right) p_{m,n} \Gamma_{m,u,0,n} + N_0 B},
$$

where $p_{0,n}$ denotes the transmit power of macro-cell node at RB $n$, $\Gamma_{0,k,m,n}$ is the channel gain between base station at cell $i$ and user $k$ being served at cell $m$ in RB $n$, $N_0$ is the noise power spectral density and $B$ is the bandwidth of each RB.

Similarly, the SINR of SUE $k$ in cell $m$ at RB $n$ can be given by:

$$
\gamma_{k,m,n} = \frac{p_{m,n} \Gamma_{m,k,m,n}}{p_{0,n} \Gamma_{0,k,m,n} + \sum_{i=1, i \neq m}^{M} \left( \sum_{l \in \mathcal{K}_i} \phi_{l,i,n} \right) p_{i,n} \Gamma_{i,k,m,n} + N_0 B}.
$$

The rate of each user (SUE or MUE) can be expressed by the Shannon-Hartley Theorem as follows:

$$
R_{k,m,n} = B \log_2 (1 + \gamma_{k,m,n}).
$$

It should be noted that although (3.3) is not a practically achievable rate, it is used as a performance indicator for comparison purposes.

### 3.2.2 Maximum Interference Allowance

A minimum overall data rate demand for a MUE can be translated into a minimum data rate demand at each RB, allocated to that specific MUE. Moreover, the minimum MUE demand data rate at RB $n$ can be translated into a specific minimum required $\gamma_{u,0,n}^\text{req}$ SINR value [78]. Having identified the minimum SINR value and considering (3.1) we can find the maximum interference power $\Omega_{u,n}^\text{max}$ that MUE $u$ can tolerate in RB $n$ from all small-cell nodes to obtain this rate threshold:

$$
\Omega_{n}^\text{max} = \frac{p_{0,n} \Gamma_{0,u,0,n}}{\gamma_{u,0,n}^\text{req}} - N_0 B.
$$
If the potential channel gain from any small-cell $m$ to the MUE is denoted as $\Gamma^{(m)}_{0,u,n}$, the total interference caused to it by all small-cells in each RB can be given by:

$$\Omega^\text{sum}_n = \sum_{m=1}^{M} \left( \sum_{k \in K_m} \phi_{k,m,n} \right) p_{m,n} \Gamma^{(m)}_{0,u,n} = \sum_{m=1}^{M} \left( \sum_{k \in K_m} \phi_{k,m,n} \right) \omega^m_{0,u,n}, \quad (3.5)$$

where $\omega^m_{0,u,n} \triangleq p_{m,n} \Gamma^{(m)}_{0,u,n}$ can be interpreted as the interference that is caused to user $u$ in cell 0 (macro-cell) on RB $n$ from small-cell $m$.

### 3.3 Optimal Resource Allocation (ORA)

Our problem is defined as a maximisation of the sum rate of all active users in the small-cells, while: 1) the individual rate of any MUE is ensured to be greater than a minimum value and; 2) SC transmit power as well as RB allocation constraints are satisfied.

The achievable sum rate of all active users in small-cells over the whole allocated system bandwidth is given by:

$$R = \sum_{n=1}^{N} \sum_{m=1}^{M} \left( \sum_{k \in K_m} \phi_{k,m,n} R_{k,m,n} \right), \quad (3.6)$$

where $R_{k,m,n}$ denotes the achievable rate of $k^{\text{th}}$ user served by small-cell $m$ on RB $n$. From equation (3.6), considering also (3.2) and (3.3), it can be observed that the SUEs sum rate is a function of both small-cell RB and power allocation policy, i.e. $R = f(\phi, p)$. In the following we formulate the respective sum rate optimisation problem and examine its solution.

#### 3.3.1 Problem Formulation and Solution Approach

The general sum rate optimisation problem comprising the objective function and the imposed constraints can be formulated as follows:

$$\max_{p,\phi} R \quad (3.7)$$
subject to:

\[ \phi_{k,m,n} \in \{0,1\}, \forall k \in K \setminus K_0, m \in M, n; \quad (3.8a) \]
\[ \sum_{k \in K_m} \phi_{k,m,n} \in \{0,1\}, \forall m \in M, n; \quad (3.8b) \]
\[ \Omega^\text{sum}_n \leq \Omega^\text{max}_n, \forall n; \quad (3.8c) \]
\[ \sum_{n=1}^{N} \left( \sum_{k \in K_m} \phi_{k,m,n} \right) p_{m,n} \leq P^\text{max}, \forall m \in M; \quad (3.8d) \]
\[ p_{m,n} \geq 0, \forall m \in M, n. \quad (3.8e) \]

Constraint (3.8b) indicates that RBs are exclusively allocated to one user served by each cell pair to avoid intra-cell interference; constraint (3.8c) denotes the total maximum interference that a MUE served by macro-cell on RB \( n \) can tolerate from all small-cells in the macro area in order to satisfy its minimum rate needs; finally, constraints (3.8d)-(3.8e) stand for the maximum and minimum transmission power constraints at each small-cell node.

The optimisation problem in (3.7) contains both continuous\(^3\) (\( p \)) and binary (\( \phi \)) decision variables and it is categorised in general as a mixed integer non-linear programming problem (MINP) since the objective function (\( R \)) is non-linear in \( p \) considering equations (3.2) and (3.3). Finding the optimal solution to these non-convex problems requires computationally complex exhaustive search, rendering its implementation in practical systems impossible and becomes even harder when QoS constraints are added on top (as is the case here with the minimum MUE rate constraints). However, to make the problem tractable, we relax the resource allocation integer constraints to take any real value between 0 and 1. This time-sharing condition essentially considers the time sharing of each sub-carrier in practice and it is proved in [87] that the duality gap of any optimisation problem satisfying the time sharing condition is negligible as the number of sub-carriers becomes sufficiently large. Therefore, our relaxed optimisation problem of (3.7) can be solved optimally by using the dual method [87, 88].

### 3.3.2 Dual Method for Optimal Joint Power and RB Allocation

The dual method applied in our case will comprise the following steps [88]: a) translating the original optimisation problem into its Lagrangian dual, associating QoS and

---

\(^3\) Considering that small-cells allocate power to RBs according to some predefined power levels, vector \( p \) can instead contain integer variables. This of course renders the optimisation problem even harder to solve.
power constraints with dual variables; b) decomposing the dual problem into independently solvable sub-problems by removing the coupling between RBs via Lagrangian relaxation; c) further decomposing the sub-problems through a two phase second level primal decomposition where power and RB allocation optimisation is performed sequentially and; d) using the sub-gradient method to iteratively update the dual variables in parallel until they (and essentially the original problem) converge into the optimal values. In the following, the various steps of the dual method are presented in detail.

3.3.2.1 Dual Problem

The Lagrangian function of the problem in (3.7) can be given by:

\[ L(\phi, p, \lambda, \mu) = \sum_{n=1}^{N} \sum_{m \in \mathcal{M}} \sum_{k \in \mathcal{K}_m} \phi_{k,m,n} R_{k,m,n} + \sum_{n} \lambda_n \left( \sum_{m=1}^{M} \Omega_n^{\text{max}} - \left( \sum_{k \in \mathcal{K}_m} \phi_{k,m,n} \right) p_{m,n} \Gamma_{0,u,n}^m \right) + \sum_{m} \mu_m (P_{\text{max}} - \sum_{n} \left( \sum_{k \in \mathcal{K}_m} \phi_{k,m,n} \right) p_{m,n}) \]

\[ = \sum_{n} \left[ \sum_{m} \sum_{k \in \mathcal{K}_m} \phi_{k,m,n} R_{k,m,n} - \lambda_n \left( \sum_{m=1}^{M} \phi_{k,m,n} p_{m,n} \Gamma_{0,u,n}^m \right) \right] + \sum_{n} \lambda_n \Omega_n^{\text{max}} + \sum_{m} \mu_m P_{\text{max}}, \]

where \( \lambda = [\lambda_1, ..., \lambda_N] \) and \( \mu = [\mu_1, ..., \mu_M] \) are the dual variable vectors associated with the individual interference constraints on MUEs and the small-cells transmit power constraint, respectively. The Lagrangian dual function can be given as:

\[
g(\lambda, \mu) = \begin{cases} \max_{\phi, p} L(\phi, p, \lambda, \mu), \\ s.t. \\ 0 \leq \phi_{k,m,n} \leq 1, \forall k \in \mathcal{K}, m \in \mathcal{M}, n; \\ \sum_{k \in \mathcal{K}_m} \phi_{k,m,n} \leq 1, \forall m \in \mathcal{M}, n; \\ p_{m,n} \geq 0, \forall m \in \mathcal{M}, n. \end{cases} \]

Hence, the dual optimisation problem is formulated as:

\[
\min_{\lambda, \mu \geq 0} \quad g(\lambda, \mu).
\]
3.3.2.2 Decomposition

The coupling between RBs can be removed by Lagrangian relaxation and equation (3.10) can be decomposed into $N$ sub-problems at each RB with each sub-problem given as:

$$
\max_{\phi, p} L_n (\phi_n, p_n) = \left\{ \begin{array}{l}
\max \phi_R \left( \sum_{m} \sum_{k \in K_m} \phi_{k,m,n} R_{k,m,n} \\
- \lambda_n \left( \sum_{m=1}^{M} \left( \sum_{k \in K_m} \phi_{k,m,n} \right) p_{m,n} \Gamma_{0,u,n}^m \right) \\
- \sum_{m} \mu_m \left( \sum_{k \in K_m} \phi_{k,m,n} \right) p_{m,n}
\end{array} \right.
\right.
\quad s.t.
\begin{align*}
0 &\leq \phi_{k,m,n} \leq 1, \forall k \in K \setminus K_0, m \in M, n; \\
\sum_{k \in K_m} \phi_{k,m,n} &\leq 1, \forall m \in M, n; \\
p_{m,n} &\geq 0, \forall m \in M, n,
\end{align*}
\tag{3.12}
$$

where $\phi_n \triangleq [\phi_{1,1,n} \ldots \phi_{k,m,n}]$ and $p_n \triangleq [p_{1,1,n} \ldots p_{m,n}]$. This dual problem can be further decomposed through a second level primal decomposition and solved in two phases: optimal power allocation and optimal RB allocation.

3.3.2.3 Optimal Power Allocation for a Given RB Allocation

Let for RB $n$, $\phi_{k,m,n} = 1$. Then, optimal power allocation over this RB can be determined by the following problem:

$$
\max_{p_{m,n}} L_n, \forall m \quad s.t. \quad p_{m,n} \geq 0.
\tag{3.13}
$$

In the following, without loss of generality, we consider the scenario where small-cell to small-cell interference is negligible compared to macro to small-cell interference to simplify mathematical analysis. This assumption is generally valid in scenarios with small-cells overlaid by a macro-cell and users are also provisioned to be served by the
3.3. Optimal Resource Allocation (ORA)

macro-cell when small-cell coverage is weak. In that case the rate of each SUE (and subsequently $R$) becomes linear in $p$:

$$R_{k,m,n} = B \log_2 \left(1 + \frac{p_{m,n} \Gamma_{k,m,n}}{p_0 \Gamma_{k,m,n} + N_0 B}\right) \triangleq B \log_2 (1 + p_{m,n} \alpha_{k,m,n}).$$

(3.14)

Thus, we substitute the rate equation (3.14) in (3.13) and differentiate $L$ with respect to $p_{m,n}$, getting:

$$\frac{\partial L}{\partial p_{m,n}} = \alpha_{k,m,n} \ln(2)(1 + p_{m,n} \alpha_{k,m,n}) - \lambda_n \Gamma_{0,u,n}^m - \mu_m.$$  

(3.15)

Furthermore, applying the Karush-Kuhn-Tucker (KKT) condition [88], the optimal power allocation can be obtained by setting (3.15) equal to zero as follows:

$$p_{m,n}^* = \left[\frac{1}{\ln(2)(\lambda_n \Gamma_{0,u,n}^m + \mu_m)} - \frac{1}{\alpha_{k,m,n}}\right]^+, \quad (3.16)$$

where $[x]^+ = \max[x,0]$. This process is explained in detail in Appendix A.1.

### 3.3.2.4 Optimal RB allocation

By eliminating the power variable in equation (3.13) and substituting into equation (3.9), the dual function can be alternatively expressed as:

$$g(\lambda, \mu) = \begin{cases} 
\max \phi \sum_n \sum_{m,k \in M_k} \phi_{k,m,n} H_{k,m,n}(\lambda, \mu) \\
+ \sum_n \lambda_n \Omega_{n}^{\text{max}} + \sum_m \mu_m P_{\text{max}}, 
\end{cases}$$

\text{s.t.}

$$0 \leq \phi_{k,m,n} \leq 1, \forall k \in K \setminus K_0, m \in M, n;$$

$$\sum_{k \in K_m} \phi_{k,m,n} \leq 1, \forall m \in M, n$$

(3.17)

where the function $H_{k,m,n}(\lambda, \mu)$ is given by:

$$H_{k,m,n} = \log_2(1 + p_{n,m}^* \alpha_{k,m,n}) - \lambda_n p_{n,m}^* \Gamma_{0,u,n}^m - \mu_m p_{n,m}^*.$$  

(3.18)

Here, $H_{k,m,n}$ can be regarded as the potential profit or loss from small-cell $m$ transmitting to its $k^{th}$ user on RB $n$. Intuitively we can define the first term of the expression as the maximum achieved rate of a user if its serving small-cell transmits on RB $n$. 


