Cross-layer Techniques for Enhancing The Performance of Heterogeneous OFDMA Based Cellular Systems

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Abstract

Increasing licensed spectrum utilisation can be achieved through physical (PHY) and/or medium access control (MAC) layer approaches. In the PHY layer, resource utilisation can be increased by implementing multiple input multiple output (MIMO) transmission. On the other hand, a low-cost solution of the MAC layer approach is the resource utilisation improvement by implementing femtocells based heterogeneous network (HetNet) that allows end-users to deploy small-size basestations (BSs) in their own premises. While this also reduces the installation and maintenance cost of the operators, it results in higher interference levels in the network.

This research proposes solutions in both, PHY and MAC layers, to improve the licensed spectrum efficiency. In the case of the PHY layer approach, this thesis proposes a new pairing cooperative technique in the uplink transmission that can provide spatial diversity and constructive interference exploitation in uplink orthogonal frequency division multiple access (OFDMA) systems. Both synchronous and asynchronous transmission scenarios are considered. The performance of this technique is evaluated through Monte Carlo simulations and accurate mathematical analysis. It is shown that the proposed scheme provides significant BER reductions, especially at low SNR, as well as, throughput improvements relative to existing cooperative transmission techniques.

In the case of the MAC layer approach, this research proposes a novel interference mapping based RRM that combines network routing protocols and cooperation between BSs and the cellular management system to produce an effective way of utilising the spectrum. It will be shown through mathematical analysis and computer simulations that this proposal improves the overall bit rate and quality of service (QoS), enhances the energy efficiency and provides a good platform to manage femtocell accessibility.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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List of Abbreviations

4G	4th Generation of cellular network
AAA	Authentication Authorisation and Accounting
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BSs	Basestations
CAPEX	Capital Expenditure
CC	Coded Cooperation
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CF	Compress and Forward
CFO	Carrier Frequency Offset
CP	Cyclic Prefix
\mathbf{CS}	Consecutive Scheduling
CSI	Channel State Information
DFT	Discrete Fourier Transform
DS-CDMA	Direct Sequenc CDMA
DSTC	Distributed Space Time Code
FAP	Femto Access Point
FFR	Fractional Frequency Re-use
FGW	Femto Gateway
FMS	Femto Management System

HetNets	Heterogeneous Networks
HoNet	Homogeneous Network
ICI	Intercarrier Interference
IDFT	Inverse Discrete Fourier Transform
IP	Internet Protocol
ISI	Intersymbol Interference
ISP	Internet Service Provider
LMS	Least Mean Square
LOS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MBS	Macro Basestation
MC-CDMA	Multicarrier CDMA
MCN	Mobile Core Network
MF	Maximum Fairness
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MoC	Matrix of Conflict
MR	Measurement Report
MRC	Maximum Ratio Combining
MSR	Maximum Sum Rate
MUI	Multiuser Interference
NLOS	Non Line Of Sight
OAM	Operation And Management
OFDM	Orthogonal Frequency Divition Multiplexing
OFDMA	Orthogonal Frequency Divition Multiple Access

OPEX	Operational Expenditure
PAPR	Peak to Averare Power Ratio
PCI	Physical Layer Cell Identities
PF	Proportional Fairness
РНҮ	Physical Layer
PR	Parallel Resource
PRC	Proportional Rate Constraint
PT	Pairing Technique cooperative diversity
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RB	Resource Block
RE	Resource Element
RF	Radio Frequency
RISIC	Residual ISI Cancellation
RLS	Recursive Least Square
RNC	Radio Network Controller
RRC	Radio Resource Control
RRM	Radio Resource Management
RRT	Repetition based RT cooperative diversity
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RT	Relay Type cooperative diversity
SBS	Small Basestation
SD	Source-to-Destination
SFR	Soft Frequency Re-use (SFR)

SINR	Signal-to-Interference and Noise Ratio		
SIR	Signal-to-Interference ratio		
SISO	Single Input Single Output		
SNR	Signal-to-Noise Ratio		
SON	Self-Organizing Network		
STBC	Space Time Block Code		
TDMA	Time Division Multiple Access		
UE	User Equipment		
UMA	Unlicensed Mobile Access		
WiMAX	Wireless Microwave Access		
DVRP	Distance Vector Routing Protocol		

List of Symbols

α_{cu_z}	Pathloss between T_c and u_z				
α_{muz}	Pathloss between T_m and u_z				
$oldsymbol{lpha}_{m,t}$	Instantaneous pathloss between T_m and its users				
Λ_i	Allowable PRs at i^{th} PRs group for BS T_m				
Λ_i	Allowable PRs at i^{th} PRs group				
${\zeta}_{{ m B},i}$	The Matrix of Conflict of B_i BSs group				
ζ_m	The local Matrix of Conflict of T_m				
\mathbb{Q}_i	UEs of $\mathbb{T}_{\mathbf{B},i}$				
$\mathbb{T}_{\mathrm{B},i}$	BSs that require conflicts to be resolved at a particular time and the $i^{\rm th}$ PRs group index				
$\mathbb{T}_{m,C}$	Neighbouring base stations set of ${\cal T}_m$				
\mathbb{T}	Basestations set				
U	Users set				
$\mathcal{A}_{m,i}$	Allowable PRs at i^{th} PRs group for BS T_m				
$\mathcal{A}_{\mathrm{B},i}$	Temporary allocated PRs at i^{th} PRs group for B_i BSs group.				
\mathcal{A}_i	Temporary allocated PRs at i^{th} PRs group				
${\mathcal I}_{\mathscr T}$	\mathscr{T} by \mathscr{T} Identity matrix				

Priority PRs at i^{th} PRs group				
Priority PRs at i^{th} PRs group for B_i BSs group.				
Partial forbidden PRs at i^{th} PRs group at a given B_i BSs when priority is considered				
Partial forbidden PRs at i^{th} PRs group for B_i BSs group.				
Entire forbidden PRs at i^{th} PRs group				
Entire forbidden PRs at i^{th} PRs group for B_i BSs group.				
Entire forbidden PRs at i^{th} PRs group				
Priority levels in multilevel priority scheduling				
Global Matrix of Conflict				
Time domain small scale fading channel				
Set of initial PRs for all users within B_i group				
Set of $N_{b,i}$ values within B_i BSs group				
Frequency domain version of ε_p				
Noise of l^{th} relay to destination transmission				
Noise at source to relay transmission				
Noise of source to l^{th} relay transmission				
Inter Carrier Interference Energy				
Inter Symbol Interference Energy				
Equalised $X_{\vartheta_p}[n]$				
The maximum received signal from T_m to its UEs at time slot t				

$oldsymbol{\kappa}_{m,t}$	Transmitted bits at n^{th} subcarrier for u_z user
$\mathbf{x}_{\ddot{t} \ddot{t}-1}$	The $(\ddot{t} - 1)^{\text{th}}$ vector symbol transmitted data that affect the \ddot{t}^{th} symbol
$\mathbf{y}_{\ddot{t} \ddot{t}-1}$	The $(\ddot{t} - 1)^{\text{th}}$ OFDM symbol that has contribution to the \ddot{t}^{th} symbol
$\mathbf{E}_{C_m,t}$	Received power from T_m 's neighbour BSs to its UEs
$\mathbf{E}_{C_m,t}$	Received power from T_m 's neighbour BSs to its UEs
\mathbf{h}_{δ}	Impulse response matrix that results in ISI
$\mathbf{x}_{ec{t}}$	The \ddot{t}^{th} OFDM symbol
$\mathbf{y}_{\ddot{t} \ddot{t}}$	The \ddot{t}^{th} OFDM symbol that has contribution to the \ddot{t}^{th} symbol
$\mathbf{y}_{\ddot{t}}$	Mathematical model of the real or imaginary part of the received signal at the $\ddot{t}^{\rm th}$ OFDM symbol
С	BS receives the correct combination symbol using the proposed pairing technique
\mathcal{C}_{12}	$\mathrm{U}_{\mathrm{p}1}$ and $\mathrm{U}_{\mathrm{p}2}$ exchange their symbols correctly
\mathcal{C}_{1or2}	$\mathrm{U}_{\mathrm{p}1}$ and $\mathrm{U}_{\mathrm{p}2}$ exchange their symbols correctly
${\cal G}$	Discrete signal CP period
\mathcal{N}_0	Additive White Gaussian Noise
R	Number of receiving antennas
P_{ξ}	Probability of bit error for BPSK in Rayleigh fading channel
$\mathrm{P}_{\mathfrak{C}_{\mathcal{O}},\ddot{t}}$	The probability of detecting the wrong symbol per sub-carrier at the \ddot{t}^{th} OFDM symbol after the \mathcal{O}^{th} iteration with SINR, $\psi_{R_{\mathcal{O}},\vec{t}}$
P_{φ}	Probability of receiving a correct QPSK symbol with two diversity channels detected using the MRC combining scheme

T	Number of transmitting antennas
ν	Event of receiving correct symbol and its adjacent constellation is given by
$\overline{\gamma_{12}}$	Average inter-user signal-to-noise ratio (SNR)
$\phi_p[n]$	Phase error of modulating the combined pairing symbol.
$\psi_{R_{\mathcal{O}},\ddot{t}}$	SINR at the \ddot{t}^{th} OFDM symbol after the \mathcal{O}^{th} iteration
$\psi_{u_z}(n)$	SINR using the MoC based RRM at a UE, u_z , which is served by T_m , and $n^{\rm th}$ subcarrier
ρ	Owner active probability
$h_{BP}(t)$	Bandpass filter used to remove one of the OFDM side bands
v_{min}	Minimum data rate approximation
Υ	Average interference energy after the RISIC equalizer
ε	BS receives the wrong combination symbol using the proposed pairing technique
$\varepsilon_p(t)$	Error detection due to inter-user channel
$\widehat{\mathcal{C}}_{12}$	Neither U_{p1} or U_{p2} receives its partner's symbols correctly
Ξ_q	Equivocation of a transmitted symbol
b_{cu_z}	Binary multiplier of interference from BS T_c into user u_z
C_m	Number of neighbouring BSs of T_m
d_{cu_z}	Distance between T_c and u_z
d_{muz}	Distance between T_m and u_z
D_{Z_m}	Information of allocated user at each PR

E_S	Wanted signal energy
$f_{D_{MU_z}}$	PDF of d_{mu_z}
$f_{R_{mc}}$	PDF of r_{mc}
$h_p(t)$	Small scale fading channel of the pairing transmission
H_{p_I}	Transfer function corresponding to h_{p_I}
h_{p_I}	Impulse response experienced by the quadrature signal
H_{p_R}	Transfer function corresponding to h_{p_R}
h_{p_R}	Impulse response experienced by the inphase signal
$h_{RD_l}(t)$	$l^{\rm th}$ relay to destination small scale fading channel
$h_{SD}(t)$	Source to destination small scale fading channel
$h_{SR_l}(t)$	Source to l^{th} relay small scale fading channel
$N_{b,i}$	Initial number of PRs b^{th} BS's users within B_i BSs group.
PL(d)[dB]	Pathloss at a given distance, d in decibel
r_{mc}	Relative distance between u_z to T_m and T_c
$S_{b,i}$	Total detected number of users by b^{th} BS within B_i BSs group.
T_m	Basestation m
x	Time domain signal
X_O	Frequency domain of OFDM signal
$x_{\vartheta_p}(t)$	Time domain versiion of $X_{\vartheta_p}(f)$
$X_{\vartheta_p}[n]$	Modulated symbol of the pairing transmission
$x_{p_1}[a]$	Time domain version of $X_{\vartheta_{p1}}[n]$

$X_{p_1}[n]$	Frequency domain of 1 Dimension OFDM modulation of $X_{\vartheta_{p1}}[n]$
$x_{p_2}[a]$	Time domain version of $X_{\vartheta_{p_2}}[n]$
$X_{p_2}[n]$	Frequency domain of 1 Dimension OFDM modulation of $X_{\vartheta_{p2}}[n]$
$x_{R_l}(t)$	The transmitted symbol from l^{th} relay terminal
$y_1(t)$	Input of the A/D for real parts
$y_2(t)$	Input of the A/D for imaginary parts
$y_i(t)$	Inphase received signal after multiplication with the Local Oscillator signal
$y_i(t)$	Inphase received signal after multiplication with the Local Oscillator signal
$y_q(t)$	Quadrature received signal after multiplication with the Local Oscil- lator signal
$y_q(t)$	Quadrature received signal after multiplication with the Local Oscil- lator signal
$y_{RD_l}(t)$	$l^{\rm th}$ relay to destination received signal
$y_{SD}(t)$	Source to destination received signal
$y_{SR_l}(t)$	Source to l^{th} relay received signal
Z_m	Number of T_m 's users
$\Pr(\mathscr{E})$	Probability of any event \mathscr{E}

1. Introduction

1.1. Future Cellular Networks

It is widely accepted that wireless capacity has doubled every 30 months over the last 104 years [1]. Much of this increase is generated indoors and is related to video related applications. Furthermore, the pressure for reducing carbon emission in all aspects of technology requires cellular operators to provide better energy efficiency. However, the available spectrum for cellular systems is limited and expensive. In fact, spectrum licensing for two 5 MHz of 800 MHz spectrum in the UK could cost up to £ 217 millions for a 20 year license period [2]. This means, in order to satisfy such increase, a more efficient technique to utilize radio cellular spectrum has to be employed by the operators.

One way to increase data rate application is by implementing a multiple input multiple output (MIMO) system. This system provides an extra degree of freedom in the spatial domain that can be exploited to achieve diversity gain or/and spatial multiplexing gain [3]. This, generally, translates into improved performance, power efficiency, data rate, or a combination of. While MIMO can be practically implemented in basestations (BSs), it is more challenging to do so in users' equipments (UEs) due to some reasons such as size constraint, complexity and rising cost, amongst others. A more common way to empower UEs with spatial diversity is through multiuser cooperation [4]. By allowing users to transmit each other's signals in real time, cooperative diversity is created. Although this kind of cooperation could also be applicable on the downlink, it is more common on the uplink which is the focus of this project.

An alternative way of increasing the spectrum utilisation is by implementing the heterogeneous networks (HetNets) architecture. The conventional HetNets architecture contains macrocells together with micro- and picocells [5] where a picocell

is widely used within indoor environment or heavily shadowed urban area which covers a small area [6]. While picocells provide good solution to provide coverage in the indoor environment, this solution is expensive due to the channel measurement survey requirement, site leasing, amongst others [7]. Furthermore, the speed of installing picocells is slower compared to the required increase of wireless capacity. These problems can be solved by implementing the femtocell technology that allows a free deployment by the end-users. This reduces the cost and installation time for surveying, site leasing and making a dedicated backhaul connection. However, since it is installed by the end-users, the femtocell technology increases interference. This reduces the achievable data rate and the quality of service (QoS) to the users. Furthermore, interfering signals render such signals as wasted transmitted power. This means that a good interference avoidance scheme is needed to aid the implementation of the femtocell technology to support the capacity increase and energy efficiency requirements of cellular networks.

Similar to the link layer transmission, cooperation also holds the key to the adaptability and efficiency of femtocell networks. All femtocell access points have to be synchronised and agree in which spectrum can be used at any instant. This may require communication between basestations and/or with a central computer through a self-organisation capability [8] in order to facilitate this framework.

1.2. Cooperative Diversity

Cooperative diversity coordinates the signal transmission to create a virtual antennas system. This cooperation strategy involves several users within close proximity to exchange their information using certain protocols besides transmitting their users and their cooperating users' signals [9]. This additional channel path(s) that are orthogonal with the direct transmission channel path create spatial diversity that can be exploited to create spatial diversity gain.

Cooperative diversity can be achieved using two major schemes, which are relay type (RT) [10, 11] and pairing type (PT) [12, 9] schemes. With the RT technique some users act as relays for other active users. In this scheme, the orthogonality requirement can be achieved in time and frequency and can be implemented with the penalty of reduced spectral efficiency. This implies that the diversity order, L,

increases proportionally with the number of relay terminals at the cost of reduced spectral efficiency and data rate [13, 14]. On the other hand, a maximum of two preferred users are partnered in such a way that they both transmit a common signal within the same time-slot and spectrum and achieve a similar throughput. This means that the only available orthogonal channel for the conventional PT scheme is achieved through orthogonal code. PT techniques were mainly developed for code division multiple access (CDMA) systems. In [15], the users of each pair broadcast their data alternately. During a transmission period, one of the users performs broadcasting while the second user and BS receiving. The broadcasted symbol is the sum of the two symbols belonging to the user pair. The symbol from one user is detected after the other user performs broadcasting in order to allow the BS to have signals from direct and indirect paths. Recently, a more effective pairing technique has been proposed in [12] where parts of the license-exempt spectrum are utilised for inter-user communications. This technique not only reduces the number of required spreading codes, but also achieves a diversity order of two [16, 17].

1.3. Radio Resource Management

1.3.1. Interference Avoidance

Radio resource management (RRM) is a robust method to tackle the interference problem caused by femtocells in 4G networks such as WiMAX release 2 (802.16m) and LTE-Advanced because these networks use synchronised and parallel transmission in the time and frequency domains which allows a high level of flexibility in managing the transmission channel [18]. In these technologies, RRM includes spectrum and power transmission management [19], where spectrum management is considered to be a more promising approach due to its simplicity by using frequency partition of interfering femtocells [20, 19]. For the sake of simplifying the notations, throughout this thesis, WiMAX and LTE terminologies are used to represent WiMAX release 2 and LTE-Advanced, respectively.

WiMAX technology uses orthogonal frequency division multiple access (OFDMA) transmission in both downlink and uplink transmissions [21]. Users are allocated

with a set of subcarriers forming a subchannel at a given OFDM symbol. Subcarriers within a subchannel can be allocated to user either in distributed or adjacent subcarrier permutation mode [22]. On the other hand, LTE uses OFDMA system in downlink transmission and single carrier frequency division multiple access (SC-FDMA), which is an extension of OFDMA with addition of FFT after the bits to modulation converter, in the uplink transmission. A frame of signal transmission is divided into T_{fr} subframes. Each subframe contains N_{RB} resource blocks (RBs) where each RB contains 12 subcarriers or resource elements (REs). 1 RB within a subframe is allocated to a user [23]. Compared to WiMAX technology, LTE allocates the subcarriers of users in a block by block manner.

Managing spectrum to reduce interference faces the challenge of balancing the spectrum utilisation and achieving a good interference level as well as adapting to the dynamic nature of cellular networks. A high level of spectrum partitioning reduces interference at the price of reducing spectrum utilisation and achievable data rate. Furthermore, very low interference per transmitted channel that translates a very high signal to interference ratio (SIR) do not always translate high data rate per transmitted channel. This is because there is a maximum limit of modulation order per subcarrier, e.g. LTE Release 11 and the upcoming Release 12 has a maximum of modulation order of 64QAM and 256QAM, respectively [24, 25]. In addition, the dynamic nature of cellular networks requires the RRM to adapt with the users movement.

In OFDMA based HetNets, downlink interference is practically reduced using radio resource management (RRM). This includes frequency spectrum allocation and power control [20, 19], where in the case of interfering BSs, spectrum allocation minimises interference by allocating different subsets of subcarriers to those BSs. This, however, reduces the ability of the interfering BSs to fully exploit multiuser diversity and consequently reduces the achievable throughput. Thus, in order to capture this, it is important to evaluate the combined performance of RRM and scheduling together.

OFDMA RRMs can be classified into two types, Channel State Information (CSI) based and Self-organizing network (SON). Both types make a decision of resource allocation in distributed and/or centralized manners. In the case of CSI based RRM [19], the resources are allocated such that the interference is minimised. This requires the information of interference and/or the channel gain at all bands [19, 26].

Distributed CSI based RRM works by allowing each small base station (SBS) to allocate its UEs' subcarriers based on measurements of the interference received [27, 28, 29], while the centralised CSI based RRM uses a central node to compute the subcarriers allocation for all UEs [19]. On the other hand, SON RRM utilizes a number of SON functionalities to manage the resource. Among these approaches, the centralised CSI based RRM method is associated with higher levels of complexity due to the requirement of CSI for the entire spectrum to achieve the most appropriate allocation [19].

1.3.2. Scheduling Consideration

Due to channel gain variations that may affect signals transmission across various users and frequency spectrum, scheduling is often required to utilize multiuser diversity and improve the achievable bit rate. The most popular scheduling algorithms in OFDMA systems include maximum sum rate (MSR), maximum fairness (MF), proportional rate constraints (PRC), proportional fairness (PF) [22] and the cumulative distribution function (CDF) based scheduling policy [30], which retains a similar characteristic to PF scheduler [31] that maximises multiuser diversity and users' fairness. Due to this reason, PF based scheduler is commonly applied in the cellular environment [32]. Although fairness of a system can be assessed with proportion of resources assigned to a user with some normalisation factor [31], the interest of this thesis is to assess fairness in terms of quality of service (QoS) improvement. Since QoS has been the main interest besides sum rate, this project considers only the scheduling strategies that balance the QoS as well as utilising multiuser diversity.

1.3.3. Femtocell Access

Accessibility of femtocells is a crucial aspect for the cellular provider. Conventional access schemes include *open* and *closed* access. With open access, outside or unregistered users can access a particular femtocell. On the other hand, closed access scheme block any outside or unregistered users from accessing the femtocell.

Open access can be beneficial to the overall network capacity in comparison to closed access. However, multiple access to different femtocells results in high probability of handover between one femtocell to other femtocells [33]. On the contrary, the closed access scheme is very beneficial for the femtocell owner and avoid multiple handover problems with the penalty of reducing the performance of the surrounding users. A more preferable access scheme employed by the network operator is the hybrid scheme [34], which allocates most of the available resource to the femtocell owner and allows visitor to access the rest of the femtocell's resource.

1.4. Motivation

Inspired by the novel implementation of PT in CDMA shown in [12] and the growing popularity of license-exempt spectrum for cellular systems such as the Unlicensed Mobile Access (UMA) [35], this work investigates a new PT diversity technique for uplink orthogonal frequency division multiple access (OFDMA). It is expected that by implementing the same principle, a diversity order of two with uncompromising data transmission rate can be achieved. It is worthwhile highlighting that other diversity techniques, such as the RT techniques, offer diversity at the expense of data rate reduction.

The need to achieve a more efficient and adaptive femtocell based HetNets, prompts an investigation to find robust radio resource management (RRM) algorithms that can achieve the best balance between resource utilisation and interference minimisation. This investigation focuses on the impact of overall sum rate performance and quality of service (QoS) in terms of minimum bit rate as well as the environmental impact such as power consumption and energy efficiency in order to show the effect of supporting the requirement to satisfy data rate increase and satisfy the green communication requirement.

After the investigation of interference avoidance schemes, the impact of scheduling in such limited spectrum needs to be examined. Similar to RRM investigation, the scheduling implementation study is focused on the overall performance and QoS performance as well as the energy efficiency impact.

Finally, a comprehensive method of scheduling access for femtocells needs to be investigated. This is because a femtocell is partially owned by the end-users. Users may deploy various type of access scheme. Typical access strategies are designed in

the interference free scenario. For this reason, this research investigates a comprehensive access policy in the interference scenario.

1.5. Research Objectives and Contributions

The aim of this research is "to improve the performance of cellular networks in both physical and medium access control (MAC) layers using the cooperative communication frameworks". This aim will be achieved through physical (PHY) and MAC layer approaches. The PHY layer manages the signal transmission through radio frequency (RF) while the MAC layer controls the resource allocation for a given PHY layer method [36]. The PHY layer approach focuses on improving the signal transmission while a MAC layer method investigates the method to increase the throughput performance.

1.5.1. PHY Layer Objectives

- Design an OFDMA based PT scheme as an alternative to the RT cooperative scheme.
- Analyse and simulate the performance of OFDMA based PT scheme and compare the performance with the RT alternative under both ideal and non-ideal channel conditions.

1.5.2. MAC Layer Objectives

- Design an interference avoidance RRM algorithm using cooperative frameworks.
- Performance evaluation by considering the homogeneous network (HoNet) that contains the femtocells network only and heterogeneous network (HetNet) that contains other cell sizes, e.g. macrocell and/or microcell besides femtocell.
- Evaluate the impact of scheduling implementation on the spectrum limited resource allocation.

- The designed RRM is assessed based on the overall achievable data rate, QoS and power consumption as well as energy efficiency performance.
- Design a new scheduling strategy to accommodate further investigation on access strategy.
- Design a comprehensive femtocell access strategy based on the designed interference avoidance scheme and evaluate the impact of the access strategy to the femtocell owner and the surrounding users.

1.6. Publications

This work has resulted in a number of contributions including one patent, one accepted IEEE Transactions on Communications journal and four IEEE peer reviewed conference papers.

- Pramudito, W and Alsusa, E. (2012). "Femtocell technology in 4G systems", UK Patent No. GB1214642.9. Status: filed in August 2012, finalisation stage before publication after 7 January 2014.
- IEEE Transaction on Communication: W. Pramudito and E. Alsusa, "A Hybrid Resource Management Technique for Energy and QoS Optimization in Fractional Frequency Reuse Based Cellular Networks.". *Status: Accepted subject to minor revision (TCOM-TPS-13-0066).*
- W. Pramudito, and E. Alsusa, "Joint Dynamic Frequency Allocation and Routing Strategy for Optimizing the Power Consumption and Data Rate of OFDMA based Femtocell Networks," in Wireless Communications and Networking Conference (WCNC), 2013 IEEE, April 2013.
- W. Pramudito, and E. Alsusa, "Adaptive Radio Resource Management for QoS Optimization in Green Long Term Evolution Network," in Communications (ICC), 2013 IEEE International Conference on, June 2013.
- W. Pramudito, and E. Alsusa, "A Dynamic Pairing Diversity with Interference Exploitation for High Throughput 4G Systems" in Personal Indoor and Mobile Radio Communications (PIMRC) 2013 IEEE 24th International Symposium, September 2013.

• W. Pramudito, and E. Alsusa, "Joint Dynamic Energy-efficient Spectrum Allocation and Routing in Two-tiered 4G Cellular Systems." Globecom 2013.

1.7. Thesis Structure

This thesis reports the work of developing various strategies to enhance the performance of heterogeneous cellular networks and is divided in eight chapters. The current chapter, Chapter 1, has introduced the overview of this research.

Chapter 2 provides all the theoretical background of 4G heterogeneous networks, which include orthogonal frequency division multiplexing/multiple access, signal propagation, multiple antennas and virtual multiple antennas systems, femtocell in 4G heterogeneous cellular networks (HetNets) and radio resource management in femtocell based 4G HetNets.

Chapter 3 proposes a novel cooperative diversity specifically designed for OFDMA based uplink transmission by utilising the single dimensional OFDM modulation and unlicensed band to achieve a diversity order of two and a transmission rate of one symbol/second/Hz. Both performance analysis and simulation results are presented in this chapter.

Chapter 4 and chapter 5 propose and evaluate a novel radio resource management in order to reduce the interference of femtocell based HetNets using a novel interference mapping. The analysis is presented in chapter 4 and the simulation results are presented in chapter 5.

Chapter 6 reviews the implementation of scheduling strategy in the proposed interference mapping radio resource management and proposes a novel scheduling strategy that provides flexibility in various real cellular networks scenario.

Chapter 7 proposes a scheme to implement various femtocell access strategies and provides a compensation scheme in order to encourage the femtocell owner to provide the accessibility of femtocell.

Chapter 8 concludes the discussion and shows future works recommendation.

Finally, the appendices of this report provide the throughput consideration in this research, effect of time mis-synchronisation to the pairing users in PT scheme and proof of Lemma 1.

2. 4G Cellular Networks Deployment

This chapter provides theoretical background of important aspects of the link and system levels implementation of Wireless Microwave Access (WiMAX) and Long Term Evolution (LTE). This includes signal propagation, modulation schemes, multiple antennas system, femtocell technology implementation and radio resource allocation consideration. This chapter is organised as follows. First, basic signal propagation is explained in section 2.1. After that, OFDM/A system, which is essential for 4G networks, is described in section 2.2. Then, multiple-input and multiple output (MIMO) and virtual MIMO are discussed in section 2.3 and section 2.4, respectively. The implementation of femtocell technology is described in section 2.5 while the radio resource management for femtocell is described subsection 2.6.2. Finally, this chapter is summarised in section 2.7.

2.1. Signal Propagation

Signal propagation from transmitter to receiver can be classified into two types. They are large-scale, which occurs due to variations in both the terrain profile, and small scale fading channels, which occurs due to multiple reflections around the receiver. Large scale fading channels is characterised by slow variations of the received signal power over distance, while the small scale fading is characterised by rapid signal fluctuation over short distance or time and frequency.

2.1.1. Large Scale Fading

This type of fading is characterised by slow variations of the received signal power over the distance, which decreases over distance logarithmically [37]. The difference

between the transmitted power and the received power is called path loss. This received signal across the distance measured in dBm, P_r [dBm], is related to pathloss, PL(d) [dB], which is given by [37].

$$P_r(d)[dBm] = P_t[dBm] - PL(d)[dB]$$
(2.1)

where $P_t[dBm]$ is the transmitted power measured in dBm. The pathloss is affected by different environment and frequency carrier.

There are two propagation scenarios considered in this research, which are outdoor and indoor propagation models. In both cases, this thesis only considers pathloss models that work on typical WiMAX and LTE licensed spectrum, which are 800 MHz, 1.8 GHz, 2.3 GHz, 2.5 GHz, 2.6 GHz and 3.5 GHz [38, 2, 39, 40]. A widely used model for outdoor propagation scenario at these frequency spectrums are the Hatta and Stanford University Interim (SUI) models [38, 37]. On the other hand, a widely used model for indoor propagation is the log normal shadowing model [37].

Hatta model which works up to 1.5 GHz is given by $[38, 37]^{-1}$

$$PL(d) [dB] = 69.55 + 26.16 \log_{10} (f_c) - 13.82 \log_{10} (h_{te}) - a (h_{re}) + (44.9 - 6.55) \log_{10} (d)$$
(2.2)

where f_c is the carrier frequency in MHz between 150 MHz and 1500 MHz, h_{te} is the basestation (BS) antenna height (in meters) ranging between 30 m and 200 m, h_{re} is the receiver antenna height between 1 m and 10 m, d is the distance between transmitter and receiver (in km) and $a(h_{re})$ is the mobile antenna correction factor affected in decibel by the size of coverage area [37]. As shown in [37], the correction factor in the case of large city is given by

$$a(h_{re}) [dB] = \begin{cases} 8.29 \left(\log_{10} \left(1.54h_{re} \right) \right)^2 - 1.1 & f_c \le 300 \text{MHz} \\ 3.2 \left(\log_{10} \left(1.54h_{re} \right) \right)^2 - 4.97 & f_c > 300 \text{MHz} \end{cases}$$
(2.3)

and in the case of small to medium city is given by

$$a(h_{re}) [dB] = (1.1 \log_{10} (f_c) - 0.7) h_{re} - (1.56 \log_{10} (f_c) - 0.8)$$
(2.4)

SUI model distinguishes the environment into three Terrain types, A, B and C [38].

¹For clarity reason, Hatta model shown in this chapter is only in the case of urban areas.

$$PL(d)[dB] = Q + 10\varphi \log_{10}(d/100) + X_f + X_h + s$$
(2.5)

where $Q = 20\log_{10}\left(\frac{4\pi 100}{\lambda}\right)$, φ is given by

$$\varphi = a - bh_{te} + \frac{c}{h_{te}} + \chi_a \sigma_\gamma \tag{2.6}$$

 X_f is given by $X_f = 6 \log_{10} \left(\frac{f_c}{2000}\right), X_h$ is given by [38]

$$X_{h} = \begin{cases} 10.8 \log_{10} \left(\frac{2.0}{h_{re}}\right) & \text{for Terrain types A and B} \\ 20 \log_{10} \left(\frac{2.0}{h_{re}}\right) & \text{for Terrain types C} \end{cases}$$
(2.7)

and s is given by

$$s = \chi_b \left(\mu_\sigma + \chi_c \sigma_\sigma \right) \tag{2.8}$$

where χ_a , χ_b and χ_c are Gaussian random variables with zero mean.

Model	Terrain type A	Terrain type B	Terrain type C
parameters			
a	4.6	4	3.6
$b \ (m^{-1})$	0.0075	0.0065	0.005
c(m)	12.6	17.1	20
σ_{γ}	0.57	0.75	0.59
μ_{σ}	10.6	9.6	8.2
σ_{σ}	2.3	3.0	1.6

Table 2.1.: Parameters of the SUI propagation model [38, 40]

The log normal shadowing model used to represent indoor propagation is given by

$$PL(d)[dB] = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 10\beta \log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma}$$
(2.9)

²In the case of 3.5 GHz, [39] shows that SUI model provides the most accurate results for NLOS compared to existing propagation models. However, it gives high error due to the fact that this model distinguishes into three terrain types which may be chosen arbitrarily.
where d_0 is the reference distance close to the transmitter that is usually one meter, d is the distance between transmitter and receiver, λ is the signal wavelength, β is the pathloss exponent differs for each type of environment and X_{σ} is log normal shadowing.

As can be seen from SUI and lognormal pathloss models, these models have shadowing effect given by s and X_{σ} , respectively. The shadowing effect to Equation 2.9 and Equation 2.5 is random fluctuation to the pathloss besides the average value caused by the distance between transmitter and receiver. Hence, two points at different locations with the same distance with a transmitter does not always mean similar pathloss. This happens due to obstructions such as buildings, trees and hills in the case of outdoor scenario and walls, open and closed doors in the case of indoor scenario [37].

2.1.2. Small Scale Fading

Small scale fading occurs as a result of multipath arrival of the same signal from the transmitter to the receiver and the relative movement between the receiver and the surroundings in the vicinity of the mobile. This type of fading causes rapid fluctuation of the received signal over a short distance and affects the magnitude as well as the phase of the received signal that can lead to increase the error probability of making received signal interpretation. Moreover, this also causes interference that makes the error rate of the received signal worse.

Small scale fading results in similar effect to convolving a signal with a certain random variable in Digital Signal Processing. This makes the small scale fading best represented by an impulse response. The channel impulse response is given by $h(\tau, t)$ where τ describes the delay path occurs as a result of multipath fading and tdescribes time varying channel occurs as a result of relative movement. Therefore, the received signal, y(t), is related to the transmitted signal, x(t) by

$$y(t) = x(t) * h(\tau, t)$$
 (2.10)

A) Statistical Model of Small Scale Fading

Small scale fading can be classified as either with line-of-sight (LOS) or no line-of-sight (NLOS). The small scale fading channel envelope, H, is a complex envelope given by

$$H = H_r + jH_i \tag{2.11}$$

where H_r and H_i are the inphase and quadrature part of fading channel. A widely used model assumes H_r and H_i as independent Gaussian random variables that is distributed according to $\mathcal{N}(m_r, \sigma^2)$ and $\mathcal{N}(m_i, \sigma^2)$, respectively. This assumption is used throughout this research.

When the channel has NLOS, the received signal does not have the significant path. In this case and Gaussian random variables assumption of H_r and H_i , real and imaginary components have the same mean given by $m_r = m_i = 0$, and the fading envelope, |H|, is classified as Rayleigh envelope. The probability density function (PDF) of Rayleigh fading envelope at any given x value is given by [41]

$$f_{|H|}(\mathsf{x}) = \begin{cases} \frac{\mathsf{x}}{\sigma^2} e^{-\frac{\mathsf{x}^2}{2\sigma^2}} & \mathsf{x} > 0\\ 0 & \text{otherwise} \end{cases}$$
(2.12)

On the other hand, when the received signal contains LOS, m_r and $m_i > 0$. This model, which is classified as Ricean fading envelope, has the PDF given by

$$f_{|H|}(\mathbf{x}) = \begin{cases} \frac{\mathbf{x}}{\sigma^2} I_0\left(\frac{w\mathbf{x}}{\sigma^2}\right) e^{-\frac{\mathbf{x}^2 + w^2}{2\sigma^2}} & \mathbf{x} > 0\\ 0 & \text{otherwise} \end{cases}$$
(2.13)

where $I_0(x)$ denotes the modified Bessel function of the first kind and order 0, which is given by [41]

$$I_0(\mathsf{x}) = \sum_{k=0}^{\infty} \left(\frac{\mathsf{x}^k}{2^k k!} \right)$$
(2.14)

and w is given by

$$w = \sqrt{m_r^2 + m_i^2} \tag{2.15}$$

Since the LOS contains direct signals which is higher than the reflected signal ar-

rivals, Ricean fading envelope can be described by a *Rice factor*, K, as

$$K = \frac{w^2}{2\sigma^2}.$$
(2.16)

This ratio is equivalent to the ratio between the direct signal and the multipath signal powers [42]. At high ratio, the fading envelope becomes equivalent to a Gaussian noise channel because of small channel variation. On the other hand, when the ratio is 0, this envelope becomes Rayleigh fading envelope.

B) Fading Effects as a Result of Multipath Arrival Signals

Multipath fading creates several copies of the transmitted signal arriving at the receiver in different time slots. The different arrival times are called the path delay, τ . The attenuation and phase shift of the channel associated with different path delays are usually uncorrelated [41]. For this reason, fading analysis can begin by considering the correlation between different attenuation and phase shift of different path delays.

In order to understand multipath fading, a number of useful correlation functions and power spectral density function need to be developed. This will lead to some useful parameters and the effect of having different value of these parameters. The autocorrelation function of the channel impulse response with uncorrelated scattering assumption in delay spread domain, τ , is given by [41]

$$\mathbf{R}_{h}\left(\tau_{1}; \Delta t\right) \delta\left(\tau_{2} - \tau_{1}\right) = \mathbf{E}\left[h^{*}\left(\tau_{1}; t\right) h\left(\tau_{2}; t + \Delta t\right)\right]$$

$$(2.17)$$

In the frequency domain, the autocorrelation can be analysed by taking the Fourier transform of $h(\tau; t)$ to obtain H(f; t), which is given by $H(f; t) = \int_{-\infty}^{\infty} h(\tau; t) e^{-j\pi f\tau} d\tau$. Assuming that the channel is wide sense stationary, the autocorrelation function in frequency domain is given by

$$\mathbf{R}_{H}(f_{2}, f_{1}; \Delta t) = \mathbf{E} \left[H^{*}(f_{1}; t) H(f_{2}; t + \Delta t) \right]$$
(2.18)

Equation 2.18 can be simplified into

$$\mathbf{R}_{H}\left(f_{2}, f_{1}; \Delta t\right) = \mathbf{R}_{H}\left(\Delta f; \Delta t\right) \tag{2.19}$$

where $\Delta f = f_2 - f_1$.

By setting $\Delta t = 0$, the autocorrelation function, $\mathbf{R}_h(\tau, 0) = \mathbf{R}_h(\tau)$, is equal to the average power output of the channel as a function of delay path, τ , which is called *delay power spectrum* [41]. Equivalently, the autocorrelation function in the frequency domain, which is called *spread-frequency correlation function*, is related by

$$\mathbf{R}_{H}\left(\bigtriangleup f\right) = \int_{-\infty}^{\infty} \mathbf{R}_{h}\left(\tau\right) e^{-j2\pi f\tau} d\tau \qquad (2.20)$$

The relationship of the spread-frequency correlation function and delay power spectrum is illustrated in



Figure 2.1.: Autocorrelation and power spectral density of the channel as a results of multipath arrival of signals [41]

The range of delay path, τ , where $\mathbf{R}_h(\tau)$ is non zero is called the *multipath spread* or *delay spread* of the channel, τ_m . Hence, τ_m determines the length of the channel impulse response. Equivalently, the range of frequency difference where $\mathbf{R}_H(\Delta f)$ is non zero is called coherence bandwidth of the channel, $(\Delta f)_c$ [41]. This parameter determines how wide the bandwidth of the channel remains flat in frequency domain. These two parameters are the parameters used to define the effect of multipath fading in the channel and are related by ³

$$(\Delta f)_c \propto \frac{1}{\tau_m} \tag{2.21}$$

When the coherence bandwidth is wider than the signal bandwidth or the delay spread is shorter than the symbol period, the channel is defined as a flat fading

³This relation only true in the case of negative exponential delay profile as shown by Figure 2.1.

channel. On the other hand, when the coherence bandwidth is smaller than the signal bandwidth or the delay spread is longer than the symbol period, the channel is defined as a frequency-selective fading channel.

A flat fading channel is equivalent to multiplying a signal with a certain coefficient. This is because all the signals arrive within one symbol period and hence, it only affects the symbol energy. In addition, a flat fading channel can be represented by impulse response with one tap coefficient. This is because in the receiver, the received signal is digitised with sampling period twice the symbol period.

Different behaviour occurs when the delay spread is larger than the symbol period. This result in frequency selective fading channel is equivalent to convolving a signal with a series of channel coefficient. So, frequency selective fading channel can be represented by impulse response with number of taps equals with τ_m/T_{sampl} where T_{sampl} is the sampling period. The received signal is then can be represented by the convolution of transmitted signal with the channel plus added noise.

C) Fading Effect as a Result of Relative Movement

In wireless communication, the relative movement of the transmitter and receiver results in a time varying channel. In the frequency domain, it results in the Doppler shift phenomenon. The fundamental effect of the relative movement in signal transmission is in the difference between channel impulse response detected by the pilot signal and the actual impulse response experienced by the signal.

In classic physics, when a source transmits a wave to the receiver at certain wavelength, λ , to a destination with relative movement to one another at a speed, v, results in a Doppler frequency shift given by

$$f_{\mathcal{D}} = \frac{v}{\lambda} \cos \theta \tag{2.22}$$

where θ is the angle arrival of the wave. So, the maximum Doppler shift occurs when the angle arrive at 0 and π . In the case of the electromagnetic wave with speed of light equals 300,000 km/s, the maximum Doppler shift is given by

$$f_{\mathcal{D}_{max}} = \frac{v}{c}f \tag{2.23}$$

where f is the electromagnetic wave frequency.

Similar argument with the derivation of correlation function and power spectral of multipath fading channel, the derivation in this section is used to develop a good understanding of the time variant channel, its parameters and the effect of varying the parameter value. The channel time variation can be analysed by taking the correlation of the channel, \mathbf{R}_H , in term of Δt . In order to observe the effect of Doppler shift, another parameter is required as the variable results in a Fourier transform, which is Doppler frequency, v. By taking the Fourier transform of the channel power spectral density can be obtained. So, the channel power spectral density is given by

$$\mathbf{S}_{H}\left(\triangle f;\upsilon\right) = \int_{-\infty}^{\infty} \mathbf{R}_{H}\left(\triangle f;\triangle t\right) e^{-j2\pi\upsilon t} d\triangle t \qquad (2.24)$$

By setting $\Delta f = 0$, the power spectrum is left with one parameter, which is Doppler frequency, v, and called the *Doppler power spectrum* of the channel, $\mathbf{S}_H(v)$, which is given by

$$\mathbf{S}_{H}(\upsilon) = \int_{-\infty}^{\infty} \mathbf{R}_{H}(\Delta t) \, e^{-j2\pi\upsilon t} d\Delta t \qquad (2.25)$$



Figure 2.2.: Autocorrelation and power spectral density of the channel as a results of relative movement [41]

Doppler power spectrum and channel autocorrelation can be illustrated from Figure 2.2. The range of Doppler frequencies with non-zero power spectrum is called *Doppler* spread, $\mathcal{W}_{\mathcal{D}}$, and the range of time varying parameter, t, over which the channel is considered to be static or not varying is called *coherence time*, $(\Delta t)_c$ [41].

