PERFORMANCE ENHANCING INTERFERENCE MANAGEMENT TECHNIQUES FOR FUTURE CELLULAR SYSTEMS

A thesis submitted to the University of Manchester for the degree of Doctor of Philosophy in the Faculty of Science and Engineering

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By
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Abstract

The limited bandwidth available for cellular networks has necessitated on current wireless technologies, such as long-term evolution (LTE), to devise new strategies to improve the spectrum reuse and the capacity of cellular networks. Multi-tier heterogeneous networks is a low-cost solution in which the traditional macrocells are underlaid with small cells such as femto- and pico- cells that are centered around users to improve the network capacity. In this regard, radio resource management (RRM) based interference avoidance techniques have been widely used to minimize the interference incurred as a result of small cell deployment. This thesis proposes novel interference management techniques for improving the spectrum reuse efficiency in cellular networks. An RRM that utilizes a sleep mode (SL) strategy is proposed to identify the small cells that maximize the reuse efficiency outcome when set to sleep mode without requiring an exhaustive search. To improve the association of the switched off cells users and improve the overall performance, an interference aware user association technique that allows seamless association between BSs and users is introduced to increase access to resources. To enhance both the overall throughput and quality of service (QoS) metrics, a map of the various interference levels is constructed to be used for two purposes: First to satisfy QoS constrains by orthogonalizing certain interfering BSs/users, and second to maximize the resource utilization using an adaptive power control scheme. To reduce the signaling overhead on the back-haul network, a distributed RRM is presented to allow BSs to independently adjust their bandwidth usage to reduce the inter-cell interference. With the lack of central management and coordination among cells, this information is estimated locally by monitoring the uplink spectrum.
Declaration

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Preface

Ms. Aysha Ebrahim received her B.Sc. degree (with first class honours) in Computer Engineering from the University of Bahrain in 2009. In the same year, she was appointed as a graduate assistant in the Computer Engineering department in the University of Bahrain where she participated as a lecturer. She received her M.Sc. degree (with Distinction) in Electronic Engineering from the University of York in 2011. Since September 2012, she has been pursuing her Ph.D. degree in Electrical and Electronic engineering at the University of Manchester. Her research focuses on radio resource management techniques for heterogeneous wireless networks.
To My Family,
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AMC</td>
<td>Adaptive Modulation and Coding</td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
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<tr>
<td>BCH</td>
<td>Broadcast Channel</td>
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<td>BLIM</td>
<td>Bi-Level Interference Mapping</td>
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<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>CAPEX</td>
<td>Capital Expenditure</td>
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<tr>
<td>CDA</td>
<td>Coupling/Decoupling Association</td>
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<td>CDF</td>
<td>Cumulative Distribution Function</td>
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<td>CP</td>
<td>Cyclic Prefix</td>
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<td>CQI</td>
<td>Channel Quality Indicator</td>
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<tr>
<td>CRP</td>
<td>Conventional Resource Partitioning</td>
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<td>DCG</td>
<td>Dynamic Color Graph</td>
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<td>DL</td>
<td>Downlink</td>
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<td>DL-SCH</td>
<td>Downlink Shared Channel</td>
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<tr>
<td>ECR</td>
<td>Energy Consumption Ratio</td>
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<tr>
<td>FDD</td>
<td>Frequency-Division Duplexing</td>
</tr>
<tr>
<td>FDM</td>
<td>Frequency-Division Multiplexing</td>
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<tr>
<td>FFR</td>
<td>Fractional Frequency Reuse</td>
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<td>FMS</td>
<td>Femtocell Management Unit</td>
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<tr>
<td>GPRS</td>
<td>General Packet Radio Service</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>GSM</td>
<td>Global System for Mobile Communication</td>
</tr>
<tr>
<td>IARP</td>
<td>Interference Aware Resource Partitioning</td>
</tr>
<tr>
<td>ICI</td>
<td>Inter-Carrier Interference</td>
</tr>
<tr>
<td>ICIC</td>
<td>Inter-Cell Interference Coordination</td>
</tr>
<tr>
<td>IFFT</td>
<td>Inverse Fast Fourier Transform</td>
</tr>
<tr>
<td>ILP</td>
<td>Integer Linear Programming</td>
</tr>
<tr>
<td>IRC</td>
<td>Interference Rejection Combining</td>
</tr>
<tr>
<td>ISI</td>
<td>Inter-Symbol Interference</td>
</tr>
<tr>
<td>LTE</td>
<td>Long-Term Evolution</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control Layer</td>
</tr>
<tr>
<td>MAX-RSS</td>
<td>Maximum Reference Signal Received Power</td>
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<tr>
<td>MBS</td>
<td>Macrocell Base Station</td>
</tr>
<tr>
<td>MLIM</td>
<td>Multi-Level Interference Mapping</td>
</tr>
<tr>
<td>MR</td>
<td>Measurement Report</td>
</tr>
<tr>
<td>NCM</td>
<td>Network Capacity Maximization</td>
</tr>
<tr>
<td>NoC</td>
<td>Number of Conflicts</td>
</tr>
<tr>
<td>OAM</td>
<td>Operational and Management Unit</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>OPEX</td>
<td>Operational Expenditure</td>
</tr>
<tr>
<td>PCI</td>
<td>Physical Cell Identity</td>
</tr>
<tr>
<td>PDCP</td>
<td>Packet Data Convergence Protocol</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>PDU</td>
<td>Protocol Data Unit</td>
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<tr>
<td>PIC</td>
<td>Parallel Interference Cancellation</td>
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<td>PRB</td>
<td>Physical Resource Block</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
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<td>--------------------------------------------------</td>
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<tr>
<td>PHY</td>
<td>Physical Layer</td>
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<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RAT</td>
<td>Radio Access Technology</td>
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<tr>
<td>RE</td>
<td>Ready Mode</td>
</tr>
<tr>
<td>RE</td>
<td>Resource Element</td>
</tr>
<tr>
<td>RLC</td>
<td>Radio Link Control</td>
</tr>
<tr>
<td>RNC</td>
<td>Radio Network Controller</td>
</tr>
<tr>
<td>RRC</td>
<td>Radio Resource Control</td>
</tr>
<tr>
<td>RRM</td>
<td>Radio Resource Management</td>
</tr>
<tr>
<td>RSRP</td>
<td>Reference Signal Received Power</td>
</tr>
<tr>
<td>SBA</td>
<td>Single Base Station Association</td>
</tr>
<tr>
<td>SIC</td>
<td>Successive Interference Cancellation</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal-to-Interference-plus-Noise Ratio</td>
</tr>
<tr>
<td>SIR</td>
<td>Signal-to-Interference Ratio</td>
</tr>
<tr>
<td>SL</td>
<td>Sleep Mode</td>
</tr>
<tr>
<td>SLCM</td>
<td>Sleep Mode for Capacity Maximization</td>
</tr>
<tr>
<td>SMBA</td>
<td>Single/Multi- BS Association</td>
</tr>
<tr>
<td>SON</td>
<td>Self-Organizing Network</td>
</tr>
<tr>
<td>TDM</td>
<td>Time-Division Multiplexing</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UL</td>
<td>Uplink</td>
</tr>
<tr>
<td>UL-SCH</td>
<td>Uplink Shared Channel</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication System</td>
</tr>
<tr>
<td>UTRA</td>
<td>UMTS Terrestrial Ratio Access</td>
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# List of Mathematical Notations

<table>
<thead>
<tr>
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<tr>
<td>$\sin(.)$</td>
<td>Sine function</td>
</tr>
<tr>
<td>$\cos(.)$</td>
<td>Cosine function</td>
</tr>
<tr>
<td>$\arccos(.)$</td>
<td>Inverse trigonometric function of cosine</td>
</tr>
<tr>
<td>$\arctan(.)$</td>
<td>Inverse trigonometric function of tangent</td>
</tr>
<tr>
<td>$\sum$</td>
<td>summation symbol</td>
</tr>
<tr>
<td>$f(.)$</td>
<td>Probability density function</td>
</tr>
<tr>
<td>$\Pr(x)$</td>
<td>Probability of $x$</td>
</tr>
<tr>
<td>$\mathbb{E}(x)$</td>
<td>Expected value of $x$</td>
</tr>
<tr>
<td>$\log_x(.)$</td>
<td>Logarithmic function to base $x$</td>
</tr>
<tr>
<td>$\min$</td>
<td>Argument of the minimum</td>
</tr>
<tr>
<td>$\max$</td>
<td>Argument of the maximum</td>
</tr>
<tr>
<td>$\mathbb{R}^+$</td>
<td>Set of positive real numbers</td>
</tr>
</tbody>
</table>
List of Symbols

\( B \)  \hspace{1cm} \text{Set of BSs}
\( K \)  \hspace{1cm} \text{Set of Users}
\( \mathcal{N} \)  \hspace{1cm} \text{Set of available physical resource blocks (PRB)}
\( B \)  \hspace{1cm} \text{Total number of BSs}
\( K \)  \hspace{1cm} \text{Total number of users}
\( N \)  \hspace{1cm} \text{Total number of PRBs}
\( S_i \)  \hspace{1cm} \text{UEs Served by BS} \ i
\( T_i \)  \hspace{1cm} \text{Number of detected UEs within BS} \ i \ \text{Coverage}
\( \Psi_k \)  \hspace{1cm} \text{Number of allocated resources for UE} \ k
\( \Psi_{tot} \)  \hspace{1cm} \text{Total allocated resources in the networks}
\( \Omega_i \)  \hspace{1cm} \text{Number of allocated resources for BS} \ i \ \text{UEs}
\( \Omega_j \)  \hspace{1cm} \text{Number of allocated resources for BS} \ j \ \text{UEs}
\( i \)  \hspace{1cm} \text{An arbitrary BS} \ i \ \text{from the set} \ B
\( j \)  \hspace{1cm} \text{A neighboring cell of BS} \ i
\( k \)  \hspace{1cm} \text{An arbitrary user} \ k \ \text{from the set} \ K
\( \Upsilon_{k,n} \)  \hspace{1cm} \text{SINR of user} \ k \ \text{at PRB} \ n
\( \beta \)  Signal-to-Interference (SIR) Threshold
\( \eta_0 \)  Additive White Gaussian Noise (AWGN)
\( h \)  Channel Gain
\( P_l \)  Pathloss
\( \varphi \)  Pathloss Exponent
\( f_c \)  Carrier Frequency
\( \chi_\epsilon \)  Log-normal Shadowing
\( \chi_{k,n} \)  Binary multiplier to indicate the allocation of UE \( k \) in PRB \( n \)
\( \phi_i \)  SL State of BS \( i \)
\( \zeta \)  Interference Map
\( A \)  Allocation Map
\( W \)  PRB bandwidth in Hz
\( T_{Ofdm} \)  OFDM symbol period in seconds
\( P_{DLi} \)  Power consumption of BS \( i \)
\( P_{TXi} \)  Femtocell \( i \) transmission power
\( \mu_{PA} \)  Power amplifier efficiency
\( \mu_{PS} \)  Power supply efficiency
\( P_{SP} \)  Signal processing power
\( P \)  Total power consumption by all BS
\( P_{SL} \)  Operation Power of Femtocell in SL Mode
\( P_{RE} \)  Operation Power of Femtocell in RE Mode
\( N_{SL} \) Number of femtocells in SL Mode
\( \bar{N}_{RE} \) Number of femtocells in RE Mode
\( \varphi \) BS selected for SL mode
\( \mathcal{H}_i \) Handover Ratio of BS \( i \)
\( L_i \) Percentage of BS’s \( i \) UEs in Handover Area
\( P_i \) Sum of received signal power of all UEs connected to BS \( i \)
\( I_i \) Sum of received interference Power received by BS \( i \) UEs
\( d_{i,k} \) Distance between BS \( i \) and UE \( k \)
\( d_{j,k} \) Distance between neighboring BS \( j \) and UE \( k \)
\( R \) Cell radius
\( R_0 \) Radius of the inner area of the cell
\( \rho_{i,n} \) Transmission power of BS \( i \) at resource \( n \)
\( \Gamma_{i,k,n} \) Received signal power from BS \( i \) to user \( k \) at resource \( n \)
\( \alpha \) User association indicator
\( C_{tot} \) Total achievable network capacity
\( \varpi \) Matrix to indicate the proximity of UEs and BSs in the UL
\( \Phi \) Matrix to indicate UEs in the handover area of BSs
\( \psi \) Matrix to indicate the association between BSs and UEs
\( \delta_{f,u} \) Resources offered by BS \( f \) to user \( u \)
\( \lambda_u \) Number of resources allocated to user \( u \)
\( \varrho_f \) Total occupied resources by BS’s \( f \) UEs
\( \phi_{\text{lower}}^k \) Lower interference bound of UE \( k \)

\( \phi_{\text{upper}}^k \) Upper interference bound of UE \( k \)

\( \gamma_1 \) Maximum achievable SINR

\( \gamma_2 \) Minimum acceptable SINR

\( \xi_i \) Interference level map of BS \( i \)

\( \Theta \) Instantaneous interference level map

\( \nu \) Matrix to indicate UL interference power

\( \Delta \) Matrix to indicate PRBs experiencing high interference

\( \sigma \) Noise rise threshold

\( \epsilon \) Vector to indicate number of estimated interfered UEs per BS
Chapter 1

Introduction

1.1 Aim and Motivation

The continuing increase in the usage of smart phone devices and the growing demand for higher data rates have led to a considerable rise in the amount of information transmitted over the radio spectrum. In wireless communication, the radio spectrum is a shared resource and therefore it is rigidly regulated by governments and organizations such as the international telecommunication union (ITU), to minimize interference and promote effective spectrum utilization. These regulations have restricted the spectrum allocation and therefore effective management techniques need to be employed to maximize the capacity of cellular systems and satisfy the future demands.

Traditionally, increasing the network capacity can be achieved through deploying additional macro base stations (BSs) or using extra frequency bands. However, these solutions are not cost-effective and require high capital costs (CAPEX) and operational costs (OPEX) [1]. An alternative popular approach is to apply cell-densification within heterogeneous networks by adding low-cost small cells, such as pico- and femto-cells within the coverage area of macrocell networks to enhance capacity and coverage [2]. In order to procure the benefits expected from small cells deployment, technologies such as LTE and LTE-advanced opted to have a universal frequency reuse system, where the entire available frequency resources can be reused in all cells.

However, the unplanned distribution of small cells poses several challenges; cross-tier and co-tier inter-cell interference are major concerns that can negatively impact the performance of cellular systems [3]. Co-tier interference
results from the densification of small cells, which creates a large number of overlapped cell boundaries exposing the users that are reusing the resources among these cells to a high level of interference. On the other hand, excessive cross-tier interference caused by the macrocell can seriously degrade the performance of the low-power nodes due to the massive transmission power disparity [4].

One approach to deal with this sort of interference is to apply conventional interference avoidance techniques such as reducing the frequency reuse factor to avoid the inter-cell interference. Unfortunately, this will eventually decrease the bandwidth usage and hence the capacity of cellular systems. Therefore, novel RRM techniques are pivotal to alleviate interference and guarantee efficient spectrum utilization.

Motivated by the scarcity of radio wireless resources, and the pressing need for more reliable data services, this thesis aims to investigate low-complexity interference management techniques for improving the performance of modern cellular networks. The study focuses on optimizing the network bandwidth usage through efficient partitioning of resources among cells/users, taking into account the cell/user specific interference conditions. The objective is to enhance the network-wide throughput by increasing the resource utilization in addition to maintaining the QoS by incorporating measures in the design of the RRM techniques to bring co-channel inter-cell interference to the lowest possible level. The performance of the proposed techniques is assessed using metrics including the average network throughput, QoS, power consumption and energy efficiency.

1.2 Key Contributions

The main contributions in the work presented in this thesis are briefly highlighted below:

- Development of a Sleep mode based resource allocation scheme that uses a set of criteria to identify interference scenarios in which switching off certain small cells can increase frequency reuse and hence network capacity.

- Investigation of user association schemes to improve the performance
of cellular networks. The proposed schemes are augmented with an interference aware resource partitioning technique to maximize the frequency re-use, bearing in mind the interference that can be generated as a result of manipulating the user associations.

- Development of a multi-level interference mapping technique, in which the level of interference between base stations (BSs) and users is characterized by utilizing the maximum and minimum interference bounds of users to allow the network throughput to be maximized without compromising the QoS of cell-edge users.

- Design of a distributed RRM technique that obtains the information needed to manage the inter-cell interference without requiring central management or coordination between cells. The necessary information is estimated at the cell level by analyzing the interference induced by nearby users in the uplink, and restricting the resource usage to control the inter-cell interference accordingly.

- Derivation of a theoretical model that accurately predicts the received interference from neighboring cells by considering the randomness of the user location to study the impact of interference on some key parameters in the system.

1.3 Thesis Organization

The remainder of this thesis is organized as follows: Chapter 2 presents an overview of the background related to interference management in femtocell assisted networks, including a brief history of femtocell technology, and a discussion of some interference coordination techniques in cellular networks. Chapter 3 discusses a radio resource management technique enhanced with sleep mode technology for improving the capacity and energy efficiency in cellular networks. Furthermore, an analytical model is presented to model the received interference from neighboring cells. Chapter 4 investigates user association strategies for enhancing the capacity of heterogeneous networks by introducing a mechanism to optimize the association pairs in the Uplink
and Downlink. Chapter 5 presents a multi-level interference mapping technique that utilizes the upper and lower interference bounds of users for improving the reuse efficiency of the system. Chapter 6 discusses a distributed RRM scheme for managing interference in femtocell networks without requiring centralized control and any sort of coordination between cells. Chapter 7 concludes the thesis and outlines potential future extension of the work presented in the thesis.

1.4 List of Publications

The proposed methods and results presented in this thesis have been peer reviewed and published in distinguished conferences and journals in wireless communications.

Journal Papers


Published Conference Papers


CHAPTER 1. INTRODUCTION

Submitted Conference Papers


In Preparation


Chapter 2

Background and Related Work

Since the main objective of this thesis is to study the performance of interference management techniques in femtocell assisted cellular systems, a brief background on femtocells is introduced in this chapter. Furthermore, an overview of radio resource management in femtocell networks and a discussion of state-of-art techniques is provided. A more focused discussion of the literature is also presented in the introductions of chapters 3, 4, 5 and 6 to discuss the existing and conventional techniques that are most related to the work presented in these chapters.

2.1 The concept of Femtocells

The main concept of introducing femtocells in the cellular hierarchy is to enhance the capacity and coverage of indoor mobile devices. This can be achieved by placing femtocells in indoor premises to reduce the transmission and reception distance between femtocells and mobile users and thereby provide enhanced signal quality. The tremendous capacity gain achieved from femtocell deployment is a result of the following facts: First, deploying femtocells close-by from mobile devices allow these devices to transmit at lower power and can significantly improve the signal quality. Secondly, since femtocells are deployed in indoor environments, the penetration and propagation losses reduces the interference from other aggressor BSs/users. Last but not least, users are free to enjoy a wider range of resources since femtocells only serve a limited number of mobile devices.
2.1.1 A brief history

The increasing requirement for high-data-rate services has mandated the need to re-consider the configuration of cellular systems in order to address this issue. The addition of small cells in the cellular hierarchy is a promising solution that is beginning to attract the attention of cellular operators due to their small size, which makes them ideal for deployment in indoor environments to enhance the coverage. Femtocells are small cellular BSs that allow mobile devices to be connected to the mobile core network through the Internet. In 1999, Bell Labs and Alcatel-Lucent studied the idea of femtocells for the first time [5]. In 2002, Motorola started to test the possibility of applying small cells to be used in mobile communication [6]. Since 2004, some companies have become interested in the idea of small cells; companies such as Ubiquisys and 3WayNetworks have been established in the United Kingdom to focus on the field of femtocells [7] [8].

2.1.2 Technical features

2.1.2.1 Access modes

Since only a small number of users can be supported by femtocells, they need to be configured in a certain way in order to be able to grant or restrict access to users. There are three standard access modes, which can be categorized as follows:

- Open Access mode: Access to the femtocell is granted to all users.
- Closed Access mode: Only subscribers are allowed to be connected to the femtocell.
- Hybrid Access mode: Partial femtocell resources are dedicated to particular non-subscribed users.

Femtocell access modes have significant impact on the interference generated; with open access, the total capacity of the system can be boosted since macro-cell users in the vicinity of femtocells can be granted access, which reduces the received interference from the femtocell to the macrocell users. The disadvantage of this access mode is the consequential security issues, and the
fact that femtocell owners prefer not to allow non-subscribers to share their resources.

The closed access mode is most commonly applied to residential femtocells. The drawback of this type of access mode is the rising interference experienced by the femtocell if passing users start to increase their transmission power, especially when the received signal from the macrocell is not sufficiently high. This problem can be eliminated in hybrid access modes by allowing part of the resources to be shared with non-subscribers.

### 2.1.2.2 Sleep mode

A small cell can be set to operate in ready mode (RE) or sleep mode (SL) [9]. In RE, all of the hardware parts of a small cell are switched on, whilst in SL, part of the hardware components can operate at low power, while other parts are fully switched off. The decision about which parts to be switched off is determined by the energy saving algorithm [9]. The transition between SL and RE states can be controlled either by the small cell, the user, or the core network. In small cell controlled SL mode, the small cell can turn off the pilot transmission when it senses no active mobile users using a low-power sniffing capability. In core network controlled SL, the transition between states is carried out by the core network via the back-haul. In the case of the user-controlled SL, a user can wake-up nearby small cells by broadcasting wake-up signals.

### 2.1.2.3 Sensing the radio channel

Femtocells need to be conscious of the network conditions and the activity of nearby femtocells, in order to be able to manage the interference and enable self-organization. The methods used by femtocells to learn about the surrounding environment are listed as follows:

- Network listening mode: The network listening mode (aka sniffer) is a built-in feature available in femtocells to allow monitoring of the air interface to identify close-by cells. The sniffing capability is a very important feature to enable self-organization, which can be done by regularly scanning the network to learn about the interference and manage the resource allocation accordingly [10].
• Message broadcasting: Femtocells are capable of coordinating with each other by broadcasting messages that contain information related to the interference, such as the received signal strength and the local allocation of power and frequency resources. This allows femtocells to coordinate their actions, taking into consideration the activity of the femtocells that are present in the neighborhood. Those messages can be exchanged among neighboring femtocells through the femtocell gateway, where femtocells send messages to the gateway which is then forwarded to the destination femtocell or broadcast to a group of cells. It is worth noting that the message exchange and the network listening mode capabilities can be performed among the femtocells that reside only within the coverage range of each other [10].