3.4 Efficient Suboptimal Resource Allocation (ESRA)

the second term as the interference penalty and the third term as the power constraint price. Thus, the optimal RB allocation will be obtained according to the following criterion:

\[ \phi_{k,m,n}^* = \begin{cases} 1, & k^* = \arg \max_{k \in K} H_{k,m,n} \text{ and } H_{k^*,m,n} > 0 \\ 0, & \text{otherwise,} \quad \forall m \in M, n. \end{cases} \] (3.19)

### 3.3.2.5 Variable Update

As the dual function in equation (3.10) is convex by definition, the sub-gradient method is used to minimise \( g(\lambda, \mu) \) [88]. Thus, dual variable vectors \( \lambda \) and \( \mu \) are updated in parallel using the appropriate sub-gradients of \( g(\lambda, \mu) \) at each iteration (see Appendix A.2):

\[ \lambda_n(i + 1) = \left[ \lambda_n(i) + \psi(i) \left( \sum_n \sum_{m=1}^M \left( \sum_{k \in K_m} \phi_{k,m,n}^* \right) p_{m,n}^* \Gamma_{u,n}^m - \Omega_{n}^\max \right) \right], \] (3.20)

\[ \mu_m(i + 1) = \left[ \mu_m(i) + \kappa(i) \left( \sum_n \left( \sum_{k \in K_m} \phi_{k,m,n}^* \right) p_{m,n}^* - P_{\max} \right) \right]. \] (3.21)

where, \( \psi(i) \) and \( \kappa(i) \) are the diminishing step sizes and \( i \) denotes the iteration index.

If the step sizes are selected according to the diminishing step size policy [87], the sub-gradient method converges to the optimal dual variables, thus, the optimal joint power and RB allocation can be computed algorithmically.

The process of the decomposed dual problem is shown in Fig. 3.2. It can be summarised that the dual problem decomposition includes the following steps: the power allocation values are calculated using equation (3.16), which are then replaced into equation (3.18) to determine the profit matrix \( H \); further equation (3.19) is used to determine the optimal pair of power and transmitting small-cell for each RB.

### 3.4 Efficient Suboptimal Resource Allocation (ESRA)

The computational complexity of the ORA scheme will still be high for employing in a real system when the number of small-cells and users per cell grows large.
In order to simplify the problem in (3.7), we focus only on the RB allocation. To this end, we assume maximum transmit power at small-cell nodes and equal power allocation across RBs, i.e. $p_{m,n} = \frac{P_{\text{max}}}{N}$ for any small-cell $m$. In that case, the sum rate maximisation problem is transformed into a pure binary linear optimisation problem (BLP) which is formulated as follows:

$$\max_{\phi} \sum_{n=1}^{N} \sum_{m=1}^{M} \left( \sum_{k \in K_m} \phi_{k,m,n} R_{k,m,n} \right),$$
3.4. Efficient Suboptimal Resource Allocation (ESRA)

subject to:

\[ \phi_{k,m,n} \in \{0, 1\}, \forall m, n, k; \]  
\[ \sum_{k \in K_m} \phi_{k,m,n} \in \{0, 1\}, \forall m, n; \]  
\[ \sum_{m=1}^{M} \left( \sum_{k \in K_m} \phi_{k,m,n} \right) p_{m,n} \Gamma^{m}_{0,u,n} \leq \Omega^{\max}_{u,n}, \forall u \in K_m, n. \]  

The key benefit of the efficient sub-optimal RB allocation scheme is expected to come from the significant reduction of the optimisation problem search space by considering only RB allocation. This reduces the complexity and convergence time of the problem; hence, it can be easily solved for multiple or even every Transmission Time Interval (TTI) in LTE networks. The computational complexity comparison for ORA and ESRA schemes is presented in Fig. 3.3. It can be seen that as we increase the number of SCs in the network, the computational complexity increase for both the scheme. However for ESRA, this increase is relatively negligible as compare to ORA scheme.

An additional significant benefit offered by the efficient ESRA scheme, apart from the reduced complexity, is that the optimisation problem in (3.22) can be solved considering the instantaneous throughput obtained in practical OFDMA systems instead of the theoretical Shannon link capacity of (3.3). In general, the instantaneous throughput of any user \( k \) served by small-cell \( m \) on RB \( n \) in OFDMA systems can be given as [78]:

\[ \hat{R}_{k,m,n} = BR(r) \cdot [1 - BLER(r; \gamma_{k,m,n})], \]

(3.23)

where \( BR \) is the theoretical bit rate for any MCS \( r \) when there are no errors which is depended on the network configuration, i.e. for \( N^m_{SC} \) number of data sub-carriers per RB, \( N^m_{SY} \) number of symbols per RB, RB’s duration \( T^m_{RB} \) and \( e_r \) efficiency (in bits per symbol) of MCS \( r \) allocated to the user of interest, the BR for MCS \( r \) is given by:

\[ BR(r) = \frac{N^m_{SC} N^m_{SY}}{T^m_{RB}} \cdot e_r. \]

(3.24)

Moreover, BLER denotes the block error rate suffered by this user on RB \( n \) which is a function of the realised SINR and the MCS used.

Similarly the instantaneous throughput of any MUE \( u \) served on RB \( n \) can be given as:

\[ \hat{R}_{u,0,n} = BR(r) \cdot [1 - BLER(r; \gamma_{u,0,n})]. \]

(3.25)

As discussed in the previous section, a minimum overall data rate demand for a MUE can be translated into a minimum data rate demand at each RB. Moreover, according
to equation (3.25), the minimum MUE demand data rate at RB \( n \) can be translated into a specific MCS \( r_{\text{min}} \) that has to be used and a minimum required SINR value. Having identified the minimum SINR value and considering equation (3.1) we can find the maximum interference power \( \Omega_{\text{max}}^n \) that MUE being served on RB \( n \) can tolerate from all small-cells to obtain this rate threshold.

3.5 Algorithms and Implementation

In this section, a high level description is provided on how the investigated optimal and suboptimal resource allocation schemes can be implemented in LTE heterogeneous networks comprising macro-cells and small-cells. The following arguments explain how the key functions and elements of LTE architecture can be used for this reason.

A: UEs report their CQI and demand rate to their serving cells on frequent basis which determines the user channel gain on that specific RB. Based on these reports received from MUEs, equations (3.3) and (3.4) can be used to estimate the maximum interference, \( \Omega_{\text{max}}^n \), that a MUE can tolerate on a certain RB. Note that this estimation will also decide the MCS and TB size of the future transmissions from the serving node to that UE.

B: UEs also report to their serving cell, the neighbouring cell’s Reference Signal Received Quality (RSRQ) along with the PCI of the neighbouring cell. These reports are generally used for A2, A3 and A4 measurements based handovers. In our case, the respective MUE reports can be used to estimate the top neighbouring interfering small-cells; then, this information can be used to estimate the total interference caused to it by all small-cells in each RB, \( \Omega_{\text{max}}^n \), and formulates the optimisation constraint (3.8c).

C: Moreover, the addition of X2 logical interface in LTE provides the means for cells to communicate. Amongst the macro-cell and the neighbouring small-cells, X2 can act as an interface to guide the neighbouring small-cells to restrict their transmissions. Thus, X2-interface can be used to input each small-cell utility (i.e. expected rate of SUEs in the small-cell based on equation (3.3)) at each RB to the central entity at the macro-cell. The input from all small-cells, formulates our objective function in (3.6) (i.e. expected sum rate of all SUEs in the system).

D: Finally, the optimisation process of either the optimal problem in (3.7) or the suboptimal problem in (3.22) is performed at the central entity. The optimisation
function returns $\phi_{k,m,n}$ and $p_{m,n}$ for the optimal case and only $\phi_{k,m,n}$ for the suboptimal case. These parameters are passed to small-cells over the X2-interface and act as a restriction matrix for each small-cell. Furthermore, in order to avoid introducing unnecessary control overheads into the network, restriction matrix can only be forwarded subject to change in the optimisation parameters, $\phi_{k,m,n}$ and $p_{m,n}$. In that case, small-cells continue to use the last updated restriction matrix until a new update is passed by the central entity.

The following tables provide a summarising pseudocode for the processes required at each scheme.

**Algorithm 1 ORA Scheme**

1. Calculate: $\Omega_{u,n}^{\text{sum}}, R_{k,m,n}, \Omega_{u,n}^{\text{max}}$ using eq (3.4), (3.5) and (3.14)
2. Initialize $\lambda_n$ and $\mu_m$
3. while $g(\lambda, \mu)$ is not converged in eq (3.10), do
    4. Calculate: $P^*_{m,n}$ in eq (3.16)
    5. Calculate: $H_{k,m,n}$ using eq (3.18)
    6. Update: $\phi_{k,m,n}$ using eq (3.19)
    7. if $H_{k,m,n} > 0$ then update $\phi_{k,m,n} = 1, 0$ otherwise
    8. Calculate: $g(\lambda, \mu)$ using eq (3.17)
    9. Update: $\lambda_n$ and $\mu_m$ using eq (3.20) and (3.21)
10. end
11. Notify neighbouring small-cells with $P^*_{m,n}$ and $\phi_{k,m,n}$

**Algorithm 2 ESRA Scheme**

1. Calculate: $\Omega_{u,n}^{\text{sum}}, \hat{R}_{k,m,n}, \Omega_{u,n}^{\text{max}}$ using eq (3.4), (3.5) and (3.23)
2. $[\phi_{k,m,n}, \hat{R}_{k,m,n}] = \text{bintprog}(\hat{R}_{k,m,n}, \Omega_{u,n}^{\text{max}}, \Omega_{u,n}^{\text{sum}})$
3. Notify neighbouring small-cells with $\phi_{k,m,n}$

The time complexity of the optimal exhaustive search in our case shall be exponential in nature and extremely infeasible to implement in a real network. However, for the ORA scheme, the complexity is mainly dependent on solving the dual problem. The number of computations required to solve the RB allocation is $K(M+1)$ and $N$ number of allocations are required to solve for all RBs. The complexity for each complete iteration is $O(NK(M+1))$. The total complexity of the sub-gradient method is polynomial in
3.6 Simulation Results for Data Channel Resource Allocation

In this section, we evaluate the performance of the dynamic resource allocation schemes in the context of a real-world cellular network scenario. We simulate a single LTE macro-cell with a fixed number of users attached to it and several small-cells, within the operational area of the macro-cell. Macro-cell serves the MUEs with a persistent scheduling (resource allocation within the macro-cell remains fixed for multiple frames). On the other hand each small-cell has a single user attached to it, being served with the potential to use all the available RBs. Further details of the simulation parameters are given in Table 3.1.

Figure 3.3: Computational complexity comparison between ORA and ESRA scheme.

the number of dual variable, and is $O(N + M)$. Therefore, the overall complexity of the ORA scheme is $O((N + M)^2(NMK))$. The ESRA scheme is solved by binary linear integer programming. There are several linear programming relaxations applied to such algorithms, which make them very effective in practice but it is difficult to prove theoretical complexity bounds on the performance of such algorithms. A comparison in terms of number of iterations between the ORA and ESRA scheme is presented in Fig. 3.3, emphasizing on the lower complexity, therefore, higher the practicality of the ESRA scheme.
3.6. Simulation Results for Data Channel Resource Allocation

Table 3.1: Simulation Parameters for Data Channel RA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Macro-cell</th>
<th>Small-cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cells</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2.1 GHz</td>
<td>2.1 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Node transmit power</td>
<td>43 dBm</td>
<td>23 dBm</td>
</tr>
<tr>
<td>Path loss model</td>
<td>$128.1 + 37.6 \log_{10}(d[\text{Km}])$</td>
<td>$128.1 + 37.6 \log_{10}(d[\text{Km}])$</td>
</tr>
<tr>
<td>Number of UEs</td>
<td>5</td>
<td>1 UE per SC</td>
</tr>
<tr>
<td>Noise Figure at UE</td>
<td>9 dB</td>
<td>9 dB</td>
</tr>
<tr>
<td>Thermal noise density</td>
<td>$-174 \text{ dBm/Hz}$</td>
<td>$-174 \text{ dBm/Hz}$</td>
</tr>
<tr>
<td>Cell Radius</td>
<td>800m</td>
<td>50m</td>
</tr>
</tbody>
</table>

Figure 3.4: CDF of MUE data rates, for MUE Demand of 0.5Mbps.

In order to evaluate the average performance of the ORA and ESRA scheme, we first consider a large number of system snapshots with uniform distribution of randomly deployed MUE and SC nodes within the macro-cell area at each snapshot. We also compare the performance of the proposed dynamic resource allocation schemes with the two benchmark cases: a) Reuse-1, where macro-cell and SCs transmit on all the RBs, and b) Static FFR, where 50% of the RBs are reserved for macro-cell and the remaining 50% RBs are shared amongst SCs. At the second step we validate and compare in more detail, the operation of ORA and ESRA schemes considering deterministically placed nodes.
3.6. Simulation Results for Data Channel Resource Allocation

![CDF of MUE data rates](image1)

Figure 3.5: CDF of MUE data rates, for MUE Demand of 1.2Mbps.

![CDF of SUE data rates](image2)

Figure 3.6: CDF of SUE data rates, for MUE Demand of 0.5Mbps.