Doppler spread, $\mathcal{W}_{\mathcal{D}}$, is related to the Doppler maximum frequency shift by $\mathcal{W}_{\mathcal{D}}$ =

2 $f_{\mathcal{D}_{max}}[37]$. $(\triangle t)_c$ is related to $\mathcal{W}_{\mathcal{D}}$ by ⁴

$$(\Delta t)_c \propto \frac{1}{\mathcal{W}_{\mathcal{D}}} \tag{2.26}$$

The Doppler spread often is explained by the normalised Doppler spread, $T_S f_{\mathcal{D}_{max}}$, where T_S is symbol period.

2.2. Orthogonal Frequency Division Multiplexing

2.2.1. OFDM Transceiver

OFDM signal can be generated by two methods. The first method, which is called conventional OFDM transmission throughout this report, utilises N point discrete Fourier transform (DFT) and inverse discrete Fourier transform (IDFT) for N subcarriers [43]. The second method, described in [41], uses the fundamental Nyquist sampling criterion, which requires a sampling/desampling frequency twice larger than the baseband bandwidth signal. This is called Nyquist criterion OFDM transmission. Hence, in order to modulate and demodulate a \tilde{N} m-array quadrature amplitude modulated (M-QAM) subcarriers, $N = 2 \tilde{N}$ DFT and IDFT points are required.



Figure 2.3.: OFDM Transceiver

⁴This relation only true in the case of Jake's circle scattering model [41].

A) Conventional OFDM Transceiver

In this system, a N DFT points are allocated for N subcarriers. Assume the transmitted signal in the frequency domain is given by X[n], n = 0, 1, ..., N - 1, the output of IDFT is a complex time domain discrete signal, x[a], a = 0, 1, ..., N - 1. In order to modulate a complex time domain, real and imaginary parts of x[a] are converted into analogue signals, separately, with sampling/desampling period, T_S , equals to T_O . After that, real and imaginary parts are multiplied by $\cos(2\pi f_c t)$ and $\sin(2\pi f_c t)$, respectively. The results of these processes are signal with the spectral efficiency shown in Figure 2.4.

At the receiver, the real and imaginary parts are detected by having two matched filters. The matched filter works in equivalent with multiplying the received signal with the carrier frequency at one symbol period. Hence, this can be represented by multiplying the received signal with $\cos(2\pi f_c t)$ for the real part and with $\sin(2\pi f_c t)$ for the imaginary part. Since this also yields $2f_c$ frequency component, a low pass filter (LPF) is required before digital-to-analogue converter (D/A).

B) Nyquist criterion OFDM Transceiver

Assuming that the transmitted \widetilde{N} subcarriers are given by X[n], $n = 0, 1, ..., \widetilde{N}$ -1, it would be required to re-arrange these into $X_O[n]$, n=0,1,...,N-1, as follows

$$X_{O}[n] = X[n], \qquad n = 1, ..., \tilde{N} - 1$$

$$X_{O}[N - n] = X^{*}[n], \qquad n = 1, ..., \tilde{N} - 1$$

$$X_{O}[0] = Re(X[0])$$

$$X_{O}[\tilde{N}] = Im(X[0])$$
(2.27)

Thus invoking the N-point IDFT generates real-valued discrete time-domain signal,

$$x[a] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_O[n] \exp\left(j\frac{2\pi na}{N}\right)$$
(2.28)

for a = 0, 1, ..., N - 1. As the baseband signal is upconverted by multiplying x(t) with $\cos(2\pi f_c t), 2(\widetilde{N} - 1)$ subcarriers will be allocated around f_c , as in $f_c - f_{\widetilde{N}-1}$ to $f_c + f_{\widetilde{N}-1}$. Since subcarriers $f_c - f_1$ to $f_c - f_{\widetilde{N}-1}$ represent the lower sideband, hence contain the same information as subcarriers $f_c + f_1$ to $f_c + f_{\widetilde{N}-1}$, which represent the upper sideband, a bandpass filter can be used to remove one of them, so to

achieve identical bandwidth requirement as the conventional method. It is worth emphasising that the same cannot be done with the conventional OFDM signal as the lower half and upper halves do not represent the lower and upper sidebands. The spectrum occupancy of the Nyquist criterion OFDM system is illustrated by example in Figure 2.4.



Figure 2.4.: Occupied spectrum by various OFDM transceiver

Although the number of DFT points using this method is initially twice the conventional OFDM signal, the symbol period is reduced to the same period as the conventional OFDM symbol by employing a sampling/desampling period of half the conventional OFDM symbol. Therefore, the resulting 1D OFDM signal has similar spectrum efficiency as the conventional one. The advantage of modulating an OFDM signal in such a way lies in the fact since the channel is complex (inphase and quadrature), this makes it possible to exploit the second dimension (the quadrature) for diversity purposes and to allow interference exploitation, as well as, minimize sensitivity to timing-misalignment between members of each cooperative pair as will be shown in the next chapter.

2.2.2. OFDM in Multiple Access

Because of the characteristics of the OFDM symbol, OFDM can be combined with any multiple-access schemes, which are frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA). The combination of the OFDM with the multiple access techniques inherits advantages and disadvantages of all the multiple access as well as the immunity from frequency selective fading channels.

OFDM and TDMA combination is possible by allocating different users in different OFDM symbol period. At a particular period, the assigned user occupies all the orthogonal frequency spectrum. By doing so, the orthogonality of the symbols from all users are maintained. The combination of OFDM and TDMA system gives easier power control managed by the base station, flexible data rate assignment to different users and Inter Symbol Interference (ISI) resistance.

Combination of OFDM and CDMA can be achieved by employing multicarrier CDMA (MC-CDMA) and multicarrier DS-CDMA. MC-CDMA works by spreading the data before serial-to-parallel and DFT process like in normal OFDM system. On the other hand, the spreading data is performed after serial-to-parallel and before DFT process in multicarrier DS-CDMA [44]. It results in different spreading sequence will be allocated at different sub-carriers. Although the OFDM-CDMA combination system is able to gain overall user capacity increases, which happens in single carrier CDMA system as well as having ISI immunity [45]. However, a CDMA system experiences self interference as a result of detecting the transmitted symbol from the spreading sequence code. This interference occurs even in the absence of other users [46].

The most interesting combination scheme is a combination of OFDM with FDMA. The result of this combination is orthogonal frequency division multiple access (OFDMA) [47]. This system works by allocating each user with subcarriers. The key advantage of this system is the ability of applying user resource allocation, dynamic scheduling [48] and adaptive modulation. User resource allocation and dynamic scheduling applications allow maximising throughput of overall system by dynamically assigning the best channel with best user. Adaptive modulation works by assigning a good channel with high constellation modulation while the bad channel with low constellation. Another advantage of OFDMA is the scalability of the bandwidth usage while fixing the time and frequency resource [46]. This minimises the impact to higher layers. Therefore, with minimum modification on the physical interface, flexible spectrum allocation can be obtained digitally by modifying the input of IDFT. This feature however, cannot be achieved in OFDM-TDMA based system.

With the time and frequency equalisation techniques, which will be described in next section, it is clear that combination between OFDM and FDMA system is the most appropriate in current technology. For this reason, this research will use OFDMA system whenever multiuser OFDM system is required.

2.2.3. Implementation Issues in OFDM Based Communication System

As mentioned earlier, OFDM transmission has an advantage of simplifying equalisation in multipath frequency selective fading environment. However, there are some challenging issues in implementing this technique, especially in the case of uplink transmission.

The main issues in OFDM implementation can be summarised as a result of four factors, which are peak-to-average power ratio (PAPR), channel estimation, time synchronisation and frequency offset [41, 49, 50]. PAPR occurs when signals from all subcarriers add the phase constructively. Using the central limit theorem in order to model the combined N subcarriers, the PAPR is proportional to when N, number of subcarriers, is large [41]. This problem results in saturation when using a power amplifier, which leads to inter modulation distortion, and clipping of D/A output voltage. So, PAPR becomes a serious problem for uplink OFDMA. Fortunately, PAPR can be reduced by employing pseudo random phase shift insertion in each sub-carrier and modulating a small amount of the sub-carriers distributed across the frequency band with flexible design of dummy symbols [41]. Furthermore, the most attractive way to reduce the impact of frequency offset is by employing single carrier FDMA (SC-FDMA). This is a modified OFDMA based system that able to reduce the impact of PAPR besides reducing the impact of frequency offset [51]. Hence, the PAPR problem will not be considered further in this research.

Frequency offset occurs as results of Doppler shifts described in previous section and frequency asynchronisation [41, 52]. It destroys the orthogonality of all subcarriers and results in inter-carrier interference (ICI). This interference degrades the performance significantly. The effect of Doppler shifts into the multicarrier system is shown by Figure 2.6. The ICI effect caused by Doppler shifts in an OFDM system is almost similar with ISI in single carrier. Hence, minimum mean-square-error (MMSE), recursive least square (RLS) and least mean square (LMS) can be used to equalise the ICI [41].

The effect of frequency asynchronousity mainly arises in the uplink transmission. This is because in the downlink transmission, there is only single source of signal. Hence, the equalisation is almost similar with the single user OFDM transmission, such as the equalisation technique described in [53, 54, 55]. The frequency asynchronousity in uplink can be equalised in two steps, which are carrier frequency offset (CFO) estimation and CFO correction [56]. Some good techniques in estimation CFO were presented in [55, 57, 50, 58]. CFO correction basically works using by using the same equaliser to reduce ICI as a result of Doppler shifts. [56] shows that the proposed methods reduce the interference energy into negligible amount. Therefore, the frequency synchronisation problem will not be considered further in this report.

Channel estimation is a standard issue in any communication system. In multicarrier system, the channel is estimated by inserting pilot carriers, which are known by the receiver, in the OFDM transmission. This estimation, however, will not be perfect in reality. So, this is important to take into consideration the channel estimation error.

The estimated channel will always have errors from the actual channel because the received signal always has additive noise. When the estimated channel error is considered throughout this research, it is simulated by adding noise onto the channel response such that the mean-absolute-percentage-error (MAPE) [59, 60] between the actual and the estimated channel transfer function, which is given by

$$MAPE = \sum_{n=0}^{N-1} \left| \frac{H_{est} - H}{H} \right| / N \tag{2.29}$$

Time mis-synchronisation can be represented by time shifts, $\Delta \theta$, in the received

OFDM signal. If $-\mathcal{G} + \tau - 1 \leq \Delta \theta$ where \mathcal{G} is the cyclic prefix (CP) length and τ is the maximum delay spread, using the Fourier transform property for time shifts in the time domain, the time shifts introduces phase shifts by $2\pi f_k \Delta \theta$ in the frequency domain of the received signal. By knowing the length of $\Delta \theta$, the time mis-synchronisation can be eliminated by simply compensating the phase shifts. However, when $-\mathcal{G} + \tau - 1 > \Delta \theta$, inter-symbol interference (ISI) occurs and the orthogonality cannot be maintained.

Time mis-synchronisation or mis-alignment more likely occurs in the uplink OFDMA system. This is because the OFDM symbols from different users arrive at different times. In this situation, the times arrival of all signals from different users need to be predicted accurately. Even though the signal arrivals from all users can be predicted, for instances using the technique proposed in [58, 61, 62], multiuser interference (MUI), which destroys the orthogonality of the sub-carrier, can still exist when the total length of the impulse response between the different users and BS exceed the CP period [63, 64]. The effect of MUI in uplink transmission when the signals' time arrivals are known is almost identical with the effect of residual ISI in the downlink transmission. Residual ISI in downlink occurs when the delay spread exceeds the CP period. Therefore, the easiest way to overcome the effect of MUI is by having the length of the CP period exceed the total period between the first and the last arrival signal from all users [63, 64]. This method will surely mitigate the MUI problem in uplink transmission. However, extending the guard intervals is a very expensive solution since it reduces the bandwidth efficiency significantly.

An alternative to increasing the length of the CP would be to use receiver based interference cancellation techniques such as the MMSE, RLS and LMS based linear time-domain equaliser which are widely accepted [41]. For the interference effect, as a result of residual ISI, the Residual ISI Cancellation (RISIC) algorithm, proposed in [65], shows very promising results and is simpler to implement than the MMSE, RLS and LMS based equalisers. Therefore, if time mis-synchronisation is considered, RISIC equaliser is used as an equalisation method. Detail steps of RISIC equaliser implementation can be seen from chapter 3 on page 76.

2.2.4. Impact of Small Scale Fading to OFDMA

A) Impact of Multipath fading



Figure 2.5.: Effect of multipath fading channel to OFDM based system.

If an OFDM system with 64 subcarriers and where each subcarrier is modulated with QPSK modulation, delay spread and CP period of 10% are assumed, the performance of an OFDM signal under small scale fading channel under Rayleigh and Ricean fading envelopes is shown by Figure 2.5. As can be seen from Figure 2.5, Rayleigh fading envelope gives worse performance than the Ricean fading envelope. This happens since the channel gain is more varying in the case of the Rayleigh envelope than the Ricean which increases the number of deep fade subcarrier.

Figure 2.5 also shows that as the ratio of LOS and reflected signal increases, the bit error rate (BER) performance improves significantly. The biggest performance improvement occurs when the ratio is increased from k equals to 3 dB to 10 dB. As the ratio increases, the performance difference is getting less difference. The performance improvement will stop as the ratio goes to infinity, which is the case of AWGN channel.

B) Impact of Relative Movement

Assuming an OFDM system with 64 subcarriers and where each subcarrier is modulated with QPSK modulation, a delay spread and CP period of 10%, and Rayleigh fading envelope, the effect of Doppler spread on a QPSK system is shown by Figure 2.6. As can be seen from this figure, increasing the normalised Doppler spread $T_S f_{\mathcal{D}_{max}}$ degrades the BER performance and reduces the SINR because increasing the normalised Doppler spread value increases the interference of adjacent subcarriers. Furthermore, there is no significant difference between normalised Doppler value equals with 0.001 and 0.01. This means, at those values, the time varying channel becomes almost negligible. If it is assumed typical OFDM symbol period



Figure 2.6.: Effect of Doppler spread to the OFDM symbols transmission. (a) BER of OFDM based with QPSK system in Rayleigh frequency selective fading channel. (b) Signal-to-noise and interference ratio (SINR) against SNR per bit.

of 10^{-4} s and carrier frequency of 2.3 GHz, this means the minimum speed in order the Doppler spread start to affect the performance is 13.04 m/s or 46 km/h. Since typical pedestrian users moves in a much slower performance than this, this effect will not be considered further in this project.

2.3. MIMO System

Multiple-input and multiple-output (MIMO) transmission can undoubtedly provide additional degrees of freedom that can be used for spatial multiplexing or spatial diversity. Spatial multiplexing can achieve a maximum of \mathscr{T} symbols/second/Hz where \mathscr{T} is the number of transmitting antennas at the price of requiring a similar number of receiving antennas \mathfrak{R} [66]. On the other hand, spatial diversity provides signal quality improvement with similar maximum throughput with single-input and single-output (SISO) system [41]. Since MIMO system is part of the PHY layer solution and this research focuses on signal quality improvement in the case of PHY layer approach, only spatial diversity will be considered further in this thesis.

2.3.1. Channel of MIMO System

A MIMO system has \mathscr{T} transmitting antennas and \mathfrak{R} receiving antennas. Signal from each antennas will experience different paths. At the receiver, the signal from every antennas is combined and detected. So, the time-varying impulse response of a MIMO system can be defined as [41]

$$\boldsymbol{h}(\tau;t) = \begin{bmatrix} h_{11}(\tau;t) & h_{12}(\tau;t) & \dots & h_{1\mathscr{T}}(\tau;t) \\ h_{21}(\tau;t) & h_{22}(\tau;t) & \dots & h_{2\mathscr{T}}(\tau;t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{\Re 1}(\tau;t) & \dots & \dots & h_{\Re\mathscr{T}}(\tau;t) \end{bmatrix}$$
(2.30)

In the receiver, the received signal is given by [41]

$$y_m(t) = \sum_{n=1}^{\mathscr{T}} h_{nm}(\tau; t) * s_n(\tau) + \eta_m(t), \qquad m = 1, 2, \dots, \mathfrak{R}$$
(2.31)

where s_n is the transmitted signal at n^{th} antenna, h_{nm} is the impulse response of the signal received at antenna m from the transmitting antenna n and $\eta_m(t)$ additive white Gaussian noise (AWGN) signal. For simplicity, Equation 2.31 can be explained in the matrix form and is given by [41]

$$\boldsymbol{y}(t) = \boldsymbol{h}(\tau; t) * \boldsymbol{s}(\tau) + \boldsymbol{\eta}(t)$$
(2.32)

where $\boldsymbol{y} \in \mathbb{C}^{\mathfrak{R} \times 1}$, $\boldsymbol{s} \in \mathbb{C}^{\mathscr{T} \times 1}$, $\boldsymbol{\eta} \in \mathbb{C}^{\mathfrak{R} \times \mathscr{T}}$.

2.3.2. MIMO for Spatial Diversity

Spatial diversity in MIMO systems can be achieved by two methods, which are spacetime trellis code and space-time block code (STBC). Amongst these two, STBC that was first proposed by [67] provides simpler detection, lower complexity and full diversity order. In this method, the number of time slots equals the number of transmitting antennas, \mathscr{T} . At the first time slot, all \mathscr{T} symbols are transmitted from \mathscr{T} transmitting antennas. The symbols are arranged in certain manner so a real $\mathscr{T} \times \mathscr{T}$ generator matrix, \mathbf{G} , with elements of $g_1, -g_1, g_2, -g_2, \ldots, g_{N_T}, -g_{N_T}$ has orthogonal property, which is given by [41]

$$\boldsymbol{G}^{H}\boldsymbol{G} = \left(\sum_{i}^{\mathscr{T}} g_{i}^{2}\right)\boldsymbol{\mathcal{I}}_{\mathscr{T}}$$
(2.33)

where $\mathcal{I}_{\mathscr{T}}$ is $\mathscr{T} \times \mathscr{T}$ identity matrix.

[68, 69] show that orthogonal design code yields spatial rate of less than one depending when the number of transmit antennas, \mathscr{T} , is bigger than two. However, using Quasi-orthogonal STBC, some number of transmit antennas yields full diversity as well as maximise the spatial rate [41]. These numbers are two, four and eight.

For $\mathscr{T} = 4$, the quasi-orthogonal generates the generator matrix, G, as shown below

$$\boldsymbol{G} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & -s_4^* & s_1^* & s_2^* \\ s_4 & -s_3 & -s_2 & s_1 \end{bmatrix}^T$$
(2.34)

In the case of $\mathscr{T} = 2$, the generator only uses the first two rows and columns. In the receiver, the received signal, y, is given by

$$\boldsymbol{Y} = \boldsymbol{G}\boldsymbol{H}_{MIMO} \tag{2.35}$$

that can be expanded as

$$\begin{bmatrix} Y_{11} & \dots & Y_{1\mathfrak{R}} \\ \vdots & \ddots & \vdots \\ Y_{\mathscr{T}\mathfrak{R}} & \dots & Y_{\mathscr{T}\mathfrak{R}} \end{bmatrix} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & -s_4^* & s_1^* & s_2^* \\ s_4 & -s_3 & -s_2 & s_1 \end{bmatrix} \begin{bmatrix} H_{11} & \dots & H_{1\mathfrak{R}} \\ \vdots & \ddots & \vdots \\ H_{41} & \dots & H_{4\mathfrak{R}} \end{bmatrix}$$
(2.36)

The detection is performed in the following steps:

1. First change the received signal vector, \boldsymbol{Y} , into the rearranged received signal vector, $\widetilde{\boldsymbol{Y}}$, so transmitted symbol, \boldsymbol{S} , can be detected by inverse channel

detector. For $\mathscr{T} = 4$, the received symbol

$$\widetilde{\boldsymbol{Y}} = \begin{bmatrix} Y_{11} & \dots & Y_{1\Re} \\ Y_{21}^* & \dots & Y_{2\Re}^* \\ Y_{31}^* & \dots & Y_{3\Re}^* \\ Y_{41} & \dots & Y_{4\Re} \end{bmatrix}$$
(2.37)

and the rearranged transfer function, \widetilde{H} , is given by

$$\widetilde{\boldsymbol{H}} = \begin{bmatrix} \widetilde{\boldsymbol{H}}_{1} & \dots & \widetilde{\boldsymbol{H}}_{\Re} \end{bmatrix}$$
(2.38)
$$\widetilde{\boldsymbol{H}}_{r} = \begin{bmatrix} H_{r1} & H_{r2} & H_{r3} & H_{r4} \\ H_{r2}^{*} & -H_{r1}^{*} & H_{r4}^{*} & -H_{r3}^{*} \\ -H_{r3}^{*} & -H_{r4}^{*} & H_{r1}^{*} & H_{r2}^{*} \\ H_{r4} & -H_{r3} & -H_{r2} & H_{r1} \end{bmatrix}$$
(2.39)

Therefore, relation between the rearranged transmitted symbol with the rearranged transfer function and the transmitted symbol is given by

$$\widetilde{\boldsymbol{Y}} = \widetilde{\boldsymbol{H}}\boldsymbol{S} \tag{2.40}$$

2. The predicted transmitted symbol, \tilde{S} , is then recovered by multiplying the pseudoinverse of the re-arranged transfer function, \tilde{H} . So, the predicted transmitted symbol is given by

$$\widetilde{\boldsymbol{S}} = \widetilde{\boldsymbol{H}}^{-1} \widetilde{\boldsymbol{Y}} \tag{2.41}$$

If it is assumed an OFDM system with 64 subcarriers and where each subcarrier is modulated with QPSK modulation, maximum delay spread and cyclic prefix period of 10% and Rayleigh fading envelope, the impact of STBC implementation in OFDM signal is shown by Figure 2.7. This figure shows that STBC application improves the BER and spectrum efficiency performance of OFDM based communication system. Figure 2.7 (a) shows that $\mathscr{T} \times \mathfrak{R}$ MIMO system with STBC code provides an equivalent of $\mathscr{T} \times \mathfrak{R}$ diversity orders. This is a practical solution in the case of transmission when the receiving end cannot have a massive number of antenna due to size constraint, complexity, etc.



Figure 2.7.: Performance of STBC in OFDM based system. (a) BER result. (b) Spectrum efficiency result.

2.4. Cooperative Diversity

The basic principle of cooperative diversity is shown by Figure 2.8. User Equipments (UEs) are allowed to communicate with each others besides communicating with the BSs. Normally, users are cooperated with the close vicinity users as illustrated in



Figure 2.8.: Cooperation strategy

this figure. As been described in the first chapter, cooperative diversity can be classified into two major types, which are relay type (RT) and pairing type (PT). As been mentioned in section 1.2 on page 25, the available PT techniques works in CDMA scheme. For this reason, only RT cooperative diversity scheme that will be discussed in this chapter.

RT cooperative diversity is depicted in Figure 2.9. In the first phase, the source



Figure 2.9.: RT cooperative diversity model

terminals (users) broadcast their own symbol to the destination and their L relay terminals. At this phase, the received signal of direct source to destination (SD) transmission is given by

$$y_{SD}(t) = h_{SD}(t) * x(t) + \eta_{SD}(t)$$
(2.42)

and the received signal of source to l^{th} relay (SR) transmission is given by

$$y_{SR_l}(t) = h_{SR_l}(t) * x(t) + \eta_{SR_l}(t)$$
(2.43)

where x(t) is the transmitted symbol from the source, $h_{SD}(t)$ is the impulse response of the SD channel, $h_{SR_l}(t)$ is the impulse response between source and l^{th} relay, $\eta_{SD}(t)$ is the noise signal at the destination of the SD transmission and $\eta_{SR_l}(t)$ is the noise signal at the l^{th} relay terminal. In the second phase, L relay terminals forward the received symbol into the destination. The l^{th} relay to destination received signal is given by

$$y_{RD_l}(t) = h_{RD_l}(t) * x_{R_l}(t) + \eta_{RD_l}(t)$$
(2.44)

where $x_{R_l}(t)$ is the transmitted symbol from the l^{th} relay terminal, $h_{RD_l}(t)$ is the channel impulse response of the RD transmission and $\eta_{RD_l}(t)$ is noise at the destination. After all the signals from first and second phase are received, the destination terminal can then combine the two signals to achieve diversity.

Although a high number of relay terminals, L, provides more signal transmission

paths that eventually improves the signal reception quality, this reduces the spectral efficiency taken by the source's signal to destination and eventually reduces the maximum achievable throughput of the system. In order to achieve a balance between signal quality and achievable throughput, L = 2 that will be considered further in this project.

Based on the method of relay-retransmission to the destination, RT category includes repetition-based RT (RRT), coded-cooperation (CC), compress-and-forward (CF) and distributed space-time coded (DSTC) [10, 11, 70]. In the case of RRT, the relay users only forward the entire received signal from the source. This type of RT achieves a maximum of half a symbol/second/Hz for one relay. Due to its simplicity, relay terminal can either retransmit with or without decoding [71] where it is shown in [72] that decoding before retransmission achieve a better performance than simply re-transmitting the signal to destination in the case of reliable interusers channel transmission. Since cooperation diversity is mostly applied to close proximity users that provides a good inter-user channel, only decode-and-forward (DF) RT scheme is considered further.

On the other hand, CC, CF and DSTC are more flexible schemes in terms of spectral efficiency as they allow the relays to modify the received signal before retransmission. In [73] and [74], it was shown that for the same spectrum efficiency and code-rate, CC and CF have similar performance to RRT while DSTC have better performance due to combining the source to destination signal with the STBC signals from the source & relay terminals, [75], which creates the equivalent of three diversity orders for a single relay system.

2.4.1. Repetitive based RT Cooperative Strategy

In the RRT cooperative strategy, the l^{th} relay to destination (RD) transmission is given by

$$y_{RD_l}(t) = h_{RD_l}(t) * \hat{x}_l(t) + \eta_{RD_l}(t)$$
(2.45)

where $\hat{x}_l(t)$ is the detected transmitted symbol at l^{th} relay terminal. In the destination, all received signals, $y_{SD}(t)$ and $y_{RD_l}(t)$, are transformed into frequency domain given by $Y_{SD}[n]$ and $Y_{RD_l}[n]$, respectively, and detected using the maximum ratio combining (MRC) scheme. If it is assumed the detection of the transmitted symbol at l^{th} relay terminal is given by

$$\hat{X}_{l}[n] = X[n] + \varepsilon_{l}[n], \qquad n = 1, \dots, N$$
(2.46)

where X[n] is the discrete frequency domain of x(t), the MRC scheme output is given by

$$\hat{X}[n] = \frac{Y_{SD}[n]H_{SD}^{*}[n] + \sum_{l=1}^{L} Y_{RD_{l}}[n]H_{RD_{l}}^{*}[n]}{|H_{SD}[n]|^{2} + \sum_{l=1}^{L} |H_{RD_{l}}[n]|^{2}}$$
(2.47)

where $H_{SD}[n]$ and $H_{RD_l}[n]$ are DFT of $h_{SD}(t)$ and $h_{RD_l}(t)$. Inserting Equation 2.46 into Equation 2.47 gives

$$\hat{X}[n] = X[n] + \frac{\sum_{l=1}^{L} \varepsilon_{l}[n] |H_{RD_{l}}[n]|^{2}}{|H_{SD}[n]|^{2} + \sum_{l=1}^{L} |H_{RD_{l}}[n]|^{2}} + \frac{N_{SD}[n]H_{SD}^{*}[n] + \sum_{l=1}^{L} \mathcal{N}_{RD_{l}}[n] H_{RD_{l}}^{*}[n]}{|H_{SD}[n]|^{2} + \sum_{l=1}^{L} |H_{RD_{l}}[n]|^{2}}$$
(2.48)

where $\mathcal{N}_{SD}[n]$ and $\mathcal{N}_{RD_l}[n]$ are the DFT of the AWGN signals $\eta_{SD}(t)$ and $\eta_{RD_l}(t)$, respectively.

2.4.2. Distributed Space Time Coded RT Cooperation Strategy



Figure 2.10.: DSTC RT Scheme

The DSTC RT scheme is shown in Figure 2.10. For simplicity, it is assumed in this figure that two users are cooperating with the first user transmits two symbols, $X_{1,1}[n]$ and $X_{1,2}[n]$, and the second user transmits two symbols, $X_{2,1}[n]$ and $X_{2,2}[n]$.

This scheme is divided into two phases. The first two periods, each user transmit

their own symbols to the destination. Lets assumes the received signals for the first and second periods in the frequency domain are given by

$$Y_{1,t}[n] = H_{1,1}[n] X_{1,t}[n] + \mathcal{N}_{1,t}[n], \qquad t = 1,2$$
(2.49)

$$Y_{2,t}[n] = H_{2,2}[n] X_{2,t}[n] + \mathcal{N}_{2,t}[n], \qquad t = 1,2$$
(2.50)

After that, a STBC style transmission is transmitted in the last two periods. In the third period, the received signals at the first and second spectrum are respectively given by

$$Y_{1,3}[n] = H_{1,1}[n] \tilde{X}_{2,1}[n] + H_{2,1}[n] \tilde{X}_{2,2}[n] + \mathcal{N}_{1,3}[n]$$
(2.51)

$$Y_{2,3}[n] = H_{1,2}[n] \tilde{X}_{1,1}[n] + H_{2,2}[n] \tilde{X}_{1,2}[n] + \mathcal{N}_{2,3}[n]$$
(2.52)

Furthermore, the fourth period received signals at the first and second periods are respectively given by

$$Y_{1,4}[n] = H_{1,1}[n] \tilde{X}_{2,2}^{*}[n] - H_{2,1}[n] \tilde{X}_{2,1}^{*}[n] + \mathcal{N}_{1,4}[n]$$
(2.53)

$$Y_{2,4}[n] = H_{1,2}[n] \tilde{X}_{1,2}^{*}[n] - H_{2,2}[n] \tilde{X}_{1,1}^{*}[n] + \mathcal{N}_{2,4}[n]$$
(2.54)

After receiving the symbols at the fourth period, the destination re-arrange the last two symbols in an STBC style as follows

$$\begin{bmatrix}
Y_{1,3}[n] \\
Y_{1,4}^{*}[n]
\end{bmatrix}_{Y_{1,5TBC}} = \underbrace{\begin{bmatrix}
H_{1,1}[n] & H_{2,1}[n] \\
-H_{2,1}^{*}[n] & H_{1,1}^{*}[n]
\end{bmatrix}_{X_{2,1}[n]} \begin{bmatrix}
\tilde{X}_{2,1}[n] \\
\tilde{X}_{2,1}[n]
\end{bmatrix}_{X_{2_{STBC}}} + \begin{bmatrix}
\mathcal{N}_{1,3}[n] \\
\mathcal{N}_{1,4}^{*}[n]
\end{bmatrix}$$
(2.55)

$$\begin{bmatrix} Y_{2,3}[n] \\ Y_{2,4}[n] \end{bmatrix} = \underbrace{\begin{bmatrix} H_{1,2}[n] & H_{2,2}[n] \\ -H_{2,2}^{*}[n] & H_{1,1}^{*}[n] \end{bmatrix}}_{H_{2_{STBC}}} \begin{bmatrix} \tilde{X}_{2,1}[n] \\ \tilde{X}_{2,1}[n] \end{bmatrix} + \begin{bmatrix} \mathcal{N}_{1,3}[n] \\ \mathcal{N}_{1,4}^{*}[n] \end{bmatrix}$$
(2.56)

Then, $Y_{\mathbf{1}_{STBC}}$ and $Y_{\mathbf{2}_{STBC}}$ are multiplied with the Hermitian transpose of $H_{\mathbf{1}_{STBC}}$ and

 $H_{2_{STBC}},$ respectively. The results of this multiplication are given by

$$Y_{1_{MRC}}[n] = \begin{bmatrix} |H_{1,1}[n]|^2 + |H_{2,1}[n]|^2 & 0 \\ 0 & |H_{1,1}[n]|^2 + |H_{2,1}[n]|^2 \end{bmatrix} \begin{bmatrix} \tilde{X}_{2,1}[n] \\ \tilde{X}_{2,2}[n] \end{bmatrix} + \\ \begin{bmatrix} H_{1,1}^*[n] & -H_{2,1}[n] \\ H_{2,1}^*[n] & H_{1,1}[n] \end{bmatrix} \begin{bmatrix} \mathcal{N}_{1,3}[n] \\ \mathcal{N}_{1,4}^*[n] \end{bmatrix}$$
(2.57)

$$Y_{2_{MRC}}[n] = \begin{bmatrix} |H_{1,2}[n]|^2 + |H_{2,2}[n]|^2 & 0 \\ 0 & |H_{1,2}[n]|^2 + |H_{2,2}[n]|^2 \end{bmatrix} \begin{bmatrix} \tilde{X}_{1,1}[n] \\ \tilde{X}_{1,2}[n] \end{bmatrix} + \\ \begin{bmatrix} H_{1,1}^*[n] & -H_{2,1}[n] \\ H_{2,1}^*[n] & H_{1,1}[n] \end{bmatrix} \begin{bmatrix} \mathcal{N}_{2,3}[n] \\ \mathcal{N}_{2,4}^*[n] \end{bmatrix}$$
(2.58)

Finally, a MRC combining scheme is used to detect all these four symbols, which are given by

$$\hat{X}_{1,s}[n] = \frac{Y_{1,t}[n] H_{1,1}^{*}[n] + Y_{2_{MRC}}[s,n] \left(|H_{1,2}[n]|^{2} + |H_{2,2}[n]|^{2} \right)}{|H_{1,1}[n]|^{2} + \left(|H_{1,2}[n]|^{2} + |H_{2,2}[n]|^{2} \right)^{2}}, \quad s = 1, 2 \quad (2.59)$$

$$\hat{X}_{2,s}[n] = \frac{Y_{2,t}[n] H_{2,2}^*[n] + Y_{1_{MRC}}[s,n] \left(|H_{1,1}[n]|^2 + |H_{2,1}[n]|^2 \right)}{|H_{2,2}[n]|^2 + \left(|H_{1,1}[n]|^2 + |H_{2,1}[n]|^2 \right)^2}, \quad s = 1, 2 \quad (2.60)$$

As can be seen from Equation 2.59 and Equation 2.60, combination of the STBC transmission and the MRC scheme provides a three order diversity system, this scheme provides approximately a three diversity orders systems.

2.5. Femtocell in 4G Heterogeneous Cellular Networks

It is known that wireless capacity has doubled every 30 months. In addition, recent surveys shows that around 80% of wireless transmission are originated indoor, which includes 50% of all voice calls and more than 70% of all data traffic [1]. This reduces the reliability of macrocell network to accommodate the capacity increase due to penetration loss in most of the transmission. Furthermore, macrocell BS consumes high amount of power other than power transmission. [76, 77] show that cooling fans and power supply consumes four and seven times more power, respectively, than the transmit power consumption. This means reducing the dependency with macro BSs (MBSs) with various technology such as microcell, picocell, femtocell and distributed relay antennas that make up a heterogeneous cellular network, is not only pivotal to improve the cellular service but also improves the energy efficiency [78].

In comparison to picocells and relay antennas, femtocells offer the lowest cost solution for green heterogeneous cellular network systems. The cost reduction is achieved by reducing and dividing the capital expenditure (CAPEX), which in the cellular network term is the cost of a cellular network provider to install new BS, and operation expenditure (OPEX), which in the cellular network term is the cost of a company to maintain the operational of its BS, required for installation and maintenance between the cellular network provider and the end-users. On the other hand, the power saving acquired by the femtocell technology not only comes from less transmission power required by the small cells but also comes from eliminating cooling fans requirement, which is required in macrocell base station (MBS), and minimising the power amplifier consumption.

User 1 User 2 User 3 User 3

2.5.1. Physical Layer of 4G Cellular Networks

(a)

Figure 2.11.: Simplified PUSC WiMAX Physical Layer. (a) Adjacent subcarriers allocation. (b) Distributed permutation subcarrier allocation.

(b)

4G technology utilises a synchronous OFDMA transmission. Using this technique, parallel transmission with maximum number of bits across different subcarriers can

be achieved. Furthermore, this feature gives an adaptive modulation scheme that can adapt the signal transmission with the channel state information and balance the signal quality with the maximum achievable throughput. For instance, transmit a high modulation order at a good channel while transmitting a low modulation order at a bad channel. There are two major types of 4G technology exist. They are WiMAX and LTE technologies.



Figure 2.12.: Simplified LTE Physical Layer [47]

A simplified physical layer resource mapping of WiMAX and LTE are shown in Figure 2.11 and Figure 2.12. In WiMAX system, users are allocated with a set of subcarriers. Set of allocated subcarriers can be allocated to user either in distributed or in adjacent mode. Therefore, the users resource allocation can be flexible around these subcarriers. Differently, a frame of transmission is divided into T_{fr} subframes in the case of LTE system. Each subframe contains N_{RB} resource blocks (RBs) where each RB contains 12 subcarriers or resource elements (REs). 1 RB within a subframe is allocated to a user [23]. Hence, the BS can schedule its users within a frame of signal transmission.

In order to simplify the terminology for different standards, a term called *parallel* resources (PRs) is used in this work to encapsulate the minimum entity of allocated resource to any user per unit transmission. In the case of WiMAX system, 1 PR is equivalent with one subcarrier while PR equals to one resource block (RB) in the LTE systems.



2.5.2. Femtocell in HetNets Architecture

Figure 2.13.: Simplified femtocell network architecture

Figure 2.13 and Figure 2.14 show a basic architecture of femtocell integration in a heterogeneous networks (HetNets) as described in [79]. As can be seen from this figure, a set of FAPs, will be connected to the macrocells networks, through a femto gateway (FGW) and the FAPs and FGW are connected through the IP backhaul provided by the ISP. The FGW, which typically supports from ten thousand to hundred thousand FAPs, provides the security to the femtocells networks, authentication authorisation and accounting (AAA) function and standard interface with mobile core network (MCN) [79]. The MCN views the FGW as another radio network controller (RNC) which acts as a gateway between macrocell BSs and the MCN. Therefore, the complexity of femtocells networks can be hidden from the macrocell networks element by FGW and it allows full macro-to-femtocell network mobility support by reusing the existing inter-radio access network (RAN) element mobility procedures [79].

Besides having a gateway function to the MCN, FGW may share operation and management (OAM) functionality with the FAPs in order to maximize the overall data rate performance while minimising the FAP complexity. The OAM of FGW includes radio resource management (RRM) assistant in FAPs, e.g. frequency, time



Figure 2.14.: Femtocell Mobile Core Network [79]

and code, as will be discussed in chapter 4, and maximising quality of service (QoS), e.g. different scheduling of data and voice over the networks.

The OAM functionality in femtocells may be viewed almost in the same way as in the picocell systems. In picocell systems, the radio control network (RCN), which controls macro-, micro- and picocell BSs, will use all functionalities except the radio transmission of a picocell. In femtocell, the OAM approach may use either a similar approach as in the case of picocells or a flatter approach [79]. Flatter approaches in FGW's OAM allow FAPs and FGW to have flexibility of functionality choice. In WiMAX and LTE system, one example of this approach may allow the FGW to help the frequency allocation management only when it is required by the FAP.

The management of femtocells networks is performed by a femtocell management system (FMS). The FMS is split into two elements. They are FAP management system to manage typically millions of FAPs and FGW management system to manage FGW [79].

2.5.3. Available Spectrum for Femtocell in 4G based HetNets

Femtocell may be deployed in the shared or different spectrum with the rest of the cellular BSs', such as macro- and microcells' BSs [80]. Spectrum partition is possible since the cellular company may acquire several separated spectrum band and can

be beneficial in the case when macrocell users are much more dynamic than the indoor users. However, this approach has poorer spectrum efficiency compared to allocating the same spectrum with the rest of the networks.

In the case of same spectrum allocation, the frequency allocation for femtocells usage in WiMAX and LTE technology can be adapted such that the transmission will not interfere with the macrocell users and vice versa due to the flexibility and orthogonality that exist in OFDMA and SC-FDMA. For this reason, spectrum allocation of femtocells needs to consider the deployment of general macrocell system. Currently, there are two standards of frequency allocation in WiMAX and LTE. They are fractional frequency re-use (FFR) and soft frequency re-use (SFR). Furthermore, it is assumed that FAPs have a *sniffing* or listening capability [79] so that they can measure the relative position to the MBS.



Figure 2.15.: Spectrum allocation of HetNets in Fractional Frequency Reuse. (a) MBS spectrum allocation. (b) SBSs spectrum allocation

A) Spectrum allocation in a Fractional Frequency Reuse

This frequency reuse scheme divides the coverage area of a macrocells into two areas, which are inner and outer region. It allocates the inner area with frequency reuse factor of one and outer area with frequency reuse factor of three or more. Furthermore, the signal transmission for inner and outer regions are performed in two separate spectrum regions. This scheme can be illustrated by Figure 2.15 (a).

By adapting with the macrocells frequency reuse pattern, the macrocell to femtocell interference or vice versa can be minimised. Therefore, the femtocells spectrum allocation of Figure 2.15 (a) illustration is depicted by Figure 2.15 (b).

B) Spectrum allocation in a Soft Frequency Reuse



Figure 2.16.: Spectrum allocation of HetNets in Soft Frequency Reuse. (a) Macrocell spectrum allocation. (b) SBSs spectrum allocation without a special interference avoidance technique.

In a soft frequency reuse (SFR) based system, macrocell BS (MBS) is able to utilise the entire spectrum for its own users as shown by Figure 2.16 (a). This maximizes the achievable data rate for macrocell users. However, this pattern causes interference problem for small cell users, especially femtocell UEs. Even though picocells' users may experience small interference, but since this cellular network is installed by the cellular operator, most of the case they are installed in the area where there is no MBS signals, e.g. at a heavily shadowed area.

Without any interference avoidance, the femtocell access point (FAP) utilises a sensing capability to determine its position. If the FAP exist within inner area, the best allocation for its users is the same allocation with the inner users of macrocell users. On the other hand, if femtocell exist within outer area, it can utilise the entire spectrum since the signal from MBS for its outer users transmission is less significant. These are illustrated in Figure 2.16 (b).

2.5.4. Femtocell Accessibility

Accessibility of femtocells can be open or closed to outside users. Open access can be beneficial to the overall network capacity in comparison to closed access. However, multiple access to different femtocells results in high probability of handover between one femtocell to other femtocells. Furthermore, since the femto access point (FAP) and the internet connection to support the femtocells system is privately owned, the open access scheme might not be undesirable by the end-users. In fact, a review shown in [81] indicates that most of the users do not wish to share their own resource to unknown users.

Closed access can prevent blocking to the owners of FAP and internet backhaul connection of a femtocell with penalty of reduced overall network capacity. Furthermore, without interference coordination between the femtocell and macrocell, closed access will cause a dead zone to macrocell's users. Dead zone is an area where the interference signal becomes very high such that reliable one bit transmission is almost impossible. Although this mostly happens in CDMA system, uncoordinated femtocell in WiMAX and LTE system could also experience this problem. This illustrated by Figure 2.17.

A much preferable access scheme employed by network operators is a hybrid scheme [34]. This scheme works by giving some of femtocell's resources reserved to the owners or registered users while giving the rest of resource open to outside users

[1]. When the primary users require more frequency spectrum, the FAP simply evacuates all the secondary users and gives the rest of spectrum to the primary users [1]. In the scenario shown in Figure 2.17, some frequency spectrum will be allocated to user B and the allocated spectrum to user C and D will be slightly reduced. Therefore, a dead zone can be avoided.