• Measurement reports (MRs): In cellular networks, measurement reports are used for cell selection and handover management and include information measured by users such as the physical layer cell identity (PCI) as well as the measurement of the signal strength from nearby BSs [11]. Measurement reports can be periodic or event-triggered. In case of periodic MRs, the users report the MRs at regular time periods, whereas in event-triggered MRs a radio resource control (RRC) message is sent from the BS to the users. Once users receive the RRC message, users begin searching for nearby BSs and identify their physical layer cell identities (PCI) in addition to measuring their reference signal received power (RSRP).

2.1.3 Femtocells and Radio Access Technologies

Femtocells are designed to adapt to different types of the present-day air interface technologies. The main categories of femtocells in terms of the type air interface can be categorized as follows:

• Second generation (2G) femtocells: The air interface technology of 2G femtocells relies on the global system for mobile communication (GSM). In 2007, Ericsson developed GSM femtocells which were desirable at the time due to their low cost [12]. However, manufacturers refrained from producing 2G femtocells due to the low performance in terms of data rate, since the data service of GSM depends on the general packet
radio service (GPRS), which is incapable of supporting high data rates. Thus, using femtocells only for enhancing the voice service did not draw the attention of manufacturers. Moreover, the co-channel interference is another concern with GSM systems due to the lack of an efficient power control mechanism [13].

- Third generation (3G) femtocells: This type of femtocells is based on the universal mobile telecommunication system (UMTS), which is referred to as UMTS terrestrial ratio access (UTRA). According to 3GPP standards, 3G femtocells are referred to as home node B (HNB) [14]. Unlike 2G femtocells, UMTS femtocells can offer high data rates and can support improved power control techniques, which help in reducing the interference to the surrounding macrocell users. Architecture-wise, the UMTS air interface provides the ability to connect to the core network via the IP-based network, which is a key enabler for femtocell deployment [13].

- Fourth generation (4G) femtocells: In 4G mobile networks, the notion of heterogeneous networks is presented, in which the cellular network consists of a hierarchy of small and large cells. 4G femtocells rely on WiMax and LTE air interfaces, and the physical layer is based on orthogonal frequency division multiplexing (OFDM). LTE femtocells are expected to become a dominant indoor technology for future mobile networks, due to their ability to provide very high data rates.

- Fifth generation (5G) femtocells: Future wireless networks are expected to extensively rely on the communication with a wide variety of wireless devices. Furthermore, the global data usage will increase greatly; studies reveal that by 2016, video streaming traffic will constitute 71% of total network traffic, and the monthly bandwidth demand of millions of smart devices will exceed 1 GB each, which is beyond the capacity of current 4G systems [15]. The deployment of femtocells within the context of heterogeneous networks is a key enabler to meet the expectations of 5G networks. The main driver for the development of 5G networks is the requirement for very high speed data services, which incorporate live-streaming with minimal delay and jitter. Therefore, future networks need innovative ideas to reduce the impact of interference, and take full
advantage of the potential higher data rates that can be offered by femtocells.

\section{Femtocells LTE cellular architecture}

LTE is a 4G wireless technology for high-speed wireless data communication, which is deployed by many of the existing service providers. Fig. 2.1 shows a high-level diagram of a simplified LTE heterogeneous network that incorporates femtocells. A mobile device also referred to as user equipment (UE) connects with a femto access point (FAP) via the air interface. A FAP (also known as femtocell) is a device that is considered as a mini macrocell, and delivers LTE services to UEs residing in houses or enterprises.

The macrocells and picocells are connected to the core network through the radio network controller (RNC) which are managed by the operation and management unit (OAM). A security gateway is used to link FAPs to the core network using a broadband connection. The main functionality of the security gateway is to secure the core network from malicious transmissions. The security gateway is linked with the femtocell gateway which is responsible for
Figure 2.2: LTE radio protocols

connecting the femtocells to the femtocell management system (FMS), which also uses the OAM unit to manage all of the femtocells in the network. Therefore, the centralized control required for all BSs in the heterogeneous network is provided by both the OMS and FMS [16] [17].

2.3 LTE Radio Protocols

LTE radio protocols are responsible for managing the radio aspect of cellular networks. This include several functionality such as the scheduling, radio resource management, re-transmissions and coding. The LTE radio interface protocols consist of three layers: layer 1 represents the physical layer (PHY); layer 2 includes the medium access control (MAC), radio link control (RLC) and packet data convergence protocol (PDCP); layer 3 includes the radio resource control (RRC) protocol [18]. The general functionality of these main three layers is described in this section.
2.3.1 Physical Layer

The main role of the physical layer is to transport the MAC layer information over the air interface. In addition, the PHY layer performs several tasks including the adaptive modulation and coding (AMC), coding/decoding, modulation/demodulation, physical-layer hybrid-ARQ and signal mapping to scheduled time/frequency physical resources [19]:

The physical layer offers service to the MAC layer through the transport channels. A physical channel is equivalent to a group of time/frequency resources that a certain transport channel uses for transmission, where transport channels are mapped to an appropriate physical channel. The main types of transport channels standardized in LTE are [19]:

- The Downlink shared channel (DL-SCH): The Downlink transport channel is used for transmitting the Downlink data.
- The Uplink shared channel (UL-SCH): The Uplink transport channel is used for transmitting the Uplink data.

2.3.2 Medium Access Control

The key functionality of the medium-access control (MAC) layer is managing the Uplink and Downlink scheduling, hybrid-ARQ re-transmissions and the logical-channel multiplexing handling [18].

2.3.2.1 Logical and transport channels

The MAC delivers services to the RLC layer through the logical channels. There are two categories of logical channels which are classified according to the type of information delivered - the control and traffic channels. The control channels are used to send the essential control and configuration information required to operate the system while the traffic channels help to carry user data. From the other side, the MAC uses services from the physical layer via the transport channels, which indicate the mechanism of transmitting information over the radio.
2.3.2.2 The MAC scheduler

One of the essential parts of the MAC layer is the MAC scheduler, which deals with the allocation of resource in the uplink and downlink. The scheduler is capable of performing the dynamic scheduling, where BSs make the scheduling decision in each 1ms period. Furthermore, the scheduler can coordinate the scheduling among multiple BSs by signaling through the X2 interface in case of the eNodeB, [20] and via message broadcasting in the case of femtocells.

In LTE, the scheduling decisions in the uplink are performed independently from the Downlink. The Downlink scheduler determines the set of terminals to which information is to be transmitted to, in addition to determining which resource blocks to transmit at to those users. Similarly, the uplink scheduler determines which users should transmit on the UL-SCH, and the set of uplink resource blocks those terminals are eligible to use for transmission.

2.3.3 Radio Link Control

The main task of the RLC is to segment the internet protocol (IP) packets received from the PDCP, which handles the compression and decompression of headers into what is called the RLC protocol data unit (PDU). Furthermore, RLC support the re-transmission capability to re-transmit the PDUs that are received in error, and to eliminate duplicates by checking the sequence number of the arriving PDUs [18].

2.4 Femtocells and Multiple Access

Multiple access schemes such as orthogonal frequency-division multiple access (OFDMA) are ideal for designing efficient resource management techniques due to the easy air-interface and the separation of resources in the frequency domain. This section provides an overview of a popular multiple access scheme used in femtocell networks.
CHAPTER 2. THEORETICAL BACKGROUND AND STATE-OF-ART

2.4.1 Fundamentals of OFDM

Orthogonal frequency-division multiplexing (OFDM) is a popular multi-carrier modulation scheme, which has been adopted by current wireless technologies such as LTE and WiMAX. In OFDM, data can be transmitted in parallel using a large set of orthogonal sub-carriers, instead of transmitting a stream of data using a single sub-carrier as in frequency-division multiplexing (FDM) [21]. OFDM is very widely used in cellular systems due to several features; the most important feature is the orthogonality among sub-carriers, which is essential to eliminate inter-carrier interference (ICI) [22]. The orthogonal nature of OFDM sub-carriers also lead to large amount of bandwidth being saved and higher spectral efficiency compared to other multiplexing techniques such as frequency-division multiplexing (FDM) and time-division multiplexing (TDM). OFDM has the ability to overcome inter-symbol interference (ISI), which results due to multipath propagation which leads to delayed versions of the signal arriving at different times, creating misaligned OFDM symbols (ISI), resulting in loss of orthogonality among sub-carriers. To address this problem, a cyclic prefix (CP) is used, in which the last part of the OFDM symbol is copied and appended to the beginning of the symbol in a
Fig. 2.3 shows the OFDM transmission model; the transmitter receives a stream of data and converts it to parallel form through the serial to parallel process. After this, each sub-carrier is modulated separately and converted to symbols using a modulation scheme, and then the inverse fast Fourier transform (IFFT) is computed on each set of symbols to convert the signal from frequency domain to time domain. The cyclic prefix is then added, and the signal is converted to analogue form for transmission. The opposite operation is performed on the signal arriving at the receiver [10].

### 2.4.2 OFDMA

OFDMA is ideal for mitigating interference in multi-layer cellular networks, since it is possible to avoid intra-cell interference and multipath fading [3]. OFDMA is a multiple access scheme based on OFDM, which allows the radio resources to be managed in two dimensions - the frequency and time domain. It allows users to be allocated in non-overlapping sub-channels, and takes advantage of the channel variations, making it ideal for designing interference avoidance techniques [24]. In OFDMA, the LTE frame is divided into 10 sub-frames, each with a 1ms period. Each sub-frame consists of two time
slots, and contains a number of physical resource blocks (PRB) depending on the system bandwidth. PRBs consist of a number of consecutive symbols in the time domain, depending on the cyclic prefix, and 12 sub-carriers (aka resource elements) in the frequency domain [25]. A PRB is considered to be the minimum resource unit that can be allocated to a user, and users in the same cell must be allocated orthogonal PRBs, whereas neighboring cell’s users are allowed to reuse the same PRBs, depending on the resource management technique employed. Fig. 2.4 illustrates the structure of the LTE frame.

2.5 Radio Resource Management in Femtocell Networks

2.5.1 Technical challenges

Although the presence of femtocells in the heterogeneous network is expected to provide tremendous capacity gains, better frequency reuse, and enhanced coverage, the randomness associated with femtocell locations and their mass deployment can pose several challenges in two-layer networks.
2.5.1.1 Interference management

Generally, the presence of femtocells in the umbrella of the macrocell can generate two types of interference: co-tier interference which occurs between cells in the same tier, and cross-tier interference between different tiers of cells.

Co-tier interference can be characterized as the undesired signals received from cells belonging to the same network tier, and can lead to degraded communication quality. In the femtocell tier, co-tier interference happens mainly between close-by femtocells. The problem of co-tier interference is illustrated in more detail in the diagram in Fig. 2.5. As seen from the figure, the co-tier interference can occur in the downlink and uplink. The figure shows an example of DL co-tier interference, where the femtocell is considered to be the source of DL interference to neighboring femtocells users within its vicinity, if both users are allocated in orthogonal resources. On the other hand, UL interference can be generated by a user to neighboring femtocells (e.g, UL interference from \( u_2 \) to \( f_1 \)).

In OFDMA networks, the impact of interference is strongly influenced by the allocation of sub-channels, and the problem of co-tier interference occurs when the source of interference (BS/UE) and the victim (BS/UE) occupy the same sub-channels. Therefore, it is critical to apply reliable RRM methods to avoid this problem.

Cross-tier interference arises when the source of interference and the victim are elements of different tiers in the heterogeneous network. Similar to co-tier interference, cross-tier interference can occur in the UL and the DL. The downlink cross-tier interference is normally caused by a femtocell generating downlink interference to a neighboring macrocell user. From Fig. 2.6, a neighboring macrocell user using the macrocell services, and located close to the femtocell, can be strongly affected by the DL interference from that femtocell, especially in closed access mode. In this case, the macrocell user is banned from accessing the femtocell causing the dead zone problem. In the uplink, the macrocell UE can cause cross-tier UL interference to a nearby femtocell when it transmits at high power close from that femtocell.
2.5.1.2 User Association

The diverse nature of the cells deployed in heterogeneous networks and the wide variation of BSs types, size and transmission power, can pose a major barrier to achieving optimal association between BSs and users. The conventional user association approach states that users should be connected with the BSs offering the strongest received signal [26]. However, this approach may not improve the network-wide throughput, according to various field experiments and simulation results, since many small cells may be left with a small number of connected users, especially in the presence of the macrocell. This issue can be managed by applying what is called cell biasing [27], through which users are pushed to the small cells. Although the SINR of the biased users drops significantly, these mobiles will enjoy the wider range of resources offered by the underutilized small cells. The effect of cross-tier interference can be decreased using OFDMA, due to the orthogonal resource access of the offloaded users to the macrocell.

Furthermore, the design of successful user association schemes closely depends on the optimization metric (e.g., throughput/QoS), the distribution of users and BSs in the network, and the traffic models being used.

2.5.2 Inter-cell Interference Management

In OFDMA systems, cell-edge users suffer from inter-cell interference when the resources are being reused. Therefore, it is necessary to utilize effective inter-cell interference mitigation techniques to avoid the interference and allow efficient frequency utilization. There are three main types of inter-cell interference mitigation techniques, classified as follows: Inter-cell interference coordination/avoidance techniques; Inter-cell interference randomization techniques; and Inter-cell interference cancellation techniques [21].

1. Interference cancellation: Interference cancellation schemes allow a receiver to work with high level of interference, whereby the interference is canceled at a receiver after receiving the signal [28]. Interference rejection combining (IRC) is one of the popular techniques that applies the interference cancellation principle. The basic idea of IRC is to recover the original transmitted signal based on statistically estimated data obtained from previously received signals and then subtract the interference from
the received signal to produce an improved wanted signal \[21\]. Successive interference cancellation (SIC) and parallel interference cancellation (PIC) are two of the most common interference cancellation techniques in wireless networks \[29\], \[30\]. SIC is a physical layer technique that allows the receiver to receive two or more signals simultaneously, and can detect one user at a time - the strongest signal is decoded first, then the next strongest, etc. On the other hand, PIC schemes can reduce the latency by allowing all users to be detected concurrently.

2. Interference randomization: This category aims at randomizing the interference to reduce its effect. There are a different variety of techniques which operate based on interference randomization, such as frequency hopping in OFDMA, random sub-carrier allocation, and cell-specific scrambling which incorporates cell-specific scrambling codes to randomize the interference \[21\].

3. Interference avoidance: In this approach, the interference is managed by applying some restrictions on the allocation of power and frequency
resources in different cells. As a result, the QoS of cell-edge users is improved without compromising the performance of the rest of the users. An overview of inter-cell interference avoidance techniques is summarized in more depth in the next section.

2.6 Overview of Inter-Cell Interference Avoidance Schemes

The future demand for higher data rates require cellular network operators to apply high frequency reuse in order to achieve the maximum possible spectrum utilization. However, high frequency reuse leads to high interference, which can eventually deteriorate the network’s capacity if not managed properly. Therefore it is vital to incorporate effective interference coordination in the design of communication systems.

Inter-cell interference coordination (ICIC) is a popular approach for controlling the interference in OFDMA networks. Interference coordination is also known as interference avoidance, in which the potential interference is prevented by allocating the interfering users orthogonally in time and frequency domains [13].

Interference avoidance schemes can be categorized into two main types, namely frequency reuse-based and cell coordination-based schemes [4]. Frequency reuse-based schemes can also be classified as conventional frequency reuse and fractional frequency reuse. Conventional frequency reuse include schemes such as reuse-1, in which the entire frequency bandwidth is reused in each cell, and reuse-3 where the frequency is divided into three sub-bands such that different sub-bands are assigned to adjacent cells. On the other hand, cell-coordination schemes have the capability of adapting to frequent changes in the network by allowing coordination between cells in order to avoid the interference.

The cell coordination schemes can be either centralized, semi-centralized or distributed [31]. In centralized schemes, a centralized server manages the interference by maintaining common information about the entire network. Semi-centralized schemes can distribute the interference coordination functionality among the centralized unit and the cells. In distributed schemes, the
interference management is performed at the cell level. The distributed approach can further be classified into coordinated and uncoordinated interference management. Coordinated-based schemes rely on the message exchange capability of femtocells, where femtocells can broadcast messages to their neighbors through the femtocell gateway to coordinate the interference [32]. On the other hand, in uncoordinated systems, the femtocells are capable of making their own resource management decisions independently, based on information extracted from the surrounding environment.

A wide variety of interference avoidance techniques have been investigated in the literature, which use a wide variety of approaches. The method described in [33] referred to as the Manchester technique, presents an interference mapping approach for enhancing QoS and energy consumption in heterogeneous cellular networks. An interference map is constructed to identify possible conflicts in the network. In addition, both centralized and distributed algorithms are used to preform the resource allocation. When interference is detected, the centralized approach is used to manage interference. Otherwise, the resource allocation is performed at the femtocell in a distributed manner.

Distributed interference management schemes are ideal for large femtocell networks, since it is inefficient to manage femtocells centrally as this can cause the back-haul network to be significantly congested. In [34], the author introduce a self organizing RRM in which each femtocell adjusts its resource allocation based on local measurement reports, in order to minimize the effect of co-channel inter-cell interference with neighboring cells. In self organizing RRM, user report measurement reports to their serving BSs at regular time intervals. The measurement reports include information about the interference power users are experiencing in each PRB which BSs use to build an interference matrix \( W \in \mathbb{R}^{S_i \times N} \) where \( S_i \) denote the number of users served by BS \( i \) and \( N \) refers to the number of PRBs. BSs then update the allocation in sub-channels in such a way that minimize the interference as follows [34]
CHAPTER 2. THEORITICAL BACKGROUND AND STATE-OF-ART

\[
\begin{align*}
\min & \quad \sum_{k=1}^{K} \sum_{n=1}^{N} w_{k,n} \cdot \chi_{k,n} \\
\text{s.t.} & \quad \sum_{k=1}^{K} \chi_{k,n} \leq 1, \quad \forall i, n \\
& \quad \sum_{n=1}^{N} \chi_{k,n} = 1, \quad \forall k.
\end{align*}
\]

where \( \chi_{k,n} \) is a binary multiplier that is equal to 1 when user \( k \) is allocated in sub-channel \( n \) and is equal to 0 otherwise.

Graph-based interference avoidance techniques have been widely utilized for mitigating the interference in femtocell networks where the connected UEs in the graph are assigned orthogonal resources, and each set of orthogonal resources are represented by a different color [35]. The authors in [36] introduced a centralized graph-based resource partitioning approach for minimizing interference to the cell-edge users. The interference avoidance is achieved by partitioning the frequency resources into sub-bands which are assigned to cells such that adjacent femtocells are allocated in orthogonal sub-bands.

Several studies were introduced in the literature to avoid cross-tier interference in heterogeneous networks. One of the standard cross-tier interference avoidance methods in two-tier networks is the split spectrum approach, which has been employed by several companies due to its reduced complexity [37]. The co-channel cross-tier interference is avoided by splitting the spectrum among the macrocells and femtocells in which each layer of cell uses an orthogonal set of resources.

Another popular technique for managing cross-tier interference is fractional frequency reuse (FFR) [38]. FFR is recommended to be used for resource management in heterogeneous networks, because of its simplicity and the minimal coordination required between cells. Fig. 2.7 illustrates the basic FFR scheme for heterogeneous networks which divides the macrocell coverage area into two parts. The center part applies a frequency reuse factor (FRF) of 1 and and the edge area uses a certain FRF which is assumed to be 3 in fig. 2.7. The macrocell cell-edge users are protected from co-tier inter-cell interference by assigning the cell-edge users of adjacent macrocells in different
frequency bands as shown in the figure. Furthermore, intra-cell co-tier interference is minimized, since users in the cell center use different frequency sub-bands from users in the cell edge. To avoid cross-tier interference, femtocells can use the part of the spectrum that is not used by the macrocell.

Figures 2.8-2.11 show a performance comparison between the interference coordination techniques discussed above in homogeneous and heterogeneous networks. The performance is evaluated in terms of the average data rate per user, the guaranteed data rate and the energy efficiency. Fig. 2.8 shows the average data rate performance comparison. The Manchester technique in [33] is evaluated using two signal-to-interference (SIR) threshold $\beta$ values of 20dB and 25dB, which are selected based on the optimization objective. It is shown that lower threshold values can improve the average rate compared to higher ones. On the other hand, lower threshold values reduce the guaranteed bit rate performance as cell-edge users become more exposed to interference due to the increased frequency reuse. The self organizing network approach that is referred to as self organizing RRM is investigated using several iterations, where the iterations are needed to achieve minimum interference. The dynamic color graph (DCG) method [36] is tested with different number of sub-bands per BS. It can be seen that the less bandwidth
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Figure 2.8: Homogeneous network data rate per user performance comparison at varying femtocell densities.

is allocated in the initial allocation (N/8), the more bandwidth left for the maximization step, which explains why N/8 achieves a better average data rate than N/4, where N denotes the total available resources. The figure also shows that DCG achieves poor performance compared with other techniques, as it is designed for cases where there are few users per cell. Fig. 2.11 shows a guaranteed data rate comparison of the aforementioned techniques in heterogeneous network, where an enterprise consisting of femtocells is located at various distances from a macrocell. It is noted that the performance improves as the building is moved away from the macrocell, since this reduces interference. In the Manchester technique, increasing the SIR threshold $\beta$ enhances the performance of the cell-edge users, which are more vulnerable to interference.
Figure 2.9: Homogeneous network guaranteed data rate performance comparison at varying femtocell densities

Figure 2.10: Homogeneous network energy consumption ratio (ECR) performance comparison at varying femtocell densities
Figure 2.11: Heterogeneous network guaranteed data rate performance comparison at varying femtocell densities
Chapter 3

Sleep Mode Based Resource Management

3.1 Introduction

Sleep mode (SL) is a promising technology that is widely adopted in cellular networks. In particular, SL techniques have been extensively employed to minimize the energy consumption by taking advantage of the times when the small cells are idle and setting them to SL mode to save power. In addition to optimizing the power consumption, this chapter presents a novel SL-based RRM technique to leverage the capacity gain of wireless networks \(^1\).

The aim is to exploit the ad-hoc nature of small cell deployment and the limited percentage of associated users, to examine the possibility of applying cell switch off to optimize the available resources. This is achieved by reducing the interference that is produced by poorly positioned small cells to allow more effective resource utilization in the neighborhood. A resource partitioning scheme is used to control the inter-cell interference by orthogonalizing the interfering cells/users. The reuse reduction that results from orthogonalization is compensated using a small cell selection algorithm which uses

\(^1\)Part of the work introduced in this chapter has been published in [39].
a set of criteria to identify the BSs that are causing the most reuse reduction and passes this information to the resource partitioning scheme to determine whether or not if deactivation can improve the network resource utilization. The performance of the proposed method is analyzed using a mathematical model that accurately model the received interference from neighboring cells.