3.6.1 Randomly Placed Nodes

To evaluate and compare the overall performance of the proposed schemes we find the achieved MUE and SUE rates for a large number of uniform random MUE and SC node placement scenarios. Results are averaged for $10^3$ independent system snapshots.

Fig. 3.4 and 3.5 show the cumulative distribution function (CDF) of the achievable MUE data rates for a MUE demand of 0.5Mbps and 1.2Mbps respectively. It can be
observed that Reuse-1 scheme results into a MUE outage (i.e. when the MUE achieved rate is below the demand rate) of 20% and 50% respectively. Static FFR also results into a 10% MUE outage but only at higher MUE demand rate (1.2Mbps). On the other hand, ORA and ESRA schemes successfully eliminate MUE outage. Moreover, comparing ORA and ESRA schemes performance, we observe that ORA scheme manages to keep the MUE achieved data rates close to the MUE demand; nearly 55% and 90% MUE achieved data rates for 0.5Mbps and 1.2Mbps MUE demand respectively. While in ESRA, MUE rates are always above the demand. The ORA approach is beneficial to facilitate SCs to maximize RB usage to serve their users. This behaviour is clearly depicted in Fig. 3.6 and 3.7, where the CDF of SUE data rates is presented for the same MUE demand rates. ORA scheme has a similar performance to that of Reuse-1, whereas ESRA scheme slightly lags behind. It can also be observed from these plots that ORA and ESRA schemes outperform FFR scheme at higher percentiles in terms of achieved SUE data rates. This is due to the fact that since FFR scheme is static in nature, the reserved bandwidth for MUEs may not be fully utilised when the MUE demand is low. Specific numerical values supporting the aforementioned observations are presented in Table 3.2, where the 50th and 95th percentile average MUE and SUE rates are given for the various MUE demand rates.
Table 3.2: Performance comparison of various data channel resource allocation schemes.

<table>
<thead>
<tr>
<th>Schemes</th>
<th>ORA</th>
<th>ESRA</th>
<th>Reuse-1</th>
<th>FFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUEs below demand rate [%]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUE Demand (Mbps)</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
<td>22.2</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>0.0</td>
<td>0.0</td>
<td>29.4</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>0.0</td>
<td>0.0</td>
<td>47.2</td>
</tr>
<tr>
<td>MUE rate 50th percentile [Mbps]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUE Demand (Mbps)</td>
<td>0.2</td>
<td>0.48</td>
<td>1.54</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.52</td>
<td>1.58</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>0.89</td>
<td>1.77</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>1.40</td>
<td>1.97</td>
<td>1.26</td>
</tr>
<tr>
<td>SUE rate 50th percentile [Mbps]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUE Demand (Mbps)</td>
<td>0.2</td>
<td>12.74</td>
<td>11.98</td>
<td>12.76</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>12.82</td>
<td>11.28</td>
<td>13.06</td>
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<tr>
<td></td>
<td>0.8</td>
<td>12.61</td>
<td>10.57</td>
<td>13.02</td>
</tr>
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<td></td>
<td>1.2</td>
<td>12.46</td>
<td>9.68</td>
<td>13.00</td>
</tr>
<tr>
<td>SUE rate 80th percentile [Mbps]</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>MUE Demand (Mbps)</td>
<td>0.2</td>
<td>17.45</td>
<td>16.25</td>
<td>17.45</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>17.27</td>
<td>15.30</td>
<td>17.27</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>17.27</td>
<td>14.63</td>
<td>17.27</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>17.17</td>
<td>14.08</td>
<td>17.17</td>
</tr>
</tbody>
</table>
3.6. Simulation Results for Data Channel Resource Allocation

3.6.2 Deterministic Node Locations

The placement of the nodes in the static scenario is illustrated in Fig. 3.8, where all the small-cell nodes are placed close to the MUEs except for one, i.e. SC-3.

In order to obtain an in depth view and compare the ORA and ESRA schemes in terms of how resource allocation is performed as well as of their precision in terms of ensuring MUE performance, we consider a static scenario (illustrated in Fig. 3.8). In this scenario all the small-cells are placed close to the MUEs, except for one, i.e. SC-3. For clearer presentation, we consider only 10 RBs in total for this case and assume that each MUE is assigned two RBs in a numeric order, i.e. MUE-x is assigned RB-(2x-1) and RB-(2x).

To this end, Fig. 3.9 (a) and (b) depict the achieved MUE data rates, for a MUE demand of 0.2Mbps: for ORA and ESRA scheme, respectively. We observe clearer now that in case of ORA, majority of the MUE’s achieved rate does not exceed the demand. However, in case of ESRA, MUE’s achieved rate is not as close to the demand.

Moreover, Fig. 3.10 shows the resource (RB and power) allocation map of the SCs for MUE demand rate of 0.2Mbps. We can see that ORA scheme mutes SC-1 and SC-2 in first four RBs on which the nearby MUEs are being served, however transmits with lower power in the RBs where MUE-3 is being served. On the other hand a complete muting for those RBs takes place in case of ESRA scheme. Similarly to protect MUE-4
3.6. Simulation Results for Data Channel Resource Allocation

Figure 3.9: MUE achieved data rate for MUE Demand of 0.2Mbps. The X-axis shows the MUE index. (a) ORA scheme (b) ESRA scheme.

Figure 3.10: SC RB Allocation Map for MUE Demand of 0.2Mbps. The Y-axis for the bar graphs indicates the transmit power of SCs (ranging from 0-20mW). The X-axis indicated the RB index (RB-1 to RB-10, from left to right). (a) ORA scheme (b) ESRA scheme.

and MUE-5, ESRA completely mutes transmissions of SC-4 and SC-5, in their serving RBs. However, the ORA scheme still transmits in some of the RBs with lower transmit power. Such a behaviour is observed since the ORA scheme has the liberty to optimise
not only the RB allocation as well as the transmit power of each small-cell. It is noted that the optimal scheme is more effective in such cases as it does not necessarily completely mutes the small-cells in such critical RBs but in fact reduces transmit power as much as needed. However, this advantageous behaviour of ORA scheme comes at the cost of extra computational complexity as explained in section 3.4. We can observe a similar trend of MUE achieved data rates and resource allocation map in Fig. 3.11 and 3.12, where the MUE demand rate is 0.5Mbps. Furthermore, focusing on SC-3 which is away from the MUEs, we observe that it is allowed to transmit on all the RBs with high power, even for the higher MUE demand case.

### 3.7 Conclusions

In this chapter, we tackled the inter-tier interference issue which deteriorates the performance of mobile macro-cell served users in a HetNet environment comprising macro-cells and small-cells sharing the same frequency band. A dynamic resource allocation algorithm is proposed for small-cells to maximise their sum data rate while at the same time the interference faced by the macro-cell served users is kept below a tolerance threshold, estimated based on their minimum rate requirement. Optimal solution to this problem analysed and further a more practical scheme is proposed which considers small-cell RB muting and significantly reduces computational complexity. Focusing
3.7. Conclusions

on the practical application of these dynamic approaches, we furthermore design algorithms to implement them in a real-world system such as LTE networks. Our simulation results compare the dynamic resource allocation schemes with the conventional Reuse-1 and static FFR scheme, and demonstrate that macro users QoS requirements can be ensured while keeping the small-cell users data rates at similar high levels.

Figure 3.12: SC RB Allocation Map for MUE Demand of 0.5Mbps. The Y-axis for the bar graphs indicates the transmit power of SCs (ranging from 0-20mW). The X-axis indicated the RB index (RB-1 to RB-10, from left to right). (a) ORA scheme (b) ESRA scheme.
In this chapter of the thesis, the aim is to not only cope with ICI in the data channel as well as in the control channel. The discussed literature for Chapter 3 of the thesis only addresses the ICI in the data channel which can not be easily applied in the control channel, since it is not flexible enough to support ICI [89]. Reliability of the control channel has direct impact on the measured performance of the data channel, as information in the control channel serves to be a key to unlock information residing inside the data channel. If the control channel information can not be decoded at the receiver, the data channel associated with that specific control channel shall also be lost. It is vital to reformulate the data-channel-only problem while considering the control channel as the constraints of both the channels are different. The data channel is aimed towards achieving higher data rates, where as the control channel is more focused towards attaining reliability.

4.1 Related Work on Control Channel Resource Allocation

The proposed eICIC framework by 3GPP is mainly focus on handling control channel interference in HetNet environments. [90] proposes an eICIC solution for control region assignment in Long Term Evolution-Advanced (LTE-A) networks with several aggregated carriers in a macro and small-cells environment. The small-cells control
signalling is restricted in certain component carriers (CC), based on indicators from the neighbouring macro-cells. While carrier aggregation (CA) based solutions are attractive for situations with large availability of spectrum and UEs with CA capability, non-CA (i.e., co-channel) based solutions are important to enable efficient heterogeneous network deployments with small bandwidth availability and legacy UEs without CA capability. [89] proposes a scheme for homogeneous LTE networks for reducing the control channel interference by minimising the transmit power and aggregation level allocated to downlink control channel.

LTE standards provide certain level of sparseness to reduce ICI in the control region, since the placement of control channels is based on a hash function of the PCI of each node [91]. Some researches have also exploited this property of LTE control channel to manage the PCI assignment minimising the control channel conflict probability [92]. This PCI optimisation technique is proven to be effective in larger cell networks, however due to limited number of PCIs and perfect protection only from fewer neighbouring cells makes this solution non feasible for small-cell networks. Nevertheless, [93] proposes a solution to protect a specific channel in the control region (PCFICH) based on PCI manipulation, where each SCAP detects the PCI of the strongest neighbouring macro-cell and manipulates its own PCI to minimise the interference. However, we believe that for enhanced performance, SC muting decisions should be more adaptive to the system dynamics and consider the presence of macro-cell served users in the vicinity of SCs. To the best of our knowledge there is no such analysis in literature which uses the idea of interference estimation to perform joint control and data channel interference management. This is a notable shortcoming, as the loss of control channel information has direct impact on the performance of the data channel.

4.2 System Model for Control and Data Channel Joint Resource Allocation

Similar to the previous chapter, we consider a system of $M + 1$ cells, comprising one macro-cell (identified as cell 0) and $M$ small-cells within the macro-cell area (depicted in Figure 4.1). The set of small-cells is defined as $\mathcal{M} = \{1, \ldots, M\}$. We assume that there are $K$ active users in the system. We consider that each user can have only one serving cell, but each cell can support multiple users; thus, $K \triangleq |\mathcal{K}| = |\mathcal{K}_0 \cup \mathcal{K}_1 \cdots \cup \mathcal{K}_M|$, where $\mathcal{K}$ denotes the set of all users in the system and $\mathcal{K}_m$ denotes the set of users served by node in cell $m$. A RE represents the smallest unit of physical resource and
a RB which is made up of a number of REs in frequency and time domain, represents
the smallest transmission unit in downlink of an OFDMA system. \( T_v \) represents the
set of all \( T_v \) REs in a RB, and \( T_{(n)} \) represents the set of all \( T_{(n)} \) REs allocated to a
user for control information regarding RB \( n \). And, super-set \( \mathcal{T} \) represents all \( T_{(n)} \) sets:
\[ \mathcal{T} = \{ T_{(1)}, \ldots, T_{(n)}, \ldots \} \]. We consider a minimal level of reliability (minimum required
BER) on the control channel of the macro-cell and small-cell served users, which is
vital for the successful decoding of the data channel. Furthermore, for the macro-cell
users we consider a minimum required rate on the data channel. For this study, we
consider only the dedicated user-specific control channel information to be protected.
SCs reuse the same resources as of the macro-cell to serve their SUEs based on a
resource allocation policy. We consider a central entity which is able to collect relevant
information to make resource allocation decisions and guide small-cells on the resource
allocation policy to be adopted. In the following subsections we express the SINR and
interference allowance representations for the control and data channels of MUEs and
SUEs. It is important to represent control and data channel parameters separately
as the constraints on the control channel are different from the data channel. The
power levels on the control channel are different from the data channel as well as the
data channel is capable of higher modulation and coding schemes, however the control
channel is usually transmitted at the most robust modulation and coding scheme.

Figure 4.1: Scenario illustration for control and data channel resource allocation
4.2. system model for control and data channel joint resource allocation

4.2.1 Control Channel: User SINR & Max Interference Allowance

The SINR of MUE \( u \) at RE \( t \in T_n \), bearing control information for MUE \( u \) is given by

\[
\gamma_{c,u,0,t} = \frac{p_{0,n}^{c} \Gamma_{u,0,n}^{0}}{\sum_{m=1}^{M} \left( \sum_{k \in K_m} \phi_{c,k,m,t} \right) p_{m,n}^{c} \Gamma_{u,0,n}^{m} + N_0 B_t},
\]

where \( p_{0,n}^{c} \) denotes the transmit power of macro-cell at RE \( t \), \( \Gamma_{i,k,m,n}^{0} \) is the channel gain between base station at cell \( i \) and user \( k \) being served at cell \( m \) in RB \( n \), \( N_0 \) is the noise power spectral density and \( B_t \) is the bandwidth of each RE. And \( \phi_{c,k,m,t} \in \{0,1\} \), where \( \phi_{c,k,m,t} = 1 \) when RE \( t \) is assigned to bear control information for \( k \)th user in small-cell \( m \); otherwise, the RE allocation parameters take zero value. \( \phi^{c} = [\phi_{c,1,1}^{c}, \ldots, \phi_{K,M,T_{t}}^{c}] \), where \( T_{t} \) is the total number of REs used for control in TTI \( t \). Similarly SINR of SUE \( k \) in cell \( m \) at RE \( t \) is expressed as

\[
\gamma_{c,k,m,t} = \frac{p_{m,n}^{c} \Gamma_{k,m,n}^{0}}{p_{0,n}^{c} \Gamma_{k,m,n}^{0} + \sum_{i=1}^{M} \sum_{l \in K_i \setminus K_m} \phi_{c,l,i,t} \left( \sum_{i \notin K_m} \phi_{c,k,m,t} \right) p_{m,n}^{c} \Gamma_{k,m,n}^{i} + N_0 B_t}.
\]

where transmit power of the SCAP node at \( m \)th cell at each RE in the control-section of \( n \)th RB is denoted by \( p_{m,n}^{c} \leq P_{\text{max}}^{c} \).