Figure 2.17.: Dead zone illustration

2.6. Resource Management in Femtocell based 4G HetNets

2.6.1. Interference Problems

The adaptation of femtocells with the surrounding is a very important issue, since they will be installed by the end-users. This causes interference signal to the surrounding users as an impact of ad-hoc nature in the femtocells networks. The interference can be classified into two types of interference. They are macro-femto interference (cross-tier interference) and femto-femto interference (co-tier interference) [18]. Both types of interference affect data and control channel transmissions.

A) Co-tier interference

Co-tier interference is an unavoidable problem when all FAPs in a certain area work without coordination. In uncoordinated scenarios, each FAP will allocate its users to all the allocated subcarriers. Hence, this gives high chance of cell edge users to receive unwanted signals from nearby femtocells. For this reason, interference reduction techniques by employing interference cancellation and interference avoidance, are always desirable in all femtocells networks with the focus on reducing co-layer interference.

B) Cross-tier interference

Cross-tier interference in a shared spectrum network can be minimised by allocating different spectrum to femtocell users as shown in subsection 2.5.3. By knowing the location and the macrocell frequency pattern, the FAP can automatically adapt its users frequency allocations. However, finding the exact location may not be a straight forward task for a FAP. For instance, if a FAP does not receive significant signal from macrocell due to shadowing while its users sense a significant amount of signal, then this can result in a significant interference to these users. This situation requires users sensing as a method to reduce the cross-tier interference.

Although interference between macrocell and femtocell in WiMAX and LTE systems can be minimised by frequency splitting, the cross-tier interference still exist since perfect frequency splitting can only be addressed in non-random scenario. Therefore, perfect frequency splitting cannot always be achieved by femtocell network.

2.6.2. Interference Avoidance for Femtocell Technology

As mentioned previously, interference occurs in both data and control channels. While data channel is mainly used to provide high data rate and/or low latency transmission, the control channel requires a reliable communication channel.

Control channel needs to carry information regarding cell ID, allocated resources, acknowledgement and Automatic Repeat reQuest (ARQ) from a BS to its users [22, 82]. This means, the size of occupied resource in the control channel region is affected by the number of users and the available channel for transmitting this information should be able to accommodate the maximum number of users per BS [82]. Due to low number of users, which is typically less than four users, femtocells require much less spectrum for transmitting their control information than the available resources [83]. This creates a sparse region in the control information of femtocell networks [83]. Using collision avoidance techniques, e.g. Carrier Sense Multiple Access, and/or frequency hopping techniques, co-tier interference of the control channel can be avoided [83]. On the other hand, cross-tier interference may still exist because macrocells most likely need to serve many users. This means, almost all resources for control information will be used. Fortunately, using Cell ID manipulation proposed in [83], control channel cross-tier interference can be avoided significantly. For this reason, interference in control channel will not be considered further in this research.

Downlink interference in the data communication channel of 4G HetNets that employ OFDMA is practically reduced using radio resource management (RRM) [20, 19, 84]. This includes frequency spectrum allocation and power control [19] where spectrum coordination in terms of time and/or frequency provides a more practical implementation [85]. Generally speaking, OFDMA RRM techniques can be classified into two categories which are Channel State Information (CSI) based and self-organizing network (SON) [19, 86, 87]. Both types make a decision of resource allocation in distributed and/or centralized manners. CSI based RRMs are resource allocation that takes care the channel state information (CSI) feedback as the main consideration. On the other hand, SON RRM that utilises SON functionality, such as self-configuration, self-optimisation and self-healing [23, 8], is a good technique for adapting to the immediate environment that allows the BSs to continuously communicate with neighboring BSs and constantly monitor the signal sources at the UEs [88] and avoid interference through negotiation or centralised node without CSI consideration. Among these approaches, the centralised CSI based RRM method is associated with higher levels of complexity due to requiring channel state information (CSI) for the entire spectrum to achieve the most appropriate allocation [19].

In the distributed CSI based RRM approach, each SBS manages resources to its UEs independently from neighboring SBSs but in such a way that can minimize interference [27, 29]. This can be achieved by requesting the UEs to continuously monitor the received interference from the surrounding environment at all spectrum subsets and report it back to the serving SBSs [89] where self adjustment in term of subcarriers and/or power will be computed to achieve interference load minimisation and utility maximisation [90]. Due to the possibility of having a large number of femtocells, adjusting the subcarriers allocation is a preferable method for HetNet systems compared to the power adjustment approach [28]. An efficient spectrum

allocation in distributed RRM is presented in [26], in which the subcarrier allocations are altered in order to minimize interference power based on feedback information. Each femtocell achieves this by allocating their users with only half of the available spectrum. To do this, self-organising RRM may require several iterations before the optimum subcarrier configuration, that results in minimum interference, can be achieved. Because only half of the subcarriers will be used in any SBS, irrespective of interference at each UE, this RRM may lead to inefficient utilisation of the resource.

SON RRM uses both the distributed and centralised approach to reduce interference. Distributed SON RRM is proposed in [88, 86]. In these method, a fixed frequency pattern allocation between adjacent femtocells obtained from SON. The frequency allocation stays fixed until new neighbouring FAP is detected. If a UE receives high interference from neighbouring FAPs, the serving FAP asks its neighbouring FAPs to configure the transmitted power or the subcarriers allocation. However, fix frequency allocation may waste frequency spectrum when neighbouring FAPs do not perform transmission. Furthermore, simple request to configure neighbouring FAPs' frequency spectrum and power transmission might not be applicable in practice because the FAPs are mainly interested to serve their own users. This will result in unresolvable conflict between femtocells. For this reason, these two techniques will not be considered further in this paper. On the other hand, SON RRM based centralised technique mostly utilises coloured graph algorithm [91, 92].

Basic coloured graph SON RRM that presented in [91] and [92] determine a fix size of colouring size between connected nodes. This objective limits the achievable sum rate of a colouring graph RRM. On the other hand, a dynamic coloured graph, which is presented in [93], allows two phases of graph colouring scheme. First, the central node, which can be in a form of Femto Management System (FMS), allocates a set of resources allocated to individual node. Then, it increases the resource allocation based on certain maximisation objectives. In this research, [91] and [93] will be considered further to represent the SON RRM.

A) Self Organisation RRM

1. Users sensing and reporting to their serving femtocells

Users are required to sense the interference from surroundings at all sub-carriers in the case of WiMAX system and sub-channels in the case of LTE system periodically every T_{sr} period. After the sensing period, they need to send a Measurement Report (MR) containing the interference at all subcarriers or subchannels to their serving FAPs.

2. FAPs frequency allocation

After receiving information from the users, femtocell F_m then can begun the updating process. This happens after a random time period between 1 and 2 T_{sr} . Prior to receiving the MR, the FAP updates interference matrix, W_m , where $W_m \in \mathbb{R}^{Z_m \times N}$, Z_m is number of connected matrix and K is the total number of PRs. F_m computes the new sub-channel allocation to its users using the following criteria to minimize the sum of overall interference suffered by all users:

$$\min \sum_{z=1}^{Z_m} \sum_{n=1}^{N} W_m(z,n) A(z,n)$$
(2.61)

subject to

$$\sum_{z=1}^{Z_m} A(z,n) \leq 1, \quad \forall n$$
(2.62)

$$A(z,n) \in \{0,1\}, \quad \forall z,n$$
 (2.63)

where A(z, n) is a binary allocated PR that is equal 1 if user z is allocated with PR n and 0 otherwise.

B) Basic Coloured Graph SON RRM

1. FAP measures the surrounding signals

Upon power ON, the femtocell measures the received signal from the surrounding femtocells. If at least one BSs has an interference potential, this FAP reports to the central node.

2. Graph colouring by the central node

After receiving the information from the FAPs, the central node forms an interference graph of a set of connected nodes. It then applies a colouring graph such as presented in [94] so that the connected nodes are not allocated with the same PRs. Each BSs is coloured with a certain amount of PRs, N_m . The amount of PRs that
will be assigned for each BS needs to be considered carefully since large number of PRs per FAP increases the chance of any FAP cannot be allocated any empty PRs that reduces the fairness and small number of PRs reduces the resource utilisation.

C) Dynamic coloured Graph SON RRM

Algorithm 2.1 Maximisation of Dynamic Coloured Graph
1 sort V based on the number of connected lines from the lowest to the highest
2 for $n = 1$ until N do
3 if n can be allocated further
4 repeat
5 allocate n to the lowest \widetilde{V} .
6 if more than one BS can be allocated due to similar number of connected
lines, assign n to the one having minimum number of already assigned resource
7 until n cannot be allocated any further
8 end if
9 end for

1. Interference measurement by users

Utilising measurement report (MR) that exists in WiMAX and LTE standards, UE can report the measured power from the surrounding BSs. With this feature, a FAP can measure the potential interference from the surrounding BSs. A user z which is served by BS F_m is classified as interfered by FAP F_c if

$$\frac{E_{z,m}}{E_{z,c}} < \gamma_{th} \tag{2.64}$$

where $E_{z,m}$ and $E_{z,c}$ is the received power from F_m and F_c , respectively. If $F'_m s$ users is interfered by F_c , F_m is virtually connected with F_c . If this is happens, F_m reports to the central node.

2. Initial resource allocation

Similar to the basic coloured graph, this method applies N_m PRs to each virtually connected nodes. In order to maximize the resource allocation, the N_m PRs is selected for T_m BS from N available PRs such that the selected PRs have been assigned the most by other BSs within a cluster of SBSs given that these PRs have not been selected for T_m 's direct neighbouring BSs.

3. Resource maximisation

After assigning all FAPs with resources, the central node maximises the resource utilisation by assigning unallocated resource consecutively one at a time. A resource will be allocated to FAP that maximise the resource allocation. This can be done using Algorithm 2.1 [93].

2.7. Summary

Important aspects for designing a cross-layer improvement scheme have been considered. Signal propagation results in large-scale and small-scale fading channels. Large scale fading affects the average received signal power while small scale fading affect the signal variation across small distances and spectrum. Small scale fading is caused by multipath signals and/or relative movement of the transmitter and receiver. It is shown that OFDM based transmission simplifies the equalisation of the multipath fading channel.

MIMO provides an additional degree of freedom that provides spatial diversity through the STBC scheme. However, due to size constraint, complexity amongst others, cooperative diversity is a much preferable method in the uplink scenario. Cooperative diversity can be classified into RT and PT cooperative diversity.

FGW and FMS play an important role in the femtocell networks architecture. Besides providing a gateway functionality, they also provides OAM functionality that can be beneficial in supporting RRM.

Accessibility to the femtocell can be made open, closed and hybrid. Open access can be beneficial to the overall network capacity in comparison to closed access. However, multiple access to different femtocells results in high probability of handover between one femtocell to other femtocells. Closed access can prevent blocking to the owners and internet backhaul connection of a femtocell with penalty of reduced overall network capacity. Furthermore, without interference coordination between the femtocell and macrocell, closed access will cause a dead zone to macrocell's users.

Flexibility and orthogonality of multiple carriers in WiMAX and LTE PHY layers allow adaptive frequency allocation to the femtocell. Depending on which frequency allocation pattern will be used by the macrocell, cross-layer interference can be minimised by adapting with the macrocell frequency allocation. This frequency adaptation requires heavily on signal energy sensing on the femtocell users to detect the macrocell carrier frequency.

There are two types of interference mitigation techniques. They are CSI and SON based RRMs. Both types make a decision of resource allocation in distributed and/or centralized manners. CSI based centralised RRM is shown to be impractical due to its requirement with the CSI exchange between FAPs and central computer. For this reason, only the distributed CSI and SON RRMs are considered further in this thesis.

3. Cooperative Diversity in OFDMA based Transmission

Inspired by lack of development of the pairing technique (PT) cooperative diversity for orthogonal frequency division multiple access (OFDMA) based systems and the growing popularity of license-exempt spectrum for cellular systems such as the Unlicensed Mobile Access (UMA) [35], this chapter introduces a novel pairing diversity technique specifically designed for uplink OFDMA which can double the signal power at the receiver, through constructive interference exploitation, as well as offer two diversity orders with uncompromising data transmission rate. It is worthwhile highlighting that unlike other diversity techniques, such as the RT techniques, which offer diversity at the expense of data rate reduction, the proposed maintains the data rate unchanged.

The main contribution of this chapter is to utilise Nyquist criterion OFDM transmission system to combine two users' signals and produce a single dimensional OFDM signal with PT diversity. The single dimensional OFDM signal ensures orthogonality within the cooperating users while unlicensed band utilisation, for exchanging data within each pair, allows better throughput compared to RT based cooperative diversity. The paired users must map their combined data according to a predefined rule such that members of the same pair transmit the same constellations over the same subcarriers simultaneously. By doing so, the signals arriving at the BS from one pair will pass through independent channels and can combine constructively. Moreover, this allows timing synchronisation within each pair to be relaxed. It is important to emphasize that inter-user communications must be performed at much lower power level than the uplink and within the unlicensed spectrum power constraints. Furthermore, data exchange must happen simultaneously with the uplink transmission in order to avoid any unacceptable latency. In the cellular transmission, error correcting codes are required to ensure good transmission quality. Using error correcting codes such as Hamming code [95], the error rate is controlled by the size of the redundancy bits at the cost of reducing the spectral efficiency. The size of error correcting code is also determined by the channel quality and modulation order. Generally speaking, in a good channel, less redundancy bits are required compared to a bad channel quality. In order to maintain the focus of this research, the impact of the proposed scheme is focused on improving channel efficiency using various modulation schemes without using error correcting codes.

It will be shown that, for the same total transmit power, the proposed technique achieves significant throughput enhancements and BER reduction under various channel conditions in comparison to other cooperative techniques. Both time synchronous and asynchronous scenarios will be considered here. In the case of the time-asynchronous condition further design enhancement, to overcome residual destructive interference, will be presented.

The rest of this chapter is organised as follows. Section 3.1 describes the OFDM system model employed. The proposed pairing technique is fully presented in section 3.2. Section 3.3 and section 3.4 present the analysis and evaluation results under both synchronous and asynchronous conditions. Finally, summary is presented in section 3.5.

3.1. Channel Models and Spectrum Allocation

Assuming that the members of each pair are selected on the basis of best inter-user link, the channel model for each pair of users and spectrum allocation for a total of P pairs can be illustrated by Figure 3.1. In the initial step each UE receives a noisy signal from their partner during the inter-user data exchange in the unlicensed band represented as

$$y_{p,1}(t) = \mathfrak{s}_{p,1}(t) * \sqrt{\alpha_{p12}} h_{p,12}(t) + \eta_{p,1}(t)$$
(3.1)

$$y_{p,2}(t) = \mathfrak{s}_{p,2}(t) * \sqrt{\alpha_{p21}} h_{p,21}(t) + \eta_{p,2}(t)$$
(3.2)

where α_{p12} and $h_{p,12}(t)$ are inter-user pathloss and multipath fading used by U_{p1}, respectively, α_{p21} and $h_{p,21}(t)$ are inter-user pathloss and multipath fading used by



Figure 3.1.: User pairing cooperative system model

 U_{p2} , respectively, and, $\mathfrak{s}_{p,1}(t)$ and $\mathfrak{s}_{p,2}(t)$ are the original symbols of U_{p1} and U_{p2} , respectively. The partners' symbols are combined by each user based on a predefined lookup table and then transmitted simultaneously to the BS. The BS receives the composite of the two channel perturbed signals as

$$y(t) = \sum_{p=1}^{P} \left\{ x_{p_1}(t) * \sqrt{\alpha_{p_1}} h_{p_1}(t) + x_{p_2}(t) * \sqrt{\alpha_{p_2}} h_{p_2}(t) \right\} + \eta_p(t)$$
(3.3)

where * indicates a convolution process, P is the total number of user pairs, $\eta_p(t)$, $\eta_{p,1}(t)$ and $\eta_{p,2}(t)$ are the AWGN signals, $h_{p_1}(t)$ and $h_{p_2}(t)$ are the multipath fading channels between users and the BS, α_{p_1} and α_{p_2} are the pathloss coefficients between the users and BS, and, $x_{p_1}(t)$ and $x_{p_2}(t)$ are the combined symbol transmitted by U_{p1} and U_{p2}, respectively. Our model further assumes that all communication channels are quasi-static Rayleigh frequency selective fading channel.

3.2. Pairing Cooperative Diversity in OFDMA

3.2.1. Data Remapping

The first stage of the proposed technique is to group the UEs in pairs according to the best inter-user link [96], [97]. Once the pairs are defined, the members of each pair performs data exchange on a block by block basis in the unlicensed band before transmitting the resulting remapped data block to the BS using single dimensional OFDM. To clarify this further consider the block diagram in Figure 3.2 (c). For reference sake, the RRT and DSTC cooperative diversity, presented in [75], are shown in Figure 3.2 (a) and (b), respectively. It is important to note that the cooperating UEs must have a dual band transceiver in order to be able to transmit and receive simultaneously at different spectrum band.



Figure 3.2.: Transmission timing diagram. (a) RRT cooperative OFDMA scheme. (b) DSTC OFDMA scheme. (c) Constructive interference PT OFDMA scheme. Note: $W_{p1} = W_{p2} = W_p$.

Since the regulation for the maximum transmitted power density in the unlicensed band is 5 mW/MHz, [17], compared to 50 mW/MHz of a typical WiMAX mobile handset, [21], the inter-user data transmission is performed at a much lower power level that satisfies the regulation. In this chapter, it is assumed that the inter-user transmission only uses 10% of the user to BS data transmission power.

It is assumed that the p^{th} pair is made up of user U_{p1} and U_{p2} . For demonstration purposes we refer to the data bit stream of U_{p1} as $a_0, a_1, a_2, \ldots, a_F$, and that of U_{p2} as $b_0, b_1, b_2, \ldots, b_F$, where F is the maximum number of bits. For clarity, F in this illustration is chosen to be a small number of 7. We also assume here, without loss of generality, that 16QAM is used over the channel between the users and the BS. With this in mind the proposed can be described in steps as follows:

1) Inter-user data exchange

The paired users begin by exchanging their own symbols over the license-exempt band, W_{p12} and W_{p21} in Figure 3.2 (c), using any predetermined air interface technique. In this chapter, it is assumed that the users use OFDMA interface at this level as well. Also, although any modulation order can be used it is preferred to use low order modulation at this stage to ensure good BER performance. Obviously the modulation order is constrained by the available license exempt bandwidth and required system bit rate at the BS. In Figure 3.2 (c), QPSK is used.

2) Combined data bits assignment and modulation

Once the users have detected their partner's symbols, the bits of the two users are interleaved in a predetermined way. In this chapter the first $\frac{\kappa}{2}$ bits of every constellation symbol to be from U_{p1} and the second $\frac{\kappa}{2}$ bits from U_{p2} are proposed, before the symbols are modulated on 2^{κ} QAM. See Figure 3.2 (c) for example.

Let us assume the modulated symbol per sub-carrier of the combined data bits for U_{p1} and U_{p2} , if decoded correctly is given by, $X_{\vartheta_p}[n] = A_n \exp(j\theta_n)$ for $n = 0, 1, ..., \widetilde{N} - 1$ where A_n and θ_n are the actual $2^{\mathcal{K}}$ QAM modulation amplitude and phase of the combined bits, respectively. Due to possible transmission errors during inter-user communication, the modulated symbol of U_{p1} and U_{p2} are given by

$$X_{\vartheta_{p_1}}[n] = X_{\vartheta_p}[n] + \varepsilon_{p_1}[n] \exp\left(j\phi_{p_1}[n]\right)$$
(3.4)

$$X_{\vartheta_{p_2}}[n] = X_{\vartheta_p}[n] + \varepsilon_{p_2}[n] \exp\left(j\phi_{p_2}[n]\right)$$
(3.5)

for $n = 0, ..., \widetilde{N} - 1$, respectively, where $\varepsilon_{p_1}[n]$ and $\varepsilon_{p_2}[n]$ and $\phi_{p_1}[n]$ and $\phi_{p_2}[n]$ are the amplitude and the phase errors of modulating the combined symbol by U_{p1} and U_{p2}, respectively.

3) Signal transmission to BS

After applying the same interleaving and modulating scheme by each user, the corresponding data signal is transmitted simultaneously by both users over the same licensed sub-band to the BS. To achieve maximum gain, the single dimensional property of OFDM implementation by assigning U_{p1} a cosine signal and U_{p2} a sine signal is utilised. By doing this we minimize unwanted interference while achieving full diversity.

Assume the re-arranged version of $X_{\vartheta_{p_1}}[n]$ and $X_{\vartheta_{p_2}}[n]$ using 1D OFDM modulation described in section 2.2 of chapter 2, are given by $X_{p_1}[n]$ and $X_{p_2}[n]$, respectively. The baseband representation of the first and second user's transmitted symbols with cosine and sine signals respectively are given by

$$x_{p_1}[a] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_{p_1}[n] \exp\left(j\frac{2\pi na}{N}\right)$$
(3.6)

$$x_{p_2}[a] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_{p_2}[n] \exp\left(j\frac{2\pi na}{N}\right)$$
(3.7)

for a = 0, ..., N - 1. Using $x_{p_1}[a]$ and $x_{p_2}[a]$, the combined symbol in discrete time that will be transmitted by U_{p1} and U_{p2} after cyclic prefix (CP) addition are given by $x_{\vartheta_{p1}}[a]$ and $x_{\vartheta_{p2}}[a]$, respectively. $x_{\vartheta_{p1}}[a]$ and $x_{\vartheta_{p2}}[a]$ are given by

$$x_{\vartheta_{p_1}}[a + \mathcal{G}] = x_{p_1}[a], \quad \text{for } a = 0, \dots, N - 1$$

$$x_{\vartheta_{p_1}}[a] = x_{p_1}[N - \mathcal{G} + a], \quad \text{for } a = 0, \dots, \mathcal{G} - 1$$
(3.8)

$$x_{\vartheta_{p2}}[a + \mathcal{G}] = x_{p_2}[a], \quad \text{for } a = 0, \dots, N - 1$$

$$x_{\vartheta_{p2}}[a] = x_{p_2}[N - \mathcal{G} + a], \quad \text{for } a = 0, \dots, \mathcal{G} - 1$$
(3.9)

where \mathcal{G} is the discrete signal CP period. The corresponding analogue signal of U_{p1} and U_{p2} are respectively given by

$$x_{\vartheta_{p_1}}(t) = x_{\vartheta_p}(t) + \varepsilon_{p_1}(t) \tag{3.10}$$

$$x_{\vartheta_{p2}}(t) = x_{\vartheta_p}(t) + \varepsilon_{p_2}(t) \tag{3.11}$$

for $-T_{\mathcal{G}} \leq t < T_O$ where T_O is the OFDM symbol period, $T_{\mathcal{G}}$ is the analogue signal CP period, $x_{\vartheta_p}(t)$ is the actual combined symbol in time domain, $\varepsilon_{p_1}(t)$ and $\varepsilon_{p_2}(t)$ are the error in time domain due to inter-user channel. $x_{\vartheta_p}(t)$ is given by

$$x_{\vartheta_p}(t) = \frac{2}{\sqrt{N}} \sum_{k=0}^{\widetilde{N}-1} A_n \cos\left(2\pi f_n t + \theta_n\right), \qquad (3.12)$$

 $\varepsilon_{p_1}(t)$ and $\varepsilon_{p_2}(t)$ are given by

$$\varepsilon_{p_1}(t) = \frac{2}{\sqrt{N}} \sum_{n=0}^{N-1} \epsilon_{p_1}[n] \cos\left(2\pi f_n t + \phi_{p_1}[n]\right)$$
(3.13)

$$\varepsilon_{p_2}(t) = \frac{2}{\sqrt{N}} \sum_{n=0}^{\widetilde{N}-1} \epsilon_{p_2}[n] \cos\left(2\pi f_n t + \phi_{p_1}[n]\right).$$
(3.14)

After the upconversion, the first and second user's transmitted symbols are assigned orthogonally as

$$x_{p_1}(t) = 2x_{\vartheta_{p_1}}(t)\cos(2\pi f_c t) * h_{BP}(t)$$
(3.15)

$$x_{p_2}(t) = 2x_{\vartheta_{p_2}}(t)\sin(2\pi f_c t) * h_{BP}(t)$$
(3.16)

where $\eta_{BP}(t)$ represents the bandpass filter used to remove one of the side bands OFDM symbol after it is been modulated on to f_c .

Assuming that the channel is frequency-selective fading across the whole frequency spectrum and the complex channel impulse response between U_{p1} and BS is given by $h_{p_1}(t)$, and between U_{p2} and BS is given by $h_{p_2}(t)$, the received signal at the receiver, y(t), is given by Equation 3.3 where $h_{p_1}(t)$ and $h_{p_2}(t)$ are given by

$$h_{p_1}(t) = (h_{p_{1R}}(t)\cos(2\pi f_c t) + h_{p_{1I}}(t)\sin(2\pi f_c t)) * \eta_{BP}(t)$$
(3.17)

$$h_{p_2}(t) = (h_{p_{2R}}(t)\cos(2\pi f_c t) + h_{p_{2I}}(t)\sin(2\pi f_c t)) * h_{BP}(t)$$
(3.18)

 $h_{p_{1R}}(t)$ and $h_{p_{2R}}(t)$ are baseband representation of the inphase of the impulse responses between users and the BS and $h_{p_{1I}}(t)$ and $h_{p_{2I}}(t)$ are baseband representation of the quadrature of the channels' impulse responses between the users and the BS.

4) Signals reception

At the BS, shown in Figure 3.3, the real and imaginary parts of the baseband received signal are separated by multiplying the signal with $\cos(2\pi f_c t)$ for the real part and $\sin(2\pi f_c t)$ for the imaginary part. This operation however yields $2f_c$ frequency component. A low pass filter (LPF) is therefore used to remove the high frequency component before the analogue to digital converter (A/D). Hence, the inputs of the A/D for real and imaginary parts, $y_1(t)$ and $y_2(t)$ respectively. They are given by

$$y_1(t) = \sum_{p=1}^{P} \sqrt{\alpha_{p_1}} \left(h_{p_{1R}}(t) - h_{p_{2I}}(t) \right) * x_{\vartheta_p}(t) + \varepsilon_{p_R}(t) + \eta_{p_R}(t)$$
(3.19)

$$y_2(t) = \sum_{p=1}^{P} \sqrt{\alpha_{p_2}} \left(h_{p_{2R}}(t) + h_{p_{1I}}(t) \right) * x_{\vartheta_p}(t) + \varepsilon_{p_I}(t) + \eta_{p_I}(t)$$
(3.20)

where $\eta_{p_R}(t)$ and $\eta_{p_I}(t)$ are the inphase and quadrature components of the AWGN noise signal, $\eta_p(t)$, respectively, $\varepsilon_{p_R}(t)$ and $\varepsilon_{p_I}(t)$ are the inphase and quadrature components error due to probability of error in inter-user communication. $\varepsilon_{p_R}(t)$ and $\varepsilon_{p_I}(t)$ are given by

$$\varepsilon_{p_R}(t) = \left\{ \sqrt{\alpha_{p_1}} h_{p_{1R}}(t) \ast \varepsilon_{p_1}(t) - \sqrt{\alpha_{p_2}} h_{p_{2I}}(t) \ast \varepsilon_{p_2}(t) \right\}$$
(3.21)

$$\varepsilon_{p_I}(t) = \left\{ \sqrt{\alpha_{p_1}} h_{p_{1I}}(t) * \varepsilon_{p_1}(t) + \sqrt{\alpha_{p_2}} h_{p_{2R}}(t) * \varepsilon_{p_2}(t) \right\}.$$
(3.22)

Equation 3.19 and Equation 3.20 can be simplified into

$$y_1(t) = \sum_{p=1}^{P} \sqrt{\alpha_{p_1}} h_{p_R}(t) * x_{\vartheta_p}(t) + \varepsilon_{p_R}(t) + \eta_{p_R}(t)$$
(3.23)

$$y_2(t) = \sum_{p=1}^{P} \sqrt{\alpha_{p_2}} h_{p_I}(t) * x_{\vartheta_p}(t) + \varepsilon_{p_I}(t) + \eta_{p_I}(t)$$
(3.24)

where $h_{p_R}(t)$ and $h_{p_I}(t)$ are the impulse responses experienced by the inphase and quadrature signals, respectively. They are given by

$$h_{p_R}(t) = h_{1p_R}(t) - h_{2p_I}(t)$$
(3.25)

$$h_{p_I}(t) = h_{2p_R}(t) + h_{1p_I}(t).$$
 (3.26)

Let first assume synchronous communication between the UEs and BS, then the asynchronous case will be considered. The receiver first takes the Fourier transform of $y_1[a]$ and $y_2[a]$, which are the discrete signals of $y_1(t)$ and $y_2(t)$ after the CP removal. Then, the frequency domain of $y_1[a]$ and $y_2[a]$ are given by

$$Y_{1}[n] = \sum_{p=1}^{P} \sqrt{\alpha_{p_{1}}} H_{p_{R}}[n] X_{\vartheta_{p}}[n] + \epsilon_{p_{R}}[n] + \mathcal{N}_{p_{R}}[n]$$
(3.27)

$$Y_{2}[n] = \sum_{p=1}^{P} \sqrt{\alpha_{p_{2}}} H_{p_{I}}[n] X_{\vartheta_{p}}[n] + \epsilon_{p_{I}}[n] + \mathcal{N}_{p_{I}}[n]$$
(3.28)

for $n = 0, 1, \ldots, \tilde{N} - 1$ and combined using maximum ratio combining (MRC) after the DFT process. $H_{p_R}[n]$ and $H_{p_I}[n]$ are the discrete transfer functions corresponding to $h_{p_R}(t)$ and $h_{p_I}(t)$, respectively. Since different pairs of users occupy orthogonal subcarriers, which means no interference from different pairs of users in the perfect frequency synchronised system, the combined data per sub-carrier output from the MRC scheme for each pair of users is given by

$$\hat{X}_{\vartheta_{p}}[n] = X_{\vartheta_{p}}[n] + \frac{\left(\mathcal{N}_{pr}[n] + \epsilon_{p_{R}}[n]\right)H_{p_{R}}^{*}[n]}{\left(\alpha_{p_{1}}|H_{p_{R}}[n]|^{2} + \alpha_{p_{2}}|H_{p_{I}}[n]|^{2}\right)} + \frac{\left(\mathcal{N}_{p_{I}}[n] + \epsilon_{p_{I}}[n]\right)H_{p_{I}}^{*}[n]}{\left(\alpha_{p_{1}}|H_{p_{R}}[n]|^{2} + \alpha_{p_{2}}|H_{p_{I}}[n]|^{2}\right)}$$
(3.29)

Finally, the BS detects the bits in each subcarrier by demodulating \hat{X}_{ϑ_p} for $n = 0, 1, \ldots, \widetilde{N} - 1$. In accordance with the predefined remapping scheme, it will assume that the first $\frac{\kappa}{2}$ belong to U_{p1} and the second $\frac{\kappa}{2}$ bits belong to U_{p2}.

Since the members of each pair transmit the same signal in real and imaginary parts separately, the interference they inflict on each other is constructive. This therefore doubles the received signal-to-noise ratio (SNR) per symbol relative to the direct uplink transmission. Hence, the proposed technique is able to achieve two diversity order and a 3 dB gain without sacrificing data rate in comparison to conventional direct transmission OFDMA. Furthermore, the fact that each pair contains two users, hence twice the number of subcarriers, means doubling the data transmission rate which cancels out the effect of doubling the symbol duration due to the single dimensional OFDMA signal model.



Figure 3.3.: Block diagram of BS used for uplink transmission

3.2.2. Time Synchronisation and Channel Estimation

Sensitivity to time synchronisation and channel estimation errors can be a major concern for OFDMA systems [63, 50]. Channel estimation errors occur as a result of factors such as noisy received signal at the BS or/and undersampled channel. Also, time mis-synchronisation can result in loss of orthogonality as OFDM symbols from different users arrive at the BS with different time shifts. This has two implications, the first of which is between the two members of each pair and the second is between the different pairs. However, as the two members of each pair transmit the same symbol, time mis-synchronisation within each pair will only lead to additional phase randomisation which can easily be compensated as part of the channel equalisation process. To demonstrate that additional phase randomisation effect due to time mis-alignment within each pair we must consider their signal model. For simplicity, lets focus on only one pair which includes U_{p1} and U_{p2} communicating together and with the BS simultaneously. This implies that P = 1 in Equation 3.3. Assume the transmitted signal of U_{p1} is given by Equation 3.15 and signal of U_{p2} is given by

$$x_{p2}(t) = 2x_{\vartheta_p}(t)\sin\left(2\pi f_c t + \theta_a\right) * \eta_{BP}(t)$$
(3.30)

where θ_a is the phase offset between signals of U_{p1} and U_{p2}. Furthermore, assume $h_{p_1}(t)$ and $h_{p_2}(t)$ are two-path fading channels with magnitudes of h_1 , h_2 and h_3 , h_4 , respectively. In addition, the time delay for $h_{p_1}(t)$ are t_{d1} and t_{d2} and for $h_{p_2}(t)$

are t_{d3} and t_{d4} . Without loss of generality lets also assume that the duration of the impulse responses is shorter than the cyclic prefix and the noise and error in interuser communication in Equation 3.4 and Equation 3.5 are negligible, the received signal at the BS is

$$y(t) = \hbar_{BP}(t) * \left\{ 2x_{\vartheta_p}(t) \cos\left(2\pi f_c t + \frac{2\pi t_{d1}}{T_O}\right) h_1 + 2x_{\vartheta_p}(t) \cos\left(2\pi f_c t + \frac{2\pi t_{d2}}{T_O}\right) h_2 + (3.31) \right.$$
$$\left. 2x_{\vartheta_p}(t) \sin\left(2\pi f_c t + \theta_a + \frac{2\pi t_{d3}}{T_O}\right) h_3 + 2x_{\vartheta_p}(t) \sin\left(2\pi f_c t + \theta_a + \frac{2\pi t_{d4}}{T_O}\right) h_4 \right\}$$

For simplicity of notations, the following substitution is used below: $\theta_{d1} = \frac{2\pi t_{d1}}{T_O}$, $\theta_{d2} = \frac{2\pi t_{d2}}{T_O}$, $\theta_{d3} = \frac{2\pi t_{d3}}{T_O}$ and $\theta_{d4} = \frac{2\pi t_{d4}}{T_O}$. Equation 3.31 can be expanded as

$$y(t) = \hbar_{BP}(t) * 2x_{\vartheta_{p}}(t) \{h_{1} [\cos (2\pi f_{c}t) \cos (\theta_{d1}) - \sin (\theta_{d1}) \sin (2\pi f_{c}t)] + h_{2} [\cos (2\pi f_{c}t) \cos (\theta_{d2}) - \sin (\theta_{d2}) \sin (2\pi f_{c}t)] + h_{3} [\sin (2\pi f_{c}t) \cos (\theta_{a} + \theta_{d3}) + \sin (\theta_{a} + \theta_{d3}) \cos (2\pi f_{c}t)] + (3.32) h_{4} [\sin (2\pi f_{c}t) \cos (\theta_{a} + \theta_{d4}) + \sin (\theta_{a} + \theta_{d4}) \cos (2\pi f_{c}t)] \}$$

At the BS, the received signal, y(t) is multiplied with $\cos(2\pi f_c t)$ for the inphase and $\sin(2\pi f_c t)$ for the quadrature signals. If it is assumed that there is additional time offset in the local oscillator (LO) which leads to some phase offset, θ_o , the inphase signal after multiplication with the LO signal will become

$$y_i(t) = y(t)\cos\left(2\pi f_c t + \theta_o\right) \tag{3.33}$$

and the quadrature received signal will become

$$y_q(t) = y(t)\sin(2\pi f_c t + \theta_o).$$
 (3.34)

Finally, the two signals are low pass filtered in order to remove the $2f_c$ components and get the baseband signal of the inphase, $y_1(t)$, and quadrature, $y_2(t)$, signals for maximum ratio combining in the frequency domain as illustrated in Equation 3.19 and Equation 3.20. Hence, after filtering, $y_1(t)$ and $y_2(t)$ in the absence of noise as can be seen from Appendix B are given as

$$y_{1}(t) = x_{\vartheta_{p}}(t) \{h_{1} [\cos(\theta_{d1}) \cos(\theta_{o}) + \sin(\theta_{d1}) \sin(\theta_{o})] \\ +h_{2} [\cos(\theta_{d2}) \cos(\theta_{o}) + \sin(\theta_{d2}) \sin(\theta_{o})] \\ +h_{3} [\sin(\theta_{a} + \theta_{d3}) \cos(\theta_{o}) + \cos(\theta_{a} + \theta_{d3}) \\ \sin(\theta_{o})] +h_{4} [\sin(a_{o} + \theta_{d4}) \cos(\theta_{o}) + (3.35) \\ \cos(\theta_{a} + \theta_{d4}) \sin(\theta_{o})] \}$$

$$y_{2}(t) = x_{\vartheta_{p}}(t) \{h_{1} [\cos(\theta_{d1}) \sin(\theta_{o}) + \sin(\theta_{d1}) \cos(\theta_{o})] \\ +h_{2} [\cos(\theta_{d2}) \sin(\theta_{o}) + \sin(\theta_{d2}) \cos(\theta_{o})] \\ +h_{3} [-\sin(\theta_{a} + \theta_{d3}) \sin(\theta_{o}) + \cos(\theta_{a} + \theta_{d3}) \\ \cos(\theta_{o})] + h_{4} [-\sin(\theta_{a} + \theta_{d4}) \sin(\theta_{o}) + (3.36) \\ \cos(\theta_{a} + \theta_{d4}) \cos(\theta_{o})]\}.$$

As can be clearly seen from Equation 3.35 and Equation 3.36, the phase offset within one pair, θ_a , only randomizes further the already random channel path magnitude. Moreover, it is evident that even when the BS's LO phase offset, θ_o , is not perfectly synchronised with that of the transmitters, the receiver will always be able to detect the correct signal from the pair since the inphase and quadrature contain the same baseband signal. In contrast, this is not possible in the case of complex OFDM signal because the inphase and quadrature signals are different and hence the LO imperfections will affect them differently. The worst case scenario of LO imperfection of the complex OFDM signal is when the receiver detects the inphase signal as quadrature signal, which happens when the LO is offset by $\pi/2$.

Time mis-synchronisation between the different pairs results in multiuser interference (MUI) which may exist even though the signal arrival times from all users can be predicted. This happens when the total length of the impulse response between the different users and BS exceeds the CP period [63], [64]. The effect of MUI in uplink transmission when the signals' time of arrivals are known is almost identical with the effect of residual ISI in downlink transmission. Residual ISI in downlink occurs when the delay spread exceeds the CP period. Hence, the easiest way to overcome the effect of MUI in this case is by having the length of the CP to be at least equals to the period between the first and last signals arrival from all users [64]. However, extending the guard intervals is a very expensive solution since it reduces the bandwidth efficiency significantly. An alternative would be to use receiver based interference cancellation techniques such as the Minimum mean-square-error (MMSE), recursive least square (RLS) and least mean square (LMS) based linear time-domain equalizer [41]. However, it was shown in [65] that for the interference resulting from residual ISI, the Residual ISI Cancellation (RISIC) algorithm [65], combines effectiveness with implementation simplicity. Incorporating of this equalizer in the BS block diagram is depicted in Figure 3.3. The impact of this will be analysed in a subsequent section.

The RISIC equalizer works by performing tail cancellation and cyclic reconstruction, respectively. Considering the \ddot{t}^{th} transmitted OFDM signal, $\mathbf{x}_{\ddot{t}}$, the received signal is $\mathbf{y}_{\ddot{t}}$, the impulse response is \mathbf{h}_{δ} , the RISIC equalisation steps can be summarised as follows:

- 1. Detect and re-modulate the $(\ddot{t}-1)^{th}$ OFDM symbol that affects the \ddot{t}^{th} symbol, $\mathbf{\hat{x}}_{\ddot{t}-1}$.
- 2. Performs tail cancellation to evaluate $\mathbf{y}_{\mathfrak{T},\tilde{t}}$ given by:

$$\mathbf{y}_{\mathfrak{T},\tilde{t}} = \mathbf{y}_{i} - \mathbf{h}_{\delta} \mathbf{\hat{x}}_{\tilde{t}-1}$$

$$= \mathbf{h}_{\delta} \left(\mathbf{x}_{\tilde{t}-1} - \mathbf{\hat{x}}_{\tilde{t}-1} \right) + \mathbf{x}_{\tilde{t}} \left(* \right) \mathbf{h} - \mathbf{h}_{\delta} \mathbf{x}_{\tilde{t}} + \boldsymbol{\eta}_{\tilde{t}}.$$
(3.37)

- 3. Detect and re-modulate the \ddot{t}^{th} OFDM symbol, $\mathbf{\hat{x}}_{1,\ddot{t}}$.
- 4. Perform first iteration of cyclic reconstruction to evaluate $\mathbf{y}_{\mathfrak{C}_1, \tilde{t}}$ given by:

$$\mathbf{y}_{\mathfrak{C}_{1},\tilde{t}} = \mathbf{y}_{\tilde{t}} + \mathbf{h}_{\delta} \mathbf{\hat{x}}_{1,\tilde{t}}$$

$$= \mathbf{x}_{\tilde{t}} (*) \mathbf{h} + \mathbf{h}_{\delta} \left(\mathbf{\hat{x}}_{1,\tilde{t}} - \mathbf{x}_{\tilde{t}} \right) + \boldsymbol{\eta}_{\tilde{t}}.$$

$$(3.38)$$

5. Repeat step 3) to calculate $\hat{\mathbf{x}}_{\mathcal{O},\vec{t}}$ and 4) to calculate $\mathbf{y}_{\mathfrak{C}_{\mathcal{O}},\vec{t}}$ if necessary, where subscript \mathcal{O} is the number of iterations.

Note that for the first OFDM symbol, the RISIC algorithm start from step 3) because the first symbol contains no residual ISI and hence no requirement to do

tail cancellation. Thus, $\mathbf{y}_{\tilde{t}}$, $\mathbf{x}_{\tilde{t}}$ and \mathbf{h}_{δ} are given by Equation 3.57, Equation 3.59 and Equation 3.60, respectively.

3.3. Performance Analysis

3.3.1. Synchronous Condition



Figure 3.4.: Conditional probability

For better clarity, let us assume that BPSK and QPSK modulation per subcarrier is used for inter-user and users to BS communications, respectively. Lets also define the probability notations for all the possible events shown in Figure 3.4 as follows: U_{p1} and U_{p2} exchange their symbols correctly is C_{12} , either U_{p1} or U_{p2} receives its partner's symbols incorrectly is C_{1or2} , neither U_{p1} or U_{p2} receives its partner's symbols correctly is \hat{C}_{12} , the BS receives the correct combination symbol is C and the BS receiving the wrong combination symbol is ε . Using this, the probability that the BS receives the correct symbol is given by

$$\Pr\left(\mathcal{C}\right) = \Pr\left(\mathcal{C} \cap \mathcal{C}_{12}\right) + \Pr\left(\mathcal{C} \cap \mathcal{C}_{1or2}\right) + \Pr\left(\mathcal{C} \cap \widehat{\mathcal{C}}_{12}\right). \tag{3.39}$$

Using Bayesian conditional probability theory, Pr(C) can be expanded into

$$\Pr(\mathcal{C}) = \Pr(\mathcal{C} \mid \mathcal{C}_{12}) \Pr(\mathcal{C}_{12}) + \Pr\left(\mathcal{C} \mid \widehat{\mathcal{C}}_{12}\right) \Pr\left(\widehat{\mathcal{C}}_{12}\right) + \Pr\left(\mathcal{C} \mid \mathcal{C}_{1or2}\right) \Pr\left(\mathcal{C}_{1or2}\right).$$
(3.40)

With this in mind, the probability of combined symbol error, $Pr(\varepsilon)$, is given by

$$\Pr\left(\varepsilon\right) = 1 - \Pr\left(\mathcal{C}\right) \tag{3.41}$$

and the probability of bit error of the proposed technique, P_b , is approximated by

$$P_{\rm b} \approx \frac{\Pr\left(\varepsilon\right)}{\mathcal{K}}$$
(3.42)

where \mathcal{K} is the number of bits per subcarrier for UEs to BS communication.