Recently, SL has been proposed for optimizing various aspects in cellular networks. In [40], the authors provided a survey on energy efficient techniques and power consumption models for enhancing the energy efficiency in femtocell networks. The authors in [41] presented a method for minimizing energy in heterogeneous networks by proposing a joint resource partitioning and user association method under the assumption that both tiers of cells can be switched into SL for a certain fraction of time/frequency resources. In [42], the authors introduced a sleep mode management scheme, in which the user association is coordinated between BSs such that the BSs with no active users are switched to sleep mode to reduce the energy consumption. In [43], an SL based mechanism for minimizing energy consumption and maintaining QoS is proposed for heterogeneous networks. In this technique, macrocells are put into SL and users are offloaded to neighboring macrocells or small cells. The authors in [44] proposed a method for minimizing total power consumption in heterogeneous networks by adaptively switching BS on/off taking into consideration parameters such as network coverage and the user traffic rates. An SL based technique was investigated in [45] to assess the energy efficiency and the capacity of the network. Different elements were taken into consideration to test the QoS including the transmission power of femtocells, the separation between BS and the total quantity of femtocells. The authors in [46] presented a collaborative sleep scheme that focuses on enhancing the energy saving of femtocell assisted networks by only activating the necessary femtocells to serve the users requirements. In [47], the authors introduced a cell selection scheme for scaling down the number of active femtocells while considering the QoS requirements of users. A heuristic algorithm is presented in [48] to reduce the power consumption by setting as many BSs as possible to SL to serve the users rate requirements. To ensure the minimum number of cells are active, BSs offering acceptable service to the largest number of users are activated first. In [49], the authors proposed an SL activation method for
two-tier cellular networks to reduce the interference to macrocell users.

The remaining part of this chapter is structured according to the following. Section 3.2 provides a description of the system model and assumptions. Section 3.3 and 3.4 illustrates detailed discussion of the proposed method. Section 3.5 presents a performance analysis of our proposed method. The simulation and result discussion are discussed in section 3.6. Lastly; concluding remarks are presented in section 3.7.

3.2 System Model

A downlink OFDMA system is utilized with a heterogeneous network including a macrocell and a group of small cells. Assume $B$ and $K$ denote respectively, the sets of deployed small cells and UEs in the network in which $B = \{1, 2, \ldots, i, \ldots, j, \ldots, B\}$ and $K = \{1, 2, \ldots, k, \ldots, K\}$. Let $i \in B$ and $k \in K$ represent any random BS and UE from the sets $B$ and $K$ and $j$ denote a neighboring cell of BS $i$, where a neighboring BS is a nearby cell in which a UE $k$ served by BS $i$ falls within its coverage range according to a predefined threshold. Furthermore, let $S_i$ refer to the group of UEs served by BS $i$. The system bandwidth is split to a group of $N$ PRBs which are assumed to be orthogonal and are dedicated for data transmission. The set of available PRBs is given by $N = \{1, 2, \ldots, n, \ldots, N\}$ where the variable $n$ denotes an arbitrary PRB from the set $N$.

It is assumed that a co-channel deployment scenario is used, where all tiers of cells coexist in the same frequency band. Small cells are assumed to use an open access policy and are transmitting at the maximum power level. Moreover, users use the MR capability to determine the cells identities as well as their corresponding RSRP. Users are associated with cells based on the maximum received signal strength (RSS) strategy, in which users are associated with the BSs that are providing the maximum received power [26]. The association request is initiated by users by reporting their MR readings to the BS.

The RNC unit connects the macrocell with the core network which is managed by the OAM. Femtocells are assumed to be connected to the FMS, which is responsible of managing the femtocell network through the OAM. Therefore, the centralized control required for all BSs in the heterogeneous network
is provided by both the OAM and FMS units [17].

Small cells can operate either in RE state or SL state where the transition between states is controlled by the core network through the back-haul [9]. BSs perform the frequency allocation for their connected users independently using channel quality indicator (CQI) reports sent from users to indicate the quality of the communication channel in order to select the preferred PRBs.

To evaluate the performance of the proposed algorithm in the worst case scenario, a full-buffer traffic model is utilized where BSs attempt to transmit and receive at the maximum capacity supported by the air interface.

Furthermore, same cell users occupy orthogonal resources and therefore the effect of intra-cell interference can be neglected. The synchronization in the network is assumed to be ideal and hence inter-cell interference occurs only when the allocation of users overlap in the same time and frequency. The channel variation is represented using Rayleigh fading to model the impact of the propagation environment on the radio signal.

### 3.2.1 Signal-to-Interference-plus-Noise ratio model

The SINR of user $k$ at PRB $n$ is given by [50]

$$\Upsilon_{k,n} = \frac{\Gamma_{i,k,n}h_{i,k,n}}{\eta_0 + \sum_{j=1}^{B} \Gamma_{j,k,n}h_{j,k,n}}, \quad j \neq i.$$  \hspace{1cm} (3.1)

where $\Gamma_{i,k,n}$ denotes the received signal power from BS $i$ to the served user $k$ in PRB $n$, $h_{i,k,n}$ is the channel gain which incorporates the effect of Rayleigh Fading, $\Gamma_{j,k,n}$ is the interference power received from a neighboring cell $j$ and $\eta_0$ refers to the additive white Gaussian noise (AWGN).

### 3.2.2 Energy Efficiency Model

The energy efficiency is measured using the energy consumption ratio (ECR) model in [51]. The power consumption of femtocell $i$ is calculated as follows

$$P_{DL,i} = \left( P_{TX,i}/\mu_{PA} + P_{SP} \right)/\mu_{PS}$$  \hspace{1cm} (3.2)

where $\mu_{PA}$ is the power amplifier efficiency and is assumed to be 20%,
\( \mu_{PS} \) is the power supply efficiency which is given by 85\%. \( P_{SP} \) is the signal processing power of 3.35 Watts and \( P_{TX} \) is the femtocell transmission power. To evaluate the ECR of BS \( i \), the consumed power by BS \( i \), \( P_{DLi} \) is divided by the average data rate, \( R_i \)

\[
ECR_i = \frac{P_{DLi}}{R_i}
\]

(3.3)

### 3.2.3 Power Consumption Model

The power saving of the proposed SL method is evaluated by measuring the total consumed power \( P [9] \)

\[
P = N_{Active} \cdot P_{RE} + N_{Sleep} \cdot P_{SL}
\]

(3.4)

where the number of active and sleep femtocells are denoted by \( N_{Active} \) and \( N_{Sleep} \). The powers required to operate the femtocell in RE and SL are represented by \( P_{RE} \) and \( P_{SL} \), respectively [9].

### 3.2.4 Adaptive Modulation and Coding Model

The achievable bit rate is measured using the adaptive modulation and coding (AMC) scheme [52]. In AMC, the modulation and coding schemes (MCS) can be adapted based on the quality of the wireless channel. To measure the bit rate at the \( s^{th} \) sub-carrier, the adaptive MQAM modulation scheme described in [53] is adopted assuming the bit error rate (BER), \( P_b (s) \) assumed to be less than \( 10^{-6} \). The discrete capacity at sub-carrier \( s \), \( C_d (s) \) can be expressed as

\[
C_d (s) = B_{sym} (s) - E (P_{sym} (s)),
\]

(3.5)

where \( B_{sym} (s) \) represent the number of bits per symbol and \( P_{sym} (s) \) denotes the symbol error rate at the \( s^{th} \) sub-carrier which is given by

\[
P_{sym} (s) = B_{sym} (s) \cdot P_b (s),
\]

(3.6)

\( E (P_{sym} (s)) \) represent the equivocation of the symbol for a certain \( P_{sym} (s) \),
which is given by

\[
E(P_{sym}(s)) = -P_{sym}(s) \log_2 \left( \frac{P_{sym}(s)}{2B_{sym}(s) - 1} \right) - (1 - P_{sym}(s)) \log_2 (1 - P_{sym}(s)),
\]

(3.7)

Therefore, the data rate achievable at the \( s \)th sub-carrier can be written as

\[
R(s) = \frac{C_d(s)}{T_{Ofdm}}
\]

(3.8)

where \( T_{Ofdm} \) refers to the OFDM symbol period in seconds.

### 3.3 Interference Map Approach

To identify possible conflicts in the system, the interference map approach in [33] is employed. To build the interference map, BSs utilize the MR feedback from users to estimate the DL interference. The MRs are triggered by transmitting RRC messages to the UEs as discussed in Chapter 2. UEs then scan the neighborhood to determine the PCI of neighboring BSs as well as their RSRP, which are reported back to their serving BS [11]. For instance, if we assume BS \( j \) is a neighboring cell of BS \( i \), the received interference power by user \( k \) from BS \( j \) at PRB \( n \) can be measured as follows

\[
\Gamma_{j,k,n} = \frac{\rho_j}{P_l_{j,k}}, \quad \forall k = 1, 2, \ldots, S_i
\]

(3.9)

where \( \rho_j \) denotes the DL average transmission power of BS \( j \) at PRB \( n \) and \( P_l_{j,k} \) refers to the pathloss between BS \( j \) and user \( k \).

Given this information, BS \( i \)'s local interference map \( \zeta_i \) is produced as follows [33]

\[
\zeta_i(k, j) = \begin{cases} 
0 & \Gamma_{i,k,n} > \beta \\
1 & \Gamma_{i,k,n} < \beta
\end{cases}
\]

(3.10)

where \( k \) denotes a user served by BS \( i \) and \( j \) is a neighboring BS of \( i \). \( \beta \) refers to the SIR threshold and \( \Gamma_{i,k,n} \) denotes the received power from BS \( i \) to its connected UE \( k \) at PRB \( n \). The value of the threshold can be selected
depending on the optimization objective. Generally, higher threshold values are used for maximizing the QoS while lower values are used for maximizing the throughput. For further discussion on this please refer to sec.V of [33].

When a BS updates its local interference map, the current measurement \( \zeta_{i} \) is sent to the FMS only if the previous record \( \zeta'_{i} \) is different from the current record [33]

\[
\sum_{k=1}^{S_i} \sum_{i=1}^{B} |\zeta_{i}(k,i) - \zeta'_{i}(k,i)| > 0, \tag{3.11}
\]

The universal interference map of the network is managed by the FMS, where \( \zeta \in \mathbb{R}^{K \times B} \) is expressed as [33]

\[
\zeta(k,i) = \begin{cases} 
   w, & \text{when } i \text{ is the serving BS of } k \\
   1, & \text{when } j \text{ interferes } k \\
   0, & \text{otherwise}
\end{cases} \tag{3.12}
\]

where \( w \) represent any positive integer number excluding 0 and 1.

### 3.4 SL for Capacity Maximization

The main concept of the proposed SL for capacity maximization (SLCM), scheme is to identify the scenarios in which deactivating certain small cells can be beneficial from a network-wide perspective. Towards this end, an algorithm is proposed to nominate the potential BSs, (e.g., BS \( f_1 \) from fig. 3.1), to the centralized resource allocation scheme to determine if deactivating these cells can result in improving the network-wide frequency reuse and hence capacity. If some cells are selected for deactivation, the resource allocation scheme will re-associate their users to neighboring cells and resolve any remaining co-tier interference instances through orthogonal resource partitioning. Due to the unplanned deployment of femtocells, the FMS is used in this algorithm as a centralized controller.
3.4.1 Problem formulation

The objective is to find the set of BSs which, if deactivated, could maximize the total capacity of the network. Therefore, the capacity maximization problem is formulated in this section. Generally speaking, we presume a BS operates either in active or sleep mode and the state of a BS is denoted by the indicator variable $\phi_i \in \{0, 1\}$, where $\phi_i = 1$ indicates active state and $\phi_i = 0$ indicates sleep state. The achievable capacity, $c_{k,n}$ of UE $k$ at PRB $n$ is given by

$$c_{k,n} = W \log_2 (1 + \Upsilon_{k,n})$$

(3.13)

where $W$ refers to the bandwidth of PRB $n$ which is identical for all PRBs. The capacity maximization problem can be formulated as follows

---

Note that the terms Switch off and deactivation are used interchangeably to indicate SL mode.
where $\chi_{k,n}$ is an indicator variable that is equal to 1 when UE $k$ is allocated in PRB $n$ and 0 otherwise. The notation $\Psi_k$ refers to the amount of resources assigned to user $k$ which is determined based on sec. 3.4.3. (3.15) ensures that each PRB is allocated to one UE only in the same cell. (3.16) guarantees that UE $k$ is allocated $\Psi_k$ PRBs. The problem in (3.14) is formulated as an integer linear programming (ILP) problem which is normally solved by ILP solving methods. Since the running time of ILP solvers is uncertain, more efficient techniques are needed to reduce the complexity. We propose a unique solution that divides the problem into two parts. The first part is solved by the FMS which uses a set of criteria, to be defined later, to determine the potential BSs to be deactivated. This is assisted by a resource partitioning scheme that is used to determine whether or not switching off the selected BSs can lead to increasing the resource utilization. The second part is the resource allocation within each BS, which is solved independently by each BS using the CQI reports from users and the output of the first part including the set of active BSs and the advised allocated PRBs per user. It is worth highlighting that resource partitioning involves determining the amount of resources to allocate to each user to ensure orthogonality while the resource allocation is performed by the BSs to allocate their users in the preferred resources according to the wireless channel information.

### 3.4.2 Small Cell Deactivation Criteria

This section defines the small cell deactivation criteria which are formed into 5 tests and will be used in sec. 3.4.4 to select the candidate BSs for switch off. Before proceeding to describe the deactivation methodology, it is worth...
Figure 3.2: High-level flowchart illustrating the sequence of the deactivation tests
noting that when the outcome of a given test leads to multiple candidate BSs for switching off, the algorithm will continue to run the tests until one of these candidates is selected. The high-level flowchart in Fig. 3.2 is used to illustrate the sequence of the deactivation tests, which are applied to determine the optimal BS for switching off, and are described as follows:

**Test 1**: The number of conflicts (NoC) of a BS, which is given by the total amount of interfered UEs by BS \( i \), in addition to the number of \( i \)'s connected UEs that are interfered by nearby BS. The FMS measures the NoC associated with each BS based on the interference map \( \zeta \), as follows

\[
\text{NoC}_i = \sum_{k=1}^{K} \{ \zeta(k, i) = 1 \} + \sum_{j=1}^{B} \sum_{k=1}^{S_i} \{ \zeta(k, j) = 1 \},
\]

where \( x = \{ a = b \} \) means that the value of \( x \) is equal to 1 if \( a = b \) and is equal to 0 otherwise.

**Test 2**: The proportion of UEs positioned in the handover region to the total amount of UEs belonging to the BS, which is expressed as

\[
\mathcal{H}_i = \frac{\sum_{k=1}^{S_i} L_i}{S_i},
\]

Where \( \mathcal{H}_i \) refers to the handover ratio of BS \( i \), \( S_i \) is the number of UEs served by BS \( i \) and \( L_i \) denotes the number of UEs served by \( i \) and happen to be located within the region overlapped with neighboring cells

\[
L_i(k, j) = \begin{cases} 
1 & \frac{\Gamma_{i,k,n}}{\Gamma_{j,k,n}} < \beta \\
0 & \text{Otherwise}
\end{cases},
\]

**Test 3**: The total number of UEs connected to BS \( i \), \( S_i \)

\[
S_i = \sum_{k=1}^{K} \{ \zeta(k, i) = w \},
\]

**Test 4**: The total sum of received signal power of all UEs connected to BS
CHAPTER 3. SLEEP MODE BASED RESOURCE MANAGEMENT

$i$, which is given by $\mathcal{P}_i$

$$
\mathcal{P}_i = \sum_{k=1}^{S_i} [\Gamma_{i,k,n}],
$$
(3.21)

**Test 5:** The sum of interference power received by the $i$’s user from neighboring BS, $\mathcal{I}_i$

$$
\mathcal{I}_i = \sum_{k=1}^{S_i} \sum_{j=1}^{B} \left[ \Gamma_{j,k,n} \right] \quad \text{for } j \neq i
$$
(3.22)

### 3.4.3 Resource Partitioning

The resource partitioning scheme is designed to manage the inter-cell interference by orthogonalizing resources between conflicting BS/users [33]. Given the interference map $\mathcal{\zeta}$, the maximum number of resources that BS $i$ offers to each of its connected UEs denoted by $\Omega_i$ is measured by dividing the available resources $N$, by the total number of detected users.

$$
\Omega_i = N/ \left( \sum_{k=1}^{K} \{ \zeta (k,i) = 1 \} + \sum_{k=1}^{K} \{ \zeta (k,i) = w \} \right).
$$
(3.23)

where the number of detected users is represented by the following:

- The number of interfered users located in the coverage range of BS $i$. These users are determined based on the SIR threshold as illustrated in eq. (3.10) where a given user $k$ is considered interfered by BS $i$ if the ratio of the received signal power from the serving BS of user $k$ to the received interference power from BS $j$, is less than $\beta$.

- The number of connected users of BS $i$, where users connect to the BS with maximum received power.

This value is measured and stored in the vector $\Omega_B \in \mathbb{R}^{1 \times B}$ where $\Omega_B = ...$
A given user \( k \) connected to BS \( i \) may not necessarily be allocated the maximum number of resources \( \Omega_i \). For instance, if \( \Omega_j \) of a neighboring BS \( j \) is less than \( \Omega_i \), the number of allocated resource to user \( k \) is decreased to reduce the interference to the neighboring users close from BS \( i \). Therefore, the notation \( \Psi_k \) is used to denote the number of resources allocated to user \( k \) which is determined as follows: (a) \( \Psi_k \) is set to \( \Omega_i \) if \( \Omega_j \) is not less than \( \Omega_i \), (b) \( \Psi_k \) is set to \( \Omega_j \) if \( \Omega_j \) is less than \( \Omega_i \) to allow BS \( j \) a wider range of orthogonal resource for its own users where the vector \( \Psi_K = [\Psi_1, \ldots, \Psi_k, \ldots, \Psi_K] \) stores the number of resources dedicated for each user. However if a number of neighboring BSs interfere with BS \( i \) orthogonalization, the service quality will eventually decrease. This is why our SL method targets those BS that are causing this reduction in the resource utilization of the nearby users/BS.

### 3.4.4 Small Cell Deactivation

The small cell deactivation algorithm uses the deactivation criteria described in sec. 3.4.2, and incorporates the resource partitioning scheme to switch off the unwanted BSs that when switched off, the interference reduces, the resource re-utilization improves and the capacity is increased. This objective is pursued while taking measures to prevent compromising the outage probability of the users that are connected to the switched off cells. The small cell deactivation algorithm is performed as follows

- Before beginning to execute the deactivation tests, the initial sum of PRBs allocated to all the users in the system is determined according to sec. 3.4.3, to be later compared with the updated value after the deactivation.

\[
\Psi_{tot} = \sum_{i=1}^{B} \sum_{k=1}^{S_i} \sum_{n=1}^{N} [A_{k,n} \cdot \chi_{k,n}] 
\]  

(3.24)

The notations \( \Psi_{tot} \) and \( \Psi'_{tot} \) are used to denote the current and previous total utilized resources respectively.

- Since the NoC is one of the parameters that significantly affects the reuse efficiency as will be shown later in sec. 3.5, Test 1 is applied first to
Algorithm 1 Small Cell Deactivation Algorithm

//Initialize
1: Calculate: $\Psi_{tot}$ based on (3.24)
2: do {
3: Set $\Psi'_{tot} = \Psi_{tot}$
4: // Apply Test 1
   $a = \text{max} (\text{NoC})$
5: if only 1 BS found in $a$ then
6: \hspace{1em} $\varphi = a$
7: else
8: // Apply Test 2
9: \hspace{1em} if $H = 0$ then
10: \hspace{2em} if candidate cells have different $S$ then
11: \hspace{3em} //Apply Test 3
12: \hspace{4em} $\varphi = \min (S)$
13: \hspace{2em} else
14: \hspace{3em} //Apply Test 4
15: \hspace{4em} $\varphi = \min (P)$
16: \hspace{1em} end if
17: else
18: // Apply Test 2
19: \hspace{1em} From list of BSs in $a$, calculate $b = \text{max} (H)$
20: if only 1 BS have max $H$ then
21: \hspace{1em} $\varphi = b$
22: else
23: \hspace{1em} if all BSs from $b$ have equal $H$ then
24: \hspace{2em} // Apply Test 5
25: \hspace{3em} $\varphi = \max (I)$
26: \hspace{1em} else
27: \hspace{2em} // Apply Test 4
28: \hspace{3em} $\varphi = \min (P)$
29: \hspace{1em} end if
30: end if
31: end if
32: end if
33: if $\Psi_{tot} > \Psi'_{tot}$ then
34:\hspace{1em} Deactivate $\varphi$
35:\hspace{1em} Update $\zeta$ and Cellular Association
36:\hspace{1em} Recalculate $\Psi_{tot}$
37: end
38: \} while $\Psi_{tot} > \Psi'_{tot}$
Algorithm 2 Resource Allocation Algorithm

1: \textbf{for} \( i = 1 \) until \( B \) do
2: \hspace{1em} \textbf{if} \( i \) not deactivated \textbf{then}
3: \hspace{2em} \textbf{for} \( k = 1 \) until \( S_i \) do
4: \hspace{3em} Find preferred PRBs for \( k \)
5: \hspace{2em} \textbf{for} \( n = 1 \) until \( N \) do
6: \hspace{3em} \textbf{while} allocated PRBs of \( k < \Psi_k \)
7: \hspace{4em} \textbf{if} PRB \( n \) allowed for \( k \) \textbf{then}
8: \hspace{5em} \( A(k, n) = A(k, n) \lor 1 \)
9: \hspace{4em} \textbf{end if}
10: \hspace{3em} \textbf{end for}
11: \hspace{2em} \textbf{end for}
12: \hspace{1em} \textbf{end if}
13: \hspace{1em} \textbf{end for}

\begin{align}
\varphi &= \max(\text{NoC}), \quad (3.25)
\end{align}

where, \( \varphi \) refers to the selected BS.

If only one BS is found, this BS is selected for switch off. Otherwise, in case there are multiple candidates, Test 2 is applied to identify the BS with the maximum handover ratio

\begin{align}
\varphi &= \max(\mathcal{H}), \quad (3.26)
\end{align}

- In case none of the UEs of the nominated BS are located in the handover region of nearby cells, the BS to be deactivated is selected based on Test 4 in case all BSs have equal number of users

\begin{align}
\varphi &= \min(\mathcal{P}), \quad (3.27)
\end{align}

The reason for applying (3.27) is to ensure that the selected BS is the one that offers its users less received signal power than other candidates. This is
done to enhance the overall capacity. Otherwise, Test 3 is applied and the BS with the minimum connected users is selected to reduce the probability of dropping UEs

$$\phi = \min(S),$$

(3.28)

- If the nominated BSs have UEs in the handover region of other cells, the BS that has the largest handover ratio is selected to minimize the number of dropped UEs. In case more than one BS have equal handover ratio $H$, and all their connected users happen to be located in the coverage area of nearby cells, the selection is performed based on Test 5 as follows

$$\phi = \max(I).$$

(3.29)

The reason for executing the test in (3.29) is to select the BS with the users that are receiving the maximum interference from nearby cells, since such UEs are more likely to achieve better signal quality when handed off to these cells. Otherwise, the selection decision is performed based on (3.27).