The fixed MUE demand BER at RE \( t \) can be translated into a specific minimum required \( \gamma_{c-\text{req},u,0,t} \) SINR value, given a certain aggregation level (e.g. CCE aggregation level in LTE) used for the specific user. Maximum interference power \( \Omega_{c-\text{max},u,t}^{c} \) that MUE \( u \) can tolerate in RE \( t \) from all SCs to be able to decode its UE-specific control information correctly is given by

\[
\Omega_{c-\text{max},u,t}^{c} = \frac{p_{0,n}^{c} \Gamma_{u,0,n}^{0}}{\gamma_{c-\text{req},u,0,t}} - N_0 B_t.
\]

If the potential channel gain from any small-cell \( m \) to the MUE at RE \( t \) is denoted as \( \Gamma_{0,u,n}^{m} \), the total interference caused to it by all small-cells in this RE can be given by

\[
\Omega_{c-\text{sum},u,t}^{c} = \frac{p_{0,n}^{c} \Gamma_{u,0,n}^{0}}{\gamma_{c-\text{req},u,0,t}} \sum_{m=1}^{M} \left( \sum_{k \in K_m} \phi_{c,k,m,t} \right) p_{m,n}^{c} \Gamma_{0,u,n}^{m} = \frac{p_{0,n}^{c} \Gamma_{u,0,n}^{0}}{\gamma_{c-\text{req},u,0,t}} \sum_{m=1}^{M} \sum_{k \in K_m} \phi_{c,k,m,t} \omega_{0,u,n}^{m},
\]

where \( \omega_{0,u,n}^{m} \triangleq p_{m,n}^{c} \Gamma_{0,u,n}^{m} \) can be interpreted as the interference that is caused to user \( u \) in cell 0 (macro-cell) on RE \( t \) from small-cell \( m \).

Similarly, the fixed SUE demand BER at RE \( t \) can be translated into a specific minimum required \( \gamma_{k,m,t}^{c-\text{req}} \) SINR value. This SINR value is used to estimate the Maximum
4.2 System Model for Control and Data Channel Joint Resource Allocation

interference, $\Omega_{k,m,t}^{c,\text{max}}$ that is required to decode the UE-specific control information, given by

$$\Omega_{k,m,t}^{c,\text{max}} = \frac{p_{m,n}^{c} \Gamma_{k,m,n}^{m}}{\gamma_{k,m,t}^{c,\text{req}}} - N_0 B_t.$$  (4.5)

The total interference at RE $t$ experienced by SUE $k$ from macro-cell and neighbouring SCs transmissions is given by

$$\Omega_{k,m,t}^{c,\text{sum}} = p_{0,n}^{c} \Gamma_{k,m,n}^{0} + \sum_{i=1}^{M} \left( \sum_{l \in K_i} \phi_{l,i,t}^{c} \right) p_{i,n}^{c} \Gamma_{k,m,n}^{i}. \quad \text{(4.6)}$$

4.2.2 Data Channel: User SINR & Max Interference Allowance

The SINR of MUE $u$ served in RB $n$ is given by

$$\gamma_{u,0,n}^{d} = \frac{p_{0,n}^{d} \Gamma_{u,0,n}^{0}}{\sum_{m=1}^{M} \left( \sum_{k \in K_m} \phi_{k,m,n}^{d} \right) p_{m,n}^{d} \Gamma_{u,0,n}^{m} + N_0 B_n}, \quad \text{(4.7)}$$

where $p_{0,n}^{d}$ denotes the transmit power of macro-cell node at RB $n$, $\Gamma_{k,m,n}^{i}$ is the channel gain between base station at cell $i$ and user $k$ being served at cell $m$ in RB $n$, $N_0$ is the noise power spectral density and $B_n$ is the bandwidth of each RB. $\phi_{k,m,n}^{d} \in \{0, 1\}$, where $\phi_{k,m,n}^{d} = 1$ when small-cell $m$ serves its $k^{th}$ assigned user in the $n^{th}$ RB; otherwise, the RB allocation parameters take the zero value. $\phi^{d} = [\phi_{1,1,n}^{d} \ldots \phi_{K_m,M,N}^{d}]$. Similarly the SINR of SUE $k$ in cell $m$ at RB $n$ is given by

$$\gamma_{k,m,n}^{d} = \frac{\phi_{k,m,n}^{d} \Gamma_{k,m,n}^{m}}{p_{0,n}^{d} \Gamma_{k,m,n}^{0} + \sum_{i=1}^{M} \left( \sum_{l \in K_i} \phi_{l,i,n}^{d} \right) p_{i,n}^{d} \Gamma_{k,m,n}^{i} + N_0 B_n}. \quad \text{(4.8)}$$

where transmit power of the small-cell node at $m^{th}$ cell in the data-section of $n^{th}$ RB is denoted by $p_{m,n}^{d} \leq P_{\text{max}}$. The data channel SINR expressed in (4.8) is different from the control channel SINR expressed in (4.2). Since there the power levels on the control channel differ from that in the data channel. Secondly the data channel SINR is expressed on the RB level where as for the control channel it is expressed on the RE level.
The User Data Rate (SUE or MUE) at RB \( n \) can be expressed as follows

\[
R_{k,m,n} = \log_2 \left( 1 + \gamma_{k,m,n} \right) = \log_2 \left( 1 + \phi_{k,m,n} d_{k,m,n} \alpha_{k,m,n} \right),
\]

where \( \alpha_{k,m,n} \) denotes the channel gain of the user \( k \) served by cell \( m \) at RB \( n \).

The fixed MUE demand data rate at RB \( n \) can be translated into a specific minimum required \( \gamma_{\text{d-req},u,0,n} \) SINR value (using equation (4.9)). Maximum interference power \( \Omega_{\text{max}}^{d,u,n} \) that MUE \( u \) can tolerate in RB \( n \) from all SC nodes to obtain this rate threshold is given by:

\[
\Omega_{\text{max}}^{d,u,n} = \frac{p_{0,n} \Gamma_{u,0,n}^0}{\gamma_{\text{d-req},u,0,n}} - N_0 B_n.
\]

If the potential channel gain from any small-cell \( m \) to the MUE at RB \( n \) is denoted as \( \Gamma_{0,u,n}^m \), the total interference caused to it by all small-cells in this RB can be given by:

\[
\Omega_{\text{sum}}^{d,u,n} = \sum_{m=1}^{M} \left( \sum_{k \in K_m} \phi_{k,m,n}^d \right) p_{m,n}^d \Gamma_{0,u,n}^m = \sum_{m=1}^{M} \left( \sum_{k \in K_m} \phi_{k,m,n}^d \right) \omega_{0,u,n}^m,
\]

where \( \omega_{0,u,n}^m \triangleq p_{m,n}^d \Gamma_{u,0,n}^m \) can be interpreted as the interference that is caused to user \( u \) in cell 0 (macro-cell) on RB \( n \) from small-cell \( m \).

4.2.3 Optimisation Problem for Joint Control and Data Channel Resource Allocation

Finally, the overall optimisation problem is formulated as follows:

\[
\max_{\text{p}^{\text{d}}, \text{p}^{\text{c}}, \phi^{\text{d}}, \phi^{\text{c}}, \mathcal{T}} \prod_{n=1}^{N} \sum_{m=1}^{M} \sum_{k \in K_m} \left( \prod_{t \in T(n)} c_{k,m,t} \left( \text{p}^{\text{c}}, \phi^{\text{c}} \right) \right) R_{k,m,n} \left( \text{p}^{\text{d}}, \phi^{\text{d}} \right)
\]
subject to:

\[ \phi_{k,m,n}^{d} \in \{0, 1\}, \forall k \in K \setminus K_0, m \in \mathcal{M}, n; \quad (4.13a) \]

\[ \sum_{k \in K_m} \phi_{k,m,n}^{d} \leq 1, \forall m \in \mathcal{M}, n; \quad (4.13b) \]

\[ \phi_{k,m,t}^{c} \in \{0, 1\}, \forall k \in K \setminus K_0, m \in \mathcal{M}, t; \quad (4.13c) \]

\[ \sum_{k \in K_m} \phi_{k,m,t}^{c} \leq 1, \forall m \in \mathcal{M}, t; \quad (4.13d) \]

\[ \Omega_{n}^{d-sum} \leq \Omega_{n}^{d-max}, \quad \forall n; \quad (4.13e) \]

\[ \Omega_{u,t}^{c-sum} \leq \Omega_{u,t}^{c-max}, \quad \forall t; \quad (4.13f) \]

\[ \sum_{n=1}^{N} \left( \sum_{k \in K_m} \phi_{k,m,n}^{d} \right) p_{m,n}^{d} \leq P_{\max}, \forall m \in \mathcal{M}; \quad (4.13g) \]

\[ p_{m,n}^{d} \geq 0, \forall m \in \mathcal{M}, n; \quad (4.13h) \]

\[ \sum_{n=1}^{N} \sum_{t \in T_m} \left( \sum_{k \in K_m} \phi_{k,m,t}^{c} \right) p_{m,n}^{c} \leq P_{\max}, \forall m \in \mathcal{M}; \quad (4.13i) \]

\[ p_{m,n}^{c} \geq 0, \forall m \in \mathcal{M}, n, \quad (4.13j) \]

where,

\[ c_{k,m,t} = \begin{cases} 
1, & \text{if } \Omega_{k,m,t}^{c-sum} \leq \Omega_{k,m,t}^{c-max} \\
0, & \text{otherwise.} 
\end{cases} \quad (4.14) \]

The main maximisation objective is expressed in (4.12), the sum data rates for the small-cell users is maximised. \( c_{k,m,t} \) elaborated in (4.14) being a binary multiplier to ensure that if the control channel information is not decodable in a certain instance the data channel is also lost; since, the control channel holds vital information to decode the data channel. Constraints in (4.13a) and (4.13c) express the binary nature of the \( \phi \) muting variable for data and control channel respectively. Constraints (4.13b) and (4.13d) guarantee that RB \( n \) in data region and RE \( t \) in control region is assigned to at most one user \( k \). Maximum interference tolerance constraints for the data and control channel of MUE are expressed in (4.13e) and (4.13f) respectively. There are no minimum constraints on the control or data channel of SUEs. Constraints (4.13g) and (4.13h), and (4.13i) and (4.13j) together fulfil the power constraints for the data channel and control channel respectively. It is important to mention here that we do not impose any minimum quality constraints on control and data channels of SUEs. Usually small-cells have as much resources as the larger macro-cell. However, due to restriction on maximum power, they cover a very small area, resulting in relatively very
few users in their area of coverage. Hence, the small-cells have enough resources to serve their SUEs. The formulated optimisation problem being very complex in nature is extremely difficult to solve in real network with dynamically changing environment. To address the complexity issues we devise two low complexity heuristic solutions, explained in the following section.

4.3 Proposed Resource Allocation Schemes

The proposed Small-cell Rate Maximisation (SRM) and Interference Tolerance Aware (ITA) resource allocation schemes will be presented in this section. The purpose of these schemes is to heuristically achieve the objective expressed in the optimisation problem in (4.12), and also keeping computational complexity at a very low level. The main difference between the SRM and ITA scheme is that the SRM scheme solves the same maximisation problem by binary integer programming with relaxation on the transmit power (transmit power is kept fixed). However, in case of ITA the focus is to allow SC transmissions considering minimum caused interference to the MUE in a progressively incremental order till the constrained tolerance threshold is reached.

4.3.1 Small Cell Rate Maximisation Resource Allocation (SRM)

The main objective of the proposed SRM resource allocation scheme is to maximise the overall small-cells data rate and along with that to satisfy the macro user constraints on the control and data channels. This is achieved by finding the optimal combination of SC transmissions restriction matrix using binary integer programming. The proposed algorithm first finds SCs control channel restriction matrix $\vec{\phi}_c^t$ followed by the data channel restriction matrix $\vec{\phi}_d^n$. For the control channel restriction matrix $\vec{\phi}_c^t$, initially the maximum interference allowance $\Omega_{u,t}^{c\text{-max}}$ is estimated for every RE $t$ in each RB as expressed in Equation. (4.3). Next, for every SC $m$ the interference it causes to MUE being served on that RE $t$ is updated as expressed in (4.4). Similarly, the data channel expected rate for the every SUE in every SC $m$ is estimated. The maximum interference allowance, estimated interference from each SC to macro-cell user and the estimated achievable rate of SCs is used to solve the binary integer problem. This is estimated for each RE to create and update the SCs control channel restriction matrix. Once the control channel restriction matrix is updated and notified to the respective
4.3. Proposed Resource Allocation Schemes

SCs, the restriction matrix for the data channel is solved for each RB. The binary integer problem for the data channel is solved similar to the control channel but on the RB level. The maximum interference allowance $\Omega_{u,n}^{d\text{-max}}$, estimated interference from each SC to MUE $\bar{\omega}_{u,0,n}$ and the estimated achievable rate of SCs $\bar{R}$ is used to solve the data channel restriction matrix $\bar{\phi}_{u,n}^{d}$. This restriction matrix is further notified to the SCs and remains valid until the next update is available. The steps in Algorithm 3 summarise the processes required for the SRM resource allocation scheme.