Similarly, the probability that U_{p1} receives a correct symbol from U_{p2} and vice versa, $Pr(\mathcal{C}_{12})$, is simply given by

$$\Pr(\mathcal{C}_{12}) = (1 - P_{\xi})^2 \tag{3.43}$$

where P_{ξ} is the probability of bit error for BPSK in Rayleigh fading. P_{ξ} is given by [41]

$$P_{\xi} = \frac{1}{2} \left(1 - \sqrt{\overline{\gamma_{12}} / (1 + \overline{\gamma_{12}})} \right)$$
(3.44)

where $\overline{\gamma_{12}}$ is the average signal-to-noise ratio (SNR) between U_{p1} and U_{p2} or interuser SNR. In addition, the probability that neither U_{p1} or U_{p2} receive their pair's symbols correctly, Pr (\hat{C}_{12}) , is given by

$$\Pr\left(\widehat{\mathcal{C}}_{12}\right) = \mathcal{P}_{\xi}^2. \tag{3.45}$$

Hence, the probability that either U_{p1} or U_{p2} can receive their partner's symbols correctly, $\Pr(C_{1or2})$ is given by

$$\Pr\left(\mathcal{C}_{1or2}\right) = 1 - \left\{\Pr\left(\mathcal{C}_{12}\right) + \Pr\left(\widehat{\mathcal{C}}_{12}\right)\right\}$$
(3.46)

which can be simplified into

$$\Pr(\mathcal{C}_{1or2}) = 2(1 - P_{\xi}) P_{\xi}$$
(3.47)

The probability that the BS receives the correct symbol given that U_{p1} and U_{p2} receive their partner's symbols correctly, $\Pr(\mathcal{C} \mid \mathcal{C}_{12})$, is similar to the probability of receiving a correct QPSK symbol with two diversity channels detected using the MRC combining scheme, P_{φ} . P_{φ} is given by

$$P_{\varphi} = 1 - P_{\widehat{\varphi}} \tag{3.48}$$

where $P_{\hat{\varphi}}$ is the probability of QPSK symbol error of two order diversity with MRC combining [41]

$$P_{\widehat{\varphi}} = \frac{1}{2} \left(1 - \sqrt{\frac{\overline{\gamma_c}}{1 + \overline{\gamma_c}}} \right)^2 \sum_{k=0}^{1} \left\{ \left(\begin{array}{c} 1+k\\k \end{array} \right) \left[\frac{1}{2} \left(1 + \sqrt{\frac{\overline{\gamma_c}}{1 + \overline{\gamma_c}}} \right) \right]^k \right\} \quad (3.49)$$

where $\overline{\gamma_c}$ is the SNR per bit between the users equipments and the BS. So,

$$\Pr\left(\mathcal{C} \mid \mathcal{C}_{12}\right) = 1 - \mathcal{P}_{\widehat{\varphi}}.\tag{3.50}$$

On the other hand, the combined QPSK symbol modulated by the pair of users will have a 180° of phase separation when the inter-user communication results in error symbols detected by both users. It results in signal cancellation at the receiver and leaves the received signal with the noise term. Since the noise is Gaussian distributed in the real and imaginary parts, the probability of receiving a correct symbol is similar to the probability of receiving any QPSK symbol. Therefore,

$$\Pr\left(\mathcal{C} \mid \widehat{\mathcal{C}}_{12}\right) = \frac{1}{4}.$$
(3.51)

When either U_{p1} or U_{p2} receive their partner's symbols correctly, the received signal constellation will lie between the correct symbol and its adjacent constellation, separated by 90°. Assuming the event of receiving correct symbol and its adjacent constellation is given by ν , the probability of receiving correct symbols given that either U_{p1} or U_{p2} receive their pair's symbols correctly, $\Pr(\mathcal{C} \mid \mathcal{C}_{1or2})$, can be related to this event by

$$\Pr\left(\mathcal{C} \mid \mathcal{C}_{1or2}\right) = \Pr\left(\mathcal{C} \mid \nu\right) \Pr\left(\nu\right). \tag{3.52}$$

The probability of the received signal constellation being in these two constellations, $Pr(\nu)$, equals the probability of receiving a correct BPSK symbol with dual diversity

channel combined with the MRC scheme, P_{β} . P_{β} is given by

$$P_{\beta} = 1 - \frac{1}{2} P_{\widehat{\varphi}} \tag{3.53}$$

and $\Pr(\mathcal{C} \mid \nu)$ is similar to the probability of receiving any of these two symbols. Therefore,

$$\Pr\left(\mathcal{C} \mid \nu\right) = \frac{1}{2} \tag{3.54}$$

and $\Pr(\mathcal{C} \mid \mathcal{C}_{1or2})$ is given by

$$\Pr\left(\mathcal{C} \mid \mathcal{C}_{1or2}\right) = \frac{1}{2} \left(1 - \frac{P_{\widehat{\varphi}}}{2}\right) \tag{3.55}$$

and thus, the theoretical BER, P_b , of the proposed technique with BPSK and QPSK modulation per subcarrier for inter-user and users to BS communications, respectively, is approximated by

$$P_{b} = \frac{1}{2} - \frac{1}{2} \left\{ \left(1 - \frac{1}{2} \left(1 - \sqrt{\frac{\overline{\gamma_{c}}}{1 + \overline{\gamma_{c}}}} \right)^{2} \sum_{k=0}^{1} \left(\frac{1+k}{k} \right) \left[\frac{1}{2} \left(1 + \sqrt{\frac{\overline{\gamma_{c}}}{1 + \overline{\gamma_{c}}}} \right) \right]^{k} \right) \right. \\ \left. \left(1 - P_{\xi} \right)^{2} + \frac{1}{2} \left(1 - \frac{1}{4} \left(1 - \sqrt{\frac{\overline{\gamma_{c}}}{1 + \overline{\gamma_{c}}}} \right)^{2} \sum_{k=0}^{1} \left(\frac{1+k}{k} \right) \left[\frac{1}{2} \left(1 + \sqrt{\frac{\overline{\gamma_{c}}}{1 + \overline{\gamma_{c}}}} \right) \right]^{k} \right) \\ \left. \left(2 \left(1 - P_{\xi} \right) P_{\xi} \right) + \frac{1}{4} P_{\xi}^{2} \right\}.$$

$$(3.56)$$

3.3.2. Asynchronous Condition

The performance of the asynchronous condition can be analysed by estimating the average interference energy at the output of the RISIC equalizer. This interference energy is used for BER calculations by replacing the SNR per user in Equation 3.56 with the signal-to-interference and noise ratio (SINR) per user.

1) MUI Interference Analysis

In order to analyze the interference energy output from the RISIC equalizer, first, we need to consider the MUI energy received by the RISIC equalizer as seen from Figure 3.3. Since the signal component at the real and imaginary part has similar transmitted signal and channel impulse response length, the interference energy input at both RISIC equalizers shown in Figure 3.3 are approximately identical. This makes the analysis for the real part also applicable for the imaginary part.

The mathematical model of the real or imaginary part of the received signal at the \ddot{t}^{th} OFDM symbol, $\mathbf{y}_{\dot{t}}$, is given by

$$\mathbf{y}_{\tilde{t}} = \mathbf{y}_{\tilde{t}|\tilde{t}-1} + \mathbf{y}_{\tilde{t}|\tilde{t}} + \boldsymbol{\eta}_{\tilde{t}}, \ \mathbf{y}_{\tilde{t}}, \mathbf{y}_{\tilde{t}|\tilde{t}-1}, \mathbf{y}_{\tilde{t}|\tilde{t}}, \boldsymbol{\eta}_{\tilde{t}} \in \mathbb{R}^{N}$$
(3.57)

where $\mathbf{n}_{\tilde{t}}$ is the noise signal, $\mathbf{y}_{\tilde{t}|\tilde{t}-1}$ is the $(\tilde{t}-1)^{\text{th}}$ OFDM symbol that has contribution to the \tilde{t}^{th} symbol, $\mathbf{y}_{\tilde{t}|\tilde{t}}$ is the \tilde{t}^{th} OFDM symbol that has contribution to the \tilde{t}^{th} symbol and N is number of samples or DFT point of the system. $\mathbf{y}_{\tilde{t}|\tilde{t}}$ is given by

$$\mathbf{y}_{\ddot{t}|\ddot{t}} = \mathbf{x}_{\ddot{t}} (*) \mathbf{h} - \mathbf{h}_{\delta} \mathbf{x}_{\ddot{t}}, \ \mathbf{h}_{\delta} \in \mathbb{R}^{N \times N} \mathbf{x}_{\ddot{t}}, \mathbf{h} \in \mathbb{R}^{N}$$
(3.58)

where (*) indicates a circular convolution, $\mathbf{x}_{\tilde{t}}$ is the \tilde{t}^{th} OFDM symbol, \mathbf{h} is the impulse response and \mathbf{h}_{δ} is the impulse response matrix that results in ISI. \mathbf{h} is given by $\mathbf{h} = \begin{bmatrix} h_0 & \cdots & h_{\tau-1} & 0 & \cdots & 0 \end{bmatrix}$, $\mathbf{x}_{\tilde{t}}$ is given by

$$\mathbf{x}_{\vec{t}} = \left[\begin{array}{ccc} x_{\vec{t},0} & x_{\vec{t},1} & \cdots & x_{\vec{t},N-1} \end{array} \right]$$
(3.59)

and \mathbf{h}_{δ} is given by

$$\mathbf{h}_{\delta}(m,a) = \begin{cases} \mathbf{h}_{\tau \mathcal{G}} & \mathcal{G} \le m, a \le \tau - 1\\ 0 & \text{otherwise} \end{cases}$$
(3.60)

where \mathcal{G} is the length of the CP, τ is the total length of the impulse response of the channel in the case of MUI, $\tau \geq \mathcal{G} + 1$ and $\mathbf{h}_{\tau G}$ is given by

$$\mathbf{h}_{\tau\mathcal{G}} = \begin{bmatrix} h_{\tau-1} & h_{\tau-2} & \cdots & h_{\mathcal{G}+2} & h_{\mathcal{G}+1} \\ 0 & h_{\tau-1} & \ddots & \ddots & h_{\mathcal{G}+2} \\ 0 & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & h_{\tau-1} & h_{\tau-2} \\ 0 & \cdots & 0 & 0 & h_{\tau-1} \end{bmatrix}, \ \mathbf{h}_{\tau\mathcal{G}} \in \mathbb{R}^{\varrho \times \varrho}$$
(3.61)

where $\rho = \tau - \mathcal{G} - 1$. On the other hand, $\mathbf{y}_{\tilde{t}|\tilde{t}-1}$ is given by

$$\mathbf{y}_{\ddot{t}|\ddot{t}-1} = \mathbf{h}_{\delta} \mathbf{x}_{\ddot{t}|\ddot{t}-1}, \qquad \mathbf{x}_{\ddot{t}|\ddot{t}-1} \in \mathbb{R}^{N}$$
(3.62)

where $\mathbf{x}_{\tilde{t}|\tilde{t}-1}$ is the $(\tilde{t}-1)^{\text{th}}$ vector symbol transmitted data that affect the \tilde{t}^{th} symbol and is given by

$$\mathbf{x}_{\ddot{t}|\ddot{t}-1}(m) = \begin{cases} x_{\ddot{t}-1,N-(m-\mathcal{G}+1)}, & \mathcal{G} \le m \le \tau - 1\\ 0 & \text{elsewhere} \end{cases}$$
(3.63)

Therefore, Equation 3.57 can be re-written as

$$\mathbf{y}_{\ddot{t}} = \mathbf{h}_{\delta} \mathbf{x}_{\ddot{t}|\ddot{t}-1} + \mathbf{x}_{\ddot{t}} (*) \mathbf{h} - \mathbf{h}_{\delta} \mathbf{x}_{\ddot{t}} + \boldsymbol{\eta}_{\ddot{t}}$$
(3.64)

The first, second, third and fourth terms of Equation 3.64 are the ISI, wanted signal, ICI and noise, respectively.

Having considered the mathematical model of the received signal with the residual ISI, the signal energy equation can now be calculated. The wanted signal energy, E_S , is given by

$$E_S = \|\mathbf{x}_{\ddot{t}}(*)\mathbf{h}\|^2 = (\mathbf{x}_{\ddot{t}}(*)\mathbf{h})^H (\mathbf{x}_{\ddot{t}}(*)\mathbf{h})$$
(3.65)

where \mathbf{A}^{H} denotes a Hermitian transpose of matrix \mathbf{A} . The ISI energy is given by

$$\Gamma = \left\| \mathbf{h}_{\delta} \mathbf{x}_{\tilde{i}|\tilde{i}-1} \right\|^2 = \left(\mathbf{h}_{\delta} \mathbf{x}_{\tilde{i}|\tilde{i}-1} \right)^H \left(\mathbf{h}_{\delta} \mathbf{x}_{\tilde{i}|\tilde{i}-1} \right)$$
(3.66)

and the ICI signal energy is given by

$$\eth = \left\| \mathbf{h}_{\delta} \mathbf{x}_{\tilde{t}} \right\|^2 = \left(\mathbf{h}_{\delta} \mathbf{x}_{\tilde{t}} \right)^H \left(\mathbf{h}_{\delta} \mathbf{x}_{\tilde{t}} \right)$$
(3.67)

Inserting Equation 3.60, Equation 3.63 into Equation 3.66 and Equation 3.59, Equation 3.60 into Equation 3.67, Equation 3.66 can be rewritten as

$$\Gamma = \left| h_{\tau-1} x_{\tilde{t}-1,N-(m-\mathcal{G}+1)} + \dots + h_{\mathcal{G}+2} x_{\tilde{t}-1,N-2} + h_{\mathcal{G}+1} x_{\tilde{t}-1,N-1} \right|^2 + \left| h_{\tau-1} x_{\tilde{t}-1,N-(m-\mathcal{G})} + \dots + h_{\mathcal{G}+3} x_{\tilde{t}-1,N-2} + h_{\mathcal{G}+2} x_{\tilde{t}-1,N-1} \right|^2 + \dots + \left| h_{\tau-1} x_{\tilde{t}-1,N-1} \right|^2$$
(3.68)

and Equation 3.67 can be rewritten as

$$\eth = \left| h_{\tau-1} x_{\bar{i},\mathcal{G}+1} + \dots + h_{\mathcal{G}+2} x_{\bar{i},\tau-2} + h_{\mathcal{G}+1} x_{\bar{i},\tau-1} \right|^2 + \left| h_{\tau-1} x_{\bar{i}-1,N-(m-\mathcal{G})} + \dots + h_{\mathcal{G}+3} x_{\bar{i}-1,N-2} + h_{\mathcal{G}+2} x_{\bar{i}-1,N-1} \right|^2 + \dots + \left| h_{\tau-1} x_{\bar{i}-1,N-1} \right|^2.$$

$$(3.69)$$

If the channel impulse response **h** has a Rayleigh distributed envelope, the transmitted OFDM symbol energy, E_S , is equally distributed into all samples in the time domain and the ISI energy is equal the ICI energy. Furthermore, the last term of Equation 3.31 and Equation 3.69 can be estimated as

$$\left|h_{\tau-1}x_{\tilde{t}-1,N-1}\right|^2 \approx \operatorname{var}(\mathbf{h})\frac{E_S}{N} \tag{3.70}$$

and the first term of Equation 3.31 and Equation 3.69 can be estimated as

$$\left|h_{\tau-1}x_{\bar{t}-1,N-(m-\mathcal{G}+1)} + \dots + h_{\mathcal{G}+2}x_{\bar{t}-1,N-2} + h_{\mathcal{G}+1}x_{\bar{t}-1,N-1}\right|^2 \approx (\tau - \mathcal{G})\operatorname{var}(\mathbf{h})\frac{E_S}{N}.$$
(3.71)

Since the ISI and ICI energy form a sum of arithmetic series, they are given by

$$\Gamma = \eth = \operatorname{var}(\mathbf{h}) \frac{E_S}{N} \frac{(\tau - \mathcal{G})}{2} \left(1 + (\tau - \mathcal{G})\right)$$
(3.72)

2) RISIC Equalizer Interference Reduction Analysis

As mentioned earlier, the RISIC equalizer works by performing tail cancellation and \mathcal{O} iterations cyclic reconstruction in order to remove the ISI and ICI terms shown in Equation 3.64. After the tail cancellation step, the remaining ISI energy is given by

$$\Gamma_{\mathfrak{T},\tilde{t}} = \left\| \mathbf{h}_{\delta} \left(\mathbf{x}_{\tilde{t}-1} - \mathbf{\hat{x}}_{\tilde{t}-1} \right) \right\|^2 \tag{3.73}$$

and can be approximated as

$$\Gamma_{\mathfrak{T},\tilde{t}} \approx \sqrt{2\sqrt{2} \mathcal{P}_{\delta,\tilde{t}-1}} \Gamma \tag{3.74}$$

where $P_{\delta,\tilde{t}-1}$ is the probability of detecting the wrong symbol per sub-carrier at the

 $(\ddot{t}-1)^{\text{th}}$ OFDM symbol with SINR, $\psi_{\delta,\ddot{t}-1}$, given by

$$\psi_{\delta,\tilde{t}-1} = \frac{E_S}{\eth_{\mathfrak{C}_{\mathcal{O}},\tilde{t}-1} + \mathcal{N}_0} \tag{3.75}$$

and $P_{\delta,\tilde{t}-1}$ is given by

$$P_{\delta,\tilde{t}-1} = 1 - \sqrt{\frac{\psi_{\delta,\tilde{t}-1}/2}{1 + \psi_{\delta,\tilde{t}-1}/2}}$$
(3.76)

 $\eth_{\mathfrak{C}_{\mathcal{O}},\tilde{t}-1}$ is the interference energy at the $(\tilde{t}-1)^{\text{th}}$ OFDM symbol after performing \mathcal{O}^{th} iteration of cyclic reconstruction.

After tail cancellation, the RISIC equalizer performs \mathcal{O} iterations cyclic reconstruction. The ICI energy after Equation 3.38 is given by

$$\widetilde{\mathbf{\partial}}_{\mathfrak{C}_{1},\tilde{t}-1} = \left\| \mathbf{h}_{\delta} \left(\mathbf{\hat{x}}_{1,\tilde{t}} - \mathbf{x}_{\tilde{t}} \right) \right\|^{2} \tag{3.77}$$

and can be approximated as

$$\eth_{\mathfrak{C}_{1}, \ddot{t}-1} \approx \sqrt{2\sqrt{2} \mathrm{P}_{\mathfrak{C}_{1}, \ddot{t}}} \eth$$

$$(3.78)$$

where $P_{\mathfrak{C}_1, \tilde{t}}$ is the probability of detecting the wrong symbol per sub-carrier at the \tilde{t}^{th} OFDM symbol after the first cyclic reconstruction iteration with SINR, $\psi_{\mathfrak{C}_1, \tilde{t}}$, is given by

$$\psi_{\mathfrak{C}_{1},\vec{\iota}} = \frac{E_{S}}{\eth + \Gamma_{\mathfrak{T},\vec{\iota}} + \mathcal{N}_{0}} \tag{3.79}$$

and $P_{\mathfrak{C}_1, \tilde{t}}$ is given by

$$P_{\mathfrak{C}_{1},\vec{t}} = 1 - \sqrt{\frac{\psi_{\mathfrak{C}_{1},\vec{t}}/2}{1 + \psi_{\mathfrak{C}_{1},\vec{t}}/2}}.$$
(3.80)

After the \mathcal{O}^{th} iteration of cyclic reconstruction, the ISI energy left, $\eth_{\mathcal{R}_{\mathcal{O}}, \ddot{t}}$, is given by

$$\eth_{\mathfrak{c}_{\mathcal{O}},\vec{i}} \approx \sqrt{2\sqrt{2}\mathcal{P}_{\mathfrak{c}_{\mathcal{O}},\vec{i}}}\eth$$
(3.81)

where $P_{\mathfrak{C}_{\mathcal{O}},\tilde{t}}$ is the probability of detecting the wrong symbol per sub-carrier at the \tilde{t}^{th} OFDM symbol after the \mathcal{O}^{th} iteration with SINR, $\psi_{\mathfrak{C}_{\mathcal{O}},\tilde{t}}$, given by

$$\psi_{\mathfrak{C}_{\mathcal{O}},\vec{i}} = \frac{E_S}{\eth_{\mathfrak{C}_{\mathcal{O}-1},\vec{i}} + \Gamma_{\mathfrak{T},\vec{i}} + \mathcal{N}_0}$$
(3.82)

and $P_{\mathfrak{C}_{\mathcal{O}},\vec{t}}$ is given by

$$P_{\mathfrak{c}_{\mathcal{O}},\vec{\iota}} = 1 - \sqrt{\frac{\psi_{\mathfrak{c}_{\mathcal{O}},\vec{\iota}}/2}{1 + \psi_{\mathfrak{c}_{\mathcal{O}},\vec{\iota}}/2}}$$
(3.83)

The total interference energy after the RISIC equalizer in every OFDM symbol, $\Upsilon_{\tilde{t}}$, is given by

$$\Upsilon_{\vec{t}} = \eth_{\mathfrak{C}_{\mathcal{O}}, \vec{t}} + \Gamma_{\mathfrak{T}, \vec{t}}.\tag{3.84}$$

Since all symbols are transmitted with the same energy, the average interference energy after the RISIC equalizer, Υ , is given by $\Upsilon = \Upsilon_{\vec{i}}$.

The theoretical BER of asynchronous two users pairing OFDMA equalised by the RISIC equalizer can be obtained by replacing the SNR per bit between UEs and the BS, $\overline{\gamma_c}$, in Equation 3.56 with the SINR per user between UEs and the BS, $\overline{\psi_c}$, given by

$$\overline{\psi_c} = \frac{E_S}{\Upsilon + \mathcal{N}_0} \tag{3.85}$$

3.4. Results and Discussion

 Table 3.1.: Uplink OFDMA simulation parameters

Parameter description	Parameter value
Number of subcarriers, \widetilde{N}	64
CP period, T_G	10% of T_{sym}
Impulse response length	10% of T_{sym}
Bandwidth per subcarrier W_n	$5 \mathrm{kHz}$

3.4.1. Performance under Synchronous Condition

In this simulation, the BER and throughput of the proposed technique under QPSK, 16QAM and 64QAM modulation per subcarrier is considered. Furthermore, since the users of one pair need to exchange their own data in the license-free band before transmission to BS, we examine the performance in various levels of interuser channel quality. We define the inter-user channel quality by the path loss ratio, φ , which is given as $\varphi = \alpha_p/\alpha_{12}$ where α_{12} is the inter-user pathloss and α_p is the pathloss between users and BS. Three values of φ have been considered, which are 0.05, 0.01 and 0.001 as used in [98] and [73]. It is worthwhile mentioning that power used in the data exchange channel is deducted from the uplink transmit power such that the total transmit power remains unchanged. For reference sake, the results are compared with the conventional uplink (CU) transmission, RRT and DSTC relay cooperative techniques as illustrated in Figure 3.2 (a) and (b). The inter-user SNR for PT is assumed to be 10 dB lower than the relay cooperative techniques.



Figure 3.5.: BER of two users synchronous communication with QPSK modulation per subcarrier . (a) φ is 0.05, (b) φ is 0.01 and (c) φ is 0.001.

The throughput, R, is calculated by first considering the spectral efficiency, which is given by

$$s = C_{dis} / \left(T_{sym} W \right) \tag{3.86}$$

where T_{sym} is the total OFDM period including the CP period, W is OFDM bandwidth and C_{dis} is the discrete-time channel capacity. W is given by

$$W = NW_n \tag{3.87}$$

where W_n is the bandwidth per subcarrier. W_n , T_{sym} and C_{dis} are given by

$$W_n = 1/T_O \tag{3.88}$$

$$T_{sym} = T_O + T_G \tag{3.89}$$

$$C_{dis} = \mathcal{K}_O - \Xi_q \left(P_O \right) \tag{3.90}$$

where \mathcal{K}_O is the number of bits per OFDM symbol for uplink, P_O is OFDM symbol error rate and $\Xi_q (P_O)$ is the equivocation of the OFDM symbol at a given P_O , [41]. $\Xi_q (P_O)$ is given by [99]

$$\Xi_q (P_O) = -P_O \log_2 \left(\frac{P_O}{2^{\mathcal{K}_O} - 1} \right) - (1 - P_O) \log_2 (1 - P_O)$$
(3.91)

R is related to s by

$$R = sNW_n. (3.92)$$



Figure 3.6.: BER of two users synchronous communication with 16QAM modulation per subcarrier. (a) φ is 0.001 and (b) φ is 0.01.



Figure 3.7.: BER of two users synchronous communication with 64QAM modulation per subcarrier. (a) φ is 0.001 and (b) φ is 0.01.



Figure 3.8.: Throughput of uplink OFDMA communication with QPSK. (a) φ is 0.001 and (b) φ is 0.05.

The BER of the proposed technique under QPSK modulation and three different inter-user communication SNR values will be shown separately from 16QAM and 64QAM results in order to prove the validity of the analysis presented first. On the other hand, for better clarity, the throughput will show the results of QPSK and 64QAM modulation only.



Figure 3.9.: Throughput of uplink OFDMA communication with 64QAM modulations. (a) φ is 0.001 and (b) φ is 0.05.

As can be seen from Figure 3.5, the simulation results are almost perfectly aligned with the theoretical ones, which confirms the validity of the BER analysis presented earlier. Figure 3.5, Figure 3.6 and Figure 3.7 show that the proposed PT improved the BER at low SNR per bit in comparison to the other techniques, especially when the pathloss ratio, φ , is lower than 0.01. Furthermore, at φ equals 0.001, the proposed technique achieves the best BER results at low SNR. Even though DSTC in single relay system provides three diversity orders, this technique achieves worse performance than the proposed technique because at low SNR, the direct transmission required for achieving third diversity order results in higher probability of symbols error rate compared to the proposed PT. Only when the direct transmission is reliable, which is achieved at high SNR, the DSTC achieves better BER performance than PT. Due to its low inter-user SNR compared to the RT cooperative diversity techniques, the proposed PT may not be able to provide BER improvement in comparison to the relay cooperative techniques at φ equals 0.05. This happens since low quality inter-user SNR leads to data exchange errors and wrong symbol transmission to the BS. Nevertheless, at all φ values, the proposed technique is still capable to achieve better performance than the CU direct transmission. The BER performance improvement in comparison to CU transmission is achieved without sacrificing the data rate, as can be seen from Figure 3.8 and Figure 3.9. In contrast to the RRT and DSTC techniques, which achieve improved performance in comparison to CU at low SNR values only, the proposed attains a significant improvement of throughput at all SNR values.

3.4.2. Performance under Asynchronous Condition

In order to simulate time asynchronism, all users, except the user of interest, have random time of arrivals with uniform distribution and maximum values of 10%, 20% and 30% of the OFDM symbol period as were adopted in [100]. In this simulation, the RISIC algorithm employs three cyclic reconstruction iterations. For reference sake, the results of asynchronous communication will be compared with the performance of CU and DSTC OFDMA under similar conditions.

The asynchronism impact on BER performance will be observed under two users with various received SNR values and under multiple users transmission schemes. Both conditions are simulated with φ equals 0.001. Furthermore, since the proposed technique achieves similar trend of BER improvement in comparison to other transmission techniques in all modulation orders, shown in Figure 3.5 - Figure 3.9, only

QPSK modulation is considered in this simulation. Also, in the case of asynchronous simulation the impact of imperfect channel estimation is considered. Channel estimation errors are simulated by adding noise onto the channel response such that the mean-absolute-percentage-error (MAPE) between the actual and the estimated channel transfer function, given by $MAPE = \frac{1}{N} \sum_{k=0}^{N-1} |(H_{est} - H)/H|$, is not zero [59, 60]. Simulation under non-ideal conditions, such as asynchronous communication with noisy channel estimates will be considered for various numbers of users under 10% of MAPE and 10% and 20% of time asynchronism.



Figure 3.10.: BER of asynchronous communication with QPSK modulation. (a) Up to 10% asynchronous in time, (b) Up to 30% asynchronous in time.

Figure 3.10 - Figure 3.12 show how the PT performs under non-ideal conditions. Figure 3.10 shows that the simulation results are almost perfectly aligned with the theoretical results, which confirms the validity of the BER analysis presented earlier. This figure also shows that the proposed technique is a robust scheme in asynchronous uplink transmission. Unlike DSTC scheme, the proposed technique is better than CU at any asynchronism value. This happens because the DSTC RT employs STBC scheme for relay transmission and RISIC equalizer works by slowly decode the received symbols before removing the ISI. Since decoding two sources of signal is worse than single source, so as the time arrivals increases to 30%, the RISIC equalizer becomes unable to reduce the interference in DSTC RT method and result in worse performance than the CU transmission.

Similar with the synchronous case, the BER performance improvement in comparison to CU transmission is achieved without sacrificing the data rate, as can be seen from Figure 3.11. Unlike DSTC techniques, which achieve improved throughput in comparison to CU only at low SNR value, the proposed cooperative diversity attains a significant improvement of throughput at all SNR values.



Figure 3.11.: Throughput of uplink OFDMA communication. (a) 10% asynchronous in time and (b) 30% asynchronous in time.

Similar with the synchronous case, the BER performance improvement in comparison to CU transmission is achieved without sacrificing the data rate, as can be seen from Figure 3.11. Unlike DSTC techniques, which achieve improved throughput in comparison to CU only at low SNR value, the proposed cooperative diversity attains a significant improvement of throughput at all SNR values.

Figure 3.12 shows that the PT is almost unaffected by the number of users while the BER of conventional uplink OFDMA increases slightly as the number of users increases. This is because the time asynchronism in conventional uplink OFDMA results in time shifting the impulse response while the time asynchronism in our PT results in an extended impulse response. Extended impulse response results in more distributed power over the whole impulse response energy in comparison to the time shifted one. Thus, the ratio between ISI energy and the impulse response within the CP in the extended impulse response is lower than that in the time shifted impulse response. As could be seen from this figure, the performance of the multiuser pairing technique under imperfect channel estimates only suffers slightly in comparison with the performance under perfect channel knowledge. Furthermore, the performance is still superior to the performance of the CU in 10% asynchronous. In this case the



Figure 3.12.: BER of multiuser pairing in up to 10% channel estimation error. (a) is up to 10% asynchronous in time and (b) is up to 20% asynchronous in time.

performance increases from 6×10^{-5} to almost 2×10^{-4} . In 20% asynchronous time, the performance increases from 5×10^{-4} to 8×10^{-4} .

3.4.3. Performance under Multiple Receiver Antennas

As most basestations are nowadays equipped with multiple receive antennas it is important to assess the performance of the proposed technique under this scenario. The observation will assess the performance of a ten user system in up to 10% asynchronous communication using the parameters shown in Table 3.1. In addition, the performance will be compared with synchronous CU transmission.

In the multiple receiver antennas system, the number of diversity orders using the proposed scheme is twice the number of receiving antennas. Figure 3.13 shows that the performance follows the expectation. As can be seen from this figure, the proposed technique provides up to 7 dB performance improvement in the case of two receiving antennas. Furthermore, it also shows that the most significant improvement occurs when the number of receiving antennas is increased from two to three, which is equivalent with the improvement from four to six orders diversity. The improvement becomes smaller as the number of receiving antennas is increased beyond two antennas, which is a similar trend in diversity order improvement beyond six diversity orders.



Figure 3.13.: BER of ten users pairing technique in up to 10% asynchronous communication and multiple receiver antennas with inter-user SNR per bit is 20 dB better than the SNR per bit per user at the base station

3.5. Summary

This chapter has presented a unique user pairing diversity technique for uplink OFDMA systems. The proposed utilises the unlicensed band and single dimensional OFDM modulation to achieve two diversity orders and a transmission rate of one symbol/second/Hz. It was shown that this technique provides significant BER reduction, especially at low SNR, and improves throughput compared to conventional direct transmission and RT techniques under both ideal and non-ideal channel conditions. The improvements occur as a result of three factors which are achieving two diversity orders, doubling of the received signal power, due to constructive combing of the paired users's signals, and, appropriate utilisation of free-license spectrum through reduced transmitted power and interference amongst the pairs. The performance results were verified by matching accurate analytical and simulation results.

4. Interference Mapping based RRM for 4G Cellular Networks

Motivated by the need to achieve higher spectral efficiency, this chapter presents a confederation-style SON RRM combined with a principle of routing algorithm. The confederation aspect helps in minimising overhead signaling while the routing algorithm principle, in particular distance vector routing protocol (DVRP) principle, is used to maximise spectral efficiency. The proposed uses a novel downlink interference mapping method in the form of a matrix of conflicts (MoC) to track how the BSs links affect certain UEs and locate possible interference instances per user per subcarrier. When the MoC indicates no potential interference, the BS will perform the PF scheduling for its UEs using the entire available spectrum. Otherwise, a centralised RRM-routing principle is invoked to prevent the interference instances. Generally speaking, the centralised approach is applied only when the MoC within a group of BSs undergoes certain changes. Using DVRP routing principle, the central node consecutively assigns resources to UEs of a basestation (BS) while the common information is shared amongst the conflicted BSs. The proposed technique uses the SON functionality to facilitate successful and efficient application of this approach, which is why it is categorised as SON-RRM.

The adaptive capability of the proposed technique can be implemented in both HoNet and HetNet environments. Furthermore, the proposed technique utilises all basic 4G standards for the implementation. Therefore, this method can be implemented for current 4G HetNets.

For simplicity, the proposed algorithm and the evaluation will be described in different chapters. This chapter is organised as follows. The system model assumed throughout this chapter is presented first. After that, section 4.2 describes the algorithm. Then, the analysis of the proposed technique is presented in section 4.3. Finally, the summary is given in section 4.4.

4.1. System Model

This chapter considers a downlink scenario of fractional frequency reuse (FFR) and soft frequency reuse (SFR) based HetNet [101], [102], which uses OFDMA system with adaptive modulation [103]. N parallel resources (PRs) are divided into Iseparate groups with index i and each group has N_i PRs. If it is assumed that frequency reuse factor of 3, I = 6 in the case of FFR where i = 1 until i = 3 for inner users and i = 4 and i = 6 for outer users. On the other hand, using the same assumption, I = 3 in the case of SFR where inner users will be allocated with 2 PRs groups for inner users and 1 PRs group for the outer users. As been mentioned in chapter 2, PR is the available resource within a synchronised transmission. In the case of WiMAX system, 1 PR is equivalent with one subcarrier and N PRs are equivalent with N subcarriers within one OFDM symbols. On the other hand, PR equals to one resource block (RB) and N PRs indicates the total RBs within one frame of symbols transmission in the case of LTE system.

Each SBS determines the relative position after measuring the signal power from the MBS using a *sniffing* or listening capability [79]. If an SBS senses that it exists within the range of the inner MBS's UEs, this SBS utilises the PRs groups that minimise the cross-tier interference as been illustrated by Figure 2.16 and Figure 2.15 in chapter 2.

The micro- and pico- cells are connected with the macrocell through a Radio Network Controller (RNC). On the other hand, a set of femto access points (FAPs) or Home Node BSs (HNBs) are connected to a Femto Management System (FMS), which is controlled by an Operator Management System (OMS), through the Internet Service Provider (ISP) backhaul. This is shown in Figure 4.1. While FMS provides operation and management (OAM) functionality for the femtocell networks, OMS provides OAM functionality for the macro-, micro- and pico- cells as well as to the FMS [79]. The OAM may include RRM assistant, users authentication, authorisation, accounting and optimising scheduling of data in the network. Therefore, both OMS and FMS provide central controller functionality for HetNets. Using SON capability, each BS is able to establish the neighbouring BSs link automatically. Therefore, the MBS knows exactly the identity of the SBSs in the same cell and the SBSs have the neighboring BS list registered on their memory.

Also, all UEs are capable of measuring power signals from different BSs as well as identifying their identity (ID) using the measurement report (MR) capability embedded in LTE [104]. There are two types of MR, which are periodic and event triggered. In the periodic case, MR is reported every 300 ms or 3000 ms [105]. On the other hand, in the case of event triggered MR, a BS sends a *Radio Resource Control* (RRC) connection reconfiguration message to a UE. Upon receiving this message, the UE searches for the neighboring BSs, identifies the *Physical Layer Cell Identities* (PCI) and measures their *Reference Signal Received Power* (RSRP) and/or *Reference Signal Received Quality* (RSRQ). The MR contains the PCI information and their average received power [104]. The MR is submitted by a UE before being served by a BS and/or when the signal power falls below a certain threshold due to its mobility. Normally, the MR is only used to make a decision on handover requirement to a neighboring femtocell with higher received signal. In the proposed SON RRM algorithm, this information will also be used for approximating the downlink interference.



Figure 4.1.: HetNet Architecture Example

In the considered heterogeneous network, there are (M-L) SBSs and L MBSs de-
noted in set $\mathbb{T} = \begin{bmatrix} T_1 & \ldots & T_M \end{bmatrix}$, where T_1 until T_{M-L} represent SBSs and T_{M-L+1} until T_M represent the MBSs, and their corresponding users set, $\mathbb{U} = \begin{bmatrix} U_1 & \ldots & U_Z \end{bmatrix}$, where Z is the total number of users. This set is held by the FMS. It is further assumed that BS T_m , holds its own neighboring BSs set $\mathbb{T}_{m,C} = \begin{bmatrix} T_{m,1} & \ldots & T_{m,C_m} \end{bmatrix}$, where $C_m < M$ is the number of T_m 's neighboring BSs with index c_m , and $\mathbb{T}_{m,C}$ acts as a pointer for the \mathbb{T} set held by the FMS.

BS utilizes full BS is ON spectrum BS re-allocate the No BS utilizes new BS utilizes resource Any UE(s) require to resource without resource block block allocation send Measuremen violating some allocation decided previously Report (MR) criterions Yes Yes Ask UE(s) to FMS sends the Further perform MR and subcarriers scheduling is update local matrix No criterion to all enabled in BS of conflict (MoC) conflicting BSs FMS solves the Local MoC is Report to Femto No conflicting BSs using similar with previou Management a set of rule based measurement System (FMS) on the MoC Yes No No Yes Instruction to Receive interrupt from utilize full resource FMS block Yes Performed by BS Performed by FMS

4.2. MoC Based Hybrid SON RRM

Figure 4.2.: Matrix of Conflicts based Radio Resource Management

A flow chart for the proposed technique is shown in Figure 4.2. This algorithm uses the FMS as the central controller because femtocells are installed by the enduser and causes more interference compared to other small cells. The first major step in the proposed method is to establish the MoC. Two types of MoCs must be constructed within a HetNet, which are termed local and global MoCs. A local MoC is the interference map within each BS while the global MoC is the combination of the local MoCs from all BSs. The BSs monitor their local MoCs periodically and submit their updates to the FMS whenever they change or requested by the FMS. When a BS submits its map, using a routing algorithm principle to check with the global MoC, the FMS will decide whether this BS can use a part of or the entire spectrum.

The routing strategy used by the FMS to decide the spectrum subset for the conflicting BSs works in a similar manner as the *distance vector routing protocol* (DVRP) in which each node consecutively constructs its routing table based on a certain queuing criterion and then shares this with its neighbors [106]. Similarly, the FMS consecutively assigns temporary PRs to the UEs of a BS and the common information is shared amongst these BSs in order to compute their allocated PRs set. After receiving this information from the FMS, each BS then schedules the resources using the PF algorithm. The PF scheduler uses the feedback channel and MR information to predict the interference received by each UE to estimate the gain variation across the allocated PRs.

Thus, generally speaking, the proposed revolves around constructing the MoC and accordingly deciding whether a distributed or centralised approach is needed for each basestation (BS). The process is described in details in three major stages below.

4.2.1. Constructing The MoCs

1) Local and Global MoCs Construction

When a UE wants to connect to a BS, this BS requests its MR reading. Lets assume there are Z_m UEs within BS T_m , the MR readings from all of T_m 's UEs are organised into the two matrices: $\boldsymbol{\alpha}_{m,t} \in \mathbb{R}^{Z_m \times 1}$, which is the instantaneous pathloss between T_m and its UEs, and $\mathbf{E}_{C_m,t} \in \mathbb{R}^{Z_m \times C_m \times I}$, which is the received power from T_m 's neighbor BSs to its UEs at I PRs group. Using $\boldsymbol{\alpha}_{m,t}$, is given by

$$\mathbf{E}_{m,t}(z,i) = \frac{P_{m,i}}{\boldsymbol{\alpha}_{m,t}(z)}, \ \forall z = 1,\dots, Z_m$$
(4.1)

for i = 1, ..., I where *i* is the PRs group index and $P_{m,i}$ is the average downlink transmitted power of T_m at the *i*th PR index. If $\mathbf{E}_{m,t}(z,i)/\mathbf{E}_{C_m,t}(z,c_m,i) < \gamma_{th}$ where γ_{th} is the signal-to-interference ratio (SIR) threshold, T_m will detect that u_z is interfered by T_{m,c_m} at index *i*. Based on this information, the local MoC of T_m , $\boldsymbol{\zeta}_m \in \mathbb{R}^{Z_m \times C_m \times I}$, is constructed as follows

$$\boldsymbol{\zeta}_{\boldsymbol{m}}\left(z,c_{m},i\right) = \begin{cases} w_{e}, & \mathbf{E}_{m,t}(z,i)/\mathbf{E}_{c_{m},t}\left(z,c_{m},i\right) < \gamma_{th} \& \mathbf{E}_{c_{m},t}\left(z,c_{m},i\right) > \mathcal{N}_{0} \\ 0, & \text{otherwise} \end{cases}$$

$$(4.2)$$

for $z = 1, ..., Z_m$, i = 1, ..., I, where Z_m is all the UEs of T_m , c_m is T_m 's neighboring BS index from $\mathbb{T}_{m,C}$, w_e is any positive integer number bigger than 0 and \mathcal{N}_0 is noise level. The integer value of w_e does not affect the performance of the proposed scheme because this value is only used to differentiate between the interfering and non-interfering BSs. This implies that w_e value can be equal with 1 for simplicity. Every time T_m updates ζ_m , it will check the result with the previous measurement. Assuming the previous measurement of ζ_m is given by ζ'_m , T_m will report ζ_m at the i^{th} PR index to the FMS if

$$\sum_{z=1}^{Z_m} \sum_{c_m=1}^{C_m} \left| \boldsymbol{\zeta}_m \left(z, c_m, i \right) - \boldsymbol{\zeta}'_m \left(z, c_m, i \right) \right| > 0$$
(4.3)

This MoC is sent to the FMS through the backhaul using the message structure shown by Figure 4.3. This information begins and finishes by sending a header and a tail messages to distinguish the MoC information exchange from other data transmissions. Then, the MoC is contained by sending the IP address of the interfering BSs and the MoC associated with it consecutively.