- Finally, the selected BS is deactivated and the disconnected users are handed off to nearby active BSs with the maximum received signal power. However, in case a user is not settled within the coverage range of any cell, this user will be dropped.

- The interference map $\zeta$ is then updated and $\Psi_{tot}$ is recalculated.

- The updated $\Psi_{tot}$ is compared with the previous $\Psi'_{tot}$ and the selected BS $\phi$ is set to SL mode if $\Psi_{tot}$ is greater than $\Psi'_{tot}$. The process then repeats to search for other BSs for deactivation.

These steps are formulated as a pseudo code structure in Algorithm 1.

### 3.4.5 Resource Allocation

The frequency resource allocation algorithm is implemented independently by each BS after measuring the available resources per user $\Psi_K$ as shown
in the previous part. BS use CQI reports from UEs in order to select the
preferred PRBs for each user [54]. The CQI report from a given user \( k \) includes
information about the interference power experienced by user \( k \) in every PRB. Once the preferred PRBs are determined, the allocation map that is managed
by BS is updated in the local allocation matrix \( A \). Details on this process are
illustrated in Algorithm 2.

### 3.5 Performance Analysis

In this section, the Probability Density Function (PDF) of the downlink SIR is
derived conditionally on the user location. This PDF is used to study the effect
of the SIR threshold on some key parameters in our system and compare to
our simulation results. While the model was simplified to a grid model with
stationary BS positions it also considers the randomness of the user location
to accurately model the received interference.

#### 3.5.1 Signal-to-Interference Model

The received signal power from BS, \( i \), to its served UE \( k \) is given by \( P_t d_{i,k}^{-\varphi} \),
where the transmission power of \( i \) is represented by \( P_t \), the distance between
\( i \) and \( k \) is denoted by \( d_{i,k} \) and the pathloss exponent is referred to as \( \varphi \) and the
interference power received from a nearby BS, \( j \), can be expressed as \( P_t d_{j,k}^{-\varphi} \).
If we assume \( P_t \) is identical for all BSs, user \( k \) is not considered interfered by
BS \( j \) when the received interference from this BS is lower than the threshold

\[
P_t d_{j,k}^{-\varphi} < \frac{P_t d_{i,k}^{-\varphi}}{\beta} \tag{3.30}
\]

Which can be simplified and rewritten as

\[
d_{i,k} < \left( \frac{1}{\beta} \right)^{\frac{1}{\varphi}} \tag{3.31}
\]

Where \( \beta \) denotes the SIR threshold, \( d_{i,k}/d_{j,k} \) is the distance ratio between
\( k, i \) and \( j \) and is denoted by \( D \). Therefore, user \( k \) is detected in the coverage
of BS \( j \) if \( \left( \frac{1}{\beta} \right)^{\frac{1}{\varphi}} \leq D \leq 1 \) and is not detected when \( 0 < D < \left( \frac{1}{\beta} \right)^{\frac{1}{\varphi}} \).
3.5.2 Distance Ratio Analysis

Consider a grid model where two BS denoted by $P_1$ and $P_2$ are located at the center of each square. Assuming $P_1$ and $P_2$ are positioned on the x,y-plane with $P_1$ located at the origin, and $P_2$ located at a fixed distance from $P_1$ denoted by $\ell$, at position $(x_{p_2}, y_{p_2})$. Assume a user $m$, is randomly and uniformly distributed in the circular area of $P_1$ whose location is given by $(r, \theta)$.

Assuming $r$ and $\theta$ are both random variables following a uniform distribution, the PDF of $r$, $f_R(r)$, is given by

$$f_R(r) = \begin{cases} \frac{1}{R}, & 0 < r \leq R \\ 0, & \text{elsewhere} \end{cases} \quad (3.32)$$

And the PDF of $\theta$, $f_\phi(\theta)$ is given by

$$f_\phi(\theta) = \begin{cases} \frac{1}{2\pi}, & 0 \leq \theta \leq 2\pi \\ 0, & \text{elsewhere} \end{cases} \quad (3.33)$$

Using trigonometric functions, $r$ and $\theta$ which represent the polar coordinates are transformed to the corresponding Cartesian coordinates $x$ and $y$ as follows

$$x = r \cos(\theta) \quad (3.34)$$

$$y = r \sin(\theta) \quad (3.35)$$

The random variable $\theta$, can be transformed into the form $\cos(\theta)$ using the change-of-variable method [55]

$$f_Z(z) = f_\theta [g^{-1}(z)] \cdot \left| \frac{dg^{-1}(z)}{dz} \right| \quad (3.36)$$

Where

$$g^{-1}(z) = \arccos(z) \quad (3.37)$$

and
\[
\frac{dg^{-1}(z)}{dz} = -\frac{1}{\sqrt{1 - z^2}}
\]  
(3.38)

For symmetry, the term in (3.39) is multiplied by 2

\[
f_z(z) = 2 \cdot \left( \frac{1}{2\pi} \cdot \frac{-1}{\sqrt{1 - z^2}} \right)  
\]  
(3.39)

Therefore, \( f_z(z) \) can be re-written as

\[
f_z(z) = \begin{cases} 
\frac{1}{\pi \sqrt{1 - z^2}}, & -1 < z < 1 \\
0, & \text{elsewhere}
\end{cases}
\]  
(3.40)

Similarly, the probability density of the transformation of \( \sin(\theta) \), is given by

\[
f_v(v) = \begin{cases} 
\frac{1}{\pi \sqrt{1 - v^2}}, & -1 < v < 1 \\
0, & \text{elsewhere}
\end{cases}
\]  
(3.41)

The probability density, \( f_X(x) \) as stated in (3.34) can be expressed as

\[
f_X(x) = \int_{-\infty}^{+\infty} f_{Z/X} \left( \frac{z}{x} \right) \cdot f_z(z) \cdot \frac{1}{x} dx  
\]  
(3.42)

where \( X = Z \) and \( \frac{Z}{X} = R \). From (3.32) and (3.40), \( f_X(x) \) is given by

\[
f_X(x) = \frac{1}{\pi R} \cdot \int_{\pi}^{1} \frac{1}{x} \cdot \frac{1}{\sqrt{1 - x^2}} \, dx  
\]  
(3.43)

Therefore, the PDF of \( x \) can be written as

\[
f_X(x) = \begin{cases} 
\frac{1}{\pi R} \cdot \{ \log(R) - \log(x) \} + , & -R \leq x \leq R / \{0\} \\
\log \left( 1 + \sqrt{1 - \frac{x^2}{R^2}} \right), & \text{elsewhere}
\end{cases}
\]  
(3.44)

The euclidean distance between \( P_x \) and \( m \) is defined as

\[
G = \sqrt{\Delta x^2 + \Delta y^2}  
\]  
(3.45)
The distance ratio between $P_1$, $P_2$ and $m$ is given by

$$D = G/\ell$$  \hspace{1cm} (3.46)

Assuming $x_{p_2}$ and $y_{p_2}$ are equal to a constant value denoted by $a$, the PDF of $\Delta X$, $f_{\Delta X}(x)$ can be obtained using (3.36)

$$g^{-1}(x) = x - a \quad \quad \frac{dg^{-1}(x)}{dx} = 1 \hspace{1cm} (3.47)$$

From (3.36) and (3.47), the probability density function of $\Delta x$, $f_{\Delta x}(x)$ can be written as

$$f_{\Delta X}(x) = \begin{cases} \frac{1}{\pi R} \{ \log (R) - \log (x - a) \} & a - R \leq x \leq a + R/a \\ + \log \left( 1 + \sqrt{1 - \left( \frac{x - a}{R} \right)^2} \right) & \text{elsewhere} \end{cases} \hspace{1cm} (3.48)$$

In a similar fashion, the density function of $\Delta y$, $f_{\Delta y}(y)$ is given by

$$f_{\Delta Y}(y) = \begin{cases} \frac{1}{\pi R} \{ \log (R) - \log (y - a) \} & a - R \leq y \leq a + R/a \\ + \log \left( 1 + \sqrt{1 - \left( \frac{y - a}{R} \right)^2} \right) & \text{elsewhere} \end{cases} \hspace{1cm} (3.49)$$

The joint probability density of $\Delta x$ and $\Delta y$ can be defined as

$$f_{\Delta X, \Delta Y}(x,y) = f_{\Delta X}(x).f_{\Delta Y}(y) \hspace{1cm} (3.50)$$

The PDF of $G$, $f_G(g)$ as described in (3.45) can be expressed as

$$f_G(g) = \int_{-\infty}^{+\infty} \left| \frac{g}{\sqrt{g^2 - x^2}} \right| f_{\Delta X, \Delta Y} \left( x, \sqrt{g^2 - x^2} \right) \hspace{1cm} (3.51)$$

The expressions in (3.48) and (3.49) can be simplified into quadratic form as follows

$$f_{\Delta X}(x) = p_1 x^2 + p_2 x + p_3 \hspace{1cm} (3.52)$$
\[ f_{\Delta Y}(y) = p_1(g^2 - x^2) + p_2 \sqrt{g^2 - x^2} + p_3 \] (3.53)

Therefore, the PDF of \( G \), \( f_G(g) \) can be written as

\[
\begin{align*}
  f_G(g) &= \left\{ 
  \begin{array}{ll}
    f_{G_1}(g) & , \quad \sqrt{2l_1} < g < \sqrt{l_1^2 + l_2^2} \\
    f_{G_2}(g) & , \quad \sqrt{l_1^2 + l_2^2} < g < \sqrt{2l_2} \\
    0 & , \quad \text{elsewhere}
  \end{array}
\right. \\
\end{align*}
\] (3.54)

Where \( l_1 = a - R \), \( l_2 = a + R \) and \( f_{G_1}(g) \), \( f_{G_2}(g) \) are given by (3.55) and (3.56)

\[
f_{G_1}(g) = \frac{g_1^2}{8}[2l_1 \sqrt{g^2 - l_1^2} (g^2 - 2l_1^2) + g^4 \arctan \left( \frac{\sqrt{g^2 - l_1^2}}{g} \right) - g^4 \arctan \left( \frac{l_1}{\sqrt{g^2 - l_1^2}} \right)] \\
\]

\[
+ \frac{g_2^2}{2} [g^2 - 2l_1^2] + gp_1p_3 \left[ g^2 \arctan \left( \frac{\sqrt{g^2 - l_1^2}}{l_1} \right) - g^2 \arctan \left( \frac{l_1}{\sqrt{g^2 - l_1^2}} \right) \right] \\
+ 2gp_2p_3 \left[ \sqrt{g^2 - l_1^2} - l_1 \right] \\
\] (3.55)

\[
f_{G_2}(g) = \frac{g_1^2}{8}[2l_2 \sqrt{g^2 - l_2^2} (l_2^2 - g^2) + g^4 \arctan \left( \frac{l_2}{\sqrt{g^2 - l_2^2}} \right) - g^4 \arctan \left( \frac{\sqrt{g^2 - l_2^2}}{l_2} \right)] \\
\]

\[
+ \frac{g_2^2}{2} [2l_2^2 - g^2] + gp_1p_3 \left[ g^2 \arctan \left( \frac{l_2}{\sqrt{g^2 - l_2^2}} \right) - g^2 \arctan \left( \frac{\sqrt{g^2 - l_2^2}}{l_2} \right) \right] \\
+ 2gp_2p_3 \left[ l_2 - \sqrt{g^2 - l_2^2} \right] \\
\] (3.56)

Finally, the expression in (3.54) can be transformed as described in equation (3.46) using (3.36) in order to obtain the PDF of the distance ratio, \( f_D(d) \) as follows

\[
f_D(d) = \left\{ 
  \begin{array}{ll}
    f_{D_1}(d) & , \quad (\sqrt{2l_1}) / \ell < d < (\sqrt{l_1^2 + l_2^2}) / \ell \\
    f_{D_2}(d) & , \quad (\sqrt{l_1^2 + l_2^2}) / \ell < d < (\sqrt{2l_2}) / \ell \\
    0 & , \quad \text{elsewhere}
  \end{array}
\right. \\
\] (3.57)

Where \( f_{D_1}(d) \) and \( f_{D_2}(d) \) are defined as in (3.58) and (3.59)
\[ f_{D_1}(d) = \frac{dl_p^2}{8} \left[ 2l_1 \sqrt{(dl)^2 - l_1^2} \left( (dl)^2 - 2l_1^2 \right) + 2dl_p^2 + \frac{dl_p^2}{2} \left( (dl)^2 - 2l_1^2 \right) + dl_p^2 \right] \]
\[ + \frac{dl_p^2}{2} \left( (dl)^2 - 2l_1^2 \right) + dl_p^2 \left[ (dl)^2 \arctan \left( \frac{\sqrt{(dl)^2 - l_1^2}}{l_1} \right) - (dl)^2 \arctan \left( \frac{l_1}{\sqrt{(dl)^2 - l_1^2}} \right) \right] \]
\[ + (dl)^4 \arctan \left( \frac{l_1}{\sqrt{(dl)^2 - l_1^2}} \right) - (dl)^4 \arctan \left( \frac{l_1}{\sqrt{(dl)^2 - l_1^2}} \right) \]
\[ \text{(3.58)} \]

\[ f_{D_2}(d) = \frac{dl_p^2}{8} \left[ 2l_2 \sqrt{(dl)^2 - l_2^2} \left( (dl)^2 - (dl)^2 \right) + 2dl_p^2 + \frac{dl_p^2}{2} \left( 2l_2^2 - (dl)^2 \right) + dl_p^2 \right] \]
\[ + \frac{dl_p^2}{2} \left( 2l_2^2 - (dl)^2 \right) + dl_p^2 \left[ (dl)^2 \arctan \left( \frac{l_2}{\sqrt{(dl)^2 - l_2^2}} \right) - (dl)^2 \arctan \left( \frac{l_2}{\sqrt{(dl)^2 - l_2^2}} \right) \right] \]
\[ + (dl)^4 \arctan \left( \frac{l_2}{\sqrt{(dl)^2 - l_2^2}} \right) - (dl)^4 \arctan \left( \frac{l_2}{\sqrt{(dl)^2 - l_2^2}} \right) \]
\[ \text{(3.59)} \]

### 3.5.3 Number of Conflicts Analysis

As the NoC is one of the parameters that has a major impact on the BS deactivation decision, the effect of the SIR threshold, \( \beta \), on the NoC in the system is investigated based on the analysis in sec. 3.5.1 and using the PDF in (3.57). If we assume a grid scenario is used with \( \mathcal{F} \) BSs and \( S_f \) UEs connected to BS \( f \). Therefore, the number of interfered users that are detected in the coverage area of BS \( f \) is given by

\[ L_1 = S_f (\mathcal{F} - 1) \left[ \Pr \left( \left( \frac{1}{\beta} \right) \leq D \leq 1 \right) \right] \]
\[ \text{(3.60)} \]

eq. (3.60) can be re-written as

\[ L_1 = S_f (\mathcal{F} - 1) \left\{ 1 - F_D \left( \left( \frac{1}{\beta} \right) \right) \right\} \]
\[ \text{(3.61)} \]

where \( F_D (d_{i,j}) \) is the cumulative distribution function (CDF) of \( f_D (d_{i,j}) \).

The number of \( f \)'s users interfered by neighboring cells is given by
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Figure 3.3: Impact of the SIR threshold ($\beta$) on the Number of Conflicts (NoC) under different values of inter-cell distances

\[ \mathcal{L}_2 = S_f \left\{ 1 - F_D \left( \left( \frac{1}{\beta} \right)^{\frac{1}{\beta}} \right) \right\} \]  

(3.62)

Where NoC$_f$ is equal to $\mathcal{L}_1$ added to $\mathcal{L}_2$. Fig. 3.3 illustrates the SIR threshold effect on the NoC under various distances between the cell of interest and the neighboring cells. The graph shows a gradual rise in the NoC as the SIR threshold increases. This is because increasing the threshold increases the number of detected interfered users which leads to higher NoC. It can be also noticed that the NoC is higher when the neighboring cells are closer to the cell of interest.

3.5.4 Reuse Efficiency Analysis

The reuse efficiency of the system is highly influenced by the SIR threshold, therefore, the effect of the SIR threshold, $\beta$, on the resource utilization of the system is analyzed in this section.

The PDF in (3.57) is used to study the resource utilization of the system.
Assuming a system with $F$ BS and $S_f$ user per BS, the number of detected users by BS $f$ is equivalent to

$$T_f = S_f + S_f (F - 1) \left\{ 1 - F_D \left( \left( \frac{1}{\beta} \right)^{\phi} \right) \right\}$$  \hspace{1cm} (3.63)

The amount of available resources for each user can be expressed as $N_k = N/T_f$, therefore, the allocated resources per BS is given by $N_f = N_k S_f$ which can be written as

$$N_f = \frac{N}{1 + (F - 1) \left\{ 1 - F_D \left( \left( \frac{1}{\beta} \right)^{1/\phi} \right) \right\}}$$  \hspace{1cm} (3.64)

Fig. 3.4 illustrates the impact of the SIR threshold on the reuse efficiency of the system. The SIR threshold has major influence on the NoC which is one of the key parameters that affect the reuse efficiency of the system. It is shown that increasing the SIR threshold lowers the reuse efficiency as a result of higher NoC in the system as shown the previous section.
### 3.5.5 Computational Complexity

An exhaustive approach is used as an optimal benchmark in which the impact of deactivating every BS on the sum of available resources is checked using an iterative process. On the contrary, the proposed SLCM method is capable of selecting BSs to find the optimal outcome without the need to perform an exhaustive search. To illustrate this, assume $M$ denotes the total number of BS, which means that the loop runs for $M$ times as there are $M$ different possibilities to test. This shows that the optimal benchmark approach requires a complexity of $O(M)$. On the other hand, the proposed SLCM method does not need iterations to search for the most appropriate small cells to be switched off.

### 3.5.6 Signaling Overhead

The total amount of information exchange between the FMS and the BS is given by

\[ d_s = d_{fi} + d_c \]  

(3.65)

Where the total number of bits required to send the interference map from BS $f_i$ to the FMS is denoted by $d_{fi}$. Assuming BS $f_i$ has a total of $S_i$ users and $J_i$ neighboring BS, then $d_{fi}$ is given by

\[ d_{fi} = S_i.d_m.J_i \]  

(3.66)

where $d_m$ denotes the number of bits necessary to encode the local interference map of each BS. The FMS needs the local interference map feedback from each BS which can be used by the system to extract some necessary information such as the NoC, the handover ratio, $\mathcal{H}$, and the number of served users, $S$. In case more than one candidate is detected, the received power of the candidate BS users needs to be fed back to the FMS

\[ d_c = \varrho.S_i.d_t \]  

(3.67)

Where $d_t$ denotes the number of candidate BS for deactivation and $\varrho$ is the total needed bits to send the CQI feedback which is given by 4 bits. On the other hand, the FMS does not need to send feedback to the BSs as the
allocation process is performed independently by each BS.

3.6 Results and Discussion

3.6.1 Homogeneous Network Simulation

The 10x10 grid model in Fig. 3.5 is used in this simulation to represent femtocells urban deployment where the size of each apartment is 10 m×10 m, [56]. It is assumed that one femtocell and one user are randomly and uniformly dropped around the center of each apartment. Moreover, a number of femtocells are activated at random apartments following a uniform distribution. The bit rate is calculated using adaptive modulation and coding (AMC) scheme discussed in sec. 3.2.4. The pathloss between femtocells and UEs is given by [33]

\[ PL_{i,k} = PL(d_0) + 10 \log_{10} \left( \frac{d_{i,k}}{d_0} \right) + X_e \]  \hspace{1cm} (3.68)

where \( d_{i,k} \) denotes the distance between BS \( i \) and UE \( k \), \( PL(d_0) \) is given
### Table 3.1: General LTE Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier ((f_c))</td>
<td>2.3 GHz</td>
<td>OFDM symbol period</td>
<td>(1.43 \times 10^{-4})s</td>
</tr>
<tr>
<td>Number of PRBs per sub-frames</td>
<td>25/50</td>
<td>FFT</td>
<td>512/1024</td>
</tr>
<tr>
<td>Number of resource elements per RB</td>
<td>12</td>
<td>Bandwidth per resource element</td>
<td>15 kHz</td>
</tr>
<tr>
<td>Number of subframes per frame</td>
<td>10</td>
<td>OFDM symbols per subframe</td>
<td>14</td>
</tr>
<tr>
<td>Thermal Noise Density</td>
<td>-174 dBm/Hz</td>
<td>Noise Figure</td>
<td>3 dB</td>
</tr>
</tbody>
</table>

by \(20 \log_{10}(4\pi d_0/\lambda)\) where \(d_0\) is the reference distance (1m) and \(\lambda\) denotes the signal wavelength. A bandwidth of 5 MHz is utilized and the remaining simulation parameters are shown in Tables 3.1 and 3.2.

The efficiency of the proposed SLCM method is evaluated compared to the Manchester technique, which is based on the method described in [33] in terms of using the interference map which is also applied in our method to indicate the interference between BSs and users. It uses similar assumptions as our system except that the SLCM algorithm is not applied. Therefore, this method is referred to as the Always-ON to show the gain achieved by the proposed SLCM with respect to the Always-ON system. The method is also compared with an optimal approach which provides an upper bound for the system performance. Since the objective is to maximize the overall capacity, the optimal approach evaluates the effect of switching off each BS in the system on the overall throughput in each iteration and determines the BS that maximizes the overall system capacity when switched off. Normally, the first deactivated BS is the one that is causing the highest NoC in the network and is more likely to make the maximum impact when switched off. Therefore the performance of the proposed method is tested by checking the
Table 3.2: Femtocell Network Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>5 MHz</td>
<td>Resource blocks (RB)</td>
<td>25</td>
</tr>
<tr>
<td>Pathloss exponent, $\varphi$</td>
<td>3</td>
<td>Log normal shadowing, $X_c$</td>
<td>8 dB</td>
</tr>
<tr>
<td>Number of resource elements per RB</td>
<td>12</td>
<td>Wall loss, $WL$</td>
<td>18 dB</td>
</tr>
<tr>
<td>Femtocell Tx Power</td>
<td>20 dBm</td>
<td>Femtocell UEs distribution Radius</td>
<td>10 m</td>
</tr>
<tr>
<td>Femtocell antenna gain</td>
<td>0 dBi</td>
<td>Fading channel</td>
<td>Rayleigh</td>
</tr>
</tbody>
</table>

effect of switching off the first BS which is illustrated as a benchmark in the results. The threshold $\beta$ is assumed to be 20 dB. Because SL techniques are very widely used for optimizing the power consumption in cellular systems, the method presented in [48] discussed in the related work will be used as a benchmark in the comparison, which represents a lower bound for the performance since it attempts to only activate the BSs necessary to serve the users requirements.