Algorithm 3 Small-Cell Rate Maximisation Resource Allocation (SRM)

1: for $v = 1 \rightarrow (N)$
2:     for $t = 1 \rightarrow T_v$
3:         Initialise : $\bar{\phi}_{v,t}^c = \vec{0}$
4:         Calculate : $\Omega_{u,t}^{c\text{-max}}$ as in eq. 4.3
5:         for $m = 1 \rightarrow M$
6:             Calculate : $\omega_{u,0,t}^{m}$ as in eq. 4.4
7:             for $k = 1 \rightarrow K_m$
8:                 Calculate : $R_{k,m}$
9:             end
10:         end
11:     $\bar{\phi}_{v,t}^c = \text{bintprog} \ (\bar{R}, \bar{\omega}_{u,0,t}, \Omega_{u,t}^{c\text{-max}})$
12:     where, $\bar{R} = [R_{1,1}, ..., R_{K_m,M}]$; $\bar{\omega}_{u,0,t} = [\omega_{u,0,t}^{1}, ..., \omega_{u,0,t}^{M}]$
13: end
14: Notify neighbouring SCs with $\bar{\phi}_{v,t}^c$.
15: for $n = 1 \rightarrow (N)$
16:     Initialise : $\bar{\phi}_{n}^{d} = \vec{0}$
17:     Calculate : $\Omega_{u,n}^{d\text{-max}}, \omega_{u,0,n}^{m}, \bar{R}_{k,m,n}$ as in eq. 4.10 and 4.11
18:     $\bar{\phi}_{n}^{d} = \text{bintprog} \ (\bar{R}, \bar{\omega}_{u,0,n}, \Omega_{u,n}^{d\text{-max}})$
19: end
20: Notify neighbouring SCs with $\bar{\phi}_{n}^{d}$.

4.3.2 Interference Tolerance Aware Resource Allocation (ITA)

Since the SRM scheme solves the binary integer programming problem for each RE in the control channel, this scheme would still be quite computationally complex for implementation in a real network. Interference Tolerance Aware Resource Allocation (ITA) is a modified version of SRM scheme, the motivation behind this scheme is to minimise the control channel computational complexity for more feasible implementa-
4.4 Simulation Results for Control and Data Channel Resource Allocation

In this section we show the numerical results for our proposed schemes and compare them to the conventional Reuse-1 scheme. For this numerical analysis we simulate a single macro-cell along with five small-cells. The macro-cell and each SC is serving up to five SUEs. We consider shadowing and fast fading in our simulation. Proposed schemes are also analysed for variations in shadow fading environments, shadow fading affects are incorporated into path-loss estimated by addition of a zero-mean Gaussian random variable, with standard deviation $\sigma$. For these simulations the MUE minimum required data rate was set to 1.1Mbps. Further details of the simulation parameters are given in Table 4.1.
Algorithm 4 Interference Tolerance Aware Resource Allocation (ITA)

1: for $v = 1 \rightarrow (N)$
2:     for $t = 1 \rightarrow T_v$
3:         Initialise: $\vec{\phi}_t^c = \vec{0}$, $\Omega_{t}^c\text{-sum} = 0$
4:         Calculate: $\Omega_{t}^c\text{-max}$ as in eq. 4.3
5:         for $m = 1 \rightarrow M$
6:             Calculate: $\omega_{m,0,t}$ as in eq. 4.4
7:             for $k = 1 \rightarrow K_m$
8:                 Calculate: $\Gamma_{m,k,m,t}^c$
9:         end
10:     end
11:     sort $\omega_{m,0,t}^c$ into $\vec{\omega}_{m,0,t}^\text{sort}$ list, in ascending order w.r.t magnitude
12:     for $x = 1 \rightarrow \text{length} \vec{\omega}_{m,0,t}^\text{sort}$
13:         $\Omega_{u,t}^c\text{-sum} += \Omega_{u,0,t}^c$
14:         if $\Omega_{u,t}^c\text{-sum} > \Omega_{u,t}^c\text{-max}$
15:             break;
16:         else
17:             sort $\Gamma_{x,t}^c$ in descending order w.r.t magnitude
18:             for element on top of the list, find $k$ index
19:             if RE is required for control of user $k$
20:                 $\phi_{k,x,t}^c = 1$
21:             else
22:                 check for next element in list
23:         end
24:     end
25:     end
26:     end
27:     Notify neighbouring SCs with $\vec{\phi}_t^c$.
28: for $n = 1 \rightarrow (N)$
29:     Initialise: $\vec{\phi}_n^d = \vec{0}$
30:     Calculate: $\Omega_{n}^d\text{-max}$, $\omega_{u,0,n}^m$, $\hat{R}_{k,m,n}$ as in eq. 4.10 and 4.11
31:     $\phi_{n}^d = \text{bintprog} (\hat{R}, \vec{\omega}_{u,0,n}^m, \Omega_{u,n}^d\text{-max})$
32: end
33: Notify neighbouring SCs with $\vec{\phi}_n^d$. 
Table 4.1: LTE-Based Scenario - Simulation Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Macro-cell</th>
<th>Small-cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2.1 GHz</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5 MHz</td>
<td></td>
</tr>
<tr>
<td>Node transmit power</td>
<td>43 dBm</td>
<td>23 dBm</td>
</tr>
<tr>
<td>Path loss model</td>
<td>$128.1 + 37.6\log_{10}(d[\text{Km}])$</td>
<td></td>
</tr>
<tr>
<td>Number of UEs</td>
<td>5</td>
<td>1 – 5 UE per SC</td>
</tr>
<tr>
<td>Number of OFDM symbols for PDCCH</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>BER threshold for PDCCH</td>
<td>$10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Number of RE Quadruplets per PDCCH</td>
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<td></td>
</tr>
<tr>
<td>Noise Figure at UE</td>
<td>9 dB</td>
<td></td>
</tr>
<tr>
<td>Thermal noise density</td>
<td>−174 dBm/Hz</td>
<td></td>
</tr>
<tr>
<td>Cell Radius</td>
<td>800m</td>
<td>50m</td>
</tr>
</tbody>
</table>

Figure 4.2: CDF plot for MUE data rates for the lightly loaded SCs case.

The Cumulative Distribution Function plots in Figure 4.2 and 4.5 represent the macro users data rates for the case when the SCs are lightly loaded and heavily loaded respectively. We consider the control region of SC to be lightly loaded if less than 20% of the control is occupied and heavily loaded if more than 80% of the control region is occupied. We observe that for the Reuse-1 case as the shadow fading standard deviation coefficient is increased, the number of MUEs in outage increase. We simulate for cases
4.4. Simulation Results for Control and Data Channel Resource Allocation

Figure 4.3: Box and Whiskers plot for MUE Data rates for lightly loaded SCs case. Each plot ranges from 9 percentile to 91 percentile of the values where as the box expresses the lower and upper quartile (25% and 75%). Line dividing the box expresses the median and ‘+’ expresses the mean value.

where shadow fading standard derivation $\sigma$ is kept at 4, 6 and 10db. In case of lightly loaded SCAPs (in Figure 4.2), Reuse-1 scheme has an outage (where the user expected data rate is lower than the demand rate) of nearly 10% users and as the shadow fading co-efficient is increased to $\sigma = 10dB$, outage reaches upto 20%. In case of SRM and ITA the outage is kept very low as compared to Reuse-1 case. We also add a fading margin to our algorithms which can be updated based on preceding channel conditions. Similarly in case of heavily loaded SCs (in Figure 4.5, Reuse-1 has a very poor performance, outage MUEs reach up to 45% and even further as the shadow fading co-efficient is increase. The efficiency of both the proposed algorithms can be seen in Figure 4.5, where the outage MUEs are kept below 15% even in high fading environments. These results can be further analysed with the help of the Box and Whisker plots in Figure 4.3 and 4.6, indicating the range of MUE data rates between 9 and 91 percentile and also indicating the first and third quartiles of the data. For lightly loaded SCs (Figure 4.6) and shadow fading $\sigma = 10dB$, SRM and ITA manage to keep the MUE outage below 10 percentile, whereas for Reuse-1 the outage reaches close to the first quartile (25 percentile). Similarly in the heavily loaded SCs case and shadow fading $\sigma = 10dB$, SRM and ITA keep the MUE outage below the 25 percentile, whereas for Reuse-1 the outage is above the 50 percentile.
4.4. Simulation Results for Control and Data Channel Resource Allocation

Figure 4.4: CDF plot for SCs individual data rates for the lightly loaded SCs case.

Figure 4.5: CDF plot for MUE data rates for the heavily loaded SCs case.

The gains for the proposed algorithms come as a trade-off to the data rates at the SCs. In Figure 4.4 and 4.7 the SCs individual throughputs are presented, for lightly loaded SCs and heavily loaded SCs case respectively. It is evident that the Reuse-1 case has the maximum SCs throughputs, nevertheless SRM and ITA schemes have comparable throughputs with negligible degradation. We must mention here that considering the fact that a SC usually serves fewer users as compared to a macro-cell, slight degradation in the SC’s overall throughput does not severally affects its users due to ample amount
of available resources. Also to point out that in terms of SC throughputs, ITA lags slightly behind SRM which comes as a trade-off to the minimalistic computational complexity of ITA scheme.

![Box and Whiskers plot for MUE Data rates for heavily loaded SCs case.](image1)

Figure 4.6: Box and Whiskers plot for MUE Data rates for heavily loaded SCs case.

![CDF plot for SCs individual data rates for the heavily loaded SCs.](image2)

Figure 4.7: CDF plot for SCs individual data rates for the heavily loaded SCs.

In Figure 4.8 and 4.9, we present the percentage loss of PDCCH in the MUEs for various shadow fading environments. It is evident from the bar graphs that if the SCs are heavily loaded there are severe PDCCH losses, reaching nearly up to 50% in certain high shadow fading conditions for Reuse-1 case. Our proposed algorithms manage to
keep the PDCCH losses relatively low, hence protecting macro-cell users from outage.

![Bar graph for percentage of lost PDCCH in lightly loaded SC case.](image1)

![Bar graph for percentage of lost PDCCH in heavily loaded SC case.](image2)

It is also interesting to see how the shadow fading margin in our algorithms plays an important role in protecting macro users control region. The plots in Figure 4.10, 4.11, 4.12 show our simulations for a fixed shadow fading standard deviation of $\sigma=6\text{dB}$, and the margin is varied from 3dB up to 10dB to analyse the performance under extreme fading conditions. A larger margin obviously means more MUE control region protection, but also means that in return a lower SCs throughput. It is clear
that even with lower margin our proposed ITA scheme performs better than Reuse-1 case, and has a very low computational complexity.

The time complexity of the optimal algorithm (ORA in section 3.3) to solve the control channel resource allocation shall be is $O((T + M)^2(TM K))$, where $K$ represents the number of UEs, $M$ represents the number of SCs and $T$ represents the number of REs. The complexity of the exhaustive search in our case is exponential in nature and extremely infeasible to implement in a real network. The proposed SRM scheme is solved by binary linear integer programming. There are several linear programming relaxations applied to such algorithms, which make them very effective in practice but it is difficult to prove the theoretical complexity bounds on the performance of such algorithms. A comparison in terms of normalised CPU time is presented for SRM, ITA and the optimal case in Figure 4.13. It is evident that optimal case has a very high complexity and is not feasible to solve in a practice system. On the other hand SRM and ITA schemes have a significantly lower complexity. In fact ITA scheme has very minimal complexity and is very feasible to be applied in a practical network.

Figure 4.10: CDF of MUE Data rates (ITA scheme) for various fading margins.

4.5 Conclusions

Inter-tier interference deteriorates the performance of mobile macro-cell served users in a HetNet environment comprising macro and small-cells sharing the same frequency band. With most existing studies focusing on increasing the performance of small-cell
users, macro-cell users demands have been usually out of the equation. However, especially in the upcoming 5G networks envisaging the dense deployment of small-cells overlaid by a macro umbrella, inter-tier interference levels will see a huge increase affecting significantly this type of users. In this chapter, focus was to manage inter-tier interference in OFDMA-based networks though coordinated multi-cell resource allocation. Coordinated resource allocation is considered not only for the data channel but
also for the control channel whose reliability is especially important as it contains key information to successfully decode the data channel. To this end, a performance optimisation problem for this novel scenario is mathematically formulated. Two dynamic resource allocation algorithms are proposed at small-cells to maximise their sum data rate while at the same time the interference faced by the macro-cell served users is kept below a tolerance threshold. Interference tolerance is estimated based on macro user’s minimum rate requirement at the data channel and minimum BER threshold to decode the control information at the control channel. Our simulation results demonstrate that the proposed Small-cell Rate Maximisation (SRM) resource allocation scheme ensures the macro users QoS requirements while keeping the small-cell users data rates similar as compared to the conventional Reuse-1 scheme. To reduce the computational complexity we propose a low complexity Interference Tolerance Aware (ITA) resource allocation scheme. This scheme ensures nearly similar performance compared to SRM scheme. Further we also discuss the practical implementation of our proposed scheme in LTE networks. As 5G networks are expected to be even more flexible for control and data resource allocation, this implementation can serve as a guide on how to perform coordinated resource allocation in future systems for achieving high performances ubiquitously over the network.
Chapter 5

Energy Efficiency in Small Cell Networks

The previous work in Chapter 3 and 4 addressed the interference caused by SCs to macro-cell users. However, we realised that at certain extreme (high/low traffic) conditions of the network, some SCs were underutilised either due to very limited existing load or due to muting when causing high interference to macro-cell users. This observation gave us the motivation to modify our previous formulation with respect to EE, by including sleep mode capability to SCs.