Figure 4.3.: Local MoC Information Message to the FMS

Upon receiving $\boldsymbol{\zeta}_m$ updates from T_m the FMS waits for the other BSs within the $\mathbb{T}_{m,C}$ set to send their own matrix of conflicts for a certain period, which could be in terms of mili seconds, before updating the global MoC, $\boldsymbol{\zeta} \in \mathbb{R}^{Z \times M \times I}$, given by

$$\boldsymbol{\zeta}(z,a,i) = \begin{cases} w_s, & \text{if } T_a \text{ is the BS of } u_z \\ w_e, & \text{if } T_a \text{ interferes } u_z \\ 0, & \text{otherwise} \end{cases}$$
(4.4)

where w_s is any positive integer number bigger than 0 and $w_s \neq w_e$.

2) Local MoC Request Criterion by The FMS

After $\boldsymbol{\zeta}$ is updated, the FMS calculates the total detected users by T_m at the i^{th} PR index, $S_{m,i}$, which is given by

$$S_{m,i} = \sum_{z=1}^{Z} \{ \zeta(z,m,i) \sim w_s \} + \sum_{z=1}^{Z} \{ \zeta(z,m,i) \sim w_e \}$$
(4.5)

where $x = \{a \sim b\}$ means x = 1 if a is equal to b, otherwise x = 0. Then, it checks all BSs that require frequency update, which are the conflicting BS. If the previous measurement of $\boldsymbol{\zeta}$ and $S_{m,i}$ are given by $\boldsymbol{\zeta}'$ and $S'_{m,i}$, any $T_m \in \mathbb{T}$ is categorised as conflicting BS at the *i*th PRs group index if, at least, one of the following conditions is fulfilled:

I)
$$\sum_{c=1}^{M} \{ \boldsymbol{\zeta}(z,c,i) \sim w_e \} \cap \{ S_{c,i} > S'_{c,i} \} > 0, \ c \neq m, \ \forall z \subseteq Z \mid \boldsymbol{\zeta}(z,m,i) = w_s \quad (4.6)$$

II)
$$\sum_{z=1}^{Z} |[\boldsymbol{\zeta}(z,m,i) - \boldsymbol{\zeta}'(z,m,i)] \cap \{\boldsymbol{\zeta}(z,m,i) \not\sim w_s\}| > 0$$
(4.7)

III
$$\sum_{c=1}^{M} |[\boldsymbol{\zeta}(z,c,i) - \boldsymbol{\zeta}'(z,c,i)]| > 0, \quad \forall z \subseteq Z, c \neq m \mid \boldsymbol{\zeta}(z,m,i) = w_s \quad (4.8)$$

where \cap denotes the AND logic operation and $x = \{a \nsim b\}$ means x = 1 if a is not equal to b, otherwise x = 0.

After all BSs have been assessed, the FMS constructs the set of BSs that require conflicts to be resolved at a particular time and the i^{th} PRs group index is given by $\mathbb{T}_{\mathbf{B},i} = \begin{bmatrix} T_{1,i} & \dots & T_{B_{i},i} \end{bmatrix}$ with index $T_{b,i}$ where $B_i \leq M$ is the total conflicting BSs at the *i*th PRs group index and $\mathbb{T}_{\mathbf{B},i}$ acts as a pointer for the \mathbb{T} set in the FMS memory. If the MBS is among the BSs that require allocation update, $T_{M,i}$ will also include the MBS. Lets assume the UEs of $\mathbb{T}_{\mathbf{B},i}$ are given by $\mathbb{Q}_{\mathbf{B},i} = \begin{bmatrix} q_{1,i} & \dots & q_{Z_{Bi},i} \end{bmatrix}$ with index $q_{b,i}$, where $Z_{Bi} \leq Z$ is the total UEs of conflicting BSs at the *i*th PRs group index. Then, the FMS passes the $\boldsymbol{\zeta}$ information into the $\mathbb{T}_{\mathbf{B},i}$'s matrix of conflicts, $\boldsymbol{\zeta}_{\mathbf{B},i}$.

4.2.2. Routing Principle Based Centralised SON RRM

If u_z , which is served by T_m , is interfered by BS T_c , then this interference is denoted as $T_c \to T_m$ and the general case of T_m and T_c interference with each others' UEs is denoted as $T_c \rightleftharpoons T_m$. In this thesis, $T_c \longleftrightarrow T_m$ denotes that T_c and T_m are related through an interference connection. As all conflicting BSs can be assumed to be virtually connected nodes, this research proposes a new set of frequency allocation which utilises a routing protocol such as the DVRP. The routing protocol principle combined with the SON RRM in this thesis works according to the following steps:

- 1. grouping the small cells
- 2. passing the entire networks parameters
- 3. measuring queuing criterion
- 4. initial frequency allocation
- 5. underused spectrum utilisation

As mentioned previously, the FMS consecutively assigns PRs to UEs of a BS and the common information is shared amongst the connected BSs. In this algorithm, the common information is encoded in the form of binary matrices called *entire forbidden* PRs, $\Theta_i \in \mathbb{R}^{Z_{Bi} \times N_i}$, partial forbidden PRs, $\Phi_i \in \mathbb{R}^{Z_{Bi} \times N_i}$, priority PRs, $\mathcal{P}_i \in \mathbb{R}^{Z_{Bi} \times N_i}$ and temporary allocated PRs, $\mathcal{A}_i \in \mathbb{R}^{Z_{Bi} \times N_i}$, where N_i is the total available PRs per OFDM symbol at the *i*th PRs group index. Θ_i is used to indicate which PRs cannot be assigned to a particular UE due to orthogonality requirements with two or more UEs in the same BS or in other BSs while Φ_i represents the forbidden PRs due to orthogonality requirement with UEs in other BSs. On the other hand, \mathcal{P}_i is required so that the PRs can be allocated to each UE much more efficiently such

that maximum resource allocation can be achieved. In addition, \mathcal{A}_i is the matrix indicating temporary PRs allocation for these UEs. Initially, these matrices have all zeros value. After this centralised approach is performed, these matrices will be populated with binary numbers as follows:

$$\boldsymbol{\Theta}_{i}, \boldsymbol{\Phi}_{i}(z, n) = \begin{cases} 1 & n^{\text{th}} \text{ subcarrier is forbidden to } u_{z} \\ 0 & \text{otherwise} \end{cases}$$
(4.9)

$$\boldsymbol{\mathcal{P}}_{\boldsymbol{i}}\left(\boldsymbol{z},\boldsymbol{n}\right) = \begin{cases} 1 & u_{\boldsymbol{z}} \text{ is prioritised to } \boldsymbol{n}^{\text{th}} \text{subcarrier} \\ 0 & \text{otherwise} \end{cases}$$
(4.10)

$$\boldsymbol{\mathcal{A}}_{i}(z,n) = \begin{cases} 1 & n^{\text{th}} \text{ subcarrier is allocated to } u_{z} \\ 0 & \text{otherwise} \end{cases}$$
(4.11)

After performing this algorithm, the FMS sends the information of allowable PRs, $\Lambda_i = \overline{\Phi_i}$, and temporary allocated PRs, \mathcal{A}_i , back to the conflicting BSs, $\mathbb{H}_{\mathbf{B},i}$. Let assume Λ_i and \mathcal{A}_i information for T_m are given by $\Lambda_{m,i}$ and $\mathcal{A}_{m,i}$, respectively.

1) Grouping the small cells

Since the B_i BSs that require resource update may include a large number of BSs per macrocell, it is better to organise the virtual connections such that parallel computing can be performed by the FMS. This can be done by assigning small cells into the same group as illustrated from Figure 4.4. As can be seen from this example, there are three groups of SBS that are independent. The resource allocation of these groups can also be performed independently.

Algorithm 4.1 Grouping Virtual Connection of BSs
function GroupingVirtualBS ($\zeta_{\mathbf{B}}$)
1 for $q = 1$ until Z_B do
2 $\mathbb{T}_{\mathbf{B},i}(c)$ is the BS of $\mathbb{Q}_{B,i}(q)$
3 for $z = 1$ until Z_B do
4 if $\boldsymbol{\zeta}_{\mathbf{B}}(z,c) = w_e$ then
5 Assign $\mathbb{T}_{\mathbf{B},i}(c)$ with the same group with $\mathbb{T}_{\mathbf{B},i}(b)$ given
that $\mathbb{T}_{\mathbf{B},i}(b)$ is the serving BS of z
6 end if
7 end for
8 end for



Figure 4.4.: Grouping Illustration. (a) Heterogeneous network interference example. (b) Result of grouping the small cells.

The grouping is performed by Algorithm 4.1 after which there will be K_i groups of SBS at the *i*th PRs group index, with $\mathbb{V}_{k_i} = \begin{bmatrix} V_{1,k_i} & \cdots & V_{M_{k_i},k_i} \end{bmatrix}$ is a set of the k_i^{th} group of SBSs, M_{k_i} is the number of BSs within the k_i^{th} group where $M_{k_i} < B_i$. Similar to $\mathbb{T}_{\mathbf{B},i}$, \mathbb{V}_{k_i} holds the ID of \mathbb{T} in the FMS memory.

2) Passing the entire networks parameters

Since $B_i \leq M$, after the BSs have been grouped, the common information, which is contained within \mathcal{P}_i , Θ_i , Φ_i and \mathcal{A}_i needs to be passed down to $\mathcal{P}_{\mathbf{B},i}$, $\Theta_{\mathbf{B},i}$, $\Phi_{\mathbf{B},i}$ and $\mathcal{A}_{\mathbf{B},i}$. This is performed using Algorithm 4.2. Note that \cap and \cup denote bitwise AND and OR logic operations, respectively.

3) Calculate Queuing Criterion

Using $\zeta_{\mathbf{B},i}$, the total detected number of users by $T_{b,i}$ BS, $\mathcal{S}_{b,i}$, is defined as

$$S_{b,i} = \sum_{q=1}^{Z_{Bi}} \left\{ \zeta_{\mathbf{B},i}(q,b) \sim w_s \right\} + \sum_{q=1}^{Z_B} \left\{ \zeta_{\mathbf{B},i}(q,b) \sim w_e \right\}$$
(4.12)

Algorithm 4.2 Passing the Entire Network Parameters

function groupParameter $(\mathcal{A}_i, \mathcal{P}_i, \Theta_i, \Phi_i, \zeta_{\mathbf{B}, i})$ 1 for z = 1 until Z do $\mathbf{2}$ T_m is serving BS of $\mathbb{U}(z)$ if $T_m \in \mathbb{T}_{\mathbf{B},i}$ 3 $\mathbf{v}(n) = \left(\left\{\boldsymbol{\zeta}\left(z,c,i\right) \sim w_e\right\} \cup \left\{\boldsymbol{\zeta}\left(a,m,i\right) \sim w_e\right\}\right) \cap \boldsymbol{\mathcal{A}}_i(a,n)$ 4 5 $\mathcal{P}_{\mathbf{B},i}(z,n) = \mathcal{P}_{\mathbf{B},i}(z,n) \cup (\mathcal{A}_i(a,n) \land \{\zeta(z,c,i) \sim 0\})$ $\Theta_{\mathbf{B},i}(z,n) = \Theta_{\mathbf{B},i}(z,n) \cup \mathbf{v}(n)$ 6 7 $\Phi_{\mathbf{B},i}(z,n) = \Phi_{\mathbf{B},i}(z,n) \cup \mathbf{v}(n)$ $\forall n = 1, \dots, N_i, a = 1, \dots, Z, | a \neq z, T_c \text{ is serving BS of } \mathbb{U}(a),$ 8 $T_c \longleftrightarrow T_m \& T_c \notin \mathbb{T}_{\mathbf{B},i}$ 9 end if 10 end for11 return $\Theta_{\mathbf{B},i}$, $\Phi_{\mathbf{B},i}$ and $\mathcal{P}_{\mathbf{B},i}$

Using $S_{b,i}$, the initial number of PRs per user of BS $H_{b,i}$ is given by

$$N_{b,i} = \lfloor N_i / S_{b,i} \rfloor \tag{4.13}$$

where $\lfloor x \rfloor$ is the nearest integer value lower than x. This value is then copied into a set of the initial number of PRs for all conflicting BSs, $N_{B,i} = \begin{bmatrix} N_{1,i} & \dots & N_{B_i,i} \end{bmatrix}$ with the index of N_b and $N_{B,i} \in \mathbb{R}^{1 \times B_i}$. $N_{B,i}$ is then used as a basis for the set of the initial number of PRs per user, $J_i = \begin{bmatrix} J_{1,i} & \dots & J_{Z_{B_i,i}} \end{bmatrix}$ with the index $J_{q,i}$ given by

$$J_{q,i} = \min_{b:\boldsymbol{\xi}_{q,i}(b) > 0} \boldsymbol{\xi}_{q,i}(b)$$

$$(4.14)$$

where $\boldsymbol{\xi}_{q,i} \in \mathbb{R}^{1 \times B_i}$ is given by

$$\boldsymbol{\xi}_{q,i}(b) = \left\{ \boldsymbol{\zeta}_{\mathbf{B},i}(q,b) > 0 \right\} N_{b,i}, \qquad b = 1, \dots, B_i$$
(4.15)

After all required parameters have been calculated, the FMS sorts the set of updating transmitters, $\mathbb{T}_{\mathbf{B},i}$, from the lowest to the highest value, based on $N_{B,i}$. If the $\mathbb{T}_{\mathbf{B},i}$ set includes MBS, $N_{B,i}$ becomes the smallest value within $N_{B,i}$. This is because the MBS has more UEs than the SBS, the MBS becomes the first priority. On the other hand, the rest of the BSs within the $\mathbb{T}_{\mathbf{B},i}$ set are sorted locally within their own BS group, \mathbb{V}_{k_i} .

4) Initial consecutive PR allocation

Based on the $\widetilde{\mathbb{T}}_{\mathbf{B},i}$ and \mathbb{V}_{k_i} sets, consecutively allocate $q = 1, \ldots, Z_{Bi}$ users with $J_i(q)$ PRs in a pseudorandom manner into $\mathcal{A}_{\mathbf{B},i}(z,n)$ at any $n = 1, \ldots, N_i$ and $i = 1, \ldots, I | \Theta_{\mathbf{B},i}(q,n) = 0$, with priority to allocate at any $n = 1, \ldots, N_i | \mathcal{P}_{\mathbf{B},i}(q,n) = 1$.

Algorithm 4.3 Forbidden and Priority PRs Update

function passForbPrio $(\Theta_{\mathbf{B},i}, \Phi_{\mathbf{B},i}, \mathcal{P}_{\mathbf{B},i}, \mathcal{A}_{\mathbf{B},i}, \mathbb{T}_{\mathbf{B},i}, \mathbb{V}_{k_i}, \zeta_{\mathbf{B},i}, i, b, q)$ 1 $k_{b,i}$ is group of $\mathbb{T}_{\mathbf{B},i}(b)$ based on \mathbb{V}_{k_i} set 2 for p = 1 until B_i do if $(\mathbb{T}_{\mathbf{B},i}(p) \neq \mathbb{T}_{\mathbf{B},i}(b))$ & $\mathbb{T}_{\mathbf{B},i}(p) \in \mathbb{V}_{k_{b,i}}$ then 3 $\mathbf{v}(n) = \left[\left\{ \boldsymbol{\zeta}_{\mathbf{B},i}\left(q,p\right) \sim w_{e} \right\} \cup \left\{ \boldsymbol{\zeta}_{\mathbf{B},i}\left(a,b\right) \sim w_{e} \right\} \right] \cap \boldsymbol{\mathcal{A}}_{\mathbf{B},i}(q,n)$ 4 $\mathcal{P}_{\mathbf{B},i}(a,n) = \mathcal{P}_{\mathbf{B},i}(a,n) \cup \left(\mathcal{A}_{\mathbf{B},i}(q,n) \cap \left\{\boldsymbol{\zeta}_{\mathbf{B},i}(a,b) \sim 0\right\}\right)$ 56 $\Theta_{\mathbf{B},i}(a,n) = \Theta_{\mathbf{B},i}(a,n) \cup \mathbf{v}(n)$ $\Phi_{\mathbf{B},i}(a,n) = \Phi_{\mathbf{B},i}(a,n) \cup \mathbf{v}(n)$ 7 $\forall n = 1, \ldots, N_i, a = 1, \ldots, Z_{Bi}, \text{ and } a \neq q$ 8 9 else $\Theta_{\mathbf{B},i}(c,n) = \Theta_{\mathbf{B},i}(c,n) \cup \left(\mathcal{A}_{\mathbf{B},i}(q,n) \cap \left\{ \zeta_{\mathbf{B},i}(c,b) \sim w_s \right\} \right), \\ \forall n = 1, \dots, N_i, \ c = 1, \dots, Z_{Bi}, \text{ and } c \neq q$ 10 11 12 end if 13 end for14 return $\mathcal{P}_{\mathbf{B},i}, \Theta_{\mathbf{B},i}$ and $\Phi_{\mathbf{B},i}$

After the initial allocation for each user, update $\mathcal{P}_{\mathbf{B},i}$, $\Theta_{\mathbf{B},i}$ and $\Phi_{\mathbf{B},i}$ using Algorithm 4.3.

After allocating all users with initial PRs, make sure all users within $\mathbb{V}_{k_{b,i}}$ groups are allocated with resources. If at least one user do not get a PR, repeat this step with half of J_i .

5) Underused spectrum utilisation

After the initial frequency allocation it is likely that some PRs would not be assigned to any UE. In order to minimise the iterations required using consecutive scheduling, the underused spectrum utilisation step is divided into two stages. First, the empty PRs will be allocated to the *inner user* of a BS, which is defined by any *a* user registered to $T_{b,i}$ where $\sum_{c=1}^{B_i} \zeta_{\mathbf{B},i}(a,c) = 0$ for $c \neq b$. The PRs will be allocated into $\mathcal{A}_{\mathbf{B},i}(a,n)$ with PRs at any $n = 1, \ldots, N_i$ and $i = 1, \ldots, I \mid \Theta_{\mathbf{B},i}(a,n) = 0$. After allocation, update $\Theta_{\mathbf{B},i}$, $\mathcal{P}_{\mathbf{B},i}$ and Φ_i using Algorithm 4.3. Second, repeat step 2 until the PR allocation indicator, $S_{a,i}$, equals $N_i Z_{Bi}$, where $S_{a,i}$ is given by

$$S_{a,i} = \sum_{q=1}^{Z_{Bi}} \sum_{n=1}^{N_i} \left\{ \mathcal{A}_{\mathbf{B},i}(q,n) \cup \Theta_{\mathbf{B},i}(q,n) \right\}$$
(4.16)

Remark 1: After receiving the MoC information from the BSs, the FMS computes the resource allocation for the conflicting BSs. The worst case scenario occurs when the entire network is densely packed which will require a fully central process to manage the SBSs of the entire network. Because in reality the small cells in the network will be sporadically dense, this means that these BSs could be clustered into separate groups and processed in parallel. For this reason, the FMS first groups the BSs using Algorithm 4.1. Since not all BSs are involved in the centralised resource allocation, Algorithm 4.2 is required to apply the centralised approach without disturbing the non-conflicting BSs. Finally the centralised approach is implemented using the routing algorithm to allocate the remaining PRs one at a time. This approach uses four matrices of allocation, which are the matrix of allocated PRs, the matrix of priority PRs and the matrices of entire and partial forbidden PRs. After allocating some PRs to a UE, Algorithm 4.3 is used to update the priority and forbidden matrices to prevent interference while maximising PR allocation.

4.2.3. Spectrum Utilisation by Individual Basestations



Figure 4.5.: Information feedback from the FMS

As been described previously, after computing the centralised approach for the conflicting BSs, the FMS sends the allowable PRs given by $\Lambda_{m,i}$ and temporary allocated PRs given by $\mathcal{A}_{m,i}$. These feedback information is sent to BS T_m using the message protocol shown by Figure 4.5. The reason for the two matrices have to be sent is to give all the conflicting BSs choice for scheduling while maintaining low interference power. If a BS choose to perform scheduling, $\Lambda_{m,i}$ matrix can be used. The considered information for this case will be described in detail in chapter 6.

Due to the orthogonality of the temporary allocated matrix within a BS, $\mathcal{A}_{m,i}$ information contains the information of allocated user at each PR that is encoded into D_{Z_m} bits, which is given by $D_{Z_m} = \lceil \log_2 Z_m \rceil$. The binary information at n^{th} PR by the FMS is given by

$$b_{n} = \begin{cases} b \{ \arg \max_{z:z \in Z_{m}} \mathcal{A}_{m,i}(z,n) \} , & \sum_{z=1}^{Z_{m}} \mathcal{A}_{m,i}(z,n) > 0 \\ b \{0\} , & \sum_{z=1}^{Z_{m}} \mathcal{A}_{m,i}(z,n) \sim 0 \end{cases}$$
(4.17)

where $b\{x\}$ means the D_{Z_m} bits binary equivalent of x. In addition, $\Lambda_{m,i}$ information simply transmit the binary map for each user in series every N_i bits.

4.3. Performance Analysis

4.3.1. The Received SINR Model

For better clarity, lets first begin by considering a homogeneous WiMAX cellular network containing only ad hoc pico- and femto- cells networks, then this will be extended to HetNets. This means, the PR as a subcarrier is being considered here. Assuming PRs group, I, equals 1 and no adaptive power control is employed in the BS, it can be easily shown that the received signal-to-interference and noise ratio (SINR) using the proposed algorithm at a UE, u_z , which is served by T_m , and n^{th} subcarrier, $\psi_{u_z}(n)$, is given by

$$\psi_{u_{z}}(n) = \frac{\mathbf{E}_{m,t}(z)}{\mathcal{N}_{0} + \sum_{c=1}^{M} \mathbf{E}_{C_{m,t}}(z,c) \, b_{cu_{z}}}, \qquad c \neq m$$
(4.18)

where \mathcal{N}_0 is the additive white Gaussian noise (AWGN), $\mathbf{E}_{C_m,t}(z,c)$ is the interference power from T_c to u_z and $\mathbf{E}_{m,t}(z)$ is the received signal power from T_m . b_{cuz} is a binary multiplier required in Equation 4.18 because as mentioned in section 4.2, user u_z is one of the detected users of BS T_c and is therefore forbidden to share the same subcarrier with any of the users in this BS if $\mathbf{E}_{C_m,t}(z,c) \geq \mathbf{E}_{m,t}(z,i)/\gamma_{th}$. This means, BS T_c only causes interference to u_z at the n^{th} subcarrier if the interference from this BS is lower than the threshold. This is simply because in this case T_c will be allowed, by the global MoC, to use the subcarrier as user u_z . Therefore b_{cu_z} is given by

$$b_{cu_z} = \begin{cases} 1 & \mathbf{E}_{C_m,t}(z,c) < \frac{\mathbf{E}_{m,t}(z)}{\gamma_{th}} \\ 0 & \text{otherwise} \end{cases}$$
(4.19)

If the distance between T_m and u_z is given by d_{mu_z} with the maximum distance of d_{MAX} , the distance between T_c and u_z is given by d_{cu_z} , and an indoor environment with path loss exponent η is assumed, then the path loss between T_m and u_z , α_{mu_z} , is given by

$$\alpha_{mu_z} = \left(\frac{4\pi}{\lambda}\right)^2 (d_{mu_z})^\eta \tag{4.20}$$

where $1 < d_{mu_z} < d_{MAX}$ and between T_c and u_z , α_{cu_z} , is given by

$$\alpha_{cu_z} = \left(\frac{4\pi}{\lambda}\right)^2 (d_{cu_z})^\eta \tag{4.21}$$

If we assume T_m and T_c transmit the same power level, P_t , and $\mathbf{E}_{C_m,t}(z,c) = \frac{P_t}{\alpha_{cuz}}$ and $\mathbf{E}_{m,t}(z) = \frac{P_t}{\alpha_{muz}}$, this means

$$b_{cu_z} = \begin{cases} 1, & 0 < \frac{\alpha_{mu_z}}{\alpha_{cu_z}} < \frac{1}{\gamma_{th}} \\ 0 & \frac{1}{\gamma_{th}} \le \frac{\alpha_{mu_z}}{\alpha_{cu_z}} \le 1 \end{cases}$$
(4.22)

and can be simplified into

$$b_{cu_z} = \begin{cases} 1, & 0 < \left(\frac{d_{mu_z}}{d_{cu_z}}\right)^{\eta} < \frac{1}{\gamma_{th}} \\ 0 & \frac{1}{\gamma_{th}} \le \left(\frac{d_{mu_z}}{d_{cu_z}}\right)^{\eta} \le 1 \end{cases}$$
(4.23)

If it is further assumed that $d_{mu_z}/d_{cu_z} = r_{mc}$ as the relative distance between u_z to T_m and T_c , so, b_{cu_z} can be simplified into

$$b_{cu_z} = \begin{cases} 1 & 0 < r_{mc} < \left(\frac{1}{\gamma_{th}}\right)^{1/\eta} \\ 0 & \left(\frac{1}{\gamma_{th}}\right)^{1/\eta} \le r_{mc} \le 1 \end{cases}$$
(4.24)

4.3.2. Relative Distance Analysis

As can be seen above, the relative distance between a UE and its neighboring BSs, r_{mc} , affects the received SINR and number of detected users by BS T_m . The PDF of r_{mc} will be analysed in here and used in the analysis presented in subsection 4.3.3 - subsection 4.3.5.

Assumption 1: We assume that the SBSs are uniformly distributed across an $l \times l$ area and users are uniformly distributed around a circle of T_m radius, with a maximum radius of $d_{MAX} \ll l$.



Figure 4.6.: PDF of the femtocell networks in l by l area

Lemma 1. The PDF of r_{mc} based on Assumption 1 is given by

$$f_{R_{MC}}(r_{mc}) = \begin{cases} \frac{4l}{3d_{MAX}} \arcsin(1) + \frac{4l}{10d_{MAX}} - 2\frac{l}{d_{MAX}}, & 0 < r_{mc} < \frac{d_{MAX}}{l} \\ \frac{4d_{MAX}^2}{3l^2 r_{mc}^3} \arcsin(1) + \frac{4d_{MAX}^4}{10l^4 r_{mc}^5} - \frac{2d_{MAX}^3}{l^3 r_{mc}^4}, & r_{mc} \ge \frac{d_{MAX}}{l} \end{cases}$$
(4.25)

Proof: See Appendix C.

4.3.3. Resource Utilisation Ratio

The minimum capacity of the femtocells' users within an $l \times l$ area can be analysed using the lower bound of the number of subcarriers per user, J_m .

Assumption 2: We assume there are M_a number of SBSs, which have a similar number of UEs, Z_m .

Lemma 2. Using Lemma 1, the number of subcarriers per user of T_m is lower bounded by

$$J_m > \frac{N}{Z_m \left[1 + (M_a - 1) \left\{ 1 - F_{R_{MC}} \left(\left(\frac{1}{\gamma_{th}} \right)^{1/\eta} \right) \right\} \right]}.$$
 (4.26)

Proof: Number of subcarriers per user of T_m 's UE is given by $J_m = N/S_m$. Since any user will be detected by T_m if $\left(\frac{1}{\gamma_{th}}\right)^{1/\eta} \leq r_{mc} \leq 1$, S_m based on Assumption 2 is upper bounded by

$$S_m < Z_m \left[1 + (M_a - 1) \Pr\left(\left(\frac{1}{\gamma_{th}}\right)^{1/\eta} \le r_{mc} \le 1 \right) \right]$$

$$(4.27)$$

which can be re-written as

$$S_m < Z_m \left[1 + (M_a - 1) \left\{ 1 - F_{R_{MC}} \left(\left(\frac{1}{\gamma_{th}} \right)^{1/\eta} \right) \right\} \right]$$

$$(4.28)$$

where $F_{R_{MC}}(r_{mc})$ is the cumulative distribution function of $f_{R_{MC}}(r_{mc})$ shown in Lemma 1.

With Assumption 2 and Lemma 2, the allocated resource to BS T_m , is given by

$$N_m = J_m Z_m \tag{4.29}$$

Therefore, N_m is lower bounded by

$$N_m > \frac{N}{1 + (M_a - 1) \left\{ 1 - F_{R_{MC}} \left(\left(\frac{1}{\gamma_{th}} \right)^{1/\eta} \right) \right\}}.$$
(4.30)



Figure 4.7.: Impact of γ_{th} values to the lower bound resource utilisation ratio.

4.3.4. Minimum Capacity Analysis

Assumption 3: It is assumed an AWGN channel and Shannon capacity and that the maximum interference from a BS is given by $E_{i_{max}} = \mathbf{E}_{m,t}(z) / \gamma_{th}$ and the minimum significant interference from a BS is given by $E_{i_{min}} = \mathbf{E}_{m,t}(z) / 100\gamma_{th}$.

Lemma 3. Minimum data rate can be approximated based on Equation 4.34 by

$$v_{min} \approx \frac{NW_f \log_2 \left(1 + \frac{\mathbf{E}_{m,t}(z)}{E_{i_{max}} B_{u_z}}\right)}{Z_m \left[1 + (M_a - 1) \left\{1 - F_{R_{MC}} \left(\left(\frac{1}{\gamma_{th}}\right)^{1/\eta}\right)\right\}\right]}.$$
(4.31)

Proof: Using Assumption 3, the data rate of T_m 's UE is lower bounded by

$$v_{u_z} > J_m W_f \log_2 \left(1 + \psi_{u_z} \right) \tag{4.32}$$

where W_f is the bandwidth per subcarriers, ψ_{u_z} is the SINR of u_z . Based on Equation 4.32, the minimum data rate UE is the one with the lowest limit of J_m , which is approximated by

$$J_{low} \approx \frac{N}{Z_m \left[1 + (M_a - 1) \left\{ 1 - F_{R_{MC}} \left((1/\gamma_{th})^{1/\eta} \right) \right\} \right]}$$
(4.33)

and receive minimum possible SINR value denoted by ψ_{min} . So, the minimum data rate is approximated by

$$v_{min} \approx J_{low} W_f \log_2 \left(1 + \psi_{min} \right). \tag{4.34}$$

If $\mathbf{E}_{C_m,t}(z,c) \gg \mathcal{N}_o, \psi_{u_z}$ is given by

$$\psi_{u_z} = \frac{\mathbf{E}_{m,t}\left(z\right)}{E_{int}} \tag{4.35}$$

where E_{int} is the total interference power received by u_z and given by

$$E_{int} = \sum_{c=1}^{M_a} \mathbf{E}_{C_m,t}(z,c) \, b_{cu_z}, \qquad c \neq m.$$
(4.36)

Using $F_{R_{MC}}(r_{mc})$, the total interfering SBSs, B_{u_z} , is given by

$$B_{u_z} = (M_a - 1) F_{R_{MC}} \left(\left(\frac{1}{\gamma_{th}} \right)^{1/\eta} \right).$$
 (4.37)

If we consider that the maximum and minimum interference based on Assumption 3, then B_{u_z} will be

$$B_{u_z} = (M_a - 1) \left\{ F_{R_{MC}} \left(\left(\frac{E_{mu_z}}{\gamma_{th}} \right)^{1/\eta} \right) - F_{R_{MC}} \left(\left(\frac{E_{mu_z}}{100\gamma_{th}} \right)^{1/\eta} \right) \right\}.$$
(4.38)

The minimum SINR occurs when all B_{u_z} BSs interferes u_z with the same amount of interference power. Therefore,

$$\psi_{min} = \mathbf{E}_{m,t}\left(z\right) / \left(E_{i_{max}}B_{u_z}\right) \tag{4.39}$$

4.3.5. Practicality Analysis

The practicality of the proposed technique can be analysed by assessing the amount of data for information exchange between the BSs and the FMS, the computational effort by the FMS to resolve the interference and the latency requirement.

A) Information exchange between BSs and the FMS

The total information exchange between BSs and the FMS is given by

$$D_m = D_{T_m} + D_{f_m} (4.40)$$

where D_{T_m} is the total number of bits required by T_m to forward the MoC to the FMS based on Figure 4.3 described earlier, and D_{f_m} is the total number of bits required by the FMS to feedback the allocated matrix information. This feedback contains the information of allocated user at each subcarrier that is encoded into D_{Z_m} bits, which is given by $D_{Z_m} = \lceil \log_2 Z_m \rceil$. If there is no user allocated at a particular subcarrier, then the D_{Z_m} bits will be zeros.

If we assume BS T_m has Z_m users and C_m neighbouring BSs, D_{T_m} based on Figure 4.3 is given by

$$D_{T_m} = (D_{IP} + Z_m D_{MoC} I) C_m + D_{he} + D_t$$
(4.41)

where D_{MoC} is the number of bits to code the local MoC by each BS, D_{IP} is the number of IP address bits and D_{he} and D_t are the header and tail bits, respectively, used to distinguish the MoC information exchange from other data transmission. Due to its simplicity, the MoC can be coded into a binary number. Hence, $D_{MoC} = 1$. On the other hand, D_{f_m} is given by

$$D_{f_m} = D_{he} + D_t + D_{Z_m} N + Z_m N (4.42)$$

For example, in the case of a system with I = 2, $Z_m = 4$ and $C_m = 6$, the available number of subcarriers, N, is 1000, $D_{he} = D_F = 64$ bits and the IPv6 standard in which $D_{IP} = 128$ bits, $D_{T_m} = 944$ bits and $D_{f_m} = 7.128$ kilobits. Therefore, the total bit exchange between this BS and the FMS is 8.072 kilobits. This information only needs to be updated occasionally only when the average received power changes by a certain amount as determined by the selected threshold. In contrast, in the case of the conventional centralised scheme that requires D_{m_c} bits exchange between the BSs and central node, which is given by

$$D_{m_c} = Z_m N D_{N_c} + D_{he} + D_F (4.43)$$

where D_{N_c} is the number of bits required to encode each subcarrier's SINR information that has a typical value of four bits, the total bits exchange between a BS and the central node equals 16.128 kilobits. This information needs to be updated frequently, compared to the proposed technique, since small scale fading, which plays an important role in influencing the SINR per subcarrier, may be changing rapidly over small distances, at least every half wavelength. This example shows that the proposed technique requires a relatively negligible amount of information exchange with the FMS.

B) Computational effort analysis

Since the proposed technique involves an iterative process for utilising subcarriers that are not assigned in the first iteration, the complexity increases as a function of the number of iterations. To assess this lets consider the following with Assumption 2.

 T_m 's UEs will be allocated with N_m subcarriers in each, which is lower bounded in Equation 4.30. If we assume M_a SBSs, which randomly exist within an l by larea, form a group \mathbb{V}_k , the priority subcarriers matrix, P_B , will ensure the same subcarriers will be allocated to more than one UEs with different BSs. In the best scenario, within each iteration, all M_a SBSs' UEs are allocated with the same subset of subcarriers. For this reason, the performance of the proposed technique converges to the \mathcal{O}^{th} iteration, which can be approximated by

$$\mathcal{O} \approx \left\lfloor o + \frac{N}{N_{m_l}} \right\rfloor \tag{4.44}$$

$$o = \begin{cases} 1, \quad \lfloor N/N_{m_l} \rfloor = 1\\ 0, \quad \text{otherwise} \end{cases}$$
(4.45)

where N_{m_l} is the lowest limit of N_m , which is approximated by

$$N_{m_l} \approx \frac{N}{1 + (M_a - 1) \left\{ 1 - F_{R_{MC}} \left(\left(\frac{1}{\gamma_{th}} \right)^{1/\eta} \right) \right\}}$$
(4.46)

and o is a constant required due to the fact that the proposed technique requires one repetition in order to double check the subcarrier allocation.

C) Latency Analysis

The timing protocols required for the proposed MoC SON RRM is shown in Figure 4.8. The latency that needs to be considered includes measurement report collection, t_{mr} ,



Figure 4.8.: MoC based SON RRM Time Protocol

and waiting periods to get the solution from the FMS which is given by

$$t_{moc} = 4t_{ip} + t_w + t_{comp} \tag{4.47}$$

where t_{ip} is period taken by a data to be transported between a BS to the FMS, t_w is the waiting period taken by the FMS after receiving an interrupt from BS as described in Figure 4.2 and t_{comp} is the computational period taken by the FMS to solve the resource allocation.

If it is assumed that $t_{ip} = 4$ ms, $t_w = 8$ ms and $t_{comp} = 2$ ms, so $t_{moc} = 26$ ms. However, the latency required to get the measurement report is slightly harder to predict compared to t_{moc} since there are two types of MRs, which are periodic and event triggered [105]. In both cases, each UE continuously measures the RSSP and RSSI every 150 ms [105]. If periodic reporting is chosen, UE sends the measurement report every 300 ms or 3 s [105]. On the other hand, in the case of event triggered, UE sends the information if the RSSP and RSSI changes based on certain threshold, set using RRC protocol. For this reason, the latency required to get this information takes between 0 and 150 ms. Therefore, it can be concluded that the latency of the proposed RRM takes between 26 ms and 176 ms.

4.4. Summary

This chapter proposes a novel hybrid RRM algorithm incorporating a new conflict paradigm to improve the performance of heterogeneous cellular networks. The conflicts between one BS and the surrounding UEs are tracked using a unique interference mapping in a form of matrix of conflict (MoC). There are two MoCs exist within a HetNet, which are local and global MoCs. A local MoC is the interference map within each BS while the global MoC is the combination of the local MoCs from all BSs. The BSs monitor their local MoCs periodically and submit their updates to the FMS whenever they are changed or requested by the FMS. When a BS submits its map, using a routing algorithm to check with the global MoC, the FMS will decide whether this BS can use a part of or the entire spectrum. If partial spectrum is applied, the FMS applies a set of rule based on DVRP routing algorithm for spectrum allocation. The spectrum allocation rules are:

- 1. grouping the small cells
- 2. passing the entire networks parameters
- 3. measuring queuing criterion
- 4. initial frequency allocation
- 5. underused spectrum utilisation

5. RRM Evaluation in Interfering 4G Cellular Networks

In this chapter, the performance of the proposed technique will be evaluated. There are two types of simulations that is observed, which are Homogeneous Networks (HoNet) and Heterogeneous network (HetNet). These observations consider the impact of the proposed RRM in WiMAX and LTE systems. The HoNet evaluation will show the ability of the proposed technique in a femtocell networks while the HetNet simulation gives the ability of the proposed technique as a method that can be implemented as general basestation (BS).

The simulation in this chapter will be focused on two main aspects, which are data rate performance and energy aspects. The data rate performance aspect will evaluate the capability of the proposed technique in satisfying the basic requirement of cellular networks. This includes the sum or the average data rate and the quality of service (QoS). The QoS can be explored by measuring the minimum data rate of various resource allocations of each simulation trial. In this chapter, this is called guaranteed data rate.

The energy aspect will describe the ability of the proposed technique in supporting green communication network. As been mentioned previously, the proposed technique adaptively vary the resource utilisation depending on the environment. Since the number of allocated subcarriers affects the total transmitted power, so the radio frequency (RF) components power consumption is also affected. Furthermore, the energy aspect of cellular network will also measures the energy efficiency of a cellular network, which is defined by the ratio of total power consumption to perform downlink transmission with the achievable data rate. Therefore, the energy aspect will simulate the RF component power consumption and energy efficiency of the cellular network. This chapter is organised as follows. As been analysed in previous chapter, SIR threshold, γ_{th} , affects the performance of the proposed technique. For this reason, this value is considered first. After that, the capability of the proposed technique in basic HoNet system is evaluated in section 5.2. Then, the HetNet performance is discussed in section 5.3. Finally, this chapter is summarised in section 5.4.

5.1. Impact of SIR Threshold



Figure 5.1.: HoNet Simulation illustration.

Table 5.1.: General HoNet Simulation Parameter
--

Parameter	Value	Parameter	Value
Carrier (f_c)	2.3 GHz	Modulation	BPSK,QPSK,
			16-64
			256-QAM
Small-scale	Rayleigh	Delay spread, τ	10% of OFDM
fading channel			symbols
Noise density (σ)	-174 dBm/Hz	SBS EIRP	100 mW
Pathloss model	PL[dB] =	$20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\beta$	$\log_{10}\left(d\right) + X_{\sigma}$
Pathloss	3	Shadowing, X_{σ}	8
exponent, β			

As shown in the analysis in previous chapter, the SIR threshold, γ_{th} , affects the guaranteed capacity of a UE and the complexity within a homogeneous network.

Parameter	Value	Parameter	Value
Number of	256	OFDM	$2 \times 10^{-4} s$
subcarriers		period, T_O	
(N_H)			
Bandwidth	10.94 kHz	Subcarrier	Distributed
per		permutations	pseudo-
subcarrier,			random
W_f			

 Table 5.2.: WiMAX HoNet Simulation Parameters



Figure 5.2.: γ_{th} impact on the guaranteed capacity to a two UEs per BS system

For this reason, this section will focus on the performance of homogeneous network containing only pico- and femto- cells in a 60 by 60 meter square area with various γ_{th} values. The rest of the simulation parameters are shown in the Table 5.1 and Table 5.2 with the exception of no small-scale fading channel where EIRP is the equivalent isotropically radiated power. The Shannon capacity formula is used instead of adaptive modulation in order to calculate the lower-bounded capacity. Based on guaranteed capacity experiment, the γ_{th} will be assessed. After that, the complexity regarding the iterations number will be evaluated.

Table 5.3.: Analytical value of the convergence point

Convergence Point	$\gamma_{th}=20 \text{ dB}$	$\gamma_{th} = 25 \text{ dB}$
\mathcal{O}_6	2	3
\mathcal{O}_{11}	4	6



Figure 5.3.: γ_{th} impact on the guaranteed capacity to a four UEs per BS system

Figure 5.2 and Figure 5.3 show that the simulation and analytical results match which supports the validity of the analysis presented in previous chapter. This figure shows that as γ_{th} increases, the guaranteed capacity improves. This indicates that increasing γ_{th} results in improving the QoS of the cellular network. Both, Figure 5.2 and Figure 5.3 also show that as the number of SBSs increases, the impact of γ_{th} on the guaranteed capacity reduces. Since Figure 4.7 shows that increasing γ_{th} reduces the overall spectrum usage per user which reduces the overall sum rate and increases the energy efficiency. Hence, very high γ_{th} value cannot achieve both high QoS system and good energy efficiency. For this reason, it is advisable to use a middle value of γ_{th} , between 20 and 25 dB, in order to reach a satisfactory compromise of QoS and overall users data rate.

After finding the γ_{th} value that achieves a good compromise between QoS and energy efficiency, the complexity of the proposed technique can be assessed. The complexity is evaluated by varying the maximum number of iterations with the sum rate and subcarriers allocation ratios. The sum rate ratio is defined as the ratio between the sum rate at a given iteration number with the achievable sum rate at an unlimited iteration number. Similarly, the subcarriers allocation ratio is the total allocated subcarriers at a given iteration number compared to the maximum possible number of allocated subcarriers. For simplicity, γ_{th} was selected to be 20 dB and 25 dB and the cases of 6 and 11 BSs will be evaluated. The analytical approximation of the convergence point is shown in Table 5.3 and the simulation results are shown in Figure 5.4.



Figure 5.4.: SIR threshold impact on the complexity. (a) Subcarriers allocation ratio. (b) Sum rate ratio.