The mean data rate and the ECR are illustrated in figures 3.6 and 3.7 at various densities of femtocells. It can be seen from Fig. 3.6 that the data rate is significantly improved in the SLCM method in comparison to the Always-ON method. This results from the improved reuse efficiency which is an outcome of reducing the interference to the nearby cells by minimizing the quantity of unnecessary active femtocells. The gap in the performance between the proposed SLCM method and the Always-ON method is noticeably increased as the network becomes denser with an improvement of 20%, 24.5% and 34% at the densities of 7, 11 and 17 respectively. Fig. 3.7 shows that the proposed method is capable of preserving the improvement in data rate as it can be noticed that the ECR gap is increased when comparing the proposed and the Always-ON methods even at higher densities. Since the objective of the
benchmark method in [48] is to minimize the energy consumption, the data rate performance appears to be lower than the other methods. Fig. 3.8 illustrates a power consumption comparison between the proposed SLCM method and the other methods. Clearly, the proposed method consumes less power than the Always-ON as the overall power consumption is reduced when some hardware parts such as the power amplifier are switched off during SL [9]. On the other hand, the benchmark method achieves lower power consumption compared to the other methods as it switches off more BS. Fig. 3.8 illustrates the average throughput CDF assuming the number of femtocells deployed in the system is 7 femtocells. It is shown that applying the proposed SL method can remarkably improve the throughput performance with approximately 30% increase compared to the Always-ON method. This results from switching off the unnecessary femtocells that are causing high amount of disturbance in the surrounding environment which leads to significant reduction in the interference and allows the neighboring BS to utilize the frequency resources more efficiently. As can be seen from Fig. 3.10, the resource utilization is increased when the proposed method is applied due to the extra resources gained by deactivating the cells that causes the frequency reuse reduction in the network.

Users are associated with the BS that provides the highest received signal strength as all femtocells are assumed to use an open access policy. Fig. 3.11 shows a comparison between the three methods in terms of the total number of deactivated femtocells. Fig. 3.12 shows the ratio of dropped users vs. the total number of UEs in the system where it is shown that the ratio slightly increases at higher user densities as the proposed SLCM method aims to minimize the number of dropped UEs.

3.6.2 Heterogeneous Network Simulation

In this part, we consider a suburban model with a macrocell overlaid with 10 femtocells deployed in $10m \times 10m$ houses which are uniformly distributed within the macrocell coverage area [56]. A total of 30 UEs are deployed with $2/3$ of the UEs generated in hotspots around femtocells and the remaining UEs are positioned within the macrocell area in a random and a uniform manner [57]. A system bandwidth of 10 MHz is used in this simulation with 50 PRBs available for transmission. The macrocell and femtocells are equipped
Figure 3.6: Data rate per user performance comparison with varying femtocell densities

Figure 3.7: Energy efficiency performance comparison with varying femtocell densities
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Figure 3.8: Power saving performance comparison with varying femtocell densities

Figure 3.9: Average throughput cumulative distribution function
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Figure 3.10: Resource utilization comparison with varying femtocell densities

Figure 3.11: Number of Deactivated Femtocells Comparison
Figure 3.12: Dropped users ratio vs. the total number of users in the system

Table 3.3: Heterogeneous Network Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Resource blocks (RB)</td>
<td>50</td>
</tr>
<tr>
<td>Macrocell Tx Power</td>
<td>46 dBm</td>
</tr>
<tr>
<td>Femtocell Tx Power</td>
<td>20 dBm</td>
</tr>
<tr>
<td>Log normal shadowing, $X_r$</td>
<td>8 dB</td>
</tr>
<tr>
<td>Antenna Pattern</td>
<td>2 Rx and 2 Tx ports, STBC</td>
</tr>
<tr>
<td>Macrocell antenna gain</td>
<td>0 dBi</td>
</tr>
<tr>
<td>Femtocells per macrocell</td>
<td>10</td>
</tr>
<tr>
<td>Macrocell UEs distribution</td>
<td>289 m (Inter-Site distance= 500m)</td>
</tr>
<tr>
<td>Femtocell UEs distribution</td>
<td>10 m</td>
</tr>
<tr>
<td>Macro-Femto Minimum Separation</td>
<td>75 m</td>
</tr>
<tr>
<td>Macro-UE Minimum Separation</td>
<td>35 m</td>
</tr>
</tbody>
</table>
with two antennas space-time-block-code (STBC) and the Stanford university interim (SUI) path loss model for Terrain type C is used to model the pathloss between the macrocell and all UEs [58]

\[
PL_k^M = A + 10\sigma \log_{10} \left( \frac{d_{M,k}}{100} \right) + X_f + X_h + s + WL \tag{3.69}
\]

where \(A = PL(d_0 = 100), d_{M,k}\) is the distance between the macrocell and UE \(k, \sigma = 3.6 - 0.005h_M + \frac{20}{h_M} + \chi_a 0.59, X_f = 6\log \left( \frac{f_c}{2000} \right), X_h = 20\log_{10} \left( \frac{2}{h_k} \right)\) and \(s = \chi_b (8.2 + \chi_x 1.6)\) where \(\chi_a, \chi_b\) and \(\chi_c\) represent Gaussian random variables. \(h_M\) and \(h_k\) represent the macrocell and the receiver heights which are given by 30m and 2m respectively.

FFR is employed to mitigate interference based on [59] where the coverage area of the macrocell is divided into inner and outer regions based on the FFR threshold which is presumed to be 20dB above the noise level. The resources allocated to the inner and outer regions are \(N/2\) and \(N/2f_r\) respectively where \(f_r\) denotes the FFR reuse factor which is assumed to be 3. First, the SIRs to the macrocell and to the closest femtocell are determined by the UE which are denoted by SIR1 and SIR2 respectively, in case SIR1 is higher

Figure 3.13: Heterogeneous network average throughput CDF
than the FFR threshold, the UE is considered inner and is connected to the macrocell if $\text{SIR}_1 > \text{SIR}_2$ and to the femtocell otherwise. On the other hand, the UE is categorized as an outer UE if $\text{SIR}_1$ is less than the FFR threshold. The access threshold of the femtocells $\mu_0$, is adjusted to offload the macrocell UEs to the femtocells where $\mu_0$ is set to 12dB. Fig. 3.13 illustrates the average throughput CDF to show the performance of the proposed SL method compared to the Always-ON and the benchmark methods which shows superior performance of the proposed method as compared to the other techniques. It is noticed that the performance improvement is less evident in heterogeneous network compared to the homogeneous simulation. This is due to the deployment of femtocells which are randomly positioned in the coverage area of the macrocell which in turn reduces the overlapped regions causing the number of deactivated cells to diminish.

3.7 Chapter Summary

A novel sleep mode based resource management method is presented in this chapter to improve the capacity and the energy efficiency for heterogeneous networks. It was shown that performance improvements can be achieved by identifying the small cells that are positioned at undesirable spots and selecting them for deactivation. The results show that the proposed SLCM method can increase the capacity gain compared to the Always-on system with up to 34% and 15.6% improvement in the data rate and the energy efficiency performance respectively and the throughput CDF shows a 30% improvement. The PDF presented in this chapter has been derived and evaluated using standard numerical methods to accurately model the signal-to-interference ratio. The results also show that the proposed SLCM technique approaches the performance of the optimal benchmark with considerably lower computational complexity. However, one limitation of the SLCM method is the lack of proper user association for the users that are handed off the switched off cells as well as the problem of dropped users. The next chapter addresses these problems by proposing techniques to improve the user association in cellular networks.
Chapter 4

User Association in Heterogeneous Networks

4.1 Introduction

The previous chapter presented a resource management method enhanced with sleep mode technology for improving the capacity of cellular networks. It was found that a tremendous capacity gain can be achieved by proper selection of the BSs for SL mode. However, users of the switched off BSs are handed off to the neighboring cells that are offering the strongest received signal power without considering the load of such cells. In addition, a small percentage of users that are not settled in the overlapping areas with other cells are dropped out. This chapter addresses this issue by investigating novel user association techniques for improving the performance in cellular systems.

Some cellular association schemes have been suggested for cellular networks in the literature. In [61], the authors presented a radio resource management scheme for improving the energy efficiency in next generation (5G) networks. The proposed scheme aims to activate the smallest number of BSs and provides a framework for optimizing the users association and spectrum allocation jointly. The authors in [62], proposed a method based on Semi-Markov Decision Process (SMDP), where a distributed load-balancing and admission control algorithm is developed to improve the overall network

\*\*The material in this chapter has been partly published in [60].\*\*
throughput while imposing blocking probability constraints on users to control the performance degradation. The authors in [63], investigated a cellular association and handover scheme in femtocell networks to maximize the network throughput and fairness. In [64] and [65] the authors considered a cellular association scheme for heterogeneous deployment in which the cellular association is performed based on range expansion taking into consideration the transmit power variability between the macrocell and small cells.

Furthermore, the concept of coupled user association was dominant for decades in cellular systems where mobile users are bound to connect to the same BS in the UL and DL. Recent research trends begun to rethink this concept and investigate the benefits of UL/DL decoupling for improving the throughput gains [66]. Current research seems to validate this view such as the work described in [67], where the authors presented a decoupling method that takes into consideration parameters such as the UL pathloss and the cell loads. In [68], the authors discussed UL user association for optimizing users packet success rate using game theory. In [69], the authors introduced a mathematical model to investigate the impact of decoupling the UL from the DL association in multi-tier heterogeneous networks, where it was shown that minimum pathloss based UL association is an ideal strategy to improve the UL rate.

In addition to the UL/DL decoupling, incorporating transmission diversity can be greatly beneficial for improving the performance of cellular systems. With transmission diversity, users are allowed to be jointly processed by several interfering BSs rather than being restricted to connect with only one BS. The author in [70] presented a multi-point transmission technique for improving the UL capacity. Users transmit in the UL to a group of macrocells that are virtually connected to process the UL transmissions by cooperating with each other. In [71], the authors proposed an optimal spatial multiplexing scheme in which BSs are equipped with multiple antennas to improve the communication quality. The sum capacity of the UL and DL sessions are used as performance metrics and the BSs use multiple antennas to allow users to simultaneously transmit and receive to/from different antennas on parallel data streams in the UL and DL.

Motivated by the transmission power disparity of different tiers of cells
and the unbalanced load distribution that results from the unplanned deployment of small cells, this chapter proposes user association techniques for improving the performance of cellular networks. A method is introduced to optimize the user association taking into consideration the variable load distribution at different cells and the interference that generates as a result of manipulating the user association. The proposed association scheme is also integrated with the SLCM method presented in Chapter 3 to rectify the association of the users that are handed off from the switched off cells. Furthermore, an adaptive De-Coupling and Multi-BS association approach is proposed to allow flexible user association, in which the users can be associated with multiple BSs and/or decoupled from the DL association in order to grant users access to more resources. The association process is managed using an overlap checking technique that only approves the pairs that do not cause harmful interference which may result from increasing the re-utilization.

The chapter is structured into three main thematic sections with relevant subsections. Section 4.2 discusses the system model including details about the DL and UL transmission models. Section 4.3 introduces the interference-aware user association method for maximizing the network reuse efficiency. In section 4.4, the user association method in section 4.3 is combined with the SLCM technique presented in Chapter 3. In section 4.5, the adaptive decoupling and multi-BS association framework is presented to optimize the user association in the network. Section 4.6 analyzes the impact of the coverage on the users association. Section 4.7 provides results and discussion. Finally, a summary for this chapter is provided in section 4.8.

4.2 System model

A network featuring a macrocell and a set of small cells and users is considered. It is presumed that the network is perfectly synchronized and that time-division duplex (TDD) technique is employed which separates the UL and DL transmission in time and therefore the transmissions in one session do not interfere with the other \[72\]. Each user from the set \( \mathcal{K} \) is allowed to be associated with a maximum of two BSs in the DL and UL.
4.2.1 Downlink signal model

Assuming the DL received power from BS $i$ to user $k$ at PRB $n$ is denoted by $\Gamma_{i,k,n}$, the channel between $i$ and $k$ is referred to as $h_{i,k,n}$, $\eta_0$ is the noise power in PRB $n$ and $\Gamma_{j,k,n}$ is the interference power received from a neighboring BSs $j$ to user $k$ at PRB $n$. Then, the DL SINR achieved by user $k$ at PRB $n$ can be expressed as

$$\Upsilon_{dl}^{k,n} = \frac{\Gamma_{i,k,n}h_{i,k,n}}{\eta_0 + \sum_{j=1}^{B} \Gamma_{j,k,n}h_{j,k,n}}, \quad j \neq i. \quad (4.1)$$

It is presumed that all BSs in the system transmit at the maximum power level and the transmission power is distributed equally among PRBs.

Users connect to the BSs offering the strongest DL received power and $\alpha_{dl} \in \mathbb{R}^{B \times K}$ is a vector that indicates the DL association between BSs and users which is defined as

$$\alpha_{i,k}^{dl} = \begin{cases} 1 & \text{if user } k \text{ is connected to BS } i \\ 0 & \text{Otherwise} \end{cases} \quad (4.2)$$

4.2.2 Uplink signal model

In the UL, the received signal power by BS $i$ from UE $k$ at PRB $n$ is referred to as $\Gamma_{k,i,n}$ and the UL interference power received by BS $i$ from UE $u$ is represented by $\Gamma_{u,i,n}$. Thus, the UL SINR of user $k$ in PRB $n$ is given by [73]

$$\Upsilon_{ul}^{k,n} = \frac{\Gamma_{k,i,n}h_{i,k,n}}{\eta_0 + \sum_{j=1}^{B} \sum_{u=1}^{S_j} \Gamma_{u,i,n}h_{i,u,n}}, \quad j \neq i. \quad (4.3)$$

where $S_j$ is the set of users connected to BS $j$.

All UEs in the system are assumed to be transmitting at the maximum power level.

Furthermore, $\alpha_{ul} \in \mathbb{R}^{B \times K}$ denotes a vector representing the association between BSs and users in the UL which is defined similar to eq. (4.2).
4.3 Network capacity maximization

This section describes the network capacity maximization (NCM) user association method that aims at maximizing the reuse efficiency by discovering an optimal match between BSs and users considering the cell loads and the received signal power from nearby cells. To minimize the impact of interference caused by manipulating the association pairs, an interference-aware resource partitioning (IARP) scheme is implemented to find the optimal proportion of resources to be assigned to each user. In summary, the NCM scheme which is executed by the central unit, determines the user association and passes this information to the IARP scheme which distributes the resources among users. BSs then use this information to perform the resource allocation which is implemented independently by each BS using the CQI feedback from the users similar to sec. 3.4.5 in Chapter 3. Fig. 4.1 shows a simplified network model to illustrate the main concept of the NCM scheme. For instance, users associated with a highly loaded BS such $f_1$, can benefit if associated with less loaded BSs such as $f_2$ and $f_4$.

4.3.1 Interference-aware resource partitioning

The IARP scheme uses information extracted from the interference map $\zeta$, to distribute the available resources among users. The objective is to increase the resource utilization of users while avoiding conflicts between the interfering parties to reduce the effect of co-channel inter-cell interference.

According to the resource partitioning scheme in sec. 3.4.3, the initial number of resources that can be allocated to each user in the coverage range of a BS, denoted by $\Omega_i$, is calculated by dividing the available PRBs $N$, by the total number of served and interfered users detected by this BS.

The IARP scheme is then used to calculate the number of resource for each user in the system $\Psi_K$. Initially, users are assigned the maximum number of resources offered from their serving BSs. When a given user $k$ is detected in the coverage range of BS $j$, the number of resources used by $j$’s users which is determined by multiplying the number of served user $S_j$ by $\Omega_j$. User $k$ can be assigned the maximum number of resources offered from BS $i$ $\Omega_i$ if no overlap is detected between user $k$ and BS $j$’s users, which is determined by the following inequality.
Association criteria

This section defined the criteria used by the NCM user association scheme to select the association pairs in order to improve the overall network throughput.

Users initially associate with the BSs that are providing the strongest received signal power. Once the initial association is determined, the number of allocated resources per user $\Psi_k$ is determined as illustrated in the previous
section. The users that are positioned in the handover area are identified in the matrix $\Phi$ based on the SIR threshold $\beta$, where $\Phi \in \mathbb{R}^{B \times K}$

$$\Phi_{j,k} = \begin{cases} 
1 & \frac{\Gamma_{i,k,n}}{\Gamma_{j,k,n}} < \beta \\
0 & \text{Otherwise} \end{cases}, \quad \forall i, j \in B \land k \in K \quad (4.5)$$

where $\Phi_{j,k} = 1$ if BS $j$ happens to cover user $k$ within its area and is equal to 0 otherwise.

Users that are able to get higher amount of resources from their neighboring cells defined in (4.5) compared to those offered from their serving cells are identified in the matrix, $\Lambda$, where $\Lambda \in \mathbb{R}^{B \times K}$

$$\Lambda_{j,k} = \begin{cases} 
1 & \Omega_j > \Omega_i \\
0 & \text{Otherwise} \end{cases}, \quad \forall i, j \in B \land k \in K \quad (4.6)$$

The list in eq. (4.6) is reduced by measuring the potential achievable rate of users at their neighboring BSs specified in $\Lambda$, based on the available bandwidth and the signal-to-noise (SNR) ratio

$$C_{j,k} = \begin{cases} 
\Omega_j \cdot W \cdot \log_2 \left(1 + SNR_{j,k,n}\right) & \text{if } \Lambda_{j,k} = 1 \\
0 & \text{otherwise} \end{cases}, \quad (4.7)$$

where $C_{j,k} \in \mathbb{R}^{B \times K}$ denotes the capacity achieved by user $k$ if associated with BS $j$ and $SNR_{j,k,n}$ refers to the signal-to-noise (SNR) ratio from BS $j$ to user $k$. Note that the formula in eq. (4.7) is used to provide an estimation of the potential gain that can be achieved by a user from the neighboring BSs.

In case the capacity achieved at any neighboring BS $j$ is greater than the capacity achieved by the serving BS $i$ of user $k$, the matrix, $\omega \in \mathbb{R}^{B \times K}$, is updated to indicate the candidate association pairs

$$\omega_{j,k} = \begin{cases} 
1 & \text{if } C_{j,k} > C_{i,k} \\
0 & \text{Otherwise} \end{cases}, \quad \forall i, j \in B \land k \in K \quad (4.8)$$

After the potential association pairs are determined, the overlap test in eq. (4.4) is carried out to ensure that the additional resources to be occupied by the new association will not result in the frequency resources being overlapped with any interfering neighbors. For every association pair that pass
the overlap checking test, the impact of associating this pair on the overall network capacity $C_{tot}$ is measured

$$C_{tot} = \sum_{i=1}^{B} \sum_{k=1}^{S_i} \{\Psi_k \cdot W \cdot \log_2 (1 + SNR_{i,k,n})\} .$$

(4.9)

Finally, the association pair that leads the maximum increase in the overall network throughput is selected and $\alpha_{dl}$ and $\zeta$ are updated and the IARP scheme is applied based on the updated user association. The process repeats until the updated total capacity $C_{tot}'$ is not higher than the previous total capacity $C_{tot}$. The pseudo code in Algorithm 3 illustrates the NCM user association technique.
In this section, the SLCM technique presented in Chapter 3 is applied jointly with the NCM user association method to amend the association of the users belonging to the switched-off cells. According to the SLCM technique, users of deactivated BSs are handed off to neighboring BSs that provide the strongest received signal strength. However, this might cause load imbalance which may lead to some BSs being left underutilized and reduced QoS of the handed-off users, who suffer degraded signal quality and inefficient resource
Algorithm 3 NCM User Association

1: // Initialize
2: Generate $\alpha_{dl}'$ and $\zeta$
3: Calculate $\Omega_B$
4: // Identify candidate association pairs
5: for $k=1$ until $K$ do
6: for $j=1$ until $B$ do
7: if $\Delta_{j,k} = 1$ then
8: $C_{j,k} = \Omega_j.W.\log(1 + SNR_{j,k,n})$
9: if $C_{j,k} > C_{\alpha_{k,k}}$ then
10: $\omega_{j,k} = 1$
11: else
12: $\omega_{j,k} = 0$
13: end if
14: end if
15: end for
16: end for
17: // Select among candidate association pairs
18: while $C_{tot} > C_{\prime tot}$
19: for $u=1$ until $K$ do
20: for $f=1$ until $B$ do
21: if $\omega_{f,u} = 1$ and $\alpha_{f,k}' \neq 1$
22: $\alpha_{f,k}' = 1$
23: Update $\zeta$
24: Recalculate $\Omega_B$ and $\Psi_K$
25: if association pair $f$ and $u$ pass overlap test then
26: $C_{tot} = \sum_{i=1}^{B} \sum_{k=1}^{S_i} \Psi_k.W.\log(1 + SNR_{i,k,n})$
27: else
28: Reject association proposal between $f$ and $u$
29: end if
30: end for
31: end for
32: if $\max(C_{tot}) > C_{\prime tot}$ then
33: Final $\zeta$ and $\alpha_{dl}'$ update
34: end if
35: end while
utilization. Therefore, the NCM method is applied jointly with the SLCM to enhance the performance of handed-off users.

Fig. 4.2 shows a high-level flowchart to illustrate the joint NCM and SLCM scheme. First the SLCM method is implemented by running the deactivation tests to select the optimum number of BSs for switching off. The algorithm continues switching off BSs as long as the updated total resources $\Psi_{tot}$ exceeds the initial value $\Psi_{tot}'$, as illustrated in Fig. 4.2. After performing the SLCM method, the NCM user association scheme is applied to optimize the user association of the switched off BSs users and the rest of users in the network. The NCM association in Fig. 4.2 (b), is implemented as discussed in sec.4.3.

### 4.5 Adaptive De-Coupling and Multi-BS Association

The objective of the proposed adaptive de-coupling and multi-BS association framework is to optimize the user association such that the frequency reuse is maximized and the UL and DL rates are improved without deteriorating the QoS. Similar to the NCM scheme, the adaptive decoupling and multi-BS association scheme is executed by the central unit to determine the optimal association. The IARP method is then implemented to assign the resources to the users and the BSs use this information to perform the resource allocation.