5.1 Introduction

Although SCs have a relatively lower power consumption profile, one of the major concern in future dense deployments is the high aggregated energy consumption. Deployment of small cells, in hotspots and cell edges is beneficial for QoS as well as from EE point of view. But these gains come at the cost of deploying SCs at ideal locations, either where data requirements are high or macro-cell performance is low [71].

However, it is difficult to predict the optimal locations of these nodes, and it gets even difficult to manage in case of subscriber deployed SCs. Considering the dense subscriber owned deployment of SCs, they may not be beneficial in terms of EE, since these small cells are operational at all times of the day. Even if there are no users to be served, a substantial amount of circuit energy is being drawn by these nodes. Considering the expected heavy deployment of SCs in the near future and the dynamic traffic demands, sleep modes could be a promising solution to overcome the wastage of energy in case of low SC utilisation.
For this work, we utilise the umbrella macro-cell to guide the SCs to change their operational state, based on the reported activity levels. We mathematically represent the optimisation problem for this scenario, and considering the time and computational limitations of a practical network we solve the problem based on a heuristic algorithm. Similar simulation parameters are used as in Chapter 3. Furthermore, we also evaluate the working of the proposed algorithm on real activity level data extracted from Telecom Italia’s network in City of Milan. The focus of this simulation exercise is to demonstrate a favour of energy saving potentials in relation to the real world traffic variations.

5.2 Energy Efficiency Performance Metrics

It is important to explain the commonly used energy performance metrics before the description of the proposed algorithm is discussed. Expressing the total energy consumed by a network in the simple units of energy (Joules) is usually beneficial when we compare two strategies to complete a specific task, maintaining a fixed QoS. We can quantify the performance on the basis of the time consumed by each scheme or the total energy consumed. Some authors in literature simplify the expression of performance comparison by presenting Percentage Savings (%), which is simply the percentage ratio of the two schemes. Alongside that, the most commonly used Energy Efficiency (EE) metric is bits/Joules, which is the number of bits transferred per unit of energy. EE is simply calculated as the total number of bits transferred divided by the total amount of energy consumed.

\[
EE = \frac{\text{Total data transferred}}{\text{Total energy consumed}} \quad \text{(bit/Joules)} \tag{5.1}
\]

This is also alternatively expressed by some authors as Energy Consumption Ratio (ECR), being amount of energy consumed to transmit one bit of information [94] [95].

\[
ECR = \frac{P}{D} \left( \frac{\text{Watt/sec}}{\text{bit}} \right) \tag{5.2}
\]

Where, \( D = \frac{B}{T} \) is the data rate in bits per second and \( P \) is the power in Watts required to deliver \( B \) bits over time \( T \). Furthermore, energy efficiency between two systems can also be expressed by Energy Consumption Gain (ECG), which is a ratio of ECR for two systems [94] [95].

\[
ECG = \frac{ECR_a}{ECR_b} \tag{5.3}
\]
Energy savings are also expressed as Energy Reduction Gain (ERG) \[94\] [95].

\[ ERG = \left( \frac{ECR_a - ECR_b}{ECR_a} \right) \times 100\% \tag{5.4} \]

For comparison of two schemes where the coverage area of the sites does not remain the same, Area Power Consumption [96] metrics is helpful in accessing the power consumption of the network relative to its size. It is the average power consumed in a cell divided by the corresponding average cell area. This metric is measured in Watts per square Kilometre.

\[ P_{Area} = \frac{P_{av}}{A_c} \tag{5.5} \]

Where, \( P_{av} \) is the average power consumed and \( A_c \) is the coverage area.

### 5.3 System Model for Energy Efficient Resource Allocation

In this chapter of the thesis, we again use a similar system model as used in Chapter 3 and 4. We consider a system of \( M + 1 \) cells, as depicted in Fig. 5.1, comprising one macro-cell (identified as cell 0) and \( M \) small cells within the macro-cell area. The set of SCs is defined as \( \mathcal{M} = \{1, \ldots, M\} \). We assume that there are \( K \) active users in the system. We consider that each user can have only one serving node, but each cell can support multiple users; thus, \( K \triangleq |\mathcal{K}| = |\mathcal{K}_0 \cup \mathcal{K}_1 \cdots \cup \mathcal{K}_M| \), where \( \mathcal{K} \) denotes the set of all users in the system and \( \mathcal{K}_m \) denotes the set of users served by node in cell \( m \).

Following the binary RB allocation nature of the OFDMA systems the total system bandwidth is divided in \( N \) RBs and each RB can be allocated to only one user in each cell. Macro-cell node can allocate all the available RBs to its associated MUE. Moreover, macro-cell users are assumed to have minimum data rate requirements.

On the other hand, small-cells reuse the same resources to serve their SUE based on a resource allocation policy. We consider a semi-distributed network controlled system (section 2.2.1). A central entity residing at each macro-cell node which is able to collect relevant information to make resource allocation decisions and guide small cells transmission and sleep/wake-up decisions.

Similar to the previous chapters we define binary indicator variables \( \phi_{k,m,n} \in \{0,1\} \), where \( \phi_{k,m,n} = 1 \) when SC \( m \) serves its \( k \)th assigned user in the \( n \)th RB; otherwise,
5.3. System Model for Energy Efficient Resource Allocation

Figure 5.1: System model illustration for sleeping mode cells

the RB allocation parameters take the zero value. Thus, we can define the vector containing all RB allocation parameters \( \phi = [\phi_1,1, \ldots, \phi_{K,M,M,N}] \), which characterizes the SCs’ RB allocation policy. To add sleep/wake-up mode functionality to our problem formulation, we also define the binary cell ON/OFF state indicator \( \psi_m \in \{0, 1\} \), where \( \psi_m = 1 \) indicates the active state of cell \( m \); otherwise, in OFF state it take the zero value. Moreover, transmit power of the \( m^{th} \) small cell in the \( n^{th} \) RB is denoted by \( p_{m,n} \leq P_{\text{max}} \), where \( P_{\text{max}} \) is the maximum allowed transmission power of any small cell. Vector \( p = [p_{1,1} \ldots p_{M,N}] \) characterizes the small cells power allocation policy.

Readers may refer to section 3.2.1 and section 3.2.2 for the user SINR and maximum interference allowance modelling respectively.

5.3.1 Network Power Optimisation Problem

The total instantaneous power of a cell can be given by the sum of circuit and the transmit power as:

\[
P_{\text{total}} = \psi_m (P_{\text{circuit}} + \Delta_m P_{\text{transmit}})
\]

(5.6)

where, \( P_{\text{circuit}} \) is the constant circuit power which is drawn if transmit node \( m \) is active and is significantly reduced if the node goes into sleep mode. \( P_{\text{transmit}} \) is the node’s transmit power and \( \Delta_m \) donates the slope of load dependent power consumption [97].

The general network power optimisation problem comprising the objective function and
the imposed constraints can be formulated as follows:

\[
\min_{p,\phi,\psi} \sum_{m=0}^{M} P_{m}^{\text{total}} \tag{5.7}
\]

subject to:

\[
\phi_{k,m,n} \in \{0, 1\}, \forall k \in K \setminus K_0, m \in M, n; \tag{5.8a}
\]

\[
\sum_{k \in K_m} \phi_{k,m,n} \in \{0, 1\}, \forall m \in M, n; \tag{5.8b}
\]

\[
\Omega_{\text{sum}}^n \leq \Omega_{\text{max}}^n, \quad \forall n; \tag{5.8c}
\]

\[
\psi_{m} \in \{0, 1\}, m \in M, n; \tag{5.8d}
\]

\[
\psi_{0} = 1; \tag{5.8e}
\]

\[
R_{k,m} \geq R_{k,m}^{\text{min}}, \forall m \neq 0; \tag{5.8f}
\]

\[
\sum_{n=1}^{N} \left( \sum_{k \in K_m} \phi_{k,m,n} \right) p_{m,n} \leq P_{\text{max}}, \forall m \in M; \tag{5.8g}
\]

\[
p_{m,n} \geq 0, \forall m \in M, n. \tag{5.8h}
\]

Constraint (5.8b) indicates that RBs are exclusively allocated to one user served by each cell pair to avoid intra-cell interference; constraint (5.8c) denotes the total maximum interference that a MUE served by macro-cell on RB \( n \) can tolerate from all SCs in the macro area in order to satisfy its minimum rate needs; constraint (5.8d) indicates the ON/OFF state of the cells and constraint (5.8e) makes sure that the macro-cell is always in active state. Constraint (5.8f) is the minimum required rate constraint for each user; finally, constraints (5.8g)-(5.8h) stand for the maximum and minimum transmission power constraints at each SC node. The formulated optimisation problem being extremely complex in nature is very difficult to solve in a real network with dynamically changing conditions. To address the complexity issues we devise a low complexity heuristic solution, explained in the following section.

### 5.4 Energy Consumption Aware Resource Allocation Scheme (ECA)

The proposed Energy Consumption Aware Resource Allocation Scheme (ECA) heuristically achieves the objective expressed in the optimisation problem in (5.7). Although the proposed scheme is a sub-optimal solution to problem in (5.7), the aim behind
5.5 Simulation Results for Deterministic Load Conditions

In this section we show the simulation results for our proposed scheme and compare the results in terms of power consumption and users’ data rate performance against the conventional Reuse-1 scheme. Details of the simulation parameters are given in Table 5.1.

For the purpose of demonstrating the function of the proposed algorithm, we simulate a network with 15 SCs and a single macro-cell. Number of users in the macro-cell and SCs are generated using Poison Arrival Process for each snapshot. Simulations are performed for four normalised load conditions of the network (0.25, 0.50, 0.75 and
Algorithm 5 Energy Consumption Aware Resource Allocation (ECA)

for $n = 1 \rightarrow N$

Initialise: $\phi_n = 0$

Calculate: $\Omega_{\text{max}}^{n}, \omega_{u,0,n}, R_{k,m,n}$ as in eq. 3.3, 3.4 and 3.5

$\phi_n = \text{binprog} (\tilde{R}_n, \tilde{\omega}_{u,0,n}, \Omega_{\text{max}}^{n})$

end

Notify SCs with their respective $\phi_{m,n}$.

Small Cell Sleep Mode Phase

Analyse Available $n$ RBs at Macrocell

if $R_{B0}^{\text{Avail}} > R_{B0}^{\text{Thres}}$

Sort small cell utilisation in descending order

while $R_{B0}^{\text{Avail}} < R_{B0}^{\text{Thres}}$

Send sleep mode activation message to SC on top of utilisation list.

Update $R_{B0}^{\text{Avail}}$, Remove top element from utilisation list.

end

Small Cell Wake-up Phase

For every SC in sleep mode do:

if $\sum_k R_{B0}^{\text{Req}} > R_{B0}^{\text{Avail}} \text{ OR } C_0 = 1$

Sort $\sum_k R_{B0}^{\text{Req}}$ in ascending order for all $m$

while $\sum_k R_{B0}^{\text{Req}} > R_{B0}^{\text{Avail}} \text{ OR } C_0 = 1$

Send wakeup message to SC on top of the list

Update $R_{B0}^{\text{Avail}}$

end

end
5.5. Simulation Results for Deterministic Load Conditions

The value of λ for the Poison Process is selected considering the load cases in our results. We consider these four variations in network loads to analyse our algorithm at different times of the day [98]. Using Monte-Carlo simulations, 1000 snapshot shots are generated for each load case and results were averaged.

The operation of the algorithm is depicted in Figure 5.3 where a deployment snapshot

---

### Table 5.1: Simulation Parameters for Energy Efficient RA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Macro-cell</th>
<th>Small-cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2.1 GHz</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
<td></td>
</tr>
<tr>
<td>Node transmit power</td>
<td>43 dBm</td>
<td>23 dBm</td>
</tr>
<tr>
<td>Path loss model</td>
<td>$128.1 + 37.6 \log_{10} (d[Km])$</td>
<td></td>
</tr>
<tr>
<td>UE Generation</td>
<td>Poison Arrival Process</td>
<td></td>
</tr>
<tr>
<td>$RB^\text{Thres}_0$</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>Noise Figure at UE</td>
<td>9 dB</td>
<td></td>
</tr>
<tr>
<td>Thermal noise density</td>
<td>$-174$ dBm/Hz</td>
<td></td>
</tr>
<tr>
<td>Cell Radius</td>
<td>800m</td>
<td>50m</td>
</tr>
<tr>
<td>$P^\text{circuit}$ [97]</td>
<td>120W</td>
<td>8.4W</td>
</tr>
<tr>
<td>$\Delta$ (slope of load dependent power consumption)</td>
<td>3.2</td>
<td>4</td>
</tr>
</tbody>
</table>
is illustrated. The blue rings show the active SCs, whereas the green rings show the SCs which are switched to sleep mode and their SUEs are being served by the macro-cell. If we consider for example SCs ‘2’ and ‘13’, both of them are switched to sleep mode and we can observe that they have some MUEs (red dots) in their vicinity. The dominant interference to these MUEs causes muting of resources at the SCs. In return, due the low utilisation of these SCs and the available capacity at the macro-cell, the users of these SCs are handovered to the macro-cell and SCs ‘2’ and ‘13’ are switched to sleep mode. This will usually happen at the low load times of the day. Sleeping SCs might be waked-up in case there is a congestion at the macro-cell or in case of increase in network load. If for example all the SUEs have similar data rate requirements, then SC ‘4’ would be waked up first, as it has more number of SUEs.