Figure 5.4 shows that the proposed technique requires a small number of iterations. Even with only one iteration, the proposed technique is able to allocate 88% of the subcarriers and provides 93% of achievable sum rate. Furthermore, Table 5.3 and Figure 5.4 show that increasing γ_{th} value increases the convergence point, which indicates increasing complexity. It is shown that the analytical value is close to the simulation case at the 99% ratio values. Even though Figure 5.4 (b) shows that the 99% of 6 BSs at $\gamma_{th} = 20$ dB is achieved in 1 iteration, because Equation 4.44 requires at least one repetition, this means the convergence point in this case is 2 iterations. Therefore, overall the complexity increase, due to the iterative process, is limited as convergence is quickly achieved within a handful of iterations as can be seen from these figures and Table 5.3.

Parameter	Value	Parameter	Value
Number of	256	Frame period,	$20 \times 10^{-3} s$
FFT points		T_F ,	
(N_{FFT})			
Bandwidth	$15 \mathrm{~kHz}$	OFDM	$1.43 \times 10^{-4} \text{ s}$
per		period, T_O	
subcarrier,			
W_f ,			
Number of	12	Number of	12
RBs per		subcarriers	
subframe		per RB	
Total	10	Total OFDM	14
subframes per		symbols per	
frame		subframe	

 Table 5.4.: LTE HoNet Simulation Parameters

5.2. HoNet Simulation

In this section, the impact of the proposed technique in the absence of MBS, which is possible in the FFR and spectrum partition between small cells and MBS systems, will be evaluated. As been mentioned earlier, there are four parameters that will be observed in this section, which are average data rate, QoS, RF power consumption and energy efficiency.

Varying the number of femtocells will be randomly placed uniformly around 60 m \times 60 m area in an indoor path loss environment, which is shown in chapter 2. Users will be placed around the HNBs with uniform random distribution and radius of 10 m. By doing so, the behaviour of the proposed technique under various densities can be explored. In addition, single omnidirectional antenna HNB system with maximum equivalent isotropically radiated power (EIRP) of 20 mW, no power control and forward error correction is incorporated in this simulation. Furthermore, the performance of the proposed technique with two and four users per BS will be shown in this section. Two users per BS represents a scenario of small family while the four users per BS represents the cellular networks in a denser population per square meter such as university students house.

An adaptive MQAM modulation at the n^{th} subcarrier such that the bit error rate (BER), $P_b(n)$, is lower than 10^{-6} is used to measure the achievable data rate at

the n^{th} subcarrier. Therefore, the discrete capacity at the n^{th} subcarrier, $C_{dis}(n)$, is given by

$$C_{dis}(n) = \kappa(n) - \Xi_q \left(P_s(n) \right) \tag{5.1}$$

where $\kappa(n)$ and $P_s(n)$ are the number of bits and symbol error rate at the n^{th} subcarrier respectively [99]. $P_s(n)$ is given by

$$P_s(n) = \kappa(n)P_b(n) \tag{5.2}$$

and $\Xi_q(P_s(n))$ is the equivocation of the symbol at a given $P_s(n)$, given by [99]

$$\Xi_q \left(P_s(n) \right) = -P_s(n) \log_2 \left(\frac{P_s(n)}{2^{\kappa(n)} - 1} \right) - \left(1 - P_s(n) \right) \log_2 \left(1 - P_s(n) \right).$$
(5.3)

Using Equation 5.1, the achievable data rate at the n^{th} subcarrier is given by

$$R(n) = \frac{C_{dis}(n)}{T_O} \tag{5.4}$$

In order to measure the ECR of the system, the power consumption model of m^{th} SBS required to perform downlink transmission can be modeled as

$$P_{DLm} = \frac{P_{RF} + P_{SP}}{\mu_{PS}} \tag{5.5}$$

where P_{RF} is the RF component power consumption, P_{SP} is the signal processing power used by the SBS hardware to compute the downlink signal transmission and μ_{PS} is the power supply efficiency. P_{RF} is given by

$$P_{RF} = \frac{P_{TXm}}{\mu_{PA}} \tag{5.6}$$

where μ_{PA} is the power amplifier efficiency of the RF component and P_{TXm} is the transmitted signal power of the m^{th} SBS. μ_{PA} and μ_{PS} are assumed to be 20% and 85%, respectively [107]. [108] shows that the total power consumption of the SBS hardware, which is used to compute the downlink and the uplink transmissions is approximately similar to Pico BS, about 6.7 W. Since the signal processing power of the downlink and uplink is almost identical, in this simulation $P_{SP} = 3.35$ W. Therefore, the ECR for the m^{th} SBS, ECR_m is related to the m^{th} SBS total data rate, R_m , by

$$ECR_m = P_{DLm}/R_m. ag{5.7}$$

Because conflicting BSs are closely determined by the γ_{th} values, two γ_{th} values that will be observed in this simulation, which are 20 and 25 dB. For reference sake, the results are compared with random assignment, distributed RRM using self organisation RRM [26], basic and dynamic coloured graph (CG) SON RRMs [93]. Since self organisation RRM requires several iterations before the minimum interference for all users is achieved, this simulation will consider one, two and ten iterations for comparison. Furthermore, the basic CG SON RRM will be allowed to utilise N/4 PRs per BS while the dynamic CG SON RRM will have N/4 and N/8initial PRs per BS. The rest of the simulation parameter is shown in Table 5.1 and Table 5.2 and Table 5.4 for WiMAX and LTE systems, respectively.

5.2.1. Average Rate

Figure 5.5 and Figure 5.6 show that the proposed technique is capable of providing average data rate improvement in various femtocell densities and systems. The improvement in comparison to random assignment reduces as the number of users per femtocell reduces because the probability of users receiving interference as the number of users per femtocell increases. In the case of four users per femtocell, the performance gap increases as the number of femtocells within a 60 m by 60 m area increases. Furthermore, these figures also display that rising γ_{th} reduces the data rate of the proposed technique as a result of resource allocation reduction as shown in Figure 4.7 in previous chapter.

It is shown by Figure 5.5 and Figure 5.6 that the performance of the random assignment outperforms the self organisation RRM and CG SON RRMs. For instance, self organisation RRM only achieves better performance than the random assignment when WiMAX system is used and there are four users per femtocell. This occurs because these RRMs utilises a fixed partial available PRs and the SINR improvement achieved by them at each PR do not translate into increasing bits because of maximum modulation order, which in here is assumed to be 256QAM or 8 bits



Figure 5.5.: Average data rate with four users per femtocell. (a) is WiMAX system and (b) is LTE system.

per subcarrier. This does not occur in the case of the proposed technique because of the ability of the proposed technique to adapt the utilised PRs based on the environment.

Dynamic CG SON RRM is shown by Figure 5.5 and Figure 5.6 is capable to achieve better performance than the basic CG SON RRM because the dynamic CG allows more spectrum to be utilised beyond the basic available PRs. Smaller initial colouring value increases the overall resource utilisation, which is indicated by increasing data rate performance of the dynamic CG SON RRM. Comparing the relative performance of the dynamic CG and other RRMs shows that the dynamic CG works better at low number of users per femtocell. This is because in high number of users



Figure 5.6.: Average data rate with two users per femtocell. (a) is WiMAX system and (b) is LTE system.

per femtocell raises the chance of a BS to be connected with the neighbouring BS and eventually reduces the resource utilisation of the entire network.

It is important to observe that the self organisation RRM performance in WiMAX system is better than in the LTE systems. This happens because this technique works by utilising half of the available resource within each OFDM symbols. Since in the LTE system each user can only utilise the resource in one or more block of 12 subcarriers rather than pseudo random interleaving, this reduces the degree of freedom achieved by the distributed RRM. On the other hand, SON RRMs are assigned with the RBs within one frame of transmission from the central node. By having a pseudo random RB allocation within one frame, similar impact with

pseudo random subcarrier interleaving in WiMAX system is achieved. Hence, the SON RRMs has the same behaviour in the WiMAX and LTE systems.



5.2.2. Guaranteed Rate

Figure 5.7.: Guaranteed rate with four users per femtocell. (a) is WiMAX system and (b) is LTE system.

Besides providing average data rate improvement, the proposed technique increases the QoS of HoNet compared to other RRMs. As can be seen from Figure 5.7 and Figure 5.8, the MoC based approach achieves the highest guaranteed rate. Different with the WiMAX system results shown in Figure 5.5 (a) and Figure 5.6 (a), the self organisation RRM in WiMAX system attains improved guaranteed data rate compared to the random assignment at all number of femtocells. On the other hand,



Figure 5.8.: Guaranteed rate with two users per femtocell. (a) is WiMAX system and (b) is LTE system.

the performance of this RRM in the LTE system only achieved better performance than the random assignment in the case of two users per femtocell. This happens due to the same reason described in subsection 5.2.1, which is lack of maneuverability for this RRM in the LTE system compared to the WiMAX system. Furthermore, the coloured graph SON RRM achieves QoS improvement only at low number of femtocells in both WiMAX and LTE systems, which are eight and 10 in the case of four and two users per femtocell, respectively. This happens because this approach utilises only a small number of PRs and the energy sensing is performed on the BS rather than the users, which is not not an accurate representation of the actual downlink interference.

Unlike the average data rate results, the guaranteed data rate of the system im-

proves as γ_{th} increases. This happens because as the threshold increases, the proposed technique becomes much more sensitive with the interference from surrounding femtocells. Hence, users in the cell edge become well protected from surrounding interference and QoS for all users can be improved.

Opposite with the data rate performance, reducing the initial colouring value reduces the guaranteed rate of the system. This is because after initial resource allocation for the connected BSs, the FMS allocate the rest of the resource such that the resource allocation is maximised. This means allocating the rest of the resource to the BS that has minimum number of connected neighbouring BSs. Hence, BSs with the maximum number of connected BSs will not be allocated more than the initial allocated resource in the next step and achieve the minimum performance.

5.2.3. RF Power Consumption

Figure 5.9 and Figure 5.10 show the power consumption of the RF component of a HNB in a varying number of femtocell. Both figures show that as the γ_{th} value increases, the RF component power consumption of the proposed technique reduces. This is because the proposed technique becomes much more sensitive with the interference from the surrounding femtocells. In order to avoid this interference, less subcarriers will be utilised by each HNB and reduces the power consumption. On the other hand, the number of iterations in the self organisation approach do not have any impact on the power consumption because the iteration only affect the allocation of a fix number of subcarriers.

Basic CG SON RRM consumes the least amount of RF component because this RRM uses a fix number of subcarriers, which are less than the proposed RRM. On the other hand, RF components of the dynamic SON RRMs only consume less power than the proposed RRM at four users per femtocell because at this number of users the probability of a BS's users interfered by its neighbouring BSs is higher than at two users per femtocell and limits the resource utilisation. This reduces the RF components power consumption with a price of poor achievable data rate as shown by Figure 5.5 - Figure 5.8.



Figure 5.9.: RF power consumption with four users per femtocell. (a) is WiMAX system and (b) is LTE system.

5.2.4. Energy Efficiency

The proposed RRM is shown to provide an energy efficient femtocell networks as shown by Figure 5.11 and Figure 5.12. These figures show that the proposed technique achieves the lowest energy to transmit 1 bit transmission. Although the coloured graph SON RRMs achieves lower RF power consumption in comparison to the proposed technique, which are shown by Figure 5.9 and Figure 5.10, this reduction is not sufficient to achieve efficient energy consumption ratio. This is because $P_{SP} = 3.35$ W, which means large power saving on the RF component becomes insufficient to reduce the energy consumption ratio of the system. Clearly, the systems that achieve the highest data rate without a significant increase on the RF



Figure 5.10.: RF power consumption with two users per femtocell. (a) is WiMAX system and (b) is LTE system.

component power consumption achieve the most efficient energy per transmitted bit.

Similar with the trend with Figure 5.5 and Figure 5.6, as the number of SBSs increases, the energy efficiency gap improves with the other subcarriers allocation techniques. This happens because as the number of SBSs increases, the proposed technique maintains the data rate improvement and the RF power consumption reduction while the other frequency allocation techniques suffer from data rate reduction and increased transmitted power due to increased interference energy received by each user as the number of SBS increases.



Figure 5.11.: Energy efficiency with four users per femtocell. (a) is WiMAX system and (b) is LTE system.

5.3. HetNet Simulation

After observing the performance of the proposed technique under HoNet environment, in this section the impact of the proposed technique on general HetNet system is evaluated. There are two frequency reuse pattern that will be evaluated in this section, which are FFR and SFR. Compare the FFR and SFR in terms of impact to SBSs spectrum allocation and their performance.

The simulation will be focused on the performance of 20 UEs with five SBSs inside a 60 m by 60 m building and 10 UEs outside the building close to an MBS illustrated in Figure 5.13. Besides these 30 UEs, there are 60 UEs registered as inner users and 20 UEs registered as outer users of the macrocell with the minimum distance


Figure 5.12.: Energy efficiency with two users per femtocell. (a) is WiMAX system and (b) is LTE system.

between these UEs and MBS of 100 m. In this simulation, a macrocell's UE will be categorised as an inner user if the received signal for inner user signal transmission is higher than 20 dB above the noise power. Otherwise, this UE will be categorised as outer user. As can be seen from Equation 5.5, P_{SP} contributes heavily to the overall energy efficiency performance. Since the P_{SP} of MBS is much higher than the P_{TX} due to the requirement for a cooling system [107]. For this reason, energy efficiency evaluation for cross-tier interference is focused on average data rate performance. Therefore, this section will consider average data rate performance and QoS results as performance comparison.

In this section, it is assumed that all BSs are equipped with two transmit antennas space-time-block-code (STBC). If we assume a simple scenario in Figure 5.14, the



Figure 5.13.: HetNet Simulation illustration.



Figure 5.14.: STBC PHY layer illustration

received signal at u_1 , which is served by F_1 and interfered by F_2 is given by

$$\begin{bmatrix} y_{11} \\ y_{21}^* \end{bmatrix} = \sqrt{\frac{1}{\alpha_1}} \begin{bmatrix} h_{11} & h_{21} \\ -h_{21}^* & h_{11}^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} + \sqrt{\frac{1}{\alpha_i}} \begin{bmatrix} h_{11i} & h_{21i} \\ -h_{21i}^* & h_{11i}^* \end{bmatrix} \begin{bmatrix} x_{12} \\ x_{22} \end{bmatrix}$$
(5.8)

where h_{11} and h_{21} are small-scale fading channel between F_1 and u_1 , h_{11i} and h_{21i} are small-scale fading channel between the interfering BS, F_2 , to the u_1 and α_1 and α_{1i} are the pathloss between the serving and interfering BSs to the user, respectively. If it is assumed that both BSs transmit similar power from each antenna given by $P_t/2$, the received power and the interference power before inverse channel detection can be modeled by

$$E_s = \frac{1}{\alpha_1} \left(|h_{11}|^2 + |h_{21}|^2 \right) \frac{P_t}{2}$$
(5.9)

Parameter	Value	Parameter	Value
Frequency reuse	3	Modulation	BPSK,QPSK,
factor, F			16-64
			256-QAM
Femtocell height, h_f	2 m	Receiver height, h_u	1.75 m
Carrier f_c	$2.3~\mathrm{GHz}$	W_w	26.2 dB
Fading channel	Ricean, $k =$	Fading channel	Rayleigh
between outdoor	20 dB	between UEs & SBSs	
UEs and MBS			
MBS EIRP for inner	2 W	MBS EIRP for outer	20 W
users		users	
MBS antenna gain	13 dBi	MBS height (h_M)	30 m
SBS EIRP	100 mW	SBS antenna gain	0 dB
Noise figure	3 dB	Noise density (σ)	-174 dBm/Hz
Pathloss exponent	3	Pathloss exponent	3.5
between HNB and		between HNB and	
indoor users, η_i		outdoor users, η_o	
X_{σ_i}	8	$X_{\sigma_{\alpha}}$	3

 Table 5.5.: General HetNet Simulation Parameters

$$E_{i} = \frac{1}{\alpha_{i}} \left(|h_{1i}|^{2} + |h_{2i}|^{2} \right) \frac{P_{t}}{2}$$
(5.10)

 Table 5.6.: WiMAX HetNet Simulation Parameters

Parameter	Value	Parameter	Value
Number of	1024	OFDM period (T_O)	$2 \times 10^{-4} s$
subcarriers (N)			
Bandwidth per	10.94 kHz	Subcarrier	Distributed
subcarrier, W_f		permutations	pseudo-
			random

The propagation from MBS to UE u_z , which is given by $PL_{u_z,M}$, uses Stanford university interim (SUI) path loss model for Terrain type C [38]. So,

$$PL_{u_z,M} [dB] = Q + 10\varphi \log_{10} \left(d_{u_z,M} / 100 \right) + X_f + X_h + s + W_w$$
(5.11)

where $d_{u_z,M}$ is distance between MBS and u_z , W_r is roof attenuation, Q is given by $Q = PL(100), \varphi$ is given by

$$\varphi = 3.6 - 0.005h_M + \frac{20}{h_M} + \chi_a 0.59 \tag{5.12}$$

Parameter	Value	Parameter	Value
Number of FFT	1024	Frame period, T_F ,	$20 \times 10^{-3} s$
points (N_{FFT})			
Bandwidth per	$15 \mathrm{~kHz}$	OFDM period, T_O	$1.43 \times 10^{-4} \text{ s}$
subcarrier, W_f ,			
Number of RBs per	50	Number of	12
subframe		subcarriers per RB	
Total subframes per	10	Total OFDM	14
frame		symbols per	
		subframe	

 Table 5.7.: LTE HetNet Simulation Parameters

 X_f is given by $X_f = 6 \log_{10} \left(\frac{f_c}{2000} \right)$, X_h is given by

$$X_h = 20\log_{10}\left(\frac{2.0}{h_u}\right) \tag{5.13}$$

and s is given by

$$s = \chi_b \left(8.2 + \chi_c 1.6 \right) \tag{5.14}$$

where χ_a , χ_b and χ_c are Gaussian random variables with zero mean. On the other hand, an indoor shadowing path loss model with path loss exponent, η , of 3 and log normal shadowing, X_{σ} , of 8 dB is used to represent the signal propagation from HNB to UE u_z given by $PL_{u_z,m}$. Hence,

$$PL_{u_z,m} \left[dB \right] = \begin{cases} PL\left(d_0\right) + 10\eta_i \log_{10}\left(\frac{d_{u_z,m}}{d_0}\right) + X_{\sigma_i}, & u_z \text{ is indoor UE} \\ PL\left(d_0\right) + 10\eta_o \log_{10}\left(\frac{d_{u_z,m}}{d_0}\right) + X_{\sigma_o} + W_w, & u_z \text{ is outdoor UE} \end{cases}$$

where $d_{u_z,m}$ is the distances between u_z and HNB, T_m , W_w is the wall loss attenuation between T_m and any outdoor UEs, $PL(d_0)$ is given by

$$PL(d_0) = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) \tag{5.15}$$

 λ is the signal wavelength and $d_0 = 1$ m is the reference distance.

Similar to the homogeneous network simulation, this section considers adaptive modulation and Equation 5.1 for data rate evaluation. Furthermore, there are three γ_{th} values that will be observed in this simulation, which are 20 and 25 dB. Since self organisation RRM requires several iterations before the minimum interference for all users is achieved, this simulation will consider one, two and ten iterations for comparison. Furthermore, the coloured graph SON RRM will be allowed to utilise N/4and N/8 PRs per BS. The rest of the simulation parameter is shown in Table 5.5 for general parameters as used in [109, 110, 37] and Table 5.6 and Table 5.7 for WiMAX and LTE systems parameters, respectively.

5.3.1. Fractional Frequency Reuse



Figure 5.15.: Indoor users sum rate. (a) is WiMAX system and (b) is LTE system.

A) Sum Rate

Figure 5.15 shows that the proposed technique achieves the best sum rate in comparison to other resource allocation techniques at all building distance from MBS by at least 1.83 Mbps and 4.31 Mbps in the WiMAX and LTE systems, respectively, while the CG SON RRMs achieve the lowest performance. Similar with HoNet case, raising the γ_{th} value increases the sum rate of indoor users where the highest sum rate is achieved at $\gamma_{th} = 20$ dB. This proves that the proposed RRM adds the capability of femtocell networks to adapt with the higher tiers of the HetNets besides the same tier ability shown in HoNet case. Furthermore, the saturation level in this figure indicates that the interference signal from macrocell does not have any further impact to the indoor users.

Similar with the HoNet case, the self organisation RRM achieves a better performance in the WiMAX system compared to LTE system. This happens because of the limitation of freedom in the case of the LTE systems. However, different with the average rate performance of the HoNet scenario, Figure 5.15 (a) and (b) show that most of the RRMs achieve better performance compared to the random assignment. This happens because in this case, the users are assumed to be uniformly distributed within the building rather than around the SBSs. This creates a wider SINR profile at different users compared to the previous case. In this situation, the impact of avoiding the interference in increasing the number of bits per subcarrier to compensate the resource utilisation reduction is more significant compared to the previous case. Hence, the data rate performance of most RRMs is higher than the random assignment.

The indoor users performance improvement using the proposed technique is achieved without sacrificing the performance of outdoor sum rate, especially at the distance further than 600 m and 800m in the WiMAX and LTE systems, respectively. However, at closer distance, the proposed technique requires the MBS to reduce its resource allocation as indicated by the global MoC. The reduction of the resource allocation for the outdoor users eventually reduces the data rate of the outdoor users compared to other RRMs. Since the available PRs in the WiMAX system assumed in this observation is much larger than the assumed LTE system, the data rate reduction impact in LTE system is more significant compared to the WiMAX system. Nevertheless, since recent surveys show that around 80% of wireless transmission are originated indoor [1] and as shown in Figure 5.15 the indoor UEs enjoy at least 1.83 Mbps and 4.31 Mbps of sum rate increases in the WiMAX and LTE systems,



Figure 5.16.: Outdoor users sum rate. (a) is WiMAX system and (b) is LTE system.

respectively, compared to 43 kbps and 161 kbps of sum rate reduction experienced by outdoor UEs in the WiMAX and LTE systems, respectively, the net result indicates that on balance the proposed technique significantly increases the overall sum rate of the FFR based 4G HetNets.

B) Guaranteed Rate

Besides the sum rate improvement for indoor users, the proposed RRM significantly guarantees higher data rate for indoor users in comparison to other scheme. This is shown from Figure 5.17. As can be seen from this figure, the proposed RRM improves the guaranteed data rate by more than 150% in comparison to self organ-



Figure 5.17.: Indoor users guaranteed data rate. (a) is WiMAX system and (b) is LTE system.

isation RRM and around 25% compared to dynamic CG SON RRM. Similarly with HoNet scenario, the guaranteed data rate improves as the γ_{th} increases. This happens as a result of more sensitivity owned by users as the γ_{th} increases. Therefore, the cell edge users become more protected from interference as this threshold value increases.

Unlike the HoNet scenario, the dynamic CG SON RRM enjoys a significant improvement in comparison to other RRMs. Smaller initial coloured value provides a significant QoS improvement compared to higher coloured value. This happens because in this simulation, users and femtocells are placed uniformly around the building. This creates a uniformly distributed connected neighbouring BSs and it is



very likely all BSs have similar connection. Therefore, the maximisation step allows all BSs to be allocated in a similar chance and increases the fairness of the network.

Figure 5.18.: Outdoor users guaranteed data rate. (a) is WiMAX system and (b) is LTE system.

Almost similar pattern with the outdoor sum rate, Figure 5.18 shows that the basic CG SON RRM achieves a slightly better guaranteed data rate at the distance closer than 600 m compared to the proposed technique. This happens due to the same reason with the outdoor users sum rate performance shown by Figure 5.16, which is reduction of the MBS's users number of subcarriers. In addition, as happens in the indoor system, raising γ_{th} value increases the QoS of the outdoor users using the proposed technique. On the other hand, increasing the number of PRs per femtocell reduces the QoS of the basic CG SON RRMs. This happens because reducing the

number of PRs utilised by the femtocell weaken the cross-tier interference experienced by the outdoor users. However, this comes with the price of low indoor data rate, which is shown by Figure 5.15.

5.3.2. Soft Frequency Reuse

A) Sum Rate



Figure 5.19.: Indoor users sum rate. (a) is WiMAX system and (b) is LTE system.

Different with the FFR based system, Figure 5.19 shows that the performance of the proposed technique under SFR based system is almost flat at distance longer than 600 m. This happens because the femtocell can utilise the entire spectrum regardless the position within the MBS position. Due to its capability to adapt the HetNet environments, the proposed technique maintains a fairly similar performance at various distance from MBS. However, this figure also shows that there are sum rate reduction at the distance of closer than 600 m in both WiMAX and LTE systems. This occurs because as the building distance is closer than 600 m, the outdoor users are categorised as inner MBS's users. As the distance increases from 400 m, the signal received by the outdoor users from MBS decreases while the signal power from SBS remains the same. This increases the cross-tier interference to the outdoor users. Beyond 600 m, some of the outdoor users started to be categorised as outer users. Hence, the amount of cross-tier interference to the outdoor users remain the same as the distance increases beyond this point.

Similar with previous scenarios, increasing γ_{th} values and number of iterations increases the performance of the proposed and self organisation RRMs. In the case of coloured graph SON RRM, increasing number of utilised PRs also increases the sum rate. In addition, these figures also show that the coloured graph SON RRM gives the worst performance because this RRM uses interference reading in the BSs, which may not be an accurate representation of the actual downlink interference. The proposed technique is capable to achieve a minimum of 2.38 Mbps and 5.26 Mbps of sum rate improvement in the WiMAX and LTE systems, respectively. Bear in mind that self organisation RRM requires a full interference report for all subcarriers in order to achieve optimum performance. This type of feedback is different from the LTE standard MR and requires a special modification in order to implement. Furthermore, since multipath fading varies rapidly above 2λ distance a frequent updates are required even when the UEs move distance of less than 0.26 m. This is not the case of the proposed RRM, since the MoC is determined by the average received signal that varies slowly over distance.

The indoor sum rate gain also comes with performance improvement in comparison with other RRMs. As shown by Figure 5.20, the proposed technique only achieves a slightly worse performance compared to the N/8 PRs coloured graph SON RRM, which happens because with a minimum of resource utilisation, the cross-tier interference to the outdoor users can be minimised. In the case of LTE system, the proposed technique is still capable of providing better performance compared to N/4PRs coloured graph SON RRM. Similar with the FFR case, Figure 5.20 (a) and (b) show that the self organisation RRM achieves worse performance than the two SON



Figure 5.20.: Outdoor users sum rate. (a) is WiMAX system and (b) is LTE system.

RRMs. This happens the objective of the SBSs are to minimise the interference received by their users. In doing so, these SBSs are not aware of the presence of near by MBS's users and increases the interference received by the outdoor users.

As can be observed from Figure 5.20 (b) that in the LTE systems, different γ_{th} value gives a slight different performance to the outdoor users sum rate. Opposite to the indoor users, at $\gamma_{th} = 25$ dB increases the sum rate of the outdoor users compared to $\gamma_{th} = 20$ dB. This happens because high γ_{th} increases the sensitivity of each user to the surrounding interference. Since most of outdoor users are served by the MBS with a minimum number of available PRs compared to SBSs' users, this increasing sensitivity increases their sum rate.

B) Guaranteed Rate



Figure 5.21.: Indoor users guaranteed data rate. (a) is WiMAX system and (b) is LTE system.

Similar with the FFR based system, Figure 5.21 shows that the proposed technique provides significant guaranteed rate improvement for indoor users transmission compared to the other RRMs schemes under various distances from MBS. As can be seen from this figure, the MoC based SON RRM achieves an increase of at least more than double compared to random assignment. Furthermore, increasing γ_{th} improves the QoS of the indoor users using the proposed technique. This happens due to the same reason as been described in subsection 5.2.2, which is increasing sensitivity to the interference as γ_{th} raises.

Different with the FFR scheme, the QoS performance of the CG SON RRMs with

N/4 PRs is slightly worse than the random assignment at the closed distance to the MBS. This happens because these RRM do not measure the interference from MBS. Since MBS occupies the entire spectrum in the case of SFR, cross tier interference becomes the dominant factor in this scenario for this RRM type. As the distance increases the dynamic CG method is capable to utilise the spectrum adaptively based on the measurement from the same tier interference, which is similar behaviour with the FFR scenario case. On the other hand, since basic CG method allows BS to measures the interference that is not experienced by the UEs, the performance becomes much worse than the random assignment, especially at distance closer than 900 m. This happens due to small amount of allocated resources regardless the interference profile at the UEs.



Figure 5.22.: Outdoor users guaranteed data rate. (a) is WiMAX system and (b) is LTE system.

Figure 5.22 shows that the proposed technique achieves a slight improvement for the outdoor users. The interference power experienced by the outdoor users communicating with HNB in SFR case is higher than the FFR based system because SFR utilise the entire spectrum for MBS transmission. This increases the effect of interference avoidance scheme application. For this reason, the proposed technique is shown to achieves the best fairness in comparison to other RRMs.

5.4. Summary

This chapter has shown the performance observation of various RRMs under HoNets and HetNets scenarios in WiMAX and LTE systems. HoNet scenario examined the capability of various RRM techniques to adapt with difference networks density. On the other hand, the HetNets scenario is used to test the behaviour of femtocell RRMs in the presence of potential cross-tier interference from macrocell when the cellular company allocates the same bands between MBS and small cells.

It was shown from HoNet simulation scenario that the proposed RRM provides superior overall rate increases and QoS improvements while supporting greener communication systems in various scenarios compared to other RRMs. Furthermore, it was demonstrated that the MoC based SON RRM is also able to satisfy the increasing demand on performance improvement in HetNets environments. It was shown that the proposed algorithm is able to improve the guaranteed data rate as well as the sum rate for all users in various distances from the MBS. The performance improvement occurs in the WiMAX and LTE systems.

6. Scheduling Strategy for MoC based RRM

After receiving a set of parallel resources (PRs) from the Femto Management System (FMS) that can be used for transmission with low interference, the basestation (BS) can use the granted PRs independently from the neighbouring BSs. These resources are allocated to various user equipments (UEs) based on the certain requirements, which are maximising the sum rate and fairness for all UEs. This chapter presents the implementation example of the proposed RRM with channel dependent users scheduling that satisfies these requirements. Considering that there are real cases where cellular networks have various priority due to subscription, data rate requirements, etc, this chapter introduces a scheduling strategy that best accommodate such case later on.

Due to variation of UEs' signal reception at various subcarriers, multiple UEs in cellular networks can be used in order to achieve multiuser diversity. Besides adaptive modulation, users scheduling is a widely known procedure to utilise the multiuser diversity. The most popular scheduling algorithms in OFDMA systems include maximum sum rate (MSR), maximum fairness (MF), proportional rate constraints (PRC) [22] and proportional fairness (PF) and the cumulative distribution function (CDF) based scheduling policy [30], where it retains a similar characteristic with PF scheduler [31] that maximises multiuser diversity and users fairness.

MSR scheduling maximises the sum rate of all UEs at a given power constraint [22]. Due to the fact that signal reception vary for various users, this scheduling strategy achieves a very poor quality of service as this scheduler may block some users from transmission and only favour short distance UEs. On the other hand, MF and PRC strategy prioritise UEs with the lowest achievable and required data rate, respectively. These approaches limit the overall achievable sum rate by the

UEs with the worst achievable and required data rate. For this reason, only PF based scheduler will be considered further in this chapter.

This chapter is organised as follows. Section 6.1 discusses the basic consideration for users scheduling in OFDMA based HetNets. The example of popular scheduling implementation in current scenario will be implemented in section 6.2. Section 6.3 and section 6.4 propose and analyse a multilevel priority that is designed for the proposed technique. Performance comparison is made in section 6.5 and section 6.6. Finally summary is presented in section 6.7.

6.1. Scheduling Consideration on OFDMA HetNets

For simplicity, let assume PRs are subcarriers within an OFDMA frame. This is because in channel point of view they behaves almost in a similar manner. Hence, the scheduling considers the subcarriers allocation within an OFDMA frame. Furthermore, let assume similar system described in section 4.1.

6.1.1. Allowable Resources

As described in chapter 4, the MoC based RRM avoid interference of conflicting BSs by introducing four main binary matrices, which are the *entire forbidden PRs*, Θ_i , partial forbidden PRs, Φ_i , priority PRs, \mathcal{P}_i and temporary allocated PRs, \mathcal{A}_i . After computing the centralised approach, the FMS sends the allowable PRs matrix information which is given by

$$\Lambda_i = \overline{\Phi_i} \tag{6.1}$$

While Θ_i provides information of the forbidden PRs due to orthogonality requirements of UEs with the same and/or other BSs, Φ_i only provides the information of the forbidden PRs due to orthogonality requirement between UEs from different BSs, which is given by the MoC. By doing this, each BS has information which resource causes interference to the neighbouring BSs' UEs and allows it to allocate the resources in distributed manner.

6.1.2. Capacity Prediction

After receiving $\Lambda_{m,i}$ from FMS, BS T_m combines this matrix for i = 1 until I into a single matrix given by $\Lambda_m \in \mathbb{R}^{Z_m \times N}$ and schedules the resource to its UEs [32, 22]. Lets assume that the instantaneous small scale fading channel between T_m and its UEs is given by $\boldsymbol{H}_{m,t} \in \mathbb{C}^{Z_m \times N}$, the received signal power of the T_m 's UEs at all subcarriers based on Equation 4.1 on page 110 and $\boldsymbol{H}_{m,t}$ is given by

$$\mathbf{E}_{H_{m,t}}(z,n) = \mathbf{E}_{m,t}(z,i) |\mathbf{H}_{m,t}(z,n)|^2, \ \forall n = 1, \dots N,$$

$$z = 1, \dots, Z_m$$
(6.2)

where i is the PRs group index.

Using $\mathbf{E}_{H_m,t}$ and $\mathbf{E}_{c_m,t}$, the instantaneous prediction of the signal-to-interference and noise ratio (SINR) is given by

$$\psi_t(z,n) = \frac{\mathbf{E}_{H_m,t}(z,n)}{\mathcal{N}_0 + \sum_{c=1}^{C_m} \mathbf{E}_{C_m,t}(z,c,i)b_{cu_z}}$$
(6.3)

 $\forall n = 1, \dots, N \text{ and } z = 1, \dots, Z_m$, where \mathcal{N}_0 is the additive white Gaussian noise (AWGN), i = 1 is PRs group and b_{cu_z} is a binary multiplier which is given by

$$b_{cu_z} = \begin{cases} 1 & \frac{\mathbf{E}_{m,t}(z)}{\mathbf{E}_{C_m,t}(z,c,i)} > \gamma_{th} \\ 0 & \text{otherwise} \end{cases}$$
(6.4)

Based on $\psi_{m,t}$ matrix, the maximum Shannon capacity per subcarrier for each individual UE, $\ddot{\mathcal{R}}_t \in \mathbb{R}^{Z_m \times N}$, is given by

$$\ddot{\mathcal{R}}_t(z,n) = \log_2 \left(1 + \boldsymbol{\psi}_t(z,n)\boldsymbol{\Lambda}_m(z,n)\right), \forall n = 1, \dots, N, \ z = 1, \dots, Z_m$$
(6.5)

Using $\ddot{\mathcal{R}}_t$, the achievable capacity for all UEs, $\ddot{\mathcal{R}}_{\Sigma,t} \in \mathbb{R}^{Z_m \times 1}$, is given by

$$\ddot{\mathcal{R}}_{\Sigma,t}(z) = \sum_{n=1}^{N} \ddot{\mathcal{R}}_t(z,n).$$
(6.6)

Since we assume the network uses adaptive modulation with a maximum of 256QAM modulation per subcarrier, BS T_m needs to hold the maximum achievable capacity

per subcarrier for each individual UE, $\in \mathbb{R}^{Z_m \times N}$. Lets assume that the minimum SINR for BPSK, QPSK, 16QAM, 64QAM and 256QAM modulation to achieve a required bit error rate (BER) are given by γ_2 , γ_4 , γ_{16} , γ_{64} and γ_{256} , respectively, $\boldsymbol{\kappa}_{m,t}$ at any z and n is given by

$$\boldsymbol{\kappa}_{m,t}(z,n) = \begin{cases} 8, \quad \boldsymbol{\psi}_{m,t}(z,n)\boldsymbol{\Lambda}_{\boldsymbol{m}}(z,n) > \gamma_{2^{8}} \\ \mathcal{K}, \quad \gamma_{2^{\mathcal{K}}} \leq \boldsymbol{\psi}_{m,t}(z,n)\boldsymbol{\Lambda}_{\boldsymbol{m}}(z,n) < \gamma_{2^{\mathcal{K}+2}} \\ 1, \quad 0 < \boldsymbol{\psi}_{m,t}(z,n)\boldsymbol{\Lambda}_{\boldsymbol{m}}(z,n) < \gamma_{2} \\ 0, \quad \text{otherwise} \end{cases}$$
(6.7)

for $\mathcal{K} = 2, 4$ and 6.

6.1.3. Power Control

Assume the scheduled UEs allocation for each frame is stored into a binary matrix, $\Omega_{m,t}$, the final step of scheduling is applying power control. Since all BSs have the objective to increase their UEs data rate, in this thesis power control is applied to any UE and subcarrier only when the data rate cannot be increased. This is done to avoid any additional conflict between the BSs. Since the system model described in chapter 5 assumes a maximum modulation order of 256QAM, increasing power when the modulation order has achieved 256QAM does not improve the throughput. For this reason, it is proposed that power control is only applied at any time t and subcarrier n given that $\kappa_{m,t}(z,n) = 8$. Therefore, the transmitted power at any t, z and $n \forall n = 1, ..., N$ and $z = 1, ..., Z_m$ is given by

$$\widehat{\boldsymbol{P}}_{m,t}(z,n) = \begin{cases} \frac{\gamma_{256}P_m \boldsymbol{\Omega}_{m,t}(z,n)}{\psi_{m,t}(z,n)}, & \boldsymbol{\kappa}_{m,t}(z,n) = 8\\ P_m \boldsymbol{\Omega}_{m,t}(z,n), & \boldsymbol{\kappa}_{m,t}(z,n) < 8 \end{cases}$$
(6.8)

6.2. Scheduling Example on MoC based SON RRM

This section presents example of how the conventional scheduling can be implemented in the proposed SON RRM. As been considered earlier, only PF scheduling is considered due to its ability to balance both the sum rate and fairness. This is achieved by introducing a window parameter, t_c . If it is assumed that $\mathbf{R}_t \in \mathbb{R}^{Z_m \times 1}$ is the matrix holding the average data rate of the T_m 's UEs within the t_c window, the PF scheduled subcarriers allocation, $\mathbf{\Omega}_{m,t} \mathbb{R}^{Z_m \times N}$, at frame slot t and subcarrier n is given by

$$z_{PF} = \arg \max_{z \in Z_m: \mathcal{\tilde{R}}_t(z,n) > 0} \frac{\mathcal{\tilde{R}}_t(z,n)}{\mathbf{R}_t(z)}$$
(6.9)

$$\Omega_{m,t}(z,n) = \begin{cases} 1, & z = z_{PF} \& \, \ddot{\mathcal{R}}_t(z,n) > 0\\ 0, & \text{otherwise} \end{cases}$$
(6.10)

. . .

for z = 1 until Z_m . The average capacity at time t + 1, $\mathbf{R}_{t+1}(z)$, is updated using the following equation

$$\mathbf{R}_{t+1}(z) = \frac{1}{t_c} \sum_{n=1}^{N} \mathbf{\Omega}_{m,t}(z,n) \ddot{\mathbf{\mathcal{R}}}_t(z,n) + \left(1 - \frac{1}{t_c}\right) \mathbf{R}_t(z), \ \forall z = 1, \dots, Z_m$$
(6.11)

After allocating the subcarriers to various UEs, the power control described from Equation 6.8 is applied to improve the performance of neighbouring cells.

As can be seen, this scheduler selects the UEs that maximises the relative sum rate. This avoids the allocation of a deep fade channel and improves the overall data rate performance. On the other hand, UEs with low average SINR will received high priority at a certain period and maintain high QoS.

 t_c essentially controls the latency of the system [22]. High value makes the average rate \mathbf{R}_t remain steady for longer period. This makes the instantaneous capacity becomes a dominant factor in selecting the UE for each frame and channel. Hence, the overall sum rate is improved with the penalty of longer period for UEs with low average SINR to be allocated. Otherwise, reducing t_c increase the variation of \mathbf{R}_t over short frame period and reduces the waiting period of under served UEs at the cost of overall sum rate reduction.



Figure 6.1.: Scheduling Problems in MoC based Solution. (a) System example, (b) Temporary and Allowable subcarriers, (c) Channel gain example and (d) scheduled transmission.

6.3. Multilevel Priority Consecutive Scheduling

6.3.1. MoC based Problem for Scheduling

Even tough the allowable subcarriers allows BSs to schedule their resources without causing interference, there is still a case where the best resources are not allocated to the appropriate users. For instance, this is illustrated in Figure 6.1. As can be seen from Figure 6.1, users are allowed to utilise the subcarriers indicated by Λ . Using opportunistic scheduling and considering the channel gain shown in Figure 6.1 (c), the scheduled transmission is allocated based on the matrix shown in Figure 6.1 (d). However, as can be seen from this figure, subcarriers 6 and 8 are unallocated from users u_1 and u_2 point of view. This is because, these subcarriers are allocated to u_4 , which does not receive any interference from F_1 .

An easy way to solve this is by allowing a further communications between F_1 and F_2 to release some of its subcarriers. By doing so, F_1 can further utilise subcarriers 6 and 8 for its benefit until further notice. However, considering HetNets have a

random nature of small BSs" position and may include a large number of small BSs (SBSs), such approach may results in high complexity. For this reason, it is better to provide a solution that maintains the distributed characteristic using the allowable set of resources, Λ_i , which is the inverse of partial forbidden subcarriers, Φ_i , shown by Equation 4.9 in subsection 4.2.2 on page 114.

The application of the partial forbidden resources to indicate the available resource for scheduling are restricted by the MoC condition. As can be seen from Algorithm 4.3 in subsection 4.2.2 of chapter 4, the partial forbidden matrix will be updated if orthogonality between users from different BSs is required. In order to allow more subcarriers utilisation without further information exchange between BSs, several users should be allowed to violate the orthogonal requirement into several constraints, e.g. only violate the condition in a very good channel. Although this may reduce the performance of some other UEs, the overall sum rate can be increased and only users that do not deserve to get high data rate that suffers the reduced data rate. This requirement can be implemented in the case of multilevel priority scenario. This scenario may exist in cellular network because of different subscription fees, data rate application, amongst others.

To accommodate this multilevel scenario, this chapter first proposes the new algorithm for updating the forbidden resources required by the FMS. After that, a multilevel scheduling scheme that allows the BS to control the data rate for various priority UEs will be explained in subsection 6.3.3.

6.3.2. Partial Forbidden Resource

Let assume a similar assumption described in section 4.1 of chapter 4. There are M BSs denoted in set $\mathbb{T} = \begin{bmatrix} T_1 & \ldots & T_M \end{bmatrix}$, $\mathbb{U} = \begin{bmatrix} U_1 & \ldots & U_Z \end{bmatrix}$, where Z is the total number of users. Furthermore, N parallel resources (PRs) are divided into I separate groups with index i and each group has N_i PRs. In addition, the set of BSs that require conflicts to be resolved at a particular time and the i^{th} PRs group index is given by $\mathbb{T}_{\mathbf{B},i} = \begin{bmatrix} T_{1,i} & \ldots & T_{B_{i},i} \end{bmatrix}$ with index $T_{b,i}$ where $B_i \leq M$ is the conflicting BSs at the i^{th} PRs group index and $\mathbb{T}_{\mathbf{B},i}$ acts as a pointer for the \mathbb{T} set in the FMS memory.