#### 4.5.1 Coupling/Decoupling Association

This section discusses the coupling/decoupling association (CDA) method which determines whether users in the UL session remain associated with the same BS in the DL or decoupled and associated with another BS. The decoupling decision is undertaken based on the NCM association method and the coupling/decoupling of a user is determined relative to the capacity gain achieved when a user is decoupled from its original BS compared to the coupled case. Users initially connect with BSs based on the DL Max-RSS. The neighboring BSs of a particular user $k$ are then determined based on the noise rise [74]. In case the interference power caused by UE $k$ to BS $j$, $\Gamma_{k,j,n}$, exceeds the noise rise threshold, then UE $k$ is considered in proximity with BS $j$ and the matrix $\varpi \in \mathbb{R}^{B \times K}$ is used to demonstrates the proximity of users and BSs.
in UL where $\omega_{j,k} = 1$ means users $k$ is in proximity to BS $j$ and is equals to 0 otherwise.

Based on IARP, the frequency resources are partitioned among users and for each $\omega_{j,k} = 1$, the BSs that provide higher resource availability than the serving BS of user $k$ are identified in $\Lambda \in \mathbb{R}^{B \times K}$ similar to (4.6).

The achieved capacity for each candidate pair identified in $\Lambda$ is then measured as follows

$$C_{j,k} = \Omega_j W \log_2 (1 + SNR_{k,j,n}),$$ (4.10)

The set of association pairs that achieve higher capacity than the initial association pair are marked in the matrix $\omega \in \mathbb{R}^{B \times K}$, where $\omega_{j,k}$ is set to 1 when the achievable UL capacity at cell $j$ $C_{j,k}$ is higher than the capacity achieved from the initial association pair and is set to 0 otherwise. The sum throughput is then measured to prioritize the association pairs that maximize the overall network capacity

$$C_{tot} = \sum_{i=1}^{B} \sum_{k=1}^{S_i} \{ \Psi_k W \log_2 (1 + SNR_{k,i,n}) \}. $$ (4.11)
The process repeats until no further improvement in the network capacity can be achieved.

4.5.2 Single/Multi-BS Association

The Single/Multi-BS Association (SMBA) scheme determines whether users can connect to multiple BSs simultaneously or remain connected to only one BS in the UL and DL. Fig. 4.3 shows a simplified model to illustrates the concept of SMBA, since user \( u \) is located in the overlapped area between BSs \( i \) and \( f \), user \( u \) can be associated with \( f \) (in addition to \( i \)) if the additional resources occupied by \( u \) offered from \( f \) do not overlap with other neighboring users that might be affected by the interference. To ensure this, the list of users detected in the coverage area of BSs are determined based on the SIR threshold in the DL and on the noise rise threshold in the UL. In the DL session, the amount of resources offered from each BS to the users falling within their coverage range is determined in the matrix \( \delta \in \mathbb{R}^{B \times K} \)

\[
\delta_{j,k} = \begin{cases} 
\Omega_j & \text{if } \Phi_{j,k} = 1 \\
0 & \text{otherwise}
\end{cases}, \quad \forall i, j \in B \land k \in K
\]  

(4.12)

Similarly, the UL \( \delta_{j,k} \) is calculated based on \( \varpi \).

The association mode of a particular user \( k \) is determined by checking three conditions, in which \( k \) is allowed to be associated with multiple BSs in case none of these conditions are violated. The main target is to ensure that the additional occupied resources by the new association pairs do not cause harmful interference to the surrounding neighbors by orthogonalizing the resources between the interfering BSs/UEs. To demonstrate this, let \( f \) and \( u \) be a candidate association pair from \( \Phi \), the association between \( f \) and \( u \) can be granted when the three overlap checking conditions are satisfied

\[
\psi_{f,u} = \begin{cases} 
1 & \text{if } C_1 \cap C_2 \cap C_3 \iff 1 \\
0 & \text{otherwise}
\end{cases}
\]  

(4.13)

where \( C_1 \), \( C_2 \) and \( C_3 \) represent the conditions to check the orthogonality of resources and are listed as follows

\( C_1 \): The first condition checks that the additional resources offered from
BS \( f \) to user \( u \), \( \delta_{f,u} \) do not overlap with the resources already allocated to user \( u \), \( \lambda_u \) from its serving BS \( i \). The orthogonality is maintained by checking that the sum of \( \delta_{f,u} \) and \( \lambda_u \) do not exceed the total available resources \( N \) as follows:

\[
[\delta_{f,u} + \lambda_u] < N, \quad \forall f = 1, \ldots, B \quad \text{and} \quad u = 1, \ldots, K
\]

\((4.14)\)

**C2:** The second condition checks the \( B \)-dimension in the matrix \( \Phi \) to check that other BSs that cover \( u \) within their area are not affected by the new association between BS \( f \) and user \( u \).

\[
[\varrho_j + \delta_{f,u} + \lambda_u] < N, \quad \forall j, f = 1, \ldots, B \quad \text{and} \quad u = 1, \ldots, K
\]

where \( \varrho_j \) represents the amount of resources occupied by BS \( j \) UEs in which \( j \) is any BS (except of BS \( f \)) that happens to cover user \( u \) within its area (e.g., BS \( j \) from Fig. 4.3).

**C3:** checks the \( K \)-dimension in \( \Phi \) to make sure that other UEs interfered by BS \( f \) (e.g., user \( k \) from fig. 4.3) are not affected by the new association as follows:

\[
[\varrho_f + \delta_{f,u} + \lambda_k] < N, \quad \forall f = 1, \ldots, B \quad \text{and} \quad u, k = 1, \ldots, K
\]

\((4.16)\)

where \( \varrho_f \) denotes the total occupied resources by BSs \( f \) UEs and \( \lambda_k \) denotes the number of resources allocated to user \( k \), in which \( k \) is a user interfered by BS \( f \) as indicated in \( \Phi \).

The impact of associating the pairs that satisfy the conditions in (4.13) on the network capacity, \( C_{\text{tot}} \in \mathbb{R}^{B \times K} \) is determined for each \( \psi_{f,u} = 1 \) as follows

\[
C_{\text{tot}} = \sum_{f=1}^{B} \sum_{u=1}^{S_i} [\delta_{f,u}W \log_2 (1 + SNR_{f,u,n})]
\]

\((4.17)\)

The priority of selection is then given to the pair that maximizes \( C_{\text{tot}} \) and the process repeats to search for other association pairs until the capacity cannot be maximized further. The association conditions are applied for the UL
and DL except for a slight modification in condition 3 in eq. (4.16) in the UL session, where it is not required to sum $\lambda_k$ with $\phi_f$ and $\delta_{f,u}$ as users within BS $f$ coverage are not affected by the UL interference from user $u$.

4.6 Coverage analysis

The coverage range of BSs plays a key role in making the association decision as discussed in the previous section. Furthermore, the number of users within the coverage area of a BS is highly dependent on the SIR threshold $\beta$. Therefore, the impact of the SIR threshold on the percentage of users detected within the coverage range of a cell is investigated in this section. For simplicity, a DL scenario is considered where the received power from BS $i$ to user $k$ is given by $P_t d_{i,k}^{-\varphi}$ and the received interference power from a nearby BS $j$ to user $k$ is $P_t d_{j,k}^{-\varphi}$, $P_t$ denotes the transmission power, $d_{i,k}$ refers to the distance between BS $i$ and user $k$ and $\varphi$ is the pathloss exponent. Therefore, user $k$ is considered to be not located within the coverage area of BS $j$ if

$$\frac{P_t d_{i,k}^{-\varphi}}{P_t d_{j,k}^{-\varphi}} > \beta,$$  \hspace{1cm} (4.18)

Assuming all BSs transmit at the same power level, the term in (4.18) can be simplified to

$$\frac{d_{i,k}}{d_{j,k}} < \left( \frac{1}{\beta} \right)^{\frac{1}{\varphi}}$$  \hspace{1cm} (4.19)

where $d_{i,k}/d_{j,k}$ is the distance ratio between BSs $i$ and $j$ and user $k$ which will be referred to as $D$.

From Chapter 3, the PDF of the distance ratio, $f_D(d)$ is given by

$$f_D(d) = \begin{cases} f_{D_1}(d) , & \left( \sqrt{2}l_1 \right) / \ell < g < \left( \sqrt{l_1^2 + l_2^2} \right) / \ell \\
 f_{D_2}(d) , & \left( \sqrt{l_1^2 + l_2^2} \right) / \ell < g < \left( \sqrt{2}l_2 \right) / \ell \\
 0 , & \text{elsewhere} \end{cases}$$  \hspace{1cm} (4.20)

Where $f_{D_1}(d)$ and $f_{D_2}(d)$ are defined as
\[ f_{D_1}(d) = \frac{d^2 p^2}{8} \left[ 2l_1 \sqrt{(d\ell)^2 - l_1^2} \left( (d\ell)^2 - 2l_1^2 \right) + 2dlp_2p_3 \left[ \sqrt{(d\ell)^2 - l_1^2} - l_1 \right] \right] + \frac{d^2 p^2}{2} \left[ (d\ell)^2 - 2l_1^2 \right] + dlp_1p_3 \left[ (d\ell)^2 \arctan \left( \frac{\sqrt{(d\ell)^2 - l_1^2}}{l_1} \right) - (d\ell)^2 \arctan \left( \frac{l_1}{\sqrt{(d\ell)^2 - l_1^2}} \right) \right] + (d\ell)^4 \arctan \left( \frac{l_1}{\sqrt{(d\ell)^2 - l_1^2}} \right) - (d\ell)^4 \arctan \left( \frac{l_1}{\sqrt{(d\ell)^2 - l_1^2}} \right) \]

\[ (4.21) \]

\[ f_{D_2}(d) = \frac{d^2 p^2}{8} \left[ 2l_2 \sqrt{(d\ell)^2 - l_2^2} (l_2^2 - (d\ell)^2) + 2dlp_2p_3 \left[ l_2 - \sqrt{(d\ell)^2 - l_2^2} \right] \right] + \frac{d^2 p^2}{2} \left[ 2l_2^2 - (d\ell)^2 \right] + dlp_1p_3 \left[ (d\ell)^2 \arctan \left( \frac{l_2}{\sqrt{(d\ell)^2 - l_2^2}} \right) - (d\ell)^2 \arctan \left( \frac{\sqrt{(d\ell)^2 - l_2^2}}{l_2} \right) \right] + (d\ell)^4 \arctan \left( \frac{l_2}{\sqrt{(d\ell)^2 - l_2^2}} \right) - (d\ell)^4 \arctan \left( \frac{\sqrt{(d\ell)^2 - l_2^2}}{l_2} \right) \]

\[ (4.22) \]

Assume there are \( f \) BSs and \( S_f \) users per BS, then the number of users detected in the coverage of BS \( f \) can be expressed as

\[ \mathcal{U}_f = S_f + S_f (f - 1) \left\{ 1 - F_D \left( \left( \frac{1}{\beta} \right)^{\frac{1}{2}} \right) \right\} \]

\[ (4.23) \]

where \( F_D (d_{i,j}) \) represents the CDF of \( f_D (d_{i,j}) \). The ratio of users located in the coverage range of BS \( f \) is given by \( \mathcal{U}_f / S_f (f - 1) \).

Fig. 4.4 shows that the percentage of users in the handover region can be controlled by varying \( \beta \). It is noticed that at higher thresholds, the percentage of users located in the coverage area of the cell is increased as a more users are detected in the coverage area. The percentage is also seen to increase when the distance between the cell of interest and the neighboring cells is reduced.

### 4.7 Capacity Upper Bound

Consider a network with a reference BS, \( B_0 \) at the origin \((0, 0)\) and 6 co-channel interferers \( B_1, \ldots B_6 \) located at fixed distances from \( B_0 \). A reference user is located at random position \((r_0, \theta_0)\) within the area of \( B_0 \). The mean capacity of the reference user is generally expressed as
CHAPTER 4. USER ASSOCIATION IN HETEROGENEOUS NETWORKS

Figure 4.4: Impact of the SIR threshold ($\beta$) on the percentage of users in the handover area

$$C = \mathbb{E} [\log_2 (1 + \gamma_0)] \quad (4.24)$$

where the $\gamma_0$ is the SINR which is defined by

$$\gamma_0 = \frac{P_0 h r_0^{-\varphi}}{\eta_0 + \sum_{b=1}^B P_b h r_b^{-\varphi}} \quad (4.25)$$

where $P_0$ denotes the required transmission power and $P_b$ is the transmission power of the $b^{th}$ co-channel interferer which are assumed to be identical. $r_0$ denotes the distance between the reference BS and the reference user and $r_b$ is the distance between the reference user and the $b^{th}$ co-channel interferer.

The upper bound on the Shannon capacity, $C$ can be obtained using Jensen’s inequality [75]

$$C \leq \log_2 (1 + \mathbb{E} (\gamma_0)) \quad (4.26)$$

Evaluating the expression in (4.26) requires measuring the average of
From [76], the distribution of the reference user in the cell-edge region is given by

\[
\begin{align*}
   f_{r_0}(r_0) &= \begin{cases} 
    \frac{2r_0}{R^2 - R_0^2}, & R_0 < r_0 < R \\
    \frac{2r_0}{R_0^2}, & 0 < r_0 < R_0
   \end{cases} 
\end{align*}
\] (4.27)

where \( R \) denotes the cell radius and \( R_0 \) is the radius of the inner area of the cell.

Using (4.27), the average of \( r_0^{-\varphi} \) can be calculated as follows [77]

\[
\mathbb{E}(r_0^{-\varphi}) = \int_0^\infty r_0^{-\varphi} \cdot f_{r_0}(r_0) \cdot dr_0
\] (4.28)

which can be expressed as

\[
\mathbb{E}(r_0^{-\varphi}) = \int_{R_0}^R r_0^{-\varphi} \cdot \frac{2r_0}{R^2 - R_0^2} \cdot dr_0
\] (4.29)

which gives

\[
\mathbb{E}(r_0^{-\varphi}) = 2 \left( \left( -R^2 - \varphi \right) + \left( R_0^2 - \varphi \right) \right) / \left( \left( R^2 - R_0^2 \right) \cdot (\varphi - 2) \right)
\] (4.30)

The distance between the \( b^{th} \) co-channel interferer and the reference user is given by [76]

\[
r_b = \sqrt{D^2 + r_0^2 - 2 \cdot r_0 \cdot D \cdot \cos (\theta_b + \phi_b)}
\] (4.31)

where \( D \) and \( \phi_b \) represent the distance and the angle between the \( B_0 \) and the \( b^{th} \) interferer respectively, \( (r_b, \theta_b) \) is the polar coordinates of the \( b^{th} \) interferer related to the reference user. Based on (4.31), the average of \( r_b^{-\varphi} \) can be obtained as follows

\[
\mathbb{E}(r_b^{-\varphi}) = \mathbb{E}\left( \left( \sqrt{D^2 + r_0^2 - 2 \cdot r_0 \cdot D \cdot \cos (\theta_b + \phi_b)} \right)^{-\varphi} \right)
\] (4.32)

which can be written as
Figure 4.5: Upper bound for the Shannon capacity

\[ \mathbb{E} \left( r_b^{-\phi} \right) = \int_{r_0}^{R} \int_{0}^{2\pi} \left( \sqrt{D^2 + r_0^2 - 2r_0D \cos (\theta_b + \phi_b)} \right)^{-\phi} f_{r_0}(r_0) f(\theta_b) \, dr_0 \, d\theta_b. \]  (4.33)

The distribution of \( f_{\theta_b}(\theta_b) = \frac{1}{2\pi} \) where \( 0 \leq \theta_b \leq 2\pi \). The expression in (4.33) does not have a closed-form solution and therefore the average can be obtained using numerical integration methods.

The average of \( \mathbb{E} (\gamma_0) \) can be obtained as follows

\[ \mathbb{E} (\gamma_0) = \frac{\mathbb{E} (r_0^{-\alpha})}{\eta_0 + \sum_{b=1}^{B} \mathbb{E} (r_b^{-\alpha})} \]  (4.34)

The upper bound of \( C \) can be obtained by substituting (4.34) in (4.26) and the theoretical upper bound for the Shannon capacity is illustrated in Fig. 4.5.
4.8 Results and discussion

4.8.1 Homogeneous network simulation

The performance of the proposed user association methods is evaluated using the $10 \times 10$ grid model. Users are randomly and uniformly distributed in the grid with an average of two users per cell. The data rate is evaluated using the AMC technique and the pathloss model presented in Chapter 3 sec. 3.6.1 is used to model the pathloss between BSs and users in the homogeneous network. The remaining simulation parameters are shown in Tables 3.1 and 3.2 from Chapter 3.

To evaluate the performance of the NCM method, the Manchester technique described in [33] is considered as a reference approach which uses the conventional Max-RSS cellular association. In Max-RSS, the user association is performed based on the received powers which is an integral part of path loss and shadowing. In addition, the conventional resource partitioning (CRP) discussed in chapter 3 in sec 3.4.3 is used to be compared with the IARP method. The IARP scheme is tested with the standard Max-RSS cellular association and with the proposed NCM association technique. Furthermore, the reuse-1 system is used as a benchmark for comparison. In reuse-1, each cell utilizes the entire available resources without applying RRM to account for co-channel inter-cell interference.

Fig. 4.6 illustrates the average data rate performance of the NCM scheme evaluated at different densities of femtocells. It can be seen that the NCM technique can slightly improve the average rate performance compared to the Max-RSS user association. This is due to the extra gain achieved by re-associating users to the cells offering more resources which increases the resource utilization and reduces the traffic from highly loaded cells. This improvement can be achieved without sacrificing the minimum bit rate performance which remains almost similar as depicted in Fig. 4.7, this indicates that the IARP method is capable of increasing the reuse efficiency without deteriorating the QoS. The result also shows a considerable improvement when IARP is applied compared to the CRP approach when both methods are using Max-RSS user association due to the ability of the IARP resource allocation technique to increase the resource utilization. It is worth noting that as the density of femtocells increases, the performance of the IARP scheme
gradually improves compared to the CRP approach. This is because of the increased handover opportunities that result from the increased overlapped areas between cells in dense femtocell deployment. On the other hand, this improvement is seen to slightly decay at very dense deployment (e.g., 15 Femtocells) due to the high interference that restricts the resource utilization. Fig. 4.7 also shows that minimum bit rate performance of the joint NCM and IARP is slightly affected which proves that in addition to improving overall network throughput, the NCM technique is able to maintain good QoS for cell-edge users.

It is noticed from Fig. 4.6 that at higher densities of femtocells, the reuse-1 technique is achieving better average data rate performance compared to the other techniques. This improvement is achieved by the inner users with good channel conditions which are not exposed to high co-channel inter-cell interference as BSs are allowed to utilize the entire available resources without considering inter-cell interference. On the other hand, Fig. 4.7 shows that the reuse-1 system is achieving very poor minimum data rate performance compared to the other schemes since the cell-edge users are highly exposed to the interference from neighboring cells in the lack of inter-cell interference management. Fig. 4.8 shows the average throughput CDF with 7 BSs deployed and two users per cell where the NCM method shows superior performance compared to the other methods.

Fig. 4.9 shows the average rate performance of the joint NCM and SLCM technique. The comparison shows the performance of the SLCM method compared with the Always-ON approach (i.e. No SLCM) discussed in Chapter 3 in addition to the joint SLCM and NCM technique. The results are evaluated by considering variable number of users per cell with one user per femtocell in Fig. 4.9 (a) and two users per femtocell in Fig. 4.9 (b). It is seen that with less deployed users, the performance gap between the SLCM and the always-ON system is higher. This is because the gain from switching off BSs is higher when there are less users in the system. In other words, in the joint SLCM and NCM scheme, no users are being dropped off and therefore cell switch off is only performed when all the connected users of the BS selected for switch off are located in the handover area with other cells. Therefore, increasing the number of users in the system limits the switching off process which in turn affects the data rate. Furthermore, the SLCM and NCM
method data rate improvement seem to gradually increase as the density of femtocells increases. This is because of the limited number of overlapping regions in sparse deployment which restrict the handover process whereas at denser deployment, more overlapping regions are created making it easier for users to be handed-off to nearby cells.

The proposed Adaptive Decoupling and Multi-BS association method is evaluated and compared to benchmarks techniques. Since the DL rate is not affected by the decoupling, as users in the DL follow the Max-RSS association policy, the CDA method is used to evaluate the UL rate. Furthermore, a Single-BS Association (SBA) approach is used as a benchmark to show the gain achieved by the SMBA method. In SBA, users are allowed to connect to only one BS based on the Max-RSS strategy in the DL and on the CDA method in the UL. In addition, all methods use IARP scheme to perform the resource allocation.

Fig. 4.10, shows the DL data rate per user performance vs. the total number of deployed femtocells. The figure compares the performance of the proposed SMBA with SBA where it is shown that the proposed method can achieve remarkable improvement compared to SBA due to the increased resource utilization in the system. It can also be noticed that the performance gap between the SMBA method and SBA reduces as the number of BSs increase due to the increased interference which limits the resource utilization at high densities. The methods are also evaluated by varying the SIR threshold $\beta$. According to the Manchester method described in [33], higher $\beta$ cause the data rate to reduce as BSs detect more interfered neighboring users within their coverage which cause BSs to decrease their resource utilization to avoid the interference. The result shows that the performance gap between the two thresholds is wider in SBA than in SMBA. This is because SMBA provides better resource utilization especially at low femtocell density, where the interference is lower and the impact of higher $\beta$ values becomes less significant. However, as the number of cells increase, the interference becomes higher as a result and the data rate reduces when higher thresholds are used.

Fig. 4.11 shows the UL average rate per user performance comparison at various femtocell densities. To show the gain achieved from decoupling the UL user association from the DL association, the SBA is evaluated with coupled and decoupled associations separately where it is shown that about 12%
improvement can be achieved by decoupling the UL association from the DL. The figure also shows that the proposed adaptive CDA and SMBA method provides significant data rate improvement especially at lower densities of femtocells.

Fig. 4.12 illustrates the CDF of the UL user throughput which is seen to be considerably improved with the proposed method due to the increased resource utilization.

### 4.8.2 Heterogeneous network simulation

This part considers a macrocell network overlaid with 10 outdoor picocells uniformly distributed in the coverage area of the macrocell. A total of 30 UEs are deployed with 2/3 of the UEs generated in hotspots within a 40 m radius from the picocells and the rest of the users are randomly and uniformly dropped within the macrocell coverage [57]. A 10 MHz bandwidth is utilized with 50 PRBs dedicated for data transmission. The performance of the proposed method is evaluated in heterogeneous network scenario compared to state-of-art techniques in which all techniques apply small cell biasing to
Figure 4.7: Minimum data rate performance comparison of NCM scheme with 2 UEs per femtocell

Figure 4.8: Cumulative distribution function of the average throughput comparison with 2 UEs per femtocell
Figure 4.9: Performance of joint NCM and SLCM schemes. (a) 1 user per femtocell, (b) 2 users per femtocell
Figure 4.10: DL data rate per user performance comparison between SBA and SMBA schemes with 2 UEs per femtocell

Figure 4.11: UL data rate per user performance of adaptive CDA and SMBA scheme with 2 UEs per femtocell
offload traffic to the small cells. To manage the cross-tier interference, frequency domain eICIC scheme is used where resources are orthogonalized between the two layers in the frequency domain. A joint resource partitioning and offloading scheme is performed where a fraction of resources to be used by the macrocell is determined according to the total offloaded users [78].