![Figure 5.3: Snapshot of the network with normalised load = 0.5. Red dots indicate the MUEs and blue dots indicate SUEs. Blue rings indicate the active SCs and green rings indicate SCs in sleep mode.](image)

The CDF for the data rates of MUEs is presented in Figure 5.4. We compare the performance of our proposed ECA scheme with Reuse-1 scheme (where all nodes transmit at the same frequency resources). It is evident from the figure that in case of Reuse-1 up to 20% of the users are in outage (below the required data rate mark, as indicated in the figure). This is due to the strong interference from the neighbouring SCs serving their users on the same resources. However, in case of ECA scheme, this inter-tier interference is minimised and nearly all the users are safe guarded from outage. This is made possible by muting some of the SCs at certain RBs where the victim MUEs...
were being served. Readers may refer to Chapter 3 to see more results on the MUE protection performance and working of the ECA algorithm, as it is similar to ESRA algorithm in 3.4. The proposed ECA scheme along with successfully safeguarding the victim MUEs present in the vicinity of SCs, also maximises the energy efficiency of the network.

The energy consumption comparison between ECA scheme and a conventional scheme with no sleep mode savings is presented in Figure 5.5. This comparison is shown for the four different considered load states of the network. This comparison for different load conditions is shown with the help of bar graphs and the y-axis of Figure 5.5 indicates the sum of total power consumption (circuit and load dependent transmit power) of all transmit nodes. The horizontal line in the middle of the plot indicates the constant circuit power of the macro-cell which is fixed for all cases. The remaining top portion of the bars indicates the sum of macro-cell’s load dependent transmit power plus the circuit and transmit power of all the active SCs. The true potential of ECA scheme can be clearly seen for low to medium network load conditions. This is due to the fact that in low traffic conditions, the macro-cell has unused capacity which can be successfully used to serve SUE of underutilised SCs. The energy saving gains come from switching off the circuitry of the SCs but as a trade-off the load dependent transmit power of the macro-cell is slightly increased. However, up to 23% saving in total network power consumption can be achieved using ECA in these traffic conditions.

![Figure 5.4: CDF plot for MUE data rates (ECA and Reuse-1)](image-url)
5.6 Analysis on Real CDR Data from City of Milan

Our analysis in the previous subsection presented working insights toward the potential energy savings of the proposed ECA resource allocation scheme. In this section we further expand our analysis based on a real network’s activity data. Such an analysis would highlight the energy saving potentials ahead from the deterministic load conditions considered in the previous subsection.

5.6.1 Introduction to Data from City of Milan and Hypothetical Conversions

The data used to present these results comes from Telecom Italia’s network in the city of Milan, Italy. For this thesis, a weeks data (01st Dec 2013 to 07th Dec 2013) is used to analyse activity trends in the metropolitan city.

The activity level data being analysed is made public by Telecom Italia in form of CDRs for calling and internet activity, which is later translated into data rate levels based on a hypothetical methodology. As visible in figure 5.6, the city of Milan is divided into several smaller grids (10,000 square grids). For each grid, a CDR value corresponding to call and internet activity is received at every 10 minutes interval. In our work, we consider that the internet activity is generated by the small-cell users and the calling activity is from the macro-cell user. The macro-cell is assumed to cover an area of 225...
square grids.

Figure 5.6: City of Milan with overlayed illustration of grid cells

Figure 5.7: Calling activity for points on the grid (week 01/12/13-07/12/13)

The calling activity for each macro-cell (accumulated calling activity for 225 square grids) is translated into data activity according to the Voice over LTE (VoLTE) standard [99]. Each call is assumed to be 3 minutes based on the average European calling
5.6. Analysis on Real CDR Data from City of Milan

As stated in [99], for the VoLTE standard approximately 300 bits of data packet is required to be transmitted by the end interface every 20ms. This brings the data rate for each VoLTE call to 15Kbps. Based on these details we translate the CDR based activity levels into data rates. Figure 5.7 shows the call activity levels for the whole Milan city for a single week (Sunday to Saturday). Similarly, figure 5.8 shows the internet calling activity for each small-cell for the whole week. There are two important observations deduced from these figures. Firstly, the activity ranges are very versatile, within the cells (some cells have high activity and some have low) as well as during different times of the day. Secondly, the internet activity is relatively very high as compared to the calling activity. From this point onwards, the calling activity will be reported as the macro-cell activity.

Since, it is observed that cells have a wide variation in the range of activity levels (some small-cells have high activity and some have very low activity). An obvious reason for this phenomenon is the number of Points of Interest (POIs) within each cell (the popularity of POIs also varies the activity levels of cells). To bring this aspect of cells with and without POIs, we consider two macro-cells as depicted in figure 5.9. The first macro-cell has no POIs with its coverage area, whereas the second macro-cell has a few POIs. In the remaining of the analysis we refer these macro-cells as Non-POI and POI cells. The plot in figure 5.9 was constructed by plotting the geographical coordinates of most popular POIs in city of Milan. Furthermore, plots in figure 5.10(a) shows the variation in activity levels at different times of the day and the geographical location of the origination of the traffic.

Figure 5.11 and 5.12 give further insights into the activity levels of the cells, macro and small-cells dependent on the time of the day respectively. It is evident from figure 5.11
that the macro-cells being classified as non-POI of POI cells, both have relatively higher activity level between 8AM and 11PM at night. During the quite hours of the day (between midnight and 6am), both non POI and POI cells have similar low activity levels. For the small-cells, figure 5.12 shows the activity levels for morning, midday and evening times. It is clear that there are mixed activity levels during other times of the day except for early in the morning. For the early morning case, majority of the cells as classified into the category of low and very low activity levels. This insight identifies the potential for energy savings in such dense networks. Figure 5.11 and 5.12 jointly motivate use to present our results for putting majority of the low activity small-cells into sleep-mode and serving their load with the macro-cell.

5.6.2 Simulation Results for Application of ECA

In this sub-section analysis is presented specific to non-POI and POI macro-cells and under-lying small-cells as visualised in figure 5.9. Figure 5.13 shows the activity levels of non-POI and POI macro-cell from Sunday until Saturday. These activity levels are presented as data rates (Mbps). As previously deduced that activity levels are high for the POI cell as compared to the non-POI cell. Another interesting aspect to consider for these two considered macro-cells is that the activity levels during the week days are relatively higher as compared to weekends.

Similar activity plots are presented for non-POI and POI small-cells in figure 5.14 and 5.15. Since there are upto 225 small cells, in the non-POI case most of the small-cells
5.6. Analysis on Real CDR Data from City of Milan

(a) Morning  
(b) Afternoon  
(c) Evening

Figure 5.10: Activity level map for a) Morning b) Afternoon c) Evening
5.6. Analysis on Real CDR Data from City of Milan

Figure 5.11: Activity level comparison for NON-POI and POI cells (Average over all the macro-cells in the city of Milan)

Figure 5.12: Activity level for NON-POI and POI small-cells (Average over all the small-cells in city of Milan)

are below the 1Mbps, whereas in case of POI small-cells several small cells have an activity level higher as compared to in case of non-POI cells. To look into further details, figure 5.16 and 5.17 are plotted to show the activity levels for a single day (hourly level) with the help of Box and Whisker plots. Each plot ranges from 9 to 91 percentile of the values where as the box expresses the lower and upper quartile (25% and 75%). Line dividing the box expresses the median and ‘+’ expresses the mean value. It can be observed that for 06:00 hrs and 18:00 hrs, the mean activity level for non-POI SCs is approximately 0.4 and 0.7 Mbps respectively. Similarly in case of
5.6. Analysis on Real CDR Data from City of Milan

Figure 5.13: Activity level for NON-POI (red) and POI (blue) macro-cells

Figure 5.14: Activity level for NON-POI small-cells
5.6. Analysis on Real CDR Data from City of Milan

Figure 5.15: Activity level for POI small-cells

POI SCs at 06:00 hrs and 18:00 hrs the mean activity levels are at 1.2 and 2.4 Mbps respectively.

The performance of the purposed ECA algorithm is presented in terms of numbers of SCs put into sleep mode in figure 5.18 and 5.19. ECA algorithms puts upto 205 non-POI SCs in sleep mode while the traffic conditions are low for the small-cells as well as for the macro-cell and for the POI case up to 160 SCs. However, generally there are far less SCs put into sleep-mode in case of POI SCs as compared to non-POI case. It can also be observed that during the peak hours of traffic load, no (a few in case of non-POI case) SCs are put to sleep mode. These sleep mode cells in off-peak hours would reflect the energy saving in the later plots.

The EE performance of non-POI and POI cells is presented in figure 5.20 and 5.21 respectively. It is interesting to observe that the EE performance of the non-POI case is significantly less than that in case of POI case. Such observed phenomenon can be explained by referring back to the definition of EE, i.e. the number of bits per Joule of energy (bits/Joule). Since the small-cells lie in the circuit power dominant regime (circuit power consumption is significantly higher as compared to transmit power consumption) and the circuit power being constant at all times. However, as it is already established that the data traffic flow in non-POI cells is lower as compared to POI cells. So it can be deduced that the non-POI cells are under-utilised, where as POI cells have higher utilisation, hence better EE performance.
5.6. Analysis on Real CDR Data from City of Milan

Figure 5.16: Activity level for NON-POI small-cells for 24 hrs of a day. Each plot ranges from 9 to 91 percentile of the values where as the box expresses the lower and upper quartile (25% and 75%). Line dividing the box expresses the median and ‘+’ expresses the mean value.

Figure 5.17: Activity level for POI small-cells for 24 hrs of a day. Each plot ranges from 9 to 91 percentile of the values where as the box expresses the lower and upper quartile (25% and 75%). Line dividing the box expresses the median and ‘+’ expresses the mean value.
5.6. Analysis on Real CDR Data from City of Milan

Figure 5.18: Number of SCs put to sleep-mode for non-POI (red) and POI (blue) case for the whole week.

Figure 5.19: Number of SCs put to sleep-mode for non-POI (red) and POI (blue) case (24hrs).
5.6. Analysis on Real CDR Data from City of Milan

Figure 5.20: EE (bits/Joule) performance for non-POI cells

Figure 5.21: EE (bits/Joule) performance for POI cells
5.6. Analysis on Real CDR Data from City of Milan

Figure 5.22: Energy Reduction Gain (ERG) performance for non-POI case.

Figure 5.23: Energy Reduction Gain (ERG) performance for POI case.
5.7. Conclusions

Nevertheless, the important aspect to observe for these plots is that the EE performance before the ECA algorithm (solid black line) is improved with the application of ECA algorithm (red in case of non-POI figure 5.20 and blue for POI 5.21). Also to note that for the non-POI cells the EE performance is significantly improved as compared to the non sleep-mode conventional case). This aspect of the performance analysis is further clarified by the help of ERG (equation 5.4) plots in figure 5.22 and 5.23 for non-POI and POI cells respectively. For the non-POI case the ERG is achieved up to 8 times in certain off-peak traffic conditions, and the same results for the POI case reach a maximum of 2 times in off-peak conditions.

5.7 Conclusions

In this chapter, we have proposed an energy efficient solution that not only minimizes the overall network energy consumption but also incorporates the inter-tier interference solution in a LTE HetNets environment, as proposed in the previous chapters. In our study, we formulate the optimisation problem taking into account the computational complexity limitation of a practical network. Furthermore, we have proposed a heuristic energy efficient small cell resource allocation algorithm. Our deterministic load based simulation results clearly indicate that nearly all macro-cell served users were protected from neighbouring small cell inter-tier interference in comparison to Reuse-1 case. In addition, during the low traffic condition, the proposed mechanism has shown to reduce a significant amount of network energy by switching the underutilized cells to sleep mode. In order to demonstrate the scale of potential energy savings in a practical network, CDR data from City of Milan was used. Rigorous analysis was performed to analyse the activity levels from the data in subject. The proposed ECA algorithm, by making use of sleep-mode in small cells shows a potential of significant energy savings especially in off-peak times of the day.
Chapter 6

Conclusions and Future Work

6.1 Summary and Conclusions

This thesis addresses some of the key challenges faced by upcoming mass deployments of large and small-cells heterogeneous networks. Since frequency resources being an expensive asset to operators, it is preferred to reuse the frequency resources in multiple neighbouring cells. Reuse of the frequency resources elevates the issue of inter-cell interference. This issue gets very severe in case of mass deployment of small-cells. Firstly, because deployment of small-cells is not as planned as in case of larger cells, hence overlapping areas of cell coverage are more probable. Moreover, the transmit powers of cells are not same. Secondly, in heterogeneous networks, especially in small cells, access is not always open to all users. Some closed subscriber group small-cells cause high interference to non-subscriber users (usually macro-cell users).