The priority levels are denoted in set $\boldsymbol{\wp} = \begin{bmatrix} \wp_1 & \dots & \wp_Z \end{bmatrix}$ where $\wp_z \in \{0, 1, \dots, \mathcal{L}\}$ and \mathcal{L} is the maximum priority level. In this set, the priority is formed in ascending order, e.g. as the number decreases, the users become more important, with the exception of $\wp_z = 0$ which is used for protected users. If $\wp_z = 0$, this means u_z will use the original method for priority and forbidden resources.

In order to accommodate the priority based resource allocation, an additional matrix of allocation is required besides the *entire forbidden PRs*, $\Theta_i \in \mathbb{R}^{Z_{Bi} \times N_i}$, *partial forbidden PRs*, $\Phi_i \in \mathbb{R}^{Z_{Bi} \times N_i}$, *priority PRs*, $\mathcal{P}_i \in \mathbb{R}^{Z_{Bi} \times N_i}$ and *temporary allocated PRs*, $\mathcal{A}_i \in \mathbb{R}^{Z_{Bi} \times N_i}$ as described in subsection 4.2.2. The new matrix is *partial forbidden subcarriers with priority*, $\mu_i \in \mathbb{R}^{Z_{Bi} \times N_i}$. This new matrix is incorporated within Line 7 of Algorithm 6.1 where $x = \{a > b\}$ means x = 1 if a > b, otherwise, x = 0. As can be seen from this algorithm, the partial forbidden subcarriers are only updated to the users that are less important. Note that \cap and \cup denote bitwise AND and OR logic operations, respectively.

Algorithm 6.1 Multilevel Priority and Forbidden Subcarriers Update function newForbPrio $(\Theta_{\mathbf{B},i}, \Phi_{\mathbf{B},i}, \mathcal{P}_{\mathbf{B},i}, \mathcal{A}_{\mathbf{B},i}, \widetilde{\mathbb{T}}_{\mathbf{B},i}, \zeta_{\mathbf{B},i}, b, q)$ 1 for p = 1 until B_i do $\mathbf{if}\,\left(\tilde{\mathbb{T}}_{\mathbf{B},i}\left(p\right)\neq\tilde{\mathbb{T}}_{\mathbf{B},i}\left(b\right)\right)\,\boldsymbol{\&}\,\,\tilde{\mathbb{T}}_{\mathbf{B}}\left(p\right)\subseteq\tilde{\mathbb{V}}_{\boldsymbol{k}_{\boldsymbol{b}}}\,\,\mathbf{then}$ 2 $\mathbf{v}(n) = \left[\left\{ \boldsymbol{\zeta}_{\mathbf{B},i}(q,p) = w_e \right\} \cup \left\{ \boldsymbol{\zeta}_{\mathbf{B},i}(a,b) = w_e \right\} \right] \cap \boldsymbol{\mathcal{A}}_{\mathbf{B},i}(q,n)$ 3 $\mathcal{P}_{\mathbf{B},i}(a,n) = \mathcal{P}_{\mathbf{B},i}(a,n) \cup \left(\mathcal{A}_{\mathbf{B},i}(q,n) \cap \left\{\boldsymbol{\zeta}_{\mathbf{B},i}(a,b) = 0\right\}\right)$ 4 5 $\Theta_{\mathbf{B},i}(a,n) = \Theta_{\mathbf{B},i}(a,n) \cup \mathbf{v}(n)$ $\Phi_{\mathbf{B},i}(a,n) = \Phi_{\mathbf{B},i}(a,n) \cup \mathbf{v}(n)$ 6 $\boldsymbol{\mu}_{\mathbf{B},i}(a,n) = \boldsymbol{\mu}_{\mathbf{B},i}(a,n) \cup (\mathbf{v}(n) \cap (\{\boldsymbol{\wp}(a) \geq \boldsymbol{\wp}(q)\} \cup \{\boldsymbol{\wp}(a) \sim 0\} \cup \{\boldsymbol{\wp}(q) \sim 0\}))$ 7 $\forall n = 1, \ldots, N_i, a = 1, \ldots, Z_{Bi}, \text{ and } a \neq q$ 8 9 else $\Theta_{\mathbf{B},i}(c,n) = \Theta_{\mathbf{B},i}(c,n) \vee \left(\mathcal{A}_{\mathbf{B},i}(q,n) \cap \left\{ \boldsymbol{\zeta}_{\boldsymbol{B},i}(c,b) = w_s \right\} \right),$ $\forall n = 1, \dots, N_i, \ c = 1, \dots, Z_{Bi}, \text{ and } c \neq q$ 1011 12end if 13 end for14 return $\mathcal{P}_{\mathbf{B},i}, \Theta_{\mathbf{B},i}, \Phi_{\mathbf{B},i}$ and $\mu_{\mathbf{B},i}$

6.3.3. Consecutive Scheduling Algorithm

In order to optimise scheduling on the MoC based SON RRM, this chapter proposes a scheduling method that reduces the unused resources as described previously by utilising multilevel priority in cellular networks. This various level may exist due to different subscription payment and data rate requirement. Using this assumption, a user is allowed to utilise a similar resources with the lower priority users in the neighbouring BSs at the penalty of low SINR performance.

Since the objectives of any cellular network is to achieve maximum fairness for every user, the objectives of the proposed technique is to maintain the quality of service (QoS) for the lower priority users at least similar to those achieved by the full spectrum usage utilising a PF scheduler. This can be achieved by both single and multiple level priority to be treated separately in t_o OFDM frames. For simplicity, it is assumed that $t_o = 2$. At $t_o = 1$, a single level system is assumed. On the other hand, the multilevel priority is considered in the second frame for solving the scheduling problem shown in Figure 6.1.

Algorithm 6.2 Multilevel Priority Scheduling function MultiLvlConsSceduling $(\Lambda_m, \Omega_m, \psi_t, \mathcal{R}_t, \ell, \mathcal{L}, t)$ 1 $c = \sum_{z=1}^{Z_m} \sum_{n=1}^{N} \left\{ \ddot{\mathcal{R}}_t(z,n) > 0 \right\}$ 2 while $c < NZ_m$ do for p = 1 until \mathcal{L} do $\ell(p)$ times 3 $n_{max} = \arg \max_{n: \mathcal{R}_t(\widetilde{z}, n) > 0} \mathcal{R}_t(\widetilde{z}, n)$ 4 5 $\mathbf{\Omega}_{m,t}(\widetilde{z}, n_{max}) = \mathbf{\Lambda}_m(\widetilde{z}, n_{max})$ 6 $\mathcal{R}_t(\tilde{z}, n_{max}) = 0$ 7 $\forall \tilde{z} = 1 \text{ until } Z_m \mid \wp(\tilde{z}) = p$ 8 end 9 recalculate c10 end 11 end 12 :return $\Omega_{m,t}$

The proposed scheduling is described by Algorithm 6.2. This algorithm works by allocating resources from the highest to the lowest priority users. For the p^{th} priority level, the scheduler allocates subcarriers that provide the maximum capacity from the available resources for this scheduling, $\Lambda_{m,s}$, and $\ddot{\mathcal{R}}_t$ information shown by Equation 6.5, one user at a time at the same priority level for $\ell(p)$ times, where $\ell \in \mathbb{R}^{\mathcal{L} \times 1}$ contains set of allocated number of subcarriers for each priority level. In order to maximize QoS of the system, the scheduler sort the order of allocated users based on $\ddot{\mathcal{R}}_{\Sigma,t}$ value which is given by Equation 6.6. By doing this, the fairness and maximum throughput can be achieved at the same time. In order to maintain a good transmission even for low priority UEs, this chapter considers a scheduling frame, t_o , of two OFDM frames. In the first frame, a single level priority is assumed. This provides equal opportunity for all UEs to achieve maximum data rate. On the other hand, the second period provides a multilevel priority chance.

A)
$$t_o = 1$$

In this period, optimising the QoS is the main scheduling criteria. In order to do so, this chapter proposes scheduling using the temporary allocated subcarriers \mathcal{A}_m and the scheduling is only applied to users with a similar MoC pattern. By doing so, the scheduling is only applied for users that have similar interference profile. Therefore, the allowable subcarriers are given by

$$\boldsymbol{\Lambda}_{\boldsymbol{m},\boldsymbol{t}}\left(z,n\right) = \begin{cases} \boldsymbol{\mathcal{A}}_{\boldsymbol{m}}\left(z,n\right) | \boldsymbol{\mathcal{A}}_{\boldsymbol{m}}\left(a,n\right) \quad \sum_{c=1}^{C_{m}} | \boldsymbol{\zeta}_{\boldsymbol{m}}(z,c) - \boldsymbol{\zeta}_{\boldsymbol{m}}(a,c) | \sim 0 \\ \boldsymbol{\mathcal{A}}_{\boldsymbol{m}}\left(z,n\right) & \text{otherwise} \end{cases}$$
(6.12)

for $a \not\sim z$ and $a = 1, \ldots, Z_m$.

B)
$$t_o = 2$$

In this frame, multilevel scheduling can be implemented. Due to users with various levels of priority receives different sets of priority subcarriers, it is important to only allocate these subcarriers only if it is not been allocated to a higher SINR. Based on $\mu(z, n)$ and $\Phi(z, n)$ sets, subcarriers that are predicted to have low SINR are given by

$$\mathbf{\Lambda}_{low}\left(z,n\right) = \boldsymbol{\mu}\left(z,n\right) \oplus \boldsymbol{\Phi}\left(z,n\right) \tag{6.13}$$

 $\forall n = 1, \dots, N, z = 1, \dots, Z_m$ where \oplus is exclusive OR operation. The predicted SINR using the MoC based SON RRM is given by

$$\boldsymbol{\psi}_{MoC}\left(z,n\right) = \begin{cases} \frac{\mathbf{E}_{H_{m}}(z,n)}{\mathcal{N}_{o} + \sum_{c=1}^{C_{m}} \mathbf{E}_{C_{m}}(z,c,i)}, & \boldsymbol{\Lambda}_{low}\left(z,n\right) = 1\\ \boldsymbol{\psi}_{m}\left(z,n\right), & \text{otherwise} \end{cases}$$
(6.14)

 $\forall n = 1, \dots, N, z = 1, \dots, Z_m$. Finally, the available subcarriers for scheduling is given by

$$\boldsymbol{\Lambda}_{m,t}\left(z,n\right) = \overline{\boldsymbol{\mu}}\left(z,n\right)\left\{\boldsymbol{\psi}_{MoC}\left(z,n\right) > \gamma_{min}\right\}$$
(6.15)

 $\forall n = 1, \ldots, N, z = 1, \ldots, Z_m$ where γ_{min} is the minimum tolerable SINR. In this

chapter, it is assumed that $\gamma_{min} = \gamma_{th} - 5 \text{ dB}$ where γ_{th} is the signal-to-interference ratio (SIR) threshold described in chapter 4.

6.4. Performance Analysis

If we assume a homogeneous network consist of femtocell access points in an l by l all BSs have the same number of transmit the same power, P_m , using the analysis shown in section 4.3 of chapter 4 that the guaranteed rate of consecutive scheduling with MoC based RRM in a homogeneous network is given by

$$v_{min} = \frac{NW_f \log_2 \left(1 + \psi_{\varrho_{min}}\right)}{Z_m \left[1 + (M-1) \left\{1 - F_{R_{MC}} \left(\left(\frac{1}{\gamma_{th}}\right)^{1/\eta}\right)\right\}\right]}$$
(6.16)

where N is the total number of available subcarriers and $\psi_{\varrho_{min}}$ is the minimum SINR that any user will receive at a given SIR threshold. $\psi_{\varrho_{min}}$ is given by

$$\psi_{\varrho_{min}} = |\varrho|^2 \,\psi_{min} \tag{6.17}$$

where ρ is the multipath fading channel with consecutive scheduling and ψ_{min} is the minimum SINR for a system with AWGN channel, which is given by

$$\psi_{min} = \frac{E_{mu_z}}{E_{i_{max}}B_{u_z}} \tag{6.18}$$

where E_{mu_z} is the received signal power from T_m , B_{u_z} is the total interfering SBSs, given by

$$B_{u_z} = (M-1)F_{R_{MC}}\left(\left(\frac{1}{\gamma_{th}}\right)^{1/\eta}\right)$$
(6.19)

and $E_{i_{max}}$ is given by

$$E_{i_{max}} = \frac{E_{mu_z}}{\gamma_{th}}.$$
(6.20)

 $F_{R_{MC}}(r_{mc})$ is the cumulative distribution function of r_{mc} ratio within an l by l area, which is given by

$$f_{R_{MC}}(r_{mc}) = \begin{cases} \frac{4l}{3d_{MAX}} \arcsin(1) + \\ \frac{4l}{10d_{MAX}} - 2\frac{l}{d_{MAX}} & 0 < r_{mc} < \frac{d_{MAX}}{l} \\ \\ \frac{4d_{MAX}^2}{3l^2 p^3} \arcsin(1) + \\ \frac{4d_{MAX}^4}{10l^4 p^5} - \frac{2d_{MAX}^3}{l^3 p^4} & r_{mc} \ge \frac{d_{MAX}}{l} \end{cases}$$
(6.21)

Using the proposed consecutive scheduling, the ρ has similar behaviour with maximum selection combining in diversity receiver system with Z_m number of observations. If we further assume that $|\boldsymbol{H}_{m,t}(n)|^2$ is distributed with Rayleigh fading envelope and $|\boldsymbol{H}_{m,t}(n)|^2 = 1$, the PDF of a scheduled subcarrier, is given by

$$f_{\rho}\left(\psi_{\varrho_{min}}\right) = \frac{Z_m}{\psi_{min}} \left(1 - e^{-\psi_{\varrho_{min}}/\psi_{min}}\right)^{Z_m - 1} e^{-\psi_{\varrho_{min}}/\psi_{min}} \tag{6.22}$$

Based on Equation 6.22, the minimum capacity of the proposed scheduling is given by

$$C_{min} = \int_{-\infty}^{\infty} v_{min} f_{\rho} \left(\psi_{\varrho_{min}} \right) d\psi_{\varrho_{min}}$$
(6.23)

Inserting Equation 6.16 to Equation 6.5 gives

$$C_{min} = \frac{NW_f Z_m}{Z_{r_{mc}} \psi_{min}} \int_{-\infty}^{\infty} \frac{\log_2 \left(1 + \psi_{\varrho_{min}}\right)}{e^{\psi_{\varrho_{min}}/\psi_{min}}} \left(1 - e^{\frac{-\psi_{\varrho_{min}}}{\psi_{min}}}\right)^{Z_m - 1} d\psi_{\varrho_{min}} \tag{6.24}$$

where $Z_{r_{mc}}$ is given by

$$Z_{r_{mc}} = Z_m \left[1 + (M-1) \left\{ 1 - F_{R_{MC}} \left(\left(\frac{1}{\gamma_{th}} \right)^{1/\eta} \right) \right\} \right]$$
(6.25)

If a homogeneous network containing femtocells in a 60 by 60 meter square area with Rayleigh fading channel, γ_{th} of 20 dB, η equals 3, 256 total subcarriers at 2.3 GHz with bandwidth per subcarrier of 10.94 kHz, 200 μs of OFDM period and 100 mW of SBS equivalent isotropically radiated power (EIRP) are assumed, the guaranteed rate of the proposed scheduling using MoC based RRM is shown by Figure 6.2. As can be seen from this figure, the analysis value is close to the simulation value



Figure 6.2.: Guaranteed rate of consecutive scheduling with various number of users

which supports the validity of the analysis presented. This figure also shows that as the networks density increases, the impact of increasing the number of users per femtocell to the guaranteed data rate decreases. This happens because the minimum bit rate of a BS using the MoC based RRM is limited to the number of affected users by this BS. In high density cellular networks, the number of affected users of all BSs becomes very close. This makes the addition of users per femtocell less significant to the overall performance.

6.5. Single Level Priority Performance Evaluation

In this section, the performance of the proposed MoC based RRM with PF and CS schedulers will be examined in HoNet and HetNet scenarios. The PF scheduler considered here has a window size $t_c = 10$ OFDM frames. On the other hand, in the case of CS scheduler, it is assumed that $\wp(z) = 0, \forall U_z \in \mathbb{U}$. This simulation considers the sum rate and guaranteed rate results as performance comparisons.

As can be observed from previous chapters, various γ_{th} values results in different sum rate and guaranteed performance of the proposed RRM. Higher threshold results in better guaranteed rate while reducing the sum rate due to resource utilisation reduction. In order to achieve good flexibility in scheduling the resource for users, the proposed scheme requires a good number of available resources. Since $\gamma_{th} =$ 20 dB is capable of providing superior sum rate and guaranteed rate performance compared to other RRMs, only this threshold value will be considered in this chapter.

6.5.1. HoNet Scenario

Different from the previous chapter, the simulation here considers the performance under various number of users. There are two number of femtocells observed within an area of 60 m by 60 m, which are five and 15. The performance will be compared with PF schedulers with full spectrum utilisation as well as self organisation and coloured graph SON RRMs. The rest of the simulation parameters are similar with section 5.2 on page 134.





Figure 6.3.: Sum rate performance. (a) 5 femtocells and (b) 15 femtocells

As can be seen from Figure 6.3, the proposed MoC based RRM achieves better sum

rate compared to other RRMs. It is shown by this figure that the proposed MoC based SON RRM provides up to 23% sum rate improvement compared to other techniques. Although entire spectrum utilisation achieves the highest performance at one user per femtocell because the chance of receiving interference is low at low number of users, both Figure 6.3 (a) and (b) show that as the number of users per femtocell increases, the performance gap between the proposed and the other RRMs increases. Furthermore, similar trend with the previous chapter, the CG based SON RRMs result in the lowest sum rate performance. Moreover, unlike other RRMs, the dynamic CG SON RRM shows sum rate reduction in the increasing number of users per femtocell. This occurs due to the fact that increasing the number of users raises the probability of a BS to be connected with the neighbouring BSs. Based on the maximisation rule, this reduces the available spectrum usage by all BSs and overall sum rate.

It is seen from Figure 6.3 (a) and (b) that the performance of the RR scheduled MoC based SON RRM increases as the number of users is raised. This happens because raising the number of users increases the probability of close distance users from the BSs. In addition, because the proposed technique assumes the interleaving subcarriers allocation, increasing the number of users increases the interleaving spreading that reduces the deep fade channel impact to the users.

Both CS scheduling and PF scheduling using the proposed scheme achieves approximately the same performance, especially in the case of low density femtocell environment. As can be seen from Figure 6.3 (b), the proposed CS achieves a slightly better performance compared to the PF scheduler. This shows that CS scheduling for the MoC based SON RRM is a good alternative compared to the PF scheduler that improves the performance compared to standard

B) Guaranteed rate

Figure 6.4 shows that the MoC based SON RRM achieves the highest guaranteed rate up to 32% compared to other RRMs with the PF scheduler at both low density and high density femtocell environments, especially at low number of users. At the number of users higher than four, the self organisation RRM with PF scheduler achieves slightly better performance than the proposed technique. This happens because the self organisation scheme utilises the full interference measurement report. This gives BSs the complete information regarding the achievable throughput for



Figure 6.4.: Guaranteed rate performance. (a) 5 femtocells and (b) 15 femtocells

the a specific user and spectrum. Since it is assumed in this simulation that the fading channels are distributed with the Rayleigh envelope, this condition creates large variations in the received interference profile by the UEs and allows BSs to maximise the minimum throughput users. However, as been described in chapter 2, this comes with the price of increase signaling between UEs and BSs due to rapid variation of fading channels across small distances. Furthermore, as been shown by Figure 6.3, this technique provides lower sum rate compared to the full spectrum utilisation at large numbers of femtocell.

Similar with the sum rate case, the performance improvement reduces as the number of femtocells increases. Moreover, the CG SON RRMs produce the worst guaranteed rate because of very low number of available resource for scheduling. Furthermore, although the full spectrum utilisation provides better sum rate compared to self organisation RRM in the case of 15 femtocells, this comes with the price of guaranteed data rate reduction as shown by Figure 6.4.

As can be seen from Figure 6.4, CS scheduling achieves a similar guaranteed rate with the PF scheduler. This indicates that the CS scheduler is also a good alternative for the proposed MoC to utilise multiuser diversity that can be implemented in a latency sensitive system. It can be concluded from Figure 6.3 - Figure 6.4 that the proposed resource allocation is not only capable of avoiding the downlink interference in HoNet scenario, but also provides a constrained flexibility for further improvement based on the channel state information (CSI) owned by individual BS.

6.5.2. HetNet Scenario

There are two scenarios simulated in this chapter: Scenario 1: considers the performance against various numbers of indoor users at a fixed distance from the MBS. This scenario is simulated in order to test the behaviour of the proposed technique in various network densities. Since only the number of indoor users will be varied, this scenario will only be observed for indoor users only. On the other hand, scenario 2: considers the performance against various distances from the MBS with a fixed number of indoor users. By doing this, the impact of the overall heterogeneous network signal can be observed. In this paper, scenario 1 considers a distance of 1 km while scenario 2 assumes a fixed 20 indoor UEs inside the building.

Besides these indoor and outdoor users, there are 60 UEs registered as inner users and 20 UEs registered as outer users of the macrocell with the minimum distance between these UEs and MBS of 100 m. These 60 inner users received SINRs are varied between 17 dB and 43 dB while the outer users have SINRs varied between 5 dB and 30 dB. The MBS signals propagate to these users with the Rayleigh fading envelope.

For reference sake, the results are compared with PF scheduling without RRM, distributed RRM using self organisation RRM with two iterations, and CG based SON RRM techniques with N/4 subcarriers of partial usage for basic method and N/8initial subcarriers for dynamic scheme. All RRMs are combined with PF scheduling. Without RRM, the HNBs use the available spectrum based on the above mentioned assumption in section 6.1. The rest of the simulation parameters are similar with the parameters described in section 5.3 on page 144.



Figure 6.5.: Indoor users sum rate performance - scenario 1



Figure 6.6.: Indoor users sum rate performance - scenario 2

A) Sum rate performance

As can be seen from Figure 6.5, CS and PF schedulers that utilise the user diversity improve the sum rate of the MoC based RRM compared to the RR allocation scheme from the FMS. In general, the proposed RRM provides the highest sum rate at various number of users. In addition, this figure also shows that the basic CG SON RRM gives the worst performance because this RRM uses interference reading in the BSs, which may not be an accurate representation of the actual downlink interference, and has limited number of available resource for BSs. Similar with the HoNet results shown by Figure 6.3, the performance of dynamic CG SON RRMs reduces in the increasing number of users. This happens due to the same reason which is increasing the probability of connecting BSs.

When combined with schedulers, the proposed scheme achieves a maximum of 6.2% sum rate improvement, which occurs at low number of users. In the large number of users, the self organisation RRM attains similar performance with the proposed SON RRM. This is achieved because the self organisation RRM collects the interference information at the entire set of subcarriers. Hence, the result of scheduling is maximised. Bear in mind that this type of feedback is different from the current standard MR and requires a special modification in order to implement this successfully. Furthermore, since multipath fading varies rapidly above 2λ distance, frequent updates are required even when the UEs move distance of less than 0.26 m. This increases the signaling between UEs and BSs. This is not the case of the proposed RRM, since the MoC is determined by the average received signal that varies slowly over distance.



Figure 6.7.: Outdoor users sum rate performance - scenario 2

Figure 6.6 shows that the proposed technique significantly improves the sum rate of the indoor users for various distances from the MBS. It is shown that the proposed RRM provides a minimum of 2.54% and 25% improvement compared to the self organisation and the dynamic CG based SON RRMs, respectively. Unlike the simple RR scheduler performance shown in the previous chapter, full spectrum utilisation with PF scheduler achieves better performance than the basic CG SON RRM, despite full spectrum utilisation increases the interference. This happens because of the limitation of the available resource achieved by the basic CG SON RRM reduces the achievable performance.

Besides improving the indoor users performance, Figure 6.7 displays that the outdoor users also gain data rate advantage from the implementation of the proposed RRM compared to the full spectrum utilisation. With PF scheduler, most interference avoidance technique achieve almost similar performance compared to full spectrum utilisation where dynamic CG SON RRM provides the best performance. This happens because most of the outdoor users are served by the MBS. Using the PF scheduler, the performance of the outdoor users is significantly affected by the other macrocell users. Since the proposed RRM requires the MBS to leave a very small percentage (<5%) of empty subcarriers for the SBSs' UEs that experience its interference to avoid cross-tier interference, this limits the sum rate improvement compared to other RRMs. Nevertheless, considering the performance improvement achieved for the indoor users shown by Figure 6.5 and Figure 6.6 and the fact that 80% of data rate comes from indoor environment, the proposed SON RRM provides significant sum rate improvement for HetNets with PF scheduler [1].



Figure 6.8.: Indoor users guaranteed rate performance - scenario 1

It is evident from Figure 6.7 that the PF scheduler achieves a significant sum rate improvement compared to the basic RR method for the proposed strategy. This shows that the PF scheduler performs much better compared to the proposed RRM for utilising the multiuser diversity to improve the overall sum rate. In spite of that, the proposed scheduler provides sum rate improvement compared to the RR scheduling without latency that occurs in PF scheduler.

B) Guaranteed rate performance



Figure 6.9.: Indoor users guaranteed rate performance - scenario 2

Besides improving the sum rate performance, the scheduling strategy also improves the overall QoS of the indoor users using the proposed RRM. As shown by Figure 6.8, CS and PF scheduler increase the QoS by at least 10% compared to RR scheduler. Furthermore, it is shown that the proposed RRM enjoys up to 50% QoS improvement compared to other RRMs when combined with the PF scheduler that occurs at 10 indoor users. Due to its ability to know the exact interference signal, Figure 6.9 displays that the self organisation is capable of providing a similar QoS at close distance with the MBS. Similar with the sum rate results, the CG based SON RRMs achieve the lowest indoor QoS.

Overall, Figure 6.8 shows that CS and PF schedulers achieve almost similar QoS performance. As displayed by Figure 6.9, the PF achieves 61 kbps higher than CS. Obviously, the drawback for PF is higher latency compared to the CS strategy.



Figure 6.10.: Outdoor users guaranteed rate performance - scenario 2 As consequence of significant data rate improvement for outdoor users achieved by
the PF scheduler, this scheduler achieves worse QoS compared to RR and CS scheduler especially at the distance closer than 1 km from the MBS. This happens due to the nature of PF scheduling that balances the overall sum rate and fairness of the system. Although the proposed scheduler do not provides a significant improvement compared to the RR scheduler, this scheduling maintains improved performance compared to RR scheduler.

With PF scheduler, only dynamic CG based SON RRM achieves better performance than the proposed SON RRM. This happens because of limitation of the available subcarriers for the MBS users. Furthermore, the dynamic CG is assumed to have N/8 initial subcarriers per femtocell and the maximisation stage of the dynamic CG method in the scenario where there are almost uniform number of users per femtocell results in a more distributed resource. This distribution of the resource utilisation across the femtocells improves the fairness compared to basic CG as shown by Figure 6.9 as well as reduces the interference to the outdoor users compared to the basic CG and self organisation method.

6.6. Multilevel Priority Performance Evaluation

After observing the performance of the proposed MoC based SON RRM in a single level scenario, the performance of various schedulers in the case when users priority is considered in this thesis. In this section, two level priority users with the same probability of occurrence are considered. Both, HoNet and HetNet scenario are considered. The HoNet case considers the scenario shown previously with 5 femtocells within a 60 m by 60 m area while the HetNet case assumes the scenario 1 described in subsection 6.5.2 on page 176.

6.6.1. HoNet Scenario

A) Sum Rate

It is evident from Figure 6.11 that the proposed scheduling provides a good flexibility to improve the sum rate of high priority users. It is shown that raising the ℓ ratio, which is described in section 6.1, increases the sum rate of the first priority users.



Figure 6.11.: Sum rate of multilevel priority users



Figure 6.12.: Sum rate for all users

As a consequence, the sum rate for the low priority users decreases. Nonetheless, the ability to utilise additional resources improves the net results of the overall system sum rate by at least 12% as shown by Figure 6.12. As the number of users increases, the sum rate improvement increases compared to other scheduling schemes.

B) Guaranteed Rate

Figure 6.13 suggests that the proposed scheduling improves the QoS of the high priority users, especially at the low number of users per femtocell. At high number of users per femtocell, this increases the conflicts between BSs and limits the available resources. Furthermore, since the assumption of high priority users do not specify the placement of various priority users, the same priority levels may exist in the same



Figure 6.13.: Guaranteed rate of multilevel priority users



Figure 6.14.: Guaranteed rate of all users

femtocell. If this happens to the first priority users, this eliminates the purpose of the proposed scheduling to improve the performance of high priority users.

Overall, Figure 6.14 displays that the proposed scheduling do not stop the transmission of low priority users. Furthermore, the QoS of the proposed RRM and scheduling with 4:1 ratio still maintain better performance than the full spectrum utilisation with PF scheduler as shown by Figure 6.13. This means the objectives described earlier, which achieves maintains performance improvement compared to the full spectrum utilization, is achieved.

6.6.2. HetNet Scenario

The observation of multilevel priority scheme assumes a two level priority scheme in a scenario 1 described previously. Similar with HoNet case, this scenario considers 2:1, 3:1 and 4:1 ratios of the proposed scheduling. Furthermore, the sum rate and guaranteed data rate will be presented.





Figure 6.15.: Indoor sum rate of multilevel priority users



Figure 6.16.: Indoor sum rate for all users

Similar with the HoNet scenario, Figure 6.15 shows that the proposed scheduling improves the sum rate of the HetNet scenario. It is shown that the first priority

user enjoys 12.5% and 14% improvement compared to PF and RR schedulers, respectively. On the other hand, second priority users loses a maximum of 21.6% and 18.61% of data rate reduction, at $\ell = 4$:1, compared to the PF and RR scheduling, respectively. Overall, the sum rate of the proposed scheduling increases by 3%s at high number of users while achieves similar performance with PF scheduler at low number of users as shown by Figure 6.16. The performance of various ratio value is approximately similar.

B) Guaranteed Rate



Figure 6.17.: Indoor guaranteed rate of multilevel priority users



Figure 6.18.: Indoor guaranteed rate for all users

Similar with the HoNet scenario, the proposed scheduling allows QoS improvement for first priority users especially in the case of number of users lower than 15. Increasing the ratio increases the QoS for these high priority users. Above that, the first priority users achieve almost similar QoS with the PF schedulers. This happens due to the same reason with the HoNet case, which is the distribution of the high priority users.

It is evident from a Figure 6.18 that the proposed scheduling maintains performance improvement compared to the full spectrum utilisation even at the 4:1 ratio. As can be seen from this figure, the fairness reduction is almost insignificant compared to the full spectrum utilisation. Hence, the sum rate of the proposed technique is improved as been shown from Figure 6.16 while satisfying the objective to achieve better performance compared to full spectrum usage at HetNet scenario.

6.7. Summary

This chapter has shown that scheduling can be incorporated with the proposed interference avoidance technique described in a previous chapter. It is shown that the proposed RRM maintains sum rate and QoS improvements at the same scheduling strategy compared to full spectrum usage. As been shown in this chapter, this condition cannot be achieved by other RRMs. This chapter also proposes a new scheduling designed for the proposed RRM that can be applied for the multilevel priority scenario. In the single level scenario case, it is shown that the proposed scheduling achieves approximately similar QoS and overall sum rate with PF with no latency is required. On the other hand, the proposed consecutive scheduling can easily increase the overall sum rate for the high priority users while maintaining the transmission for the low priority without any latency.

7. Access Strategy to Improve Femtocell Deployment

As briefly described in section 2.5 of chapter 2, due to basic nature of femtocell implementation, which is owned partially by the end-user, this technology can be implemented in various access strategy. There are three basic access strategy for femtocell deployment, which are open, closed and hybrid access. Open access strategy allows a femtocell to serve any users within its vicinity as long as the total number of users is lower than a certain value while the closed access strategy only allows the femtocell to serve the femtocell owner or registered users. While open access improves the performance of the surrounding cellular network, closed access strategy provides the best solution for the femtocell owner. A compromise solution for the opposite problem is implementing a hybrid access solution. This access strategy works by giving some of femtocell's resources reserved to the owners or registered users while giving the rest of the resource open to outside users.

Evaluations of access strategies that consider the economic perspective are proposed in [111, 112]. For instance, [111] shows that by allowing the cellular network provider to auction the access permission to the potential femtocell owner, overall social welfare can be improved in the increasing number of femtocells. These works show that compensation policy is required to increase the accessibility of femtocell technology.

Inspired by the economic perspective and motivated by the need to encourage femtocell owners to release some of the resource and as the IP backhaul subscription become unlimited, this chapter proposes various access strategies that combine the interference avoidance scheme proposed in chapter 4 with the multilevel priority consecutive scheduling strategy described in chapter 6. Furthermore, a compensation policy will be proposed in order to encourage femtocell owners to open their femtocells accessibility. The performance simulation considers the data rate of the owners and visitors as well as the surrounding users as used in [113].

This chapter is organised as follows. The system model and access strategy for the proposed scheme are explained in section 7.1. Then, the impact of the proposed strategy is examined in section 7.2. Finally, the conclusion is made in section 7.3.

7.1. Access Strategy

A multilevel scheduling strategy is assumed in this chapter. A network model shown by Figure 2.13. In order to implement the access strategy easily, a multilevel priority system is also assumed.

7.1.1. Multilevel Strategy Within Femtocell

In this access strategy, a multilevel priority strategy described in a previous chapter is assumed. Assuming there are a set of users, given by $\mathbb{U} = \begin{bmatrix} U_1 & \dots & U_Z \end{bmatrix}$, where Z is the total number of users, the priority levels stored are denoted in set $\boldsymbol{\wp} = \begin{bmatrix} \wp_1 & \dots & \wp_Z \end{bmatrix}$ where $\wp_z \in \{0, 1, \dots, \mathcal{L}\}$ and \mathcal{L} is the maximum priority levels. This chapter proposes $\mathcal{L} = 4$ in order to improve the flexibility of the femtocell access. The four priority levels are used as follows:

- $\wp_z = 0$ is used for open access and owner of closed access femtocell.
- $\wp_z = 1$ is reserved for the owner of femtocell given that it is set up using hybrid access scheme.
- $\varphi_z = 2$ until 4 are used for visitors of a hybrid based femtocell systems. The various levels may exist due to subscription policy amongst others.

7.1.2. Types of Femtocell Access Strategy

Various access scheme implementations will be explained in this section. Furthermore, a novel access scheme will also be proposed in here. This novel access scheme combines the hybrid and the closed access schemes.

1. Open access scheme

This is a conventional open access scheme. In this scheme, an access point allows any user to be connected as long as the total users are lower than the maximum number it can handle. This allows users to be connected to the strongest signal. Hence, this scheme reduces the potential interference that decreases the available resources using the MoC based RRM.

Since open access scheme provides equal opportunity for all users within HetNets, all users will be given $\wp_z = 0$. This will protect all of its users from being allocated with the same resource with the neighbouring basestations' users if the priority level is higher as shown in a previous chapter. Since this scheme provides no priority for its user(s), the femtocell owner will have the same average data rate with other users registered to the same femtocell.

2. Hybrid access with multilevel priority scheme

The conventional hybrid access scheme works by allocating most of the available spectrum to the femtocell owner. In this case, a hybrid access that utilises the multilevel priority scheduling proposed in previous chapter is utilised. As been shown previously, this scheduling strategy provides a good flexibility in controlling the data rate of various priority level scenarios while utilising the fast channel variation.

In this scheme, a femtocell owner will be branded as $\varphi_z = 1$. On the other hand, a visitor will be granted various levels depending on the information sent by the central node, e.g. femto management system (FMS).

3. Closed access scheme

This access scheme is similar with the conventional closed access scheme. In this case, a femtocell owner opt to block any user that will try to be connected to their femto access point. This creates a high potential interference and reduces the available resource using the proposed MoC based RRM technique. Similar with the open access scheme, this scheme will brand the femtocell owner as $\wp_z = 0$.

4. Hybrid closed multilevel access scheme

This is a proposed access scheme that combines the closed access and the multilevel hybrid access schemes. Since a femtocell owner may not be active all the time, this

scheme allows a femtocell access point to be accessed by any user. Hence, this scheme provides almost similar impact to the surrounding networks at low probability of active femtocell owner. At high probability of active femtocell owner, this scheme will result in a similar performance with the conventional closed access scheme.

7.1.3. Femtocell Owner

Besides proposing a new femtocell access scheme, this chapter also proposes a table of compensation a/rewards for femtocell owner by the cellular company. Instead of cost compensation, this chapter proposes data rate compensation for the femtocell owner. Using this, the impact of various types of femtocell owner when they exist not in their own premises can be varied based on its potential to support the surrounding cellular networks. Table 7.1 shows how a femtocell owner will be treated in various type of femtocell access scheme. For comparison, other users that do not own femtocell are included as comparison in this table.

7.2. Performance Evaluation

The system model of the performance evaluation is described in Figure 7.1. The evaluation focuses on the cellular networks performance within a cell edge area as depicted in Figure 7.1. As can be seen from this illustration, there are nine buildings are considered in this examination. Various number of femtocells and users within a 60 m by 60 m building will be considered in this chapter. The rest of simulation parameters are shown in Table 5.1 and Table 5.2 of chapter 5.

Two types of simulation will be considered in this chapter. The first simulation will evaluate the impact of various femtocell access to the cellular networks. The second simulation will examine the compensation impact to a femtocell owner.

7.2.1. Impact to The Network

Impact to the network will be examined into two simulation scenarios. The first scenario examines the impact of a femtocell access strategy to its users using various access. In this scenario, the impact of the a femtocell access to its direct users,

	Open	Hybrid	Hybrid	Closed	Macrocell
	access	access	closed	femtocell	basesta-
	femtocell	femtocell	access		tion
			femtocell		
			(in the		
			absence of		
			the owner)		
Open	$\wp_z = 0$	$\wp_z = 1$	$\wp_z = 1$	Blocked	Equivalent
access				from	with 5
owner				accessing	users
Hybrid	$\wp_z = 0$	$\wp_z = 2$	$\wp_z = 2$	Blocked	Equivalent
access				from	with 4
owner				accessing	users
Hybrid	$\wp_z = 0$	$\wp_z = 3$	$\wp_z = 3$	Blocked	Equivalent
closed				from	with 3
access				accessing	users
owner					
Closed	$\wp_z = 0$	$\wp_z = 4$	$\wp_z = 4$	Blocked	Equivalent
access				from	with 2
owner				accessing	users
Other	$\wp_z = 0$	$\wp_z = 4$	$\wp_z = 4$	Blocked	Equivalent
users				from	with 1
				accessing	users

 Table 7.1.: Table of Compensation

which is femtocell owner and visitors will be examined. Second, the impact of a femtocell access strategy to the surrounding users within its vicinity. For simplification, only users within the same building with the femtocell of interest will be evaluated. Both scenarios are examined in M femtocells and Z active users within each building where M is uniformly distributed integer number between 1 and 4 and Z is uniformly distributed integer number between 1 and 4 and similar configuration with Figure 7.1, the simulation is focused on the performance of a single femtocell within the building of interest shown by Figure 7.1.

A) Performance Within Femtocell of Interest

Figure 7.2 shows that the hybrid access strategy provides the best QoS for the femtocell owner. As can be seen from this figure, the hybrid access scheme provides more than 1 Mbps of bit rate. On the other hand, although the closed access scheme does not allow other users to be connected to their premises, it produces the worst



Figure 7.1.: Simulation scenario

QoS to the femtocell owner. This figure shows that the owner of the closed access femtocell scheme have a chance of getting a bit rate of less than 1 Mbps and 2 Mbps in 1% and 15%, respectively. This happens because in the case of the closed access scheme, this femtocell only has one user, which is the femtocell owner. Since the MoC based RRM works by allocating the femtocells' users in certain order from the highest number of affected users to the lowest users, the femtocell with higher number of users will have a slightly higher chance of allocating its users than the low number of users. This means, hybrid and open access schemes have a slightly higher chance of getting more resources than closed access scheme. In addition, in the case when the two femtocells have the same number of affected users, the hybrid and open access schemes femtocell have more than one users. This means, the femtocell owner of these schemes gain the multiuser diversity advantage compared to the closed access femtocell. However, the closed access provides the highest bit rate for more than 50% of femtocell owners because this scheme allows the femtocell owner to have the maximum resources during the inner users maximisation. This means, the closed access scheme provides the best overall bit rate for the owner while the hybrid scheme provides the best QoS.



Figure 7.2.: CDF of femtocell owner in their own premise



Figure 7.3.: CDF of visitor

Due to its no prioritising policy between its users, Figure 7.3 shows that the open access scheme provides the best performance for a visitor. On the other hand, the closed access scheme do not allow any visitor to the femtocell. This figure also displays that the presence of femtocell owner affect a more significant impact to the hybrid based scheme compared to the open access because of the priority levels effect.

B) Performance Within Building of Interest

The impact of active probability of various femtocell access owners to the users within a close vicinity will be observed here. For simplicity, only users within the same building are considered here. Furthermore, the owner active probability is



given by ρ . There are two ρ values considered, which are 10% and 75%.

Figure 7.4.: CDF of surrounding users' average bit rate

Figure 7.4 shows that open access provides the best overall performance for the surrounding cellular network users while the closed based access scheme gives the worst performance for the surrounding users. This figure also shows that the presence of femtocell owner is largely affecting the closed type femtocell access, especially hybrid closed access scheme. As can be seen from this figure, the proposed hybrid closed access scheme provides a compromise between conventional hybrid and closed schemes. In the case of low ρ , the performance is similar with conventional hybrid scheme. As ρ increases, the performance of surrounding users becomes identical with those of the closed access scheme. In the case of closed access scheme, the performance difference only occurs at low average bit rate. As can be seen from this figure that at $\rho = 75\%$, twice more users have lower data rate than 20 kbps, which is a typical VoIP data rate requirement.

7.2.2. Impact to Femtocell Owner

In this section, the compensation policy impact to a femtocell owner will be examined. This observation uses the environment shown by Figure 7.1. In here, it is assumed that there are five femtocells per building with the probability of femtocell owner activity of 25%. In addition there are between 10 and 30 users per building exist within the considered environment that are randomly placed around the building with uniform distribution. Furthermore, there are two scenarios considered here. The first scenario considers a case when all femtocells are hybrid access. On the other hand, the second scenario considers a case when 50% of all femtocells are hybrid access schemes while the rest are closed based femtocell access. Between these closed access schemes, conventional closed access and hybrid closed access have probability of 50% each. The examined femtocell owner is placed randomly within these buildings.



Figure 7.5.: CDF of various type of users - Scenario 1



Figure 7.6.: CDF of various type of users - Scenario 2

Figure 7.5 and Figure 7.6 show that open access femtocell owner achieves the highest data rate and QoS compared while the conventional closed scheme achieves the wost performance. In the case of scenario 1 where all femtocells have hybrid access scheme, this type of owner have almost similar performance compared to other users. The conventional closed access scheme only gain improved performance in terms of QoS compared to other users in the scenario 2. Since not all femtocells are open

in this scenario, closed access scheme gain performance improvement from higher number of subcarriers allocated by the MBS.

By comparing the results shown by Figure 7.5 and Figure 7.6 with Figure 7.4 and Figure 7.3, it can be seen that more a femtocell owner helps to improve the surrounding cellular networks, the higher the compensation they gain when they are not in their own premises. It is expected that this policy will encourage the femtocell owners to set their femtocell access to at least a hybrid access scheme.