Fig. 4.13 shows the average DL network throughput performance. The proposed NCM association is compared with the Max-RSS association in addition to the eICIC scheme which is used as a benchmark with an almost blank subframe (ABS) ratio of 50% [79]. Note that all schemes including the eICIC method apply range extension bias of 12 dB to offload the traffic from the macrocell to the small cells. The figure shows that the proposed NCM association technique provides superior performance in comparison with the other schemes with around 20% improvement when compared with the Max-RSS association. The reason for this improvement is that in the presence of small cells, the macrocell users are now able to associate with the underutilized small cells where they enjoy a wider range of frequency resources compared to the resources offered from the overloaded macrocell. Furthermore, UEs of loaded small cells may take advantage of the neighboring less loaded
### Table 4.1: Simulation Parameters [55]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier ($f_c$)</td>
<td>2.3 GHz</td>
<td>Bandwidth</td>
<td>5/10 MHz</td>
</tr>
<tr>
<td>Resource blocks (RB)</td>
<td>25/50</td>
<td>Thermal Noise Density</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>OFDM symbol period</td>
<td>$1.43 \times 10^{-4}$ s</td>
<td>Log normal shadowing</td>
<td>8 dB</td>
</tr>
<tr>
<td>Number of Macrocells</td>
<td>1</td>
<td>Number of Picocells</td>
<td>10</td>
</tr>
<tr>
<td>Macrocell Tx Power</td>
<td>46 dBm</td>
<td>Picocell Tx Power</td>
<td>30 dBm</td>
</tr>
<tr>
<td>Femtocell Tx Power</td>
<td>20 dBm</td>
<td>Macrocell UEs distribution Radius</td>
<td>289 m (Inter-Site distance=500m)</td>
</tr>
<tr>
<td>Picocell UEs distribution Radius</td>
<td>40 m</td>
<td>Femtocell UEs distribution Radius</td>
<td>10 m</td>
</tr>
<tr>
<td>Minimum Distance Macro-Pico</td>
<td>75 m</td>
<td>Minimum Distance Pico-Pico</td>
<td>30 m</td>
</tr>
<tr>
<td>Minimum Distance Macro-UE</td>
<td>35 m</td>
<td>Minimum Distance Pico-UE</td>
<td>10 m</td>
</tr>
</tbody>
</table>
Figure 4.13: Cumulative distribution function of the heterogeneous network DL throughput

Figure 4.14: Cumulative distribution function of the heterogeneous network UL throughput
small cells and associate with them to acquire more resources.

Fig. 4.14 shows the average UL throughput performance. A comparison between coupled, decoupled and pathloss based association in conducted. In coupled association, users connect with BSs based on the DL Max-RSS association whereas in decoupled association, the UL association is decoupled from the DL association and the association is performed based on the coupling/decoupling association (CDA) method. The method discussed in [80] is also used as a benchmark for comparison, where users connect to the BS with the minimum pathloss. It can be seen that the proposed decoupling approach provides significant improvement compared to the coupled association since following the DL association in the UL is inefficient where the majority of users will connect to macrocell due to the high transmission power which increase the traffic load on the macrocell and leaves the small cells underutilized. However, when the proposed decoupling is applied, the traffic is offloaded from the macrocell and better utilization of resources can be achieved by connecting to the small cells. Furthermore, the proposed decoupling outperforms the pathloss based association approach since in pathloss based association, users associate with the cells with the minimum pathloss
without considering other factors such as the load of the cells whereas the proposed decoupling takes the cell load into consideration to make the decoupling decision.

Fig. 4.15 shows the impact of varying the small cell density within the macrocell coverage on the UL mean throughput. It can be seen that as the number of deployed small cell increase, the average rate increases. This is because, increasing the number of small cells leads to more users offloaded from the macrocell to the small cells in which they are granted more resources compared to the resources offered from the congested macrocell. Additionally, at higher density of small cells, the number of overlapped cell boundaries increase making it easier for users to be re-associated with neighboring cells.

4.9 Chapter summary

This chapter investigated novel user association techniques for improving the throughput and QoS in cellular networks. Performance improvements can be achieved by careful identification of the optimal BSs and users combinations and forming these pairs in such a way that improves the overall network gain. It was shown that the proposed IARP and NCM user association improves the overall system throughput without compromising the QoS. Furthermore, with adaptive decoupling and multi-BS association method, the network frequency reuse is remarkably improved due to the increased amount of resources allotted to users which is carefully managed using the overlapping checking technique. The results show that a significant gain can be achieved with the proposed adaptive decoupling and multi-BS association method with respect to the other benchmarks and state-of-art techniques. It was also observed that the impact of decoupling the users in the UL and DL is more significant in the heterogeneous network scenario due to the transmission power disparity of the cells belonging to different tiers. Furthermore, from a co-tier perspective, the proposed decoupled association is more effective at higher density of small cells because of the increased overlapped regions at higher densities, which provides more flexibility for users to be handed-off to less loaded cells.
Chapter 5

Multi-Level Interference Mapping

5.1 Introduction

As shown in the previous chapters, the SIR threshold is employed to determine the potential conflicts between BSs and users in the network. The results showed a trade-off between selecting high and low thresholds where using low thresholds lead to maximizing the throughput while higher thresholds can be used for enhancing the QoS. However, selecting predefined thresholds might not be optimal especially when multiple objectives are required to be optimized.

This chapter proposes a method to alleviate this trade-off by introducing an interference mapping strategy that characterizes the level of interference experienced by users from the surrounding BSs in order to improve both the QoS and the overall throughput of cellular networks\(^1\). More specifically, a multi-level interference map is constructed by setting upper and lower interference bounds for individual users to exploit their channel variability; the BSs transmission power can be adapted based on this map to guarantee that the QoS of the cell-edge users is unaffected by the interference that result from increasing the network resource utilization.

There has been a considerable amount of research on interference mapping in femtocell networks. The majority of these studies are based on a predefined threshold that is used to map the interference between BSs and users as in [33]. The work in [36] introduced a graph-based method to map

\(^1\)The majority of work presented in this chapter has been published in [81].
the interference between between femtocells and users. The list of neighboring femtocells are identified according to a certain threshold, which represent the minimum required SINR per user. To enhance the performance of cell-edge users, the adjacent femtocells that are connected in the interference graph, are allocated in orthogonal sub-bands. The authors in [34] presented a resource allocation approach in which femtocells estimate the sub-channels usage probability and exchange this information with neighboring cells. Femtocells then measure the quality of sub-bands based on the usage probability as well as a sub-band quality indicator, which is determined based on the amount of interference experienced which is defined based on maximum and minimum SINR thresholds.

The chapter is organized as follows. Section 5.2 discusses the proposed multi-level interference mapping approach. Section 5.3 presents the simulation model and a discussion of the results. Finally, section 5.4 summarizes the contributions and results introduced in this chapter.

5.2 Multi-Level Interference Mapping Framework

5.2.1 The Interference Level Map Approach

The interference level map is constructed to reveal the level of interference that users are experiencing from surrounding BSs. The map determines whether users belonging to interfering BSs should be banned to reuse similar resources in the frequency domain, allowed to reuse the frequency resources, or the transmission power of the aggressor BSs should be adapted to mitigate the interference.

To construct the interference level map, the received signal strength, $\Gamma_{i,k,n}$, from femtocell $i$ to its connected user $k$ is measured by users. The upper and lower bounds of the interference for each user are then calculated by femtocells based on $\Gamma$ reported by UEs, using two thresholds $\gamma_1$ and $\gamma_2$, which represent the maximum and minimum SINRs that can be supported by the standard modulation and coding schemes [82]. The upper and lower bounds on the interference are are given by

$$\phi_{lower}^k = \frac{\Gamma_{i,k,n}}{\gamma_1}$$

(5.1)
where \( \phi_{\text{lower}}^k \) denotes the lower bound of interference experienced by user \( k \), which represents the maximum tolerable interference in order to achieve the target SINR denoted by \( \gamma_1 \) where \( \phi_{\text{lower}} = [\phi_{\text{lower}}^1, \ldots, \phi_{\text{lower}}^k, \ldots, \phi_{\text{lower}}^K] \).

In other words, the interference received by UE \( k \) from a neighboring BS \( j \) is considered negligible in case \( \Gamma_{j,k,n} \) is below \( \phi_{\text{lower}}^k \). On the other hand, \( \phi_{\text{upper}} = [\phi_{\text{upper}}^1, \ldots, \phi_{\text{upper}}^k, \ldots, \phi_{\text{upper}}^K] \) represents the upper bound of the interference experienced by \( k \) above which the interference is classified significant and will cause the signal quality of user \( k \) to drop below the minimum allowed SINR \( \gamma_2 \). It is assumed that the interference power is much more significant compared to the background noise and therefore the effect of the noise is ignored in equations (5.1) and (5.2).

Given this information, BS \( i \) constructs its local interference level map \( \xi_i \in \mathbb{R}^{B \times S_i} \) to indicate the intensity of interference between their connected users and the neighboring femtocells. The upper and lower bounds in (5.1) and (5.2) are used to construct this map as follows

\[
\xi_i(j,k) = \begin{cases} 
0 & \Gamma_{j,k,n} < \phi_{\text{lower}}^k \\
1 & \phi_{\text{lower}}^k < \Gamma_{j,k,n} < \phi_{\text{upper}}^k \\
x & \Gamma_{j,k,n} > \phi_{\text{upper}}^k 
\end{cases} \tag{5.3}
\]

The values 0, 1 and \( x \) are integer values used to indicate the interference intensity. \( \xi_i(j,k) = 0 \) indicates that the interference power from the neighbor BS \( j \) to user \( k \) is negligible as it’s below the lower interference bound \( \phi_{\text{lower}}^k \), and therefore has no impact on the signal quality of user \( k \). In this case, the frequency resources occupied by \( k \) can be reused with the resources occupied by BS \( j \) without the need to impose transmission power constraints on BS \( j \). \( \xi_i(j,k) = 1 \) means that the resources occupied by user \( k \) can be reused by the neighboring BS \( j \) implied that certain power constraints are applied on \( j \). Finally, \( \xi_i(j,k) = x \) indicates that user \( k \) receives excessive interference from BS \( j \) and therefore it is strictly forbidden to reuse the resources in this case.

Every time a BS updates its local interference map \( \xi \), it then reports the updated map to the FMS through the back-haul which maintains a global interference level map of all conflicting BSs which is denoted by \( \xi \in \mathbb{R}^{B \times K} \).
Figure 5.1: Multi-level interference mapping illustration. (a) Example Scenario, (b) Interference level map, (c) Instantaneous interference level map, (d) Allocation map

Fig. 5.1 illustrates a simplified scenario to illustrate the concept of the MLIM technique. The interference level map in fig. 5.1 (b) shows the level of interference between BSs and users. User $u_2$ served by $f_2$ is assumed to be receiving excessive interference for BS $f_1$, therefore, the users served by $f_1$ (e.g., $u_1$) is not allowed to reuse the same resources occupied by $u_2$. Assume $u_2$ is receiving moderate interference from BS $f_3$, then $f_3$ users (e.g., $u_4$) can reuse resources occupied by $u_2$ provided that power constraints are enforced on $f_3$ on the resources occupied by $u_2$ as shown in fig. 5.1 (d).

5.2.2 Initial Resource Allocation

The resource allocation is performed based on the interference level map, $\xi$. Initially, the number of detected users that satisfy the conditions $\Gamma_{j,k,n} > \phi^k_{upper}$ and $\phi^k_{lower} < \Gamma_{j,k,n} < \phi^k_{upper}$ discussed in (5.3) are determined for each BS; the number of detected interfered users of BS $i$, $I_i$ is given by
\[ I_i = \sum_{k=1}^{K} \{\xi(k, i) = 1\} + \sum_{k=1}^{K} \{\xi(k, i) = x\} \quad (5.4) \]

Note that \( I_i \) represent the users interfered by BS \( i \) excluding the served users which are associated with the BS based on the Max-RSS association policy.

The initial resources a BS can offer each of its users is calculated by dividing the total available resources by the number of served users \( S_i \) and the number of detected users of BS \( i \) determined from eq. (5.4), which is given by \( \Omega_i = N/T_i \), where \( T_i \) is the total users detected by BS \( i \) which is given by \( T_i = S_i + I_i \). After determining the number of resources for each BS \( \Omega_B \), the number of resources per user \( \Psi_k \) is then measured as discussed in Chapter 3 sec. 3.4.3.

Given \( \Psi_k \), the resource allocation is performed using the CQI feedback reported by users in order to select the preferred PRBs. The allocation matrix, \( A \in \mathbb{R}^{K \times N} \), is updated according to the placement of users in PRBs.

\[
A_{k,n} = \begin{cases} 
1 & \text{k is allocated in PRB n} \\
0 & \text{otherwise} 
\end{cases} \quad (5.5)
\]

Throughout the allocation process, the instantaneous interference level map, \( \Theta \in \mathbb{R}^{K \times N} \), is updated based on \( \xi \) to indicate the level of interference for users at the corresponding PRBs

\[
\Theta_{k,n} = \begin{cases} 
0 & \text{n is available for k} \\
1 & \text{n is conditionally available for k} \\
x & \text{n is strictly forbidden for k} 
\end{cases} \quad (5.6)
\]

This procedure is illustrated in more details in algorithm 4.

### 5.2.3 Transmission Power Adaptation

Once the initial resource allocation is performed, the power adaptation algorithm is implemented to maximize the reuse efficiency and overall throughput. This can be achieved by utilizing the resources that are conditionally available for users, where the interference power received is between the lower
Algorithm 4 Initial Resource Allocation

1: Calculate $\Psi_k$
2: for $i = 1$ until $B$
3:   for $k = 1$ until $S_i$
4:     Based on CQI report from $k$, select $\Psi_k$ PRBs from $A_{k,n}$ at any $\Theta_{k,n} = 0$
5: for $m = 1$ until $B$
6:   if $i \neq m$
7:     for $g = 1$ until $K$
8:       if $g \notin S_i$
9:         if $\xi_{i,g} = 1 \lor \xi_{m,k} = 1$ then
10:            $\Theta_{g,n} = \Theta_{g,n} \lor A_{k,n}$  $\forall n \in N$ and $g \in K$ and $g \neq k$
11:         else if $\xi_{i,g} = x \lor \xi_{m,k} = x$ then
12:             $\Theta_{g,n} = x$  $\forall n \in N$ and $g \in K$ and $g \neq k$
13:         end if
14:     end if
15:   end for
16: else
17:     $\Theta_{a,n} = \Theta_{a,n} \lor A_{k,n}$  $\forall n \in N$ and $a \in S_i$ and $a \neq k$
18: end if
19: end for
Algorithm 5 Transmission Power Adaptation
1: for $f = 1$ until $B$ do
2:     for $k = 1$ until $S_i$ do
3:         for $n = 1$ until $N$ do
4:             if $\Theta_{k,n} = 1$ then
5:                 $z =$ index of users assigned in PRB $n$
6:                 $\phi_{\text{lower}}^n = \max(z, \phi_{\text{lower}})$
7:                 $\rho_{f,k,n} = \rho_{f,k,n} - \phi_{\text{lower}}^n$
8:                 $A_{k,n} = 1$
9:             for $m = 1$ until $B$ do
10:                if $i \neq m$ then
11:                    for $g = 1$ until $K$ do
12:                        if $g \notin S_i$ then
13:                            if $\xi_{i,g} = 1 \vee \xi_{m,k} = 1$ then
14:                                $\Theta_{g,n} = \Theta_{g,n} \vee A_{k,n}$ \forall $n \in N$ and $g \in K$ and $g \neq k$
15:                            else if $\xi_{i,g} = x \vee \xi_{m,k} = 2$ then
16:                                $\Theta_{g,n} = x$ \forall $n \in N$ and $g \in K$ and $g \neq k$
17:                            end if
18:                        end if
19:                    end for
20:                else
21:                    $\Theta_{a,n} = \Theta_{a,n} \vee A_{k,n}$ \forall $n \in N$ and $a \in S_i$ and $a \neq k$
22:                end if
23:            end for
24:        end for
25:    end for
and upper interference bound, provided that certain power constraint is applied by the serving BS of $k$ in order to guarantee that the signal quality of the other users allocated in these PRBs remains unaffected. The FMS acts as a central unit to resolve the interference between conflicting BSs. The transmission power adaptation process is described as follows:

The first step is to identify the list of PRBs that are conditionally available for each user based on the instantaneous interference level map $\Theta$. Once this list is determined, the users are sorted in such a way that the priority of scheduling is given to the users with the minimum conditionally available PRBs.

After sorting the users, the algorithm begins to schedule the user with the minimum conditionally available PRBs. The indices of the available resources for a given user $k$ identified from the map $\Theta$ are sorted to indicate the preferred PRBs based on the CQI reports of this user. Before allocating user $k$ in a conditionally available PRB $n$, the list of users allocated in PRB $n$ are determined from the allocation matrix $A$. Among the identified users, the interference bound of the user having the lowest interference bound is identified based on eq. (5.1). Assuming BS $f$ is the serving BS of user $k$ and user $u$ is a user allocated in PRB $n$ that is to be reused by user $k$ and having the minimum lower interference bound $\phi_{lower}^u$, user $k$ is then allocated in PRB $n$, and the power reduction is applied to reduce the transmission power of BS $f$ at PRB $n$ in order to ensure $\phi_{lower}^u$ is not exceeded

$$\rho_{f,k,n} = \rho_{f,k,n} - \phi_{lower}^u$$

(5.7)

where $\rho_{f,k,n}$ refers to the transmission power of BS $f$ to user $k$ at PRB $n$.

Every time the allocation map is updated, the instantaneous interference level map $\Theta$, is also updated based on $\xi$, to ensure the interference is controlled. The transmission power adaptation process is represented by the pseudo code in algorithm 5.

5.3 Results and Discussion

For experimental evaluation, the simulation scenario considers a homogeneous network of femtocells where users are randomly and uniformly distributed across a $10 \times 10$ grid. The proposed algorithm is evaluated at variable
CHAPTER 5. MULTI-LEVEL INTERFERENCE MAPPING

Figure 5.2: Evaluation of average data rate per user performance with variable densities of femtocells

Figure 5.3: Evaluation of resource utilization ratio with variable densities of femtocells
For evaluation purposes, a Bi-Level interference mapping (BLIM) approach which is based on the Manchester technique in [33] is used as a reference for comparison with the MLIM method. In BLIM, a predefined threshold is used to identify conflicts between femtocells and users where the interference is mapped into two levels with ‘0’ to indicate no interference and ‘1’ to indicate interference. Fig. 5.2 shows that the proposed MLIM can remarkably improve the average data rate performance compared to the other techniques. The performance gap between the MLIM and the BLIM methods is seen to increase as the density of femtocells increases. This demonstrates the ability of the MLIM technique to enhance the resource utilization as shown in Fig. 5.3. It is worth noting that the resource utilization increase seems to almost saturate as the number of femtocell increase in the MLIM method. This is...
because increasing the resource utilization is not proportional to increasing the data rate since at high densities of femtocells, the interference bound of cell-edge users is increased causing other femtocell that are reusing resources to reduce their transmission power further and therefore the quality of the utilized resources is reduced.

Fig. 5.4 illustrates the user throughput CDF with 5 deployed femtocells and two users per femtocell. It is shown that the proposed MLIM maintains superior performance in comparison with the other schemes. This proves that the MLIM scheme is able to increase the average data rate of the network without compromising the QoS of the cell-edge users by considering the interference bounds of users in order to protect cell-edge users from the interference.

5.4 Chapter Summary

This chapter has described an interference mapping technique for enhancing QoS and throughput of cellular systems. Maximum QoS can be guaranteed by setting high thresholds for the maximum allowable interference, to ensure nearby femtocells occupy orthogonal resources. While setting the interference bound leads to limited utilization of the network available resources, the reuse efficiency can still be improved using the power adaptation scheme which exploit the variability in channel conditions to maximize resource utilization. The results show that the proposed method outperforms the performance of the other techniques techniques.
Chapter 6

Distributed Resource Management

6.1 Introduction

In the previous chapters, the radio resource management was performed either in a centralized or a semi-centralized manner. In this chapter, a distributed resource management scheme is introduced to reduce the signaling overhead burden on the back-haul infrastructure. The majority of distributed small cell networks perform the interference management using message broadcast between cells in order to collect the necessary information to coordinate the interference. Such coordination can result in delays and large signaling overhead due to the communication between cells. This problem can be tackled using fully distributed RRMs, where the resource management is performed in a decentralized and uncoordinated manner. One major drawback of fully distributed systems is however, the lack of an overall view of the network, in which independent resource allocation can potentially maximize the throughput of individual cells but does not lead to a better network wide performance. The challenge now is how to obtain the information needed by the RRM to provide an acceptable service with very limited knowledge available at BSs. This chapter shows that such knowledge can be obtained without requiring any central intervention, or any form of coordination between small cells in order to reduce the delay and the signaling overhead to the back-haul network\(^1\).

The necessary information required by the RRM is locally estimated by BSs

\(^1\)The work presented in this chapter has been accepted for publication in IEEE IWCMC 2016.
by observing the UL interference to estimate the number of users in proximity to BSs. Generally speaking, the utilized amount of resources per femtocell is restricted according to the estimated number of users in order to reduce the co-channel inter-cell interference and enhance the QoS of cell-edge users.

Distributed resource allocation is an ongoing research subject. Authors in [83] proposed a low-complexity algorithm named F-ALOHA, which is considered an enhanced version of ALOHA. F-ALOHA allocates the shared spectrum between femtocells in a distributed manner by randomizing the interference avoidance. However, this technique leads to inefficient allocation of resources due to the randomly generated patterns and lack of planning. The authors in [84] introduce a self-organized approach where each femtocell adjust its resource allocation based on local measurement reports to minimize the effect of co-channel inter-cell interference with neighboring cells. In [85], an uncoordinated algorithm is presented in which a conflict graph is created based on random graph theory to model the probability of interference between femtocells in order to achieve the optimum resource allocation. Game-theoretic approaches were presented in [86,87] where non-cooperative games are used to achieve the Nash equilibrium through optimal resource allocation. The authors in [88] presented a distributed interference mitigation scheme based on machine learning strategies. The algorithm assumes that no information exchange between femtocells is possible and that each femtocell learns by taking a set of actions and forms its own allocation strategies to reduce interference accordingly. In [89], the authors discussed a coordinated based inter-cell interference management scheme based on a game theoretical approach. The proposed method focuses on optimizing the frequency reuse patterns and the transmission power to increase the total network throughput.