Along side the interference issues, energy efficiency of the network also becomes a major challenge. Increasing number of cells in a network rapidly increases the embodied energy consumption (fix operational energy consumption even when there are no users in the cell). Management of energy resource in such a way that full potential of the deployed cells is utilised along with potentially saving energy in off-peak hours of the day is a challenge to be addressed.

In order to answer the aforementioned research questions, this thesis initially examines the current literature present to address the issue of inter-cell interference in homogeneous networks (usually large cells). Moreover, we analyse issues related to small-cell deployment and their operability along side same technology larger cells. In our analysis, we keep a consistent scenario with a single large cell and several small cells within
the area of the large macro-cell. Initially, focus of the thesis, in terms of the technical contributions is to address the resources allocation of frequency and power for joint operation of small and macro-cells, such that the macro-cell users are protected from the data channel interference of small-cells. Next, we examine the issue of control channel interference from small-cells to vulnerable macro-cell users. A detailed analysis is presented to address the aspect of control channel reliability in large and small-cell networks.

Based on these two solutions, during the course of this PhD we realised that energy efficiency is also a greater issue in such heterogeneous networks. And the objective should not only be to maximise the throughput of small-cells, in fact to optimise the operation of small-cells on need basis. This motivation lead to our work on energy efficient sleep-mode capable algorithms for small-cells. In this analysis as well, we consider a single macro-cell and several small-cells. We establish an algorithm which addresses the interference issue as well as improves the energy efficiency of the network. Such an approach provides a rather complete solution for the operation of large and small cells reusing the same limited frequency resources (to maximise the sum throughput of the network) and alongside maximising the potential energy savings in the network.

The key contributions of the research work presented in this thesis have been summarized as follows:

- A comprehensive overview of state of the art for interference management in homogeneous and heterogeneous networks was presented. A detailed taxonomy for the categorisation of different interference management techniques was presented along with their pros, cons and most appropriate use cases. The most prominent frequency planning techniques were explained in detail with the help of illustrations. The literature review section also looked into the energy efficient resource allocation techniques for cellular systems. Sleep mode techniques were discussed in detail with their potential uses for different constrained networks. Finally some basic details of LTE systems were given to better explain the applications of the proposals in this thesis. LTE frame structure and most important control channels were discussed in detail.

- The inter-tier interference scenario for joint operation of macro and small-cells was mathematically formulated along with presenting expressions for SINR and data rate calculations for the data channel. Maximum interference allowance expressions were also presented which were later used in our mathematical problem
formulation to maximise the sum data rate of small-cells. The formulated complex problem was solved by the application of well know Dual Lagrangian and sub-gradient method. The complete derivation for the optimal solution (ORA) was presented along with pseudocodes and illustration of steps involved to find the optimal solution.

- The complexity of the optimal solution was examined to be high for practical systems, hence a low complexity heuristic solution was presented based on binary linear integer programming. The computational complexity of the heuristic solution (ESRA) was found to be significantly lower than the optimal solution with minor degradation in the performance. The results were analysed on various random and deterministic parametric settings to gain insights into the working of the algorithms. A discussion on the feasibility of the application of proposed schemes in a practical LTE system was also included.

- In the next technical contribution we further looked into protecting the data channel as well as the control channel of the macro-cell victim user. This work is an extension of the previous contribution, but required redefining the mathematical formulation, now considering the granularity of control channel on each RE level. The solution to this problem was given by two heuristic algorithms. The first algorithm (SRM) was based on binary integer programming (similar to ESRA), however in order to further minimise the complexity for the algorithm to run on RE level, we proposed the second progressive iterative algorithm (ITA). The performance of both the proposals was compared for computational complexity with the optimal solution. The performance was also compared with the conventional frequency reuse schemes.

- Since the aim of the previous two contributions was to maximise the sum throughput of the small cells, while maintaining macro-cell users rate constraints. In the next contribution, we have looked at the problem from a different perspective i.e. energy efficiency of the network. The aim of this contribution was to keep the energy consumption of the small-cells low in off-peak hours of the day. The interference constraints following from the previous contributions were also considered while achieving the energy-consumption minimisation objective. The new mathematical formulation was solved with the help of another heuristic algorithm (ECA). The proposed algorithm solved the resource allocation problem on a shorter update scale, while the energy minimisation with sleep-mode is achieved on longer time scales. This is to avoid ping pong effect for the turning on and off
of the small-cell devices. The performance of the proposed algorithm is examined initially with the help of deterministic load based scenario.

- In pursuance of examining the true potential of the proposed schemes in a real network scenario, we make use of CDR data from Telecom Italia’s data from City of Milan. The data is hypothetically converted to suit the nature of our analysis, and is studied in depth to identify the off-peak hours. This data is used to analyse the performance of the algorithm. The analysis has been given another dimension by identifying the cells with underlying point of interest locations and their affect on overall user activity and energy savings. We measure the performance in various energy efficiency matrices to get key insights. It is concluded that up to 8 times energy consumption could be reduced in a single cell by employing our proposed scheme.

### 6.2 Future Work

The proposed algorithms show promising performance improvements as compared to conventional systems. However, there are other scenarios and test cases which could be reflected on as future work. Some of the potential extensions of our work done in this thesis are listed as follows:

- Although the most significant type of interference in heterogeneous networks is resulted from the transmission of the small-cells to the macro-cell users, however, interference within small-cells is also considered to be detrimental for performance reduction. Interference between small-cells (i.e. interference from SCs to neighbouring SC’s SUEs) becomes significantly dominant when there is a cluster of small-cells located in close vicinity. Small-cells have low transmit powers, so the coverage is shorter (less interference to nearby area), however, if two or more small-cells are located very close, they may develop intra-tier interference. Solving this intra-tier interference issue along with small-cell to macro-cell interference could be one of the potential extensions of our work in this thesis.

- Another possible expansion of the interference management and energy consumption minimisation techniques could be to modify them to function in a distributed manner on each small-cell. Such a modification would allow the schemes to work in networks with limited or delay prone backhaul connections. Although our proposed algorithms are semi-distributed in nature and several central entities
could be present at different macro-cells, guiding small-cells within each macro-cell. Adding complete distributed functionality to the schemes would require each small-cell to make decisions based on its own sensing capabilities such that the objective to maximise the small-cell utility is achieved and macro-cell users’ constraint are also met. Also to add that this would require some sort of extra sensing capabilities at the small-cell nodes.

- Our work in Chapter 4 focuses on control channel interference management specifically by controlling PDCCH control signals in LTE systems. While other control signals such as PCFICH and PCHICH have already been addressed in literature to be solved by use of PCI manipulation techniques. However, protection from reference signals which are present at specific locations within the LTE grid, still remains a challenge. This challenge becomes an important aspect for future studies especially when we consider small-cell devices with multiple antenna where additional reference signals are required, populating the resource grid.

- Future work could be done to analyse the delays associated with sleeping mode small-cells. And making use of hybrid sleep-modes where delay prone modules of the node could be left active (such as backhaul for synchronization with the network). Analysis could be performed by making use of modular energy models for small-cells and the consequences of partially shutting down small-cells. Smart algorithms could be developed which put certain small-cells to sleep mode in different stages. These stages could be based on historic/predictive data from the cells or current activity levels in the nearby area.

- Energy efficiency analysis could be further extended for performance examination in unusual activity patterns, such as concerts or other non-frequency events with heavy crowd displacements. We are currently looking into a similar case scenario for extension of our work for a recent version of the data from City of Milan. On a specific day within this data, a large crowd displacement event occurred. This was due to a football match happening at a stadium. Heavy crowd activity was observed in the town centre a few hours before the start of the match. Just before the match, crowd displacement occurred and later there was heavy data activity in the cells covering the stadium. Analysis on such scenarios could lead to intriguing observations and give key insights helping development of smarter algorithms.
A.1 Optimal Power for a Given RB Allocation

For the sake of simplicity of understanding, we suppress the notations in equation (3.12) and write $L$ as:

$$L = \phi R - \lambda \phi p \Gamma - \mu \phi,$$

now replacing $\phi = 1$ and $R$ with equation (3.3), we get

$$L = \log_2(1 + p \alpha) - \lambda p \Gamma - \mu p.$$

Let, $y = \log_2(1 + p \alpha)$,

$$\frac{\partial L}{\partial p} = \frac{\partial y}{\partial p} - \lambda \Gamma - \mu.$$

Now let, $x = (1 + p \alpha)$ ; $y = \log_2(x)$,

$$\frac{\partial y}{\partial p} = \frac{\partial y}{\partial x} \frac{\partial x}{\partial p} = \frac{1}{\ln(2)x} \alpha = \frac{\alpha}{\ln(2)(1 + p \alpha)},$$

$$\therefore \frac{\partial L}{\partial p} = \frac{\alpha}{\ln(2)(1 + p \alpha)} - \lambda \Gamma - \mu.$$

Applying the KKT condition, we equate $\frac{\partial L}{\partial p} = 0$;

$$\frac{\alpha}{\ln(2)(1 + p \alpha)} - \lambda \Gamma - \mu = 0.$$  It then follows,

$$\Rightarrow \frac{\alpha}{\ln(2)(1 + p \alpha)} = \mu + \lambda \Gamma,$$

$$\Rightarrow \frac{\alpha}{(1 + p \alpha)} = \ln(2)(\mu + \lambda \Gamma),$$

$$\Rightarrow (1 + p \alpha) = \frac{\alpha}{\ln(2)(\mu + \lambda \Gamma)},$$

$$\Rightarrow p \alpha = \frac{\alpha}{\ln(2)(\mu + \lambda \Gamma)} - 1,$$

and we solve for $p$ as:

$$p = \frac{1}{\ln(2)(\mu + \lambda \Gamma)} - \frac{1}{\alpha}.$$
A.2 Subgradients of Dual Function

Considering the Lagrangian dual function \( g \), in equation (3.10) at two different points \((\lambda, \mu)\) and \((\lambda', \mu')\) in the dual variable multidimensional space, where \( \lambda = (\lambda_1, \lambda_2, \ldots, \lambda_N) \), \( \lambda' = (\lambda_1, \lambda_2, \ldots, \lambda'_n, \ldots, \lambda_N) \), \( \mu = (\mu_1, \mu_2, \ldots, \mu_m, \ldots, \mu_M) \) and \( \mu' = (\mu_1, \mu_2, \ldots, \mu'_m, \ldots, \mu_M) \), we have:

\[
g(\lambda, \mu) = \begin{cases} 
\max_{\phi, p} & L(\phi, p, \lambda, \mu), \\
\text{s.t.} & 0 \leq \phi_{k,m,n} \leq 1, \forall k \in K \setminus K_0, m \in M, n; \\
& \sum_{k \in K_m} \phi_{k,m,n} \leq 1, \forall m \in M, n; \\
& p_{m,n} \geq 0, \forall m \in M, n.
\end{cases}
\]  
(A.1)

\[
g(\lambda', \mu') = \begin{cases} 
\max_{\phi, p} & L(\phi, p, \lambda', \mu'), \\
\text{s.t.} & 0 \leq \phi_{k,m,n} \leq 1, \forall k \in K \setminus K_0, m \in M, n; \\
& \sum_{k \in K_m} \phi_{k,m,n} \leq 1, \forall m \in M, n; \\
& p_{m,n} \geq 0, \forall m \in M, n.
\end{cases}
\]  
(A.2)

Substituting the values of \( \phi \) and \( p \) with the optimal values, we get the subgradient of \( g \) at \( \lambda \) as:

\[
[g(\lambda', \mu') - g(\lambda, \mu)] = \max_{\phi, p} L(\phi, p, \lambda', \mu') - \max_{\phi, p} L(\phi, p, \lambda, \mu) \geq L(\phi^*, p^*, \lambda', \mu') - L(\phi^*, p^*, \lambda, \mu),
\]

\[
= (\lambda'_n - \lambda_n) \sum_{m=1}^{M} (\sum_{k \in K_m} \phi^*_{k,m,n} P^*_{m,n} \Gamma^*_{0,u,n} - \Omega^*_{mn}) + (\mu'_m - \mu_m)(P^*_{max} - \sum_{n} (\sum_{k \in K_m} \phi^*_{k,m,n} P^*_{m,n})).
\]

(A.3)
The inequality in equation (A.3) exists because of the definition of dual function and Lagrange in equation (3.10) and (3.11).

\[ g(\lambda', \mu') \geq g(\lambda, \mu) + (\lambda'_n - \lambda_n) \sum_{m=1}^{M} (\sum_{k \in K_m} \phi^*_{k,m,n} p^*_{m,n} \Gamma_0^m 0_{u,n} - \Omega^m_n) \]

\[ - (\mu'_m - \mu_m) (P_{\text{max}} - \sum_{n} (\sum_{k \in K_m} \phi^*_{k,m,n} p^*_{m,n}) \]  

(A.4)

Hence, the subgradients of \( g(\lambda, \mu) \) at the point \( \lambda_n \) are,

\[ \Delta \lambda_n = \sum_{n} (\sum_{m=1}^{M} (\sum_{k \in K_m} \phi^*_{k,m,n} p^*_{m,n} \Gamma_0^m 0_{u,n} - \Omega^m_n) \]

\[ \Delta \mu_m = P_{\text{max}} - \sum_{n} (\sum_{k \in K_m} \phi^*_{k,m,n} p^*_{m,n}). \]  

(A.5)
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