The rest of the chapter is organized as follows. Section 6.2 describes the implementation of the proposed distributed resource management technique. Section 6.3 presents the simulation model and a discussion of the results. Finally, section 6.4 provides a summary of the chapter by highlighting the main contributions and results.
6.2 Uplink Based Resource Allocation

The estimation of the number of users present in the coverage area of BSs is performed by sensing the spectrum in the UL to listen to nearby emissions. Given the number of interfered users in each cell, a femtocell can reduce its resource usage to decrease the effect of inter-cell interference to neighboring cell-edge users. It is presumed that the channel state information (CSI) feedback from users is assumed to be perfectly known at the femtocell and femtocells are able to sense the spectrum using the network listening mode capability [32].

6.2.1 UL resource allocation

The resource allocation in the uplink session is performed in a distributed manner. To reduce inter-cell interference, each femtocell is entitled to utilize $N/4$ of the total available resources, which are equally distributed among the served users and users are allocated in adjacent PRBs [90]. Each femtocell senses the spectrum to update the interference power records periodically in which the interference power records contains information about the interference intensity experienced in each PRB. The total interference sensed by BS $i$ at PRB $n$ can be expressed as
\[ v_{i,n} = \sum_{k \in S_i}^{K} \Gamma_{k,i,n} h_{i,k,n} \chi_{k,n} + \eta_0, \quad \forall i \in B, \; n \in \mathcal{N} \]  

(6.1)

where \( \chi_{k,n} \) is given by

\[ \chi_{k,n} = \begin{cases} 
1, & \text{if } k \text{ allocated in } n \\
0, & \text{otherwise}
\end{cases} \]  

(6.2)

Where \( \Gamma_{k,i,n} \) is the UL interference power received by BS \( i \) from UE \( k \) at PRB \( n \). \( h_{i,k,n} \) represents the channel gain between \( i \) and \( k \). \( \chi_{k,n} \) is a binary multiplier defined in (6.2). Femtocell \( i \) then allocates its connected UEs \( S_i \) in the least interfered PRBs.

### 6.2.2 UL interferer identification

To detect the presence of neighboring users, additional information need to be extracted from the surroundings to estimate the quantity of UEs located within coverage range of BSs, which is performed by monitoring the UL interference originated by these UEs. To identify potential interfered UEs, femtocells scan the entire transmission band to determine the PRBs that are experiencing interference level higher than the noise rise threshold \( \sigma \) [74]. The amount of interference these PRBs are experiencing is indicated in the matrix, \( \Delta \in \mathbb{R}^{B \times N} \) as follows

\[ \Delta_{i,n} = \begin{cases} 
v_{i,n}, & v_{i,n} > \sigma, \quad \forall n \in \mathcal{N} \land i \in B \\
0, & \text{otherwise}
\end{cases} \]  

(6.3)

The threshold \( \sigma \) is given by \( \eta_0 + \gamma \) where \( \gamma \) denotes the noise rise.

The interfered PRBs are then analyzed to identify the number of UL interferers. Two challenges are considered while performing the detection process. The first challenge is to identify if multiple users are allocated in the same PRBs which is performed by monitoring the spectrum regularly and comparing the updated sensing report \( \Delta \), with the previous sensing report \( \Delta' \), in order to detect the change in the interference power produced by new users as follows
Algorithm 6 Uplink interferer identification

function UplinkInterfererDetection ($B$, $\Delta$, $v'$)
1. $\forall i \in B$ do
2. $\forall \Delta_i > \sigma$ do
3. if $v_i \approx \eta_0$
   execute Algorithm 2
4. else
   $x = \Delta_i - v'_i$
5. if $x \leq \tau$
   execute Algorithm 2 if $v'_i > \sigma$
6. else if $x > \tau$
   execute Algorithm 2
7. end if
8. end if
9. end do
10. return $\epsilon$

$$\sum_{n=1}^{N} \left| \Delta_{i,n} - \Delta'_{i,n} \right|, \forall i \in B \quad (6.4)$$

This procedure is illustrated in algorithm 6 which returns the number of detected users by each BS which is denoted by $\epsilon \in \mathbb{R}^{1 \times B}$ where $\epsilon = [\epsilon_1, \epsilon_2, \ldots, \epsilon_i, \ldots, \epsilon_B]$ and $\epsilon_i$ refers to the number of detected users by BS $i$.

The second challenge is to determine the possibility of one user occupying more than one PRB. Due to channel variations, the interference power induced by a UE can vary in different PRBs. To increase the accuracy of the detection process, femtocells monitor the level of change in the UL interference in adjacent PRBs and compares the difference with a threshold given by $\tau$ (e.g., $\pm 3$ dB), which is used to indicate the variations in the signal due to the channel effect to determine whether these PRBs are occupied by the same UE as follows

$$\{(\Delta_{i,b} < \Delta_{i,a}) \land (\Delta_{i,b} \geq \Delta_{i,a} - \tau)\} \lor \ldots, \forall a, b \in N$$

$$\{(\Delta_{i,b} > \Delta_{i,a}) \land (\Delta_{i,b} \leq \Delta_{i,a} + \tau)\}, \land i \in B \quad (6.5)$$

This process is illustrated in algorithm 7.
Algorithm 7 Detecting a user allocated in more than one RB

\textbf{function} OneUserDetection (\(\Delta_i\))

1. for every \(a\) in \(\Delta_i\) do
2. for every \(b\) in \(\Delta_i\) do
3. if \(a \neq b\) then
4. if \(\sim\{(\Delta_{i,b} < \Delta_{i,a}) \land (\Delta_{i,b} \geq \Delta_{i,a} - \tau)\} \lor \ldots\)
5. \(\sim\{(\Delta_{i,b} > \Delta_{i,a}) \land (\Delta_{i,b} \leq \Delta_{i,a} + \tau)\}\) |
6. \(\epsilon_i = \epsilon_i + 1\)
7. end if
8. end for
9. end for

return \(\epsilon_i\)

6.2.3 Resource partitioning

The number of interfered users by BS \(i\), \(\epsilon_i\) is used to calculate the amount of resources to be utilized by each user in the DL which is denoted by \(\Psi_k\). Femtocell \(i\) calculates this amount by dividing the total available PRBs by the estimated number of interfered UEs \(\epsilon_i\), added with the number of connected user, \(S_i\)

\[\Psi_k = \frac{N}{\epsilon_i + S_i}, \quad \forall k \in K.\] (6.6)

Given \(\Psi_k\), the resource allocation is performed independently by each BS using the CQI reports to select the preferred PRBs for each user [91]. The allocation process is performed in a based on sec. 3.4.5 from Chapter 3.

6.2.4 Signaling Overhead Evaluation

In this section, a comparison is performed to evaluate the signaling overhead of the proposed distributed method compared to the distributed self organizing measurement reports (MR) based method [34], which will be used in the comparison in the next section. The proposed distributed RRM does not require signaling overhead to perform the radio resource management, since all the necessary information are obtained using the the network sniffing capability and without requiring any sort of communication with other BSs. On the other hand, the self organizing method relies on regular measurement reports feedback from users to indicate the signal quality in each PRB. The UL
overhead $O_f$ required for these measurement reports for a given BS $f$ is given by [34]

$$O_f = N.d_s.S_f.f_{mr}$$ (6.7)

where $N$ denotes the number of PRBs, $d_s$ refers to the number of bits necessary to encode the received signal strength per PRB, $S_f$ is the number of users connected to femtocell $f$ and $f_{mr}$ is the frequency of reporting the measurement reports.

### 6.3 Results and Discussion

To assess the performance of the proposed distributed RRM experimentally, a 60m×60m enterprise model presented in Fig. 6.2 is utilized featuring a network of femtocells and users which are deployed in a uniform and distributed manner inside the building. The proposed scheme is evaluated for a closed-access system under variable densities of femtocells with two users connected to each cell. The path loss between femtocells and users is modeled based on the pathloss model in chapter 3. The AMC model discussed in chapter 3 is
Table 6.1: Distributed RRM Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>2.5 MHz</td>
<td>Resource blocks (PRB)</td>
<td>12</td>
</tr>
<tr>
<td>FFT size</td>
<td>256</td>
<td>Femtocell radius</td>
<td>10 m</td>
</tr>
<tr>
<td>Femtocell Tx power</td>
<td>100 mW</td>
<td>UE Tx power</td>
<td>10mW</td>
</tr>
<tr>
<td>Fading channel</td>
<td>Rayleigh</td>
<td>Traffic Model</td>
<td>Full-Buffer</td>
</tr>
</tbody>
</table>

used to evaluate the data rate. Table 6.1 illustrates the rest of the simulation parameters.

Fig. 6.3 illustrates the impact of varying the noise rise threshold, on the downlink minimum and average data rate at variable densities of femtocells. All the results are based on 5 iterations to achieve optimal allocation. It can be seen from Fig. 6.3 (a) that lowering $\gamma$ increases the minimum data rate as more neighboring users are detected causing interference higher than the threshold. Therefore, the edge users suffering bad channel conditions become more protected from co-channel inter-cell downlink interference from neighboring cells as a result of the resource reduction at these cells. On the contrary, Fig. 6.3 (b) shows that lowering $\gamma$ decreases the average rate per user as femtocells utilize less bandwidth when more neighboring users are detected within their coverage. To provide a balance between the minimum and average rate, the value of $\gamma$ is chosen to be 45$dB$ above the noise which will be used to evaluate the performance of the proposed algorithm.

Fig. 6.4 shows the performance of the proposed algorithm compared to sub-optimal benchmarks. Benchmark 1 illustrates the performance of the proposed algorithm when the number of interfered users by each femtocell is measured based on a DL interference threshold $\beta$, as discussed in sec. 3.4.3. The result shows that by controlling the noise rise threshold, the performance of the proposed technique approaches the performance of Benchmark 1. Benchmark 2 shows the performance of the proposed algorithm in the case an AWGN system is used, in which the effect of channel variations is not considered and the UL interferer identification process can be performed more
Figure 6.3: Impact of the UL interference threshold on the DL data rate of the distributed RRM. (a) Guaranteed data rate, (b) Average data rate
Figure 6.4: Performance of the proposed distributed RRM compared to benchmark approaches

Figure 6.5: Evaluation of the minimum achievable data rate performance with varying number of femtocells
Figure 6.6: Evaluation of the outage probability performance with varying number of femtocells

Figure 6.7: Evaluation of the energy efficiency performance with varying number of femtocells
accurately. It can be seen that the performance of the proposed technique approaches the AWGN system performance due to the minor over-estimation of the UL interferers in the proposed algorithm caused by the unpredictable variations due to channel effect.

The performance of the proposed method has also been compared with two other state-of-art distributed methods - The Self organizing RRM described in sec. 2.6 and the Random Allocation method, in which the interference is minimized by randomizing the allocation of users. Fig. 6.5 shows the QoS performance comparison where the proposed method is seen to provide superior performance as compared with the other distributed methods. The outage probability is evaluated in Fig. 6.6 with minimum rate requirement of 100 kbit/s. It can be seen that the proposed algorithm suffers less outage compared to the Self organizing RRM and random allocation. The ECR model discussed in Chapter 3 is used to evaluate the energy efficiency. Fig. 6.7 shows that the proposed algorithm achieves better energy efficiency due to the higher achievable data rate.

6.4 Chapter Summary

This chapter presented a distributed resource allocation algorithm which shows that inter-cell interference avoidance can be achieved in distributed systems without the complexity and overhead required by cell coordination. By analyzing the UL emissions of surrounding users, information regarding the number of users located close by from femtocells can be estimated to be used for controlling the resource utilization in order to reduce the co-channel inter-cell interference. The simulation results showed that the proposed algorithm is able to improve the minimum achievable data rate in comparison with the other techniques with a peak improvement of 36.5%. It was also shown that there is a trade-off between selecting high and low thresholds, where increasing $\sigma$ improves the minimum achievable data rate whereas decreasing the threshold increases the average data rate.
Chapter 7

Conclusions and Future Work

7.1 Conclusions

This thesis aimed to explore interference avoidance and resource management techniques to improve the performance of small cells assisted heterogeneous networks. Chapter 1 presented the thesis introduction which highlights the aims, motivations and the main contributions of the work presented in this thesis. The theoretical background and related work in Chapter 2 introduced basic concepts including the technical aspects of femtocells, the implications that arise as a result of femtocell deployment and an overview of inter-cell interference management in cellular heterogeneous networks.

The main findings in this thesis are chapter specific and are outlined in their following respective chapters: Sleep mode based resource allocation, user association in heterogeneous networks, multi-level interference mapping and distributed resource allocation. The choice of which technique is more suitable to apply depends on the system requirements and the optimization metrics. The first two methods are designed to improve the overall network gain with minimum possible complexity. However, in case the QoS is a strict requirement, the multi-level interference mapping is more suitable due to the ability to control the level of interference using the multi-level interference map. On the other hand, the distributed resource allocation approach is ideal for ultra-dense networks in which a massive number of small cells are deployed. Although distributed RRM.s suffer degraded performance compared to the centralized or semi-centralised RRM techniques, in some cases
it might be impractical to provide a centralised resource management as this will increase the signalling overhead burden on the back-haul network. Furthermore, for delay sensitive applications, it is best to provide quick RRM decisions that are undertaken independently without any communication or management among the small cells.

Unlike the majority of the preceding work, in which SL techniques are mainly applied to optimize the power consumption, chapter 3 presents a radio resource management technique enhanced with an SL scheme to improve the capacity of cellular systems. For this purpose, a set of deactivation tests have been suggested to locate the BSs that are causing the maximum interference in the neighbourhood, such that when these cells are switched off, the interference is reduced, and the neighbouring BSs are able to utilize the resources more effectively. The proposed can easily be integrated in the heterogeneous network where FFR has been employed to manage the cross-tier interference between the macrocell and the small cell layers. The simulation results show that the proposed SLCM method improves the capacity by 30% compared to the always-ON method. Furthermore, a mathematical model was introduced to provide an accurate modelling of the received interference while capturing the randomness in users location. It was shown that a good match can be achieved between the analytical and the simulations results.

Chapter 4 began by exploring the performance of a user association technique, that is integrated with an interference aware resource partitioning scheme which distribute resources among users in a way that ensures orthogonalization between the interfering BSs/UEs. The proposal has been evaluated in two scenarios one featuring a homogeneous network of femtocells and the other represents a heterogeneous network including a macrocell overlaid with small cells. Results showed that the performance improvement is more noticeable in the heterogeneous network case compared to the homogeneous network due to the significant power difference of the BSs belonging to different tiers of cells, which has big impact on the user association in two-tier networks. The throughput improvement is achieved as a result of users being offloaded from the congested macrocell to the underutilized small cells to take advantage of the wide range of resources available at these cells. The NCM method was also combined with the SLCM method from Chapter
3 to address the dropped users problem and enhance the hand-off procedure of the switched off cells users. Results showed that applying the NCM and SLCM methods jointly leads to performance improvement compared to the NCM method. Furthermore, an adaptive decoupling and multi-BS association scheme is presented to optimize the user association in the uplink and the downlink. The decoupling decision is performed based on the NCM method, where the uplink user association is decoupled from the downlink association if better performance can be achieved from the decoupling. It was shown in the results that the decoupling gain is more significant in the heterogeneous network compared to the homogeneous network as the macrocell users located far from the macrocell have the opportunity to associate with the nearby small cells which leads to better signal quality due to the smaller pathloss. The SMBA scheme was also implemented jointly with the CDA method to allow UEs be associated with multiple BSs in order to improve the spatial frequency reuse.

Different from the previous chapters, in which predefined SIR thresholds are used to identify the conflicting BSs and users, Chapter 5 introduced a method where the interference is mapped into multiple levels depending on the intensity of interference sustained by users from the nearby BSs. The interference level map is constructed using the upper and lower interference bounds of users, which exploits the channel variability to determine the users sensitivity to interference. By setting an upper bound, maximum QoS can be guaranteed by ensuring that the interfering BSs and users are allocated in orthogonal frequency resources. On the other hand, the adaptive power control algorithm is carried out to maximize the frequency re-utilization and improve the overall throughput by compensating for the reuse reduction incurred by orthogonalization. The simulation results showed that the proposed interference mapping scheme is capable of significantly improving the overall throughput while maintaining the QoS of users.

Chapter 6 introduced a fully decentralized and uncoordinated RRM, to reduce the latency and signalling overhead stemming from the communication with the central unit as in the previous chapters. The UL spectrum is monitored to examine the interference originated by users and determine the number of neighbouring users within the coverage range of BSs. This information is then used to control the resource usage of BSs depending on the
number of detected users in the coverage area to protect cell-edge users from inter-cell interference.

7.2 Future Directions

This section provides an overview of the main challenges and requirements of next generation wireless networks and the future research plan.

7.2.1 Overview of Next Generation Networks

It is believed that next generation wireless networks will lead to an evolution in terms of applications, technologies and architecture. Furthermore, the concept of internet of things (IoT) will become dominant with 100 billion wireless devices connected to the internet and up to 100 Gbps/\(Km^2\) data traffic with different QoS, latency and throughput requirements [92], [93].

To achieve the expectations of the next generation 5G networks, the following challenges need to be addressed:

- The dramatic increase in traffic volumes and flexible access and sharing of data.
- The future 5G system must be able to support a massive variety of devices including surveillance cameras, sensors, smart-home etc. To support this large volume of devices, the traditional cellular network needs to be evolved in order to allow these devices to smoothly integrate into the cellular radio network.
- A wide range of QoS requirements need to be satisfied including low latency, high data rate, seamless handover, reduced energy usage and enhanced battery life.

The densified deployment of cells and devices has already started in 4G systems are are continuing to grow with 5G. This kind of densification will lead to a fierce frequency reuse, which results in inter-cell interference causing the QoS of these devices to degrade. Towards this end, a new range of innovative technologies has been suggested to satisfy the 5G networks demands and to achieve the expected benefits. A list of the key enabling technologies for 5G networks are discussed below [92]:


CHAPTER 7. CONCLUSIONS AND FUTURE WORK

- **Ultra-dense networks**: In next generation 5G networks, the number of small cells will increase greatly and will be deployed very densely to provide flexible coverage and smooth handover.

- **Massive MIMO**: A technique that allow using a large number of antennas to enhance the spectral efficiency.

- **Full-Duplex (FD) communication**: A new physical layer method which permits the UL and DL traffic to be scheduled on the same physical resource block concurrently to offer double spectral efficiency compared to the traditional point-to-point transmission. However, a main concern to be addressed is the self-interference (SI), which results from allowing a node to operate on the same frequency in both directions in addition to the interference from neighbouring nodes.

- **Millimeter Wave (mmWave) communication**: Another enabling technology that allows 5G networks to utilize the mmWave vast amount of spectrum ranging from 30 GHz to 300 GHz [94].

- **Energy harvesting**: Uses elements from the environment to produce renewable energy to increase the battery life of wireless devices.

### 7.2.2 Planned Future Work

This section demonstrates some of the further research expansion that can be done to the work presented in this thesis and towards addressing the next generation 5G networks challenges.

1. Investigate the impact of sleep mode duration on the system performance and study other parameters that affect the switching off periods such as the distribution of users within cells and the traffic generation model.

2. The SL technique in Chapter 3 can also be extended to exploit sector based sleep mode to allow BSs to switch off certain sectors where its causing the interference, rather than completely switching off the cells. However, this requires small cells to have multiple antennas (e.g., Picocells/ Enterprise femtocells).
3. In this thesis, a static system-level simulation was considered to study the performance of the proposed algorithms for long time periods. The next step is to analyse the performance of the proposed algorithms considering a dynamical system that captures high amount of details including the mobility models of users as well as dynamic traffic model (e.g. Voip).

4. Investigate the potential of applying the adaptive decoupling and multi-BS association technique within the context of heterogeneous cloud computing, where the radio resource management is performed in a cooperative manner [95]. It is expected that cloud based cooperative resource management will be capable of supporting real-time applications such as video-streaming and mobile gaming which are sensitive to time delay. Therefore, the design of such schemes need to consider the time delay and should be flexible enough to be expanded according to the network size.

5. In Chapter 5, it is possible to increase the level of accuracy by considering additional interference levels in the interference level map. The scale of ranking can be increased to 4 levels to indicate the intensity of interference sustained by a certain user with respect to a non-serving BS in which re-utilizing the resources can be classified as completely safe, almost safe, border line safe or forbidden. Along with introducing the additional interference levels, a scheduling scheme can be developed to prioritize the allocation of the resources to the users who can utilize then better in order to improve the reuse efficiency of the network.
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Appendix A

Preliminaries in Probability Theory

A.1 Continuous Random Variables

Assuming $X$ is a random variable, $X$ is considered a continuous random variable if $X$ has a non negative probability density function $f_X(x)$ in which $x \in (-\infty, \infty)$ and $f_X(x)$ satisfies the following property

$$P\{X \in (-\infty, \infty)\} = \int_{-\infty}^{\infty} f_X(x) \, dx = 1$$

For example, let $L=[a, b]$, the probability density function of $X$ is given by

$$P\{a \leq X \leq b\} = \int_{a}^{b} f_X(x) \, dx$$

A.2 Expectations of Random Variables

If $X$ is a continuous random variable with a probability density function $f_X(x)$, then, the expected value of $X$ can be expressed as [77]

$$E[X] = \int_{-\infty}^{\infty} x \cdot f_X(x) \, dx.$$
A.3 Transformation of Random Variables

A.3.1 Change-of-variable Technique

Assume $X$ is a continuous random variable with probability density function $f_X(x)$. Let $Y = g(x)$ is a function of the random variable $X$, then, the probability density function of $Y$ is given by [55]

$$f_Y(y) = f \left[ g^{-1}(y) \right] \left| \frac{dg^{-1}(y)}{dy} \right|.$$ 

where $g^{-1}$ is the inverse function.

A.3.2 Product Distribution

Let $X$ and $Y$ be two continuous random variables with probability density functions given by $f(x)$ and $f(y)$. If $X$ and $Y$ are independent, then the probability density function of their product $Z = XY$ is defined as [55]

$$f(z) = \int_{-\infty}^{\infty} f_X(x) \cdot f_Y(z/x) \cdot \frac{1}{|x|} \, dx.$$ 

where the Jacobian is given by

$$J(z, x) = \begin{bmatrix} \frac{\partial x}{\partial z} & \frac{\partial y}{\partial z} \\ \frac{\partial x}{\partial z} & \frac{\partial y}{\partial z} \end{bmatrix}$$

and the determinant of the Jacobian is expressed as

$$\det (J(z, x)) = \frac{1}{|x|}.$$
Production Notes

This document has been typed using LYX (Version 2.1.3) typesetting system. The bibliography are formatted using Bibtex reference management software. The system-level simulations and the numerical tools are conducted using Matlab R2012a and Wolfram Mathematica 8. The system model and illustrative figures are designed using Microsoft office Power Point 2010.