7.3. Summary

This chapter has shown a flexible method of utilising a consecutive scheduling (CS) and MoC based RRM described from chapter 4 until chapter 6. It has also shown a method to carefully assign various users by utilising multilevel priority properties in the CS scheme. Furthermore, this chapter also proposes a new femtocell access strategy that combines the conventional hybrid and closed strategy that takes into consideration the inactivity of the femtocell owner. Finally, a compensation policy for femtocell owner is proposed in order to encourage the owner to help the surrounding networks.

The results show that although closed scheme provides the best possible data rate for the femtocell owner for more than 50% compared to other schemes, hybrid access is the best scheme to achieve the best QoS. On the other hand, open access scheme provides the best support to the surrounding users performance. This impact is compensated by the performance of the compensation policy that provides the open access femtocell owner to achieve the best performance when they exist not in their own premises while the conventional closed access femtocell owner have the worst overall bit rate and QoS.

8. Conclusions and Future Work

8.1. Conclusions

The aim of this project is to improve the performance of the cellular networks through both physical (PHY) and medium access control (MAC) layers using the cooperative communication frameworks which has been successfully made.

- OFDMA based pairing type (PT) cooperative diversity has been designed as an alternative to relay type (RT) cooperative diversity scheme. This is achieved by utilising the unlicensed band and single dimensional OFDM modulation to achieve two diversity orders and a transmission rate of one symbol/second/Hz. Since the channel is complex (inphase and quadrature), it is possible to exploit the second dimension (the quadrature) for diversity purposes and to allow interference exploitation, as well as, to minimise sensitivity to timing-misalignment between members of each cooperative pair.
- The OFDMA based PT cooperative diversity scheme has been analysed and simulated under both ideal and non-ideal channel conditions. It is shown that this technique provides significant BER reduction, especially at low SNR, and improves throughput performance compared to conventional direct transmission and RT techniques.
- Interference avoidance RRM algorithm using cooperative frameworks has been created through interference mapping based RRM that combines confederation-style with a routing algorithm principle and self-organising network (SON) functionality. Interference mapping in a form of matrix of conflict (MoC) is used to track the conflicts between one BS and the surrounding UEs. When a BS submits its MoC, using a routing principle to check with the global MoC,

the FMS decides whether this BS can use a part of or the entire spectrum. If partial spectrum is applied, the FMS applies a set of rule based on principle of DVRP routing algorithm for spectrum allocation.

- The performance of the interference map based RRM has been investigated in homogeneous network (HoNet) and heterogeneous network (HetNet) cases. It was shown from HoNet simulation scenario that the proposed RRM provides superior overall rate increases and QoS improvements while supporting greener communication systems in various scenarios compared to other RRMs. Furthermore, it was demonstrated that the MoC based SON RRM is also able to satisfy the increasing demand on performance improvement in HetNets environments. It was shown that the proposed algorithm is able to improve the guaranteed data rate as well as the sum rate for all users in various distances from the MBS. The performance improvement occurs in the WiMAX and LTE systems.
- Scheduling has been combined with various interference avoidance schemes. It is shown that the proposed RRM maintains a sum rate and QoS improvements at the same scheduling strategy compared to full spectrum usage. This condition can not be achieved by other RRMs.
- A new scheduler for the proposed RRM has been designed and can be applied for the multilevel priority scenario. This is a very important property that can be utilised for the scheduling investigation. In the single level scenario case, it is shown that the proposed scheduling achieves approximately similar QoS and overall sum rate to PF with no latency is required. On the other hand, the proposed consecutive scheduling can easily increase the overall sum rate for the high priority users while maintaining the transmission for the low priority without any latency.
- A comprehensive femtocell access policy has been created using the interference mapping based RRM and the new scheduler. The proposed access strategy considers detailed policy of users allocation as well as compensation policy for the femtocell owner when they are not in their own premises. Furthermore, a new femtocell access strategy that combines the conventional hybrid and closed strategy that takes into consideration the inactivity of the femtocell owner has been proposed. The results show that although closed scheme

provides the best possible data rate for the femtocell owner for more than 50% compared to other scheme, hybrid access is the best scheme to achieve the best QoS. On the other hand, the open access scheme provides the best support to the surrounding users performance. This impact is compensated by the performance of the compensation policy that provides the open access femtocell owners to achieve the best performance when they do not exist not in their own premises while the conventional closed access femtocell owner have the worst overall bit rate and QoS.

8.2. Future Work

Future works recommendation based on the knowledge acquired in this research are presented below:

- The performance improvement achieved by the proposed user pairing techniques requires further investigation of the practicality and the impact on the existing standard and issues. At this stage, the proposed technique is applied in standard OFDMA uplink transmission, by assuming the frequency offset is perfectly eliminated and PAPR is reduced significantly. However, it is mentioned in practice in subsection 2.2.3 on page 47, these two problems are usually eliminated at the same time in the uplink transmission by employing SC-FDMA. Therefore, the first thing needs to be investigated in the future related to the cooperative diversity is employing the proposed technique using SC-FDMA instead of just standard uplink OFDMA.
- The evolution of MIMO system into a massive MIMO and parasitic antennas gives various framework in the future cellular networks [114, 115]. With parasitic antennas, only one radio frequency (RF) chain is required in the transmitter that reduces the power consumption with the penalty of reducing the diversity. On the other hand, massive MIMO that installs large number of antennas at the basestation (BS) provides an alternative of cell-shrinking idea in heterogeneous networks (HetNets). This project has successfully adopted the conventional MIMO into cooperative diversity. Therefore, future investigation is required to adopt the new MIMO system into a new cooperative diversity into parasitic concept. Furthermore, since massive MIMO will still

be deployed together with the HetNets, it is worth to investigate the behaviour of the interference mapping proposed in this project in the presence of massive MIMO BSs.

- It is shown in chapter 7 that the proposed matrix of conflict (MoC) based radio resource management (RRM) provides an easy way to manage the various femtocell access scheme strategy. So far in this project, it is assumed that the users can be connected to the closest femto access point (FAP) as long as the FAP provides open access strategy. This means femtocell can be connected to many users. However, it is mentioned in [1] that there are some limitations of the number of users connected to certain femto access point (FAP). Hence, it is worth investigating the impact of the proposed RRM in such scenario. This may require some additional access policy for this load balancing scenario.
- Uplink scenario of the MoC RRM needs to be designed by considering adaptive transmitted power in the uplink and SC-FDMA system. Further investigation of the uplink scenario also needs to consider the same measurement report (MR) with downlink case.
- Although the MoC based radio RRM has shown an adaptive capability over various scenario, further investigations is required to find the signal to interference ratio (SIR) threshold, γ_{th} , value in various scenario. The first consideration regarding this is the application of multilevel γ_{th} values. By combining it with power control strategy, co-tier transmission such that the quality of service is maintained and the overall sum rate can be improved. Furthermore, since this project assumes only a full buffer scenario, a fix γ_{th} value may not be appropriate in some applications. This is because in reality, signal transmission from various users comes from various applications ranging from voice call, internet browsing and video on demand. These create a scenario where downlink buffer may not always be full. Hence, application aware adaptive γ_{th} method is still open for further investigation.
- In this research, the MoC is created using a binary principle. This matrix only indicates the source of interference with a single threshold. Due to large signal variation received by a user, it is, then, possible to create a MoC based on multilevel γ_{th} . Further investigation is required in order to find the optimised γ_{th} values and new rules of allocation.

- MoC proposed in this research tracks the power from various basestations (BSs). The FMS can gather the MoC from various BSs and collect this information as a long term prediction of users behaviour. SON framework in 4G system aims to improve the networks quality in the short and long terms. Short term solution is achieved by instantaneous RRM schemes that are adaptive with the instantaneous condition while the long term solution provides a fix resource allocation that can, by default, avoid the interference between BSs. A further study of statistical method and rules are required in further study in order to balance the requirements to maximise spectrum utilisation and minimise the interference.
- Another long term SON solution regarding the statistical MoC reading is related to switching off the basestations to reduce the power consumption of the cellular networks.
- Analysis presented in this thesis does not consider the additional random fluctuation of the pathloss as a result of shadowing. Further analysis is necessary in order to observe the shadowing impact to the performance of the proposed schemes.

Bibliography

- V. Chandrasekhar, J. Andrews, and A. Gatherer, "Femtocell Networks: A Survey," *IEEE Communications Magazine*, vol. 46, no. 9, pp. 59–67, 2008.
- [2] DotEcon and Aetha. (2012) Spectrum value of 800mhz, 1800mhz and 2.6ghz.
 [Online]. Available: http://stakeholders.ofcom.org.uk/binaries/consultations/ award-800mhz/statement/spectrum-value.pdf
- [3] E. Telatar, "Capacity of Multi-Antenna Gaussian Channels," Eur. Trans. Telecommun., vol. 10, no. 6, pp. 585 – 595, 1999.
- [4] A. Nosratinia, T. Hunter, and A. Hedayat, "Cooperative Communication in Wireless Networks," *IEEE Communications Magazine*, vol. 42, no. 10, pp. 74 - 80, 2004.
- [5] T. Yamada and P. T. Hoa, "Unified Micro-cellular Network with Pico-cells to Avoid Local Congestion," in Wireless Telecommunications Symposium (WTS '06), 2006, pp. 1–7.
- [6] R. Steele, "The Cellular Environment of Lightweight Handheld Portables," *IEEE Communications Magazine*, vol. 27, no. 7, pp. 20–29, 1989.
- H. Claussen, L. T. W. Ho, and L. G. Samuel, "An Overview of The Femtocell Concept," *Bell Labs Technical Journal*, vol. 13, no. 1, pp. 221–245, 2008.
 [Online]. Available: http://dx.doi.org/10.1002/bltj.20292
- [8] H. Hu, J. Zhang, X. Zheng, Y. Yang, and P. Wu, "Self-configuration And Selfoptimization for LTE Networks," *IEEE Communications Magazine*, vol. 48, no. 2, pp. 94–100, 2010.

- [9] A. Sendonaris, E. Erkip, and B. Aazhang, "User Cooperation Diversity. Part I. System Description," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1927 – 1938, 2003.
- [10] J. Laneman, D. Tse, and G. Wornell, "Cooperative Diversity in Wireless Networks: Efficient Protocols And Outage Behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062 – 3080, 2004.
- [11] J. Li, A. Petropulu, and H. Poor, "Cooperative Transmission for Relay Networks Based on Second-Order Statistics of Channel State Information," *IEEE Transactions on Signal Processing*, vol. 59, no. 3, pp. 1280–1291, march 2011.
- [12] A. ElKalagy and E. AlSusa, "A Novel Pairing Diversity Technique with Dynamic Code Allocation for CDMA Systems Employing Polyphase Sequences," in *IEEE Wireless Communications and Networking Conference*, 2009, pp. 1 -6.
- [13] L. Wang, L. Kong, S. X. Eg, and L. Hanzo, "To Cooperate or Not: A Capacity Perspective," in *IEEE 71st Vehicular Technology Conference (VTC-Spring)*, May 2010, pp. 1 –5.
- [14] L. Kong, S. X. Ng, R. Maunder, and L. Hanzo, "Maximum-Throughput Irregular Distributed Space-Time Code for Near-Capacity Cooperative Communications," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 3, pp. 1511 -1517, 2010.
- [15] Y. Cao and B. Vojcic, "MMSE Multiuser Detection for Cooperative Diversity CDMA Systems," in *IEEE Wireless Communications and Networking Conference*, vol. 1, 2004, pp. 42 – 47 Vol.1.
- [16] R. Pabst, B. Walke, D. Schultz, P. Herhold, H. Yanikomeroglu, S. Mukherjee, H. Viswanathan, M. Lott, W. Zirwas, M. Dohler, H. Aghvami, D. Falconer, and G. Fettweis, "Relay-based Deployment Concepts for Wireless and Mobile Broadband Radio," *IEEE Communications Magazine*, vol. 42, no. 9, pp. 80 – 89, sept. 2004.
- [17] "IEEE Standard for Information Technology Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks

- Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Std 802.11-2007 (Revision of IEEE Std 802.11-1999)*, pp. 1–1076, 12 2007.

- [18] D. Lopez-Perez, A. Valcarce, G. de la Roche, and J. Zhang, "OFDMA Femtocells: A roadmap on Interference Avoidance," *IEEE Communications Magazine*, vol. 47, no. 9, pp. 41–48, september 2009.
- [19] J. Kim and D.-H. Cho, "A Joint Power and Subchannel Allocation Scheme Maximizing System Capacity in Indoor Dense Mobile Communication Systems," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 9, pp. 4340 -4353, nov. 2010.
- [20] J. Andrews, "Interference Cancellation for Cellular Systems: A Contemporary Overview," *IEEE Wireless Communications*, vol. 12, no. 2, pp. 19 – 29, april 2005.
- [21] "IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1," *IEEE Std 802.16e-2005 and IEEE Std 802.16-2004/Cor 1-2005 (Amendment and Corrigendum to IEEE Std 802.16-2004)*, 2006.
- [22] J. G. Andrews, A. Ghosh, and R. Muhamed, Fundamentals of WiMAX: Understanding Broadband Wireless Networking. Prentice Hall, 2007.
- [23] K. Kordybach, S. Hamalainen, C. Sartori, and I. Viering, *LTE for UMTS*. John Wiley and Sons, Ltd, 2011.
- [24] 3GPP. (2012) Release 11. [Online]. Available: http://www.3gpp.org/ Release-11
- [25] (2014) Release 12. [Online]. Available: http://www.3gpp.org/Release-12
- [26] D. Lopez-Perez, A. Ladanyi, A. Juttner, and J. Zhang, "OFDMA Femtocells: A self-organizing Approach for Frequency Assignment," in *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, sept. 2009, pp. 2202 –2207.

- [27] V. Chandrasekhar and J. Andrews, "Spectrum Allocation in Tiered Cellular Networks," *IEEE Transactions on Communications*, vol. 57, no. 10, pp. 3059 –3068, october 2009.
- [28] F. Pantisano, K. Ghaboosi, M. Bennis, and M. Latva-Aho, "Interference Avoidance via Resource Scheduling in TDD Underlay Femtocells," in *IEEE* 21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops), sept. 2010, pp. 175–179.
- [29] F. Pantisano, K. Ghaboosi, M. Bennis, and R. Verdone, "A Self-organizing Solution for Interference Avoidance in TDD Underlay Femtocells," in *Confer*ence Record of the Forty Fourth Asilomar Conference on Signals, Systems and Computers (ASILOMAR), nov. 2010, pp. 492–495.
- [30] D. Park, H. Seo, H. Kwon, and B. G. Lee, "Wireless Packet Scheduling Based on The Cumulative Distribution Function of User Transmission Rates," *IEEE Transactions on Communications*, vol. 53, no. 11, pp. 1919–1929, 2005.
- [31] Y. Huang and B. Rao, "An Analytical Framework for Heterogeneous Partial Feedback Design in Heterogeneous Multicell OFDMA Networks," *IEEE Transactions on Signal Processing*, vol. 61, no. 3, pp. 753–769, 2013.
- [32] R. Kwan, C. Leung, and J. Zhang, "Proportional Fair Multiuser Scheduling in LTE," *IEEE Signal Processing Letters*, vol. 16, no. 6, pp. 461–464, june 2009.
- [33] R. Kim, J. S. Kwak, and K. Etemad, "WiMAX Femtocell: Requirements, Challenges, and Solutions," *IEEE Communications Magazine*, vol. 47, no. 9, pp. 84–91, september 2009.
- [34] A. Golaup, M. Mustapha, and L. Patanapongpibul, "Femtocell Access Control Strategy in UMTS and LTE," *IEEE Communications Magazine*, vol. 47, no. 9, pp. 117–123, 2009.
- [35] S. Kale and T. Schwengler, "Comparing Unlicensed Mobile Access (UMA) and Voice Call Continuity (VCC) Architectures," in 6th IEEE Consumer Communications and Networking Conference, jan. 2009, pp. 1–2.
- [36] G. Miao, N. Himayat, Y. G. Li, and A. Swami, "Cross-layer Optimization for Energy-efficient Wireless Communications: A Survey," Wireless

Communications and Mobile Computing, vol. 9, no. 4, pp. 529–542, 2009. [Online]. Available: http://dx.doi.org/10.1002/wcm.698

- [37] T. Rappaport, Wireless Communications: Principles and Practice, 2nd ed. Prentice Hall, 2002.
- [38] S.-S. Jeng, J.-M. Chen, C.-W. Tsung, and Y.-F. Lu, "Coverage Probability Analysis of IEEE 802.16 System with Smart Antenna System over Stanford University Interim Fading Channels," *IET Communications*, vol. 4, no. 1, pp. 91–101, 5 2010.
- [39] J. Milanovic, S. Rimac-Drlje, and K. Bejuk, "Comparison of Propagation Models Accuracy for WiMAX on 3.5 GHz," in 14th IEEE International Conference on Electronics, Circuits and Systems, 2007, pp. 111–114.
- [40] V. Erceg, L. Greenstein, S. Tjandra, S. Parkoff, A. Gupta, B. Kulic, A. Julius, and R. Bianchi, "An Empirically Based Path Loss Model for Wireless Channels in Suburban Environments," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 7, pp. 1205–1211, 1999.
- [41] J. Proakis and M. Salehi, *Digital Communication*, 5th ed. New York: McGraw Hil, 2008.
- [42] A. Abdi, C. Tepedelenlioglu, M. Kaveh, and G. Giannakis, "On The Estimation of The K Parameter for The Rice Fading Distribution," *IEEE Communications Letters*, vol. 5, no. 3, pp. 92–94, 2001.
- [43] A. F. Molisch, *Wideband Wireless Digital Communications*. New Jersey: Prentice-Hall, 2001.
- [44] L.-L. Yang and L. Hanzo, "Multicarrier DS-CDMA: A Multiple Access Scheme for Ubiquitous Broadband Wireless Communications," *IEEE Communications Magazine*, vol. 41, no. 10, pp. 116–124, 2003.
- [45] B. C. L. Hanzo, M. Munster and T. Keller, OFDM and MC-CDMA for Broadband Multi-user Communications, WLANs and Broadcasting. West Sussex: John Wiley and Sons, Ltd, 2003.
- [46] H. Yin and S. Alamouti, "OFDMA: A Broadband Wireless Access Technology," in *IEEE Sarnoff Symposium*, 2006, pp. 1–4.

- [47] M. Ergen, Mobile Broadband Including WiMAX and LTE, 1st ed. Berkeley, CA: Springer, 2009.
- [48] K. W. Choi, W. S. Jeon, and D. G. Jeong, "Resource Allocation in OFDMA Wireless Communications Systems Supporting Multimedia Services," *IEEE/ACM Transactions on Networking*, vol. 17, no. 3, pp. 926–935, 2009.
- [49] T. Pollet, M. Van Bladel, and M. Moeneclaey, "BER sensitivity of OFDM Systems to Carrier Frequency Offset and Wiener Phase Noise," *IEEE Transactions on Communications*, vol. 43, no. 234, pp. 191–193, 1995.
- [50] J.-J. van de Beek, O. Edfors, M. Sandell, S. Wilson, and P. Borjesson, "On Channel Estimation in OFDM Systems," in *IEEE 45th Vehicular Technology Conference*, vol. 2, Jul. 1995, pp. 815 –819 vol.2.
- [51] H. Myung, J. Lim, and D. Goodman, "Single Carrier FDMA for Uplink Wireless Transmission," *IEEE Vehicular Technology Magazine*, vol. 1, no. 3, pp. 30–38, 2006.
- [52] M. Morelli, C.-C. Kuo, and M.-O. Pun, "Synchronization Techniques for Orthogonal Frequency Division Multiple Access (OFDMA): A Tutorial Review," *Proceedings of the IEEE*, vol. 95, no. 7, pp. 1394–1427, 2007.
- [53] P. H. Moose, "A Technique for Orthogonal Frequency Division Multiplexing Frequency Offset Correction," *IEEE Transactions on Communications*, vol. 42, no. 10, pp. 2908–2914, 1994.
- [54] U. Tureli, H. Liu, and M. Zoltowski, "OFDM Blind Carrier Offset Estimation: ESPRIT," *IEEE Transactions on Communications*, vol. 48, no. 9, pp. 1459– 1461, 2000.
- [55] J. Li, G. Liu, and G. Giannakis, "Carrier Frequency Offset Estimation for OFDM-based WLANs," *IEEE Signal Processing Letters*, vol. 8, no. 3, pp. 80–82, 2001.
- [56] Z. Cao, U. Tureli, Y.-D. Yao, and P. Honan, "Frequency Synchronization for Generalized OFDMA Uplink," in *IEEE Global Telecommunications Conference*, vol. 2, 2004, pp. 1071–1075 Vol.2.

- [57] J. Choi, Y.-H. Lee, C. Lee, and H. won Jung, "Carrier Frequency Offset Compensation for Uplink of OFDM-FDMA Systems," in *IEEE International Conference on Communications*, vol. 1, 2000, pp. 425–429 vol.1.
- [58] S. Barbarossa, M. Pompili, and G. Giannakis, "Channel-independent Synchronization of Orthogonal Frequency Division Multiple Access Systems," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 2, pp. 474–486, 2002.
- [59] M. Brandt-Pearce, "Transmitter-based Multiuser Interference Rejection for The Down-link of A Wireless CDMA System in A Multipath Environment," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 407 -417, Mar. 2000.
- [60] E. Alsusa and C. Masouros, "Adaptive Code Allocation for Interference Management on The Downlink of DS-CDMA Systems," *IEEE Transactions on Wireless Communications*, vol. 7, no. 7, pp. 2420 –2424, 2008.
- [61] J.-J. van de Beek, P. Borjesson, M.-L. Boucheret, D. Landstrom, J. Arenas, P. Odling, C. Ostberg, M. Wahlqvist, and S. Wilson, "A Time and Frequency Synchronization Scheme for Multiuser OFDM," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 11, pp. 1900–1914, 1999.
- [62] J.-J. van de Beek, M. Sandell, and P. Borjesson, "ML Estimation of Time and Frequency Offset in OFDM Systems," *IEEE Transactions on Signal Processing*, vol. 45, no. 7, pp. 1800–1805, 1997.
- [63] M. Park, K. Ko, H. Yoo, and D. Hong, "Performance Analysis of OFDMA Uplink Systems with Symbol Timing Misalignment," *IEEE Communications Letters*, vol. 7, no. 8, pp. 376 – 378, 2003.
- [64] K. Hamdi, "Precise Interference Analysis of OFDMA Time-asynchronous Wireless AD-HOC Networks," *IEEE Transactions on Wireless Communica*tions, vol. 9, no. 1, pp. 134 –144, 2010.
- [65] D. Kim and G. Stuber, "Residual ISI Cancellation for OFDM with Applications to HDTV Broadcasting," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1590 –1599, Oct. 1998.

- [66] G. Lebrun, T. Ying, and M. Faulkner, "MIMO Transmission Over A Timevarying Channel Using SVD," in *IEEE Global Telecommunications Confer*ence, vol. 1, 2002, pp. 414–418 vol.1.
- [67] S. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, 1998.
- [68] H. Jafarkhani, Space-Time Coding Theory and Practice. Cambridge: Cambridge University Press, 2005.
- [69] V. Tarokh, H. Jafarkhani, and A. Calderbank, "Space-time Block Codes from Orthogonal Designs," *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, 1999.
- [70] J. Laneman and G. Wornell, "Distributed Space-time-coded Protocols for Exploiting Cooperative Diversity in Wireless Networks," *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2415 – 2425, oct. 2003.
- [71] M. Yu and J. Li, "Is Amplify-and-forward Practically Better than Decodeand-forward or Vice Versa?" in *IEEE International Conference on Acoustics*, *Speech, and Signal Processing*, vol. 3, 2005, pp. iii/365–iii/368 Vol. 3.
- [72] R. Nabar, H. Bolcskei, and F. Kneubuhler, "Fading Relay Channels: Performance Limits and Space-time Signal Design," *IEEE Journal on Selected Areas* in Communications, vol. 22, no. 6, pp. 1099–1109, 2004.
- [73] T. Hunter and A. Nosratinia, "Diversity Through Coded Cooperation," *IEEE Transactions on Wireless Communications*, vol. 5, no. 2, pp. 283 289, feb. 2006.
- [74] Z. Yi and I.-M. Kim, "Single-Symbol ML Decodable Distributed STBCs for Cooperative Networks," *IEEE Transactions on Information Theory*, vol. 53, no. 8, pp. 2977 –2985, aug. 2007.
- [75] P. Anghel and M. Kaveh, "On The Performance of Distributed Space-time Coding Systems with One and Two Non-regenerative Relays," *IEEE Transactions on Wireless Communications*, vol. 5, no. 3, pp. 682 – 692, march 2006.

- [76] J. He, P. Loskot, T. O'Farrell, V. Friderikos, S. Armour, and J. Thompson, "Energy Efficient Architectures and Techniques for Green Radio Access Networks," in 5th International ICST Conference on Communications and Networking in China (CHINACOM), 2010, pp. 1–6.
- [77] H. Karl, An Overview of Energy-efficiency Techniques for Mobile Communication Systems. Telecommunication Networks Group: Technical University Berlin. Tech. Rep, September 2003.
- [78] F. Cao and Z. Fan, "The Tradeoff Between Energy Efficiency and System Performance of Femtocell Deployment," in 7th International Symposium on Wireless Communication Systems (ISWCS), 2010, pp. 315–319.
- [79] S. R. Saunders, S. Carlaw, A. Giustina, R. R. Bhat, V. S. Rao, and R. Siegberg, *Femtocells: Opportunities and Challenges for Business and Technology*, S. R. Saunders, Ed. West Sussex: Wiley-Blackwell, 2009.
- [80] Y. Bai, J. Zhou, and L. Chen, "Hybrid Spectrum Sharing for Coexistence of Macrocell and Femtocell," in *IEEE International Conference on Communica*tions Technology and Applications, 2009, pp. 162–166.
- [81] M. Latham, "Consumer Attitudes to Femtocell Enabled In-home Services -Insights from A European Survey," in *Femtocells Europe*, 2008.
- [82] Z. Bharucha, G. Auer, and T. Abe, "Downlink Femto-to-macro Control Channel Interference for LTE," in *IEEE Wireless Communications and Networking Conference (WCNC)*, 2011, pp. 1259–1264.
- [83] Z. Bharucha, G. Auer, T. Abe, and N. Miki, "Femto-to-Macro Control Channel Interference Mitigation via Cell ID Manipulation in LTE," in *IEEE Vehicular Technology Conference (VTC Fall)*, 2011, pp. 1–6.
- [84] C. Esli, M. Koca, and H. Delicl§, "Iterative Joint Tone-Interference Cancellation and Decoding for MIMO-OFDM," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 5, pp. 2843–2855, 2008.
- [85] K. Zheng, Y. Wang, W. Wang, M. Dohler, and J. Wang, "Energy-efficient Wireless In-home: The Need for Interference-controlled Femtocells," *IEEE Wireless Communications*, vol. 18, no. 6, pp. 36–44, 2011.

- [86] M. Z. Chowdhury, Y. M. Jang, and Z. J. Haas, "Interference Mitigation Using Dynamic Frequency Re-use for Dense Femtocell Network Architectures," in Second International Conference on Ubiquitous and Future Networks (ICUFN), june 2010, pp. 256 –261.
- [87] H.-C. Lee, D.-C. Oh, and Y.-H. Lee, "Mitigation of Inter-Femtocell Interference with Adaptive Fractional Frequency Reuse," in *IEEE International Conference on Communications (ICC)*, may 2010, pp. 1–5.
- [88] C. G. Gerlach, I. Karla, A. Weber, L. Ewe, H. Bakker, E. Kuehn, and A. Rao, "ICIC in DL and UL with Network Distributed and Self-organized Resource Assignment Algorithms in LTE," *Bell Labs Technical Journal*, vol. 15, no. 3, pp. 43–62, 2010. [Online]. Available: http://dx.doi.org/10.1002/bltj.20456
- [89] A. Stolyar and H. Viswanathan, "Self-Organizing Dynamic Fractional Frequency Reuse for Best-Effort Traffic through Distributed Inter-Cell Coordination," in *IEEE INFOCOM*, 2009, pp. 1287–1295.
- [90] L. Zheng and C. W. Tan, "Cognitive Radio Network Duality and Algorithms for Utility Maximization," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 3, pp. 500–513, 2013.
- [91] L. Tan, Z. Feng, W. Li, Z. Jing, and T. Gulliver, "Graph Coloring Based Spectrum Allocation for Femtocell Downlink Interference Mitigation," in *IEEE Wireless Communications and Networking Conference (WCNC)*, march 2011, pp. 1248–1252.
- [92] Q. Zhang, X. Zhu, L. Wu, and K. Sandrasegaran, "A Coloring-based Resource Allocation for OFDMA Femtocell Networks," in *IEEE Wireless Communica*tions and Networking Conference (WCNC), 2013, pp. 673–678.
- [93] S. Uygungelen, G. Auer, and Z. Bharucha, "Graph-Based Dynamic Frequency Reuse in Femtocell Networks," in *IEEE 73rd Vehicular Technology Conference* (VTC Spring), 2011, pp. 1–6.
- [94] L. Weinberg, "A Simple and Efficient Algorithm for Determining Isomorphism of Planar Triply Connected Graphs," *IEEE Transactions on Circuit Theory*, vol. 13, no. 2, pp. 142–148, 1966.

- [95] U. K. Kumar and B. S. Umashankar, "Improved Hamming Code for Error Detection and Correction," in 2nd International Symposium on Wireless Pervasive Computing, 2007, pp. –.
- [96] Y. S. Jung and J. H. Lee, "Partner Assignment Algorithm for Cooperative Diversity in Mobile Communication Systems," in *IEEE 63rd Vehicular Tech*nology Conference (VTC-Spring), vol. 4, May 2006, pp. 1610–1614.
- [97] J. Laneman and G. Wornell, "Distributed Space-time-coded Protocols for Exploiting Cooperative Diversity in Wireless Networks," *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2415 – 2425, 2003.
- [98] M. Janani, A. Hedayat, T. Hunter, and A. Nosratinia, "Coded cooperation in wireless communications: space-time transmission and iterative decoding," *IEEE Transactions on Signal Processing*, vol. 52, no. 2, pp. 362 – 371, feb. 2004.
- [99] B. Sklar, Digital Communications: Fundamentals and Applications, 2nd ed. Prentice Hall, 2008.
- [100] X. Li, C. Xing, Y.-C. Wu, and S. Chan, "Timing Estimation and Resynchronization for Amplify-and-Forward Communication Systems," *IEEE Transactions on Signal Processing*, vol. 58, no. 4, pp. 2218 –2229, 2010.
- [101] T. Novlan, R. Ganti, A. Ghosh, and J. Andrews, "Analytical Evaluation of Fractional Frequency Reuse for Heterogeneous Cellular Networks," *IEEE Transactions on Communications*, vol. 60, no. 7, pp. 2029 –2039, july 2012.
- [102] Y. Yu, E. Dutkiewicz, X. Huang, M. Mueck, and G. Fang, "Performance Analysis of Soft Frequency Reuse for Inter-cell Interference Coordination in LTE Networks," in *International Symposium on Communications and Information Technologies (ISCIT)*, oct. 2010, pp. 504–509.
- [103] X. Qiu and K. Chawla, "On The Performance of Adaptive Modulation in Cellular Systems," *IEEE Transactions on Communications*, vol. 47, no. 6, pp. 884–895, Jun.
- [104] S.-F. Chou, H.-L. Chao, and C.-L. Liu, "An Efficient Measurement Report Mechanism for Long Term Evolution networks," in *IEEE 22nd International*

Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), sept. 2011, pp. 197–201.

- [105] M. Anas, F. Calabrese, P.-E. Ostling, K. Pedersen, and P. Mogensen, "Performance Analysis of Handover Measurements and Layer 3 Filtering for Utran LTE," in *IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications*, 2007, pp. 1–5.
- [106] J. Garcia-Luna-Aceves and S. Murthy, "A Path-finding Algorithm for Loopfree Routing," *IEEE/ACM Transactions on Networking*, vol. 5, no. 1, pp. 148–160, 1997.
- [107] O. Arnold, F. Richter, G. Fettweis, and O. Blume, "Power Consumption Modeling of Different Base Station Types in Heterogeneous Cellular Networks," in *Future Network and Mobile Summit*, june 2010, pp. 1–8.
- [108] I. Ashraf, L. Ho, and H. Claussen, "Improving Energy Efficiency of Femtocell Base Stations Via User Activity Detection," in *IEEE Wireless Communica*tions and Networking Conference (WCNC), april 2010, pp. 1–5.
- [109] R. Agusti and G. Junyent, "Performance of An FH Multilevel FSK for Mobile Radio in an Interference Environment," *IEEE Transactions on Communications*, vol. 31, no. 6, pp. 840–846, 1983.
- [110] G. Joshi and A. Karandikar, "Optimal Relay Placement for Cellular Coverage Extension," in National Conference on Communications (NCC), 2011, pp. 1–5.
- [111] Y. Chen, J. Zhang, Q. Zhang, and J. Jia, "A Reverse Auction Framework for Access Permission Transaction to Promote Hybrid Access in Femtocell Network," in *IEEE INFOCOM*, 2012, pp. 2761–2765.
- [112] S. Yun, Y. Yi, D.-H. Cho, and J. Mo, "Open or Close: On The Sharing of Femtocells," in *IEEE INFOCOM*, 2011, pp. 116–120.
- [113] Y.-Y. Li, L. Yen, and E. Sousa, "Hybrid User Access Control in HSDPA Femtocells," in *IEEE GLOBECOM Workshops*, 2010, pp. 679–683.

- [114] B. Han, A. Kalis, and R. Prasad, "Matching Parasitic Antenna for Single RF MIMO," in *International Conference on Microwave and Millimeter Wave Technology (ICMMT)*, vol. 1, 2012, pp. 1–4.
- [115] F. Rusek, D. Persson, B. K. Lau, E. Larsson, T. Marzetta, O. Edfors, and F. Tufvesson, "Scaling Up MIMO: Opportunities and Challenges with Very Large Arrays," *IEEE Signal Processing Magazine*, vol. 30, no. 1, pp. 40–60, 2013.
- [116] C. Shannon, "Mathematical Theory of Communication," Bell System Technical Journal, vol. 27, pp. 623–657, nov. 1948.

A. Appendix 1: Throughput Calculation

In order to calculate the bandwidth efficiency, channel capacity of the system needs to be known. Channel capacity is the maximum bit rate that can be achieved in a reliable communication system. Finding channel capacity requires knowledge of the signal being transmitted. This determines the channel models used for analysing the capacity. Because the system is digitised, the signal can be considered as discretetime and continuous-time. Discrete-time channel is used when signal transmitted for T_s period are considered as one symbol while continuous-time channel is considered when the analysis considers the overall transmitted waveform. The capacity of both channels are related by

$$C_{cont} = \frac{C_{disc}}{T_s} \tag{A.1}$$

where C_{cont} is the throughput, C_{disc} is discrete-time channel and T_s is symbol period.

The reliability in the channel capacity related to the probability of having correct message in the receiver and hence to the probability of bit error. In order to relate the probability of having error message to the rate of the message, metric for measuring the information content of the transmitted signal is required [99]. This metric is developed by Shannon [116] and is called entropy, Ξ , which is defined as the average amount of information per source output [99]. For any message, X, with M possible combinations and probability of p_1, \ldots, p_M , the entropy is given by [99]

$$\Xi(X) = \sum_{i=1}^{M} p_i \log_2 p_i \tag{A.2}$$

where $\sum_{i=1}^{M} p_i = 1$. For equally probable message signal with probability equals with

1/M, the entropy is simply given by

$$\Xi(X) = -\log_2\left(\frac{1}{M}\right) = \log_2 M \tag{A.3}$$

When there is input, X, given that it will have output, Y, conditional entropy, which is called equivocation, is required to analyse the system and is given by [99]

$$\Xi(X|Y) = -\sum_{X,Y} P(X,Y) \log_2 P(X,Y)$$
(A.4)

and can be expanded as

$$\Xi(X|Y) = -\sum_{Y} P(Y) \sum_{X} P(X|Y) \log_2 P(X|Y)$$
(A.5)

For an equally probable input signal, X, the output signal, Y, will also be equally probable and results in $\sum P(Y) = 1$. In addition, if the probability of having error symbol is given by P_s , the probability of having correct symbol is given by $(1 - P_s)$. Hence, the equivocation of equally probable input signal with M possible messages is given by

$$\Xi(X|Y) = -P_s \log_2\left(\frac{P_s}{M-1}\right) - (1-P_s) \log_2\left(1-P_s\right).$$
(A.6)

Using the entropy of the input message signal and the equivocation of the transmitted and the received signal, the discrete-time channel capacity is then given by [41]

$$C_{disc} = \Xi \left(X \right) - \Xi \left(X | Y \right) \tag{A.7}$$

and can be expanded as

$$C_{disc} = -\sum_{i=1}^{M} p_i \log_2 p_i + \sum_{Y} P(Y) \sum_{X} P(X|Y) \log_2 P(X|Y)$$
(A.8)

For equally probable input signal, the discrete-time channel capacity is then given by

$$C_{disc} = \log_2 M + P_s \log_2 \left(\frac{P_s}{M-1}\right) + (1-P_s) \log_2 (1-P_s)$$
(A.9)

It is important to note that although different input signal can be modified to have
different probability through some pre-coding; throughout this project the signals transmitted are equally probable message signal. This is because the main interest of this project is to explore the diversity technique, which is performed after the coding.

B. Appendix 2: Timing Effect Between Pairing Users in PT OFDMA

At the BS, the received signal, y(t) is multiplied with $\cos(2\pi f_c t)$ for the inphase and $\sin(2\pi f_c t)$ for the quadrature signals. If it is assumed that there is additional time offset in the local oscillator (LO) which leads to some phase offset, θ_o , the inphase signal after multiplication with the LO signal will become

$$y_i(t) = y(t)\cos\left(2\pi f_c t + \theta_o\right) \tag{B.1}$$

and the quadrature received signal will become

$$y_q(t) = y(t)\sin\left(2\pi f_c t + \theta_o\right). \tag{B.2}$$

This multiplication shifts all the information from f_c into 0 and $2f_c$ components. This means the bandpass filter representation, $\eta_{BP}(t)$, can be ignored since this multiplication shifts the non-zero values from between f_c and f_c+W , where W is the bandwidth of the transmitted signal, into the -W and W and between $2f_c$ and W components. Therefore, the inphase of y(t) is given by

$$y_i(t) = 2x_{\vartheta_p}(t) \left(h_1 \theta_{i_1} + h_2 \theta_{i_2} + h_3 \theta_{i_3} + h_4 \theta_{i_4} \right)$$
(B.3)

and similarly, the quadrature of y(t) is given by

$$y_q(t) = 2x_{\vartheta_p}(t) \left(h_1 \theta_{q_1} + h_2 \theta_{q_2} + h_3 \theta_{q_3} + h_4 \theta_{q_4} \right).$$
(B.4)

 $\theta_{i_1},\,\theta_{i_2},\,\theta_{i_3}$ and θ_{i_4} are respectively given by

$$\theta_{i_1} = (\cos(\theta_{d_1})\cos(\theta_o) [\cos(2\pi 2f_c t) - \cos(0)] - \cos(\theta_{d_1})\sin(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)] - \sin(\theta_{d_1})\cos(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)] - \sin(\theta_{d_1})\sin(\theta_o) [\cos(2\pi 2f_c t) - \cos(0)])$$
(B.5)

$$\theta_{i_2} = (\cos(\theta_{d_2})\cos(\theta_o) [\cos(2\pi 2f_c t) - \cos(0)] - \cos(\theta_{d_2})\sin(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)] - (B.6)$$
$$\sin(\theta_{d_2})\cos(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)] - \sin(\theta_{d_2})\sin(\theta_o) [\cos(2\pi 2f_c t) - \cos(0)])$$

$$\theta_{i_3} = (\sin(\theta_a + \theta_{d_3})\cos(\theta_o) [\cos(2\pi 2f_c t) - \cos(0)] + \cos(\theta_a + \theta_{d_3})\cos(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)] + \sin(\theta_a + \theta_{d_3})\cos(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)] - \cos(\theta_a + \theta_{d_3})\sin(\theta_o) [\cos(2\pi 2f_c t) - \cos(0)])$$
(B.7)

$$\theta_{i_4} = (\sin(\theta_a + \theta_{d_4})\cos(\theta_o) [\cos(2\pi 2f_c t) - \cos(0)] + \cos(\theta_a + \theta_{d_4})\cos(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)] + \sin(\theta_a + \theta_{d_4})\cos(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)] - \cos(\theta_a + \theta_{d_4})\sin(\theta_o) [\cos(2\pi 2f_c t) - \cos(0)]).$$
(B.8)

On the other hand, $\theta_{q_1}, \theta_{q_2}, \theta_{q_3}$ and θ_{q_4} are respectively given by

$$\theta_{q_1} = (\cos(\theta_{d_1})\cos(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)] + \cos(\theta_{d_1})\sin(\theta_o) [\cos(2\pi 2f_c t) + \cos(0)] + \sin(\theta_{d_1})\cos(\theta_o) [\cos(2\pi 2f_c t) + \cos(0)] - \sin(\theta_{d_1})\sin(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)])$$
(B.9)

$$\theta_{q_2} = (\cos(\theta_{d_2})\cos(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)] + \cos(\theta_{d_2})\sin(\theta_o) [\cos(2\pi 2f_c t) + \cos(0)] + \sin(\theta_{d_2})\cos(\theta_o) [\cos(2\pi 2f_c t) + \cos(0)] - \sin(\theta_{d_2})\sin(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)])$$
(B.10)

$$\theta_{q_3} = (\cos(\theta_a + \theta_{d_3})\cos(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)] - \sin(\theta_a + \theta_{d_3})\sin(\theta_o) [\cos(2\pi 2f_c t) + \cos(0)] + \cos(\theta_a + \theta_{d_3})\cos(\theta_o) [\cos(2\pi 2f_c t) + \cos(0)] + \sin(\theta_a + \theta_{d_3})\sin(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)])$$
(B.11)

$$\theta_{q_4} = (\cos(\theta_a + \theta_{d_4})\cos(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)] - \sin(\theta_a + \theta_{d_4})\sin(\theta_o) [\cos(2\pi 2f_c t) + \cos(0)] + \cos(\theta_a + \theta_{d_4})\cos(\theta_o) [\cos(2\pi 2f_c t) + \cos(0)] + \sin(\theta_a + \theta_{d_4})\sin(\theta_o) [\sin(2\pi 2f_c t) + \sin(0)])$$
(B.12)

Finally, the two signals are low pass filtered in order to remove the $2f_c$ components and get the baseband signal of the inphase, $y_1(t)$, and quadrature, $y_2(t)$, signals for maximum ratio combining in the frequency domain as illustrated in Equation 3.19 and Equation 3.20. Hence, after filtering, $y_1(t)$ and $y_2(t)$ in the absence of noise are given as If $\theta_a = 0$, then $y_1(t)$ and $y_2(t)$ become

$$y_{1}(t) = x_{\vartheta_{p}}(t) \{h_{1} [\cos(\theta_{d1})\cos(\theta_{o}) + \sin(\theta_{d1})\sin(\theta_{o})] \\ +h_{2} [\cos(\theta_{d2})\cos(\theta_{o}) + \sin(\theta_{d2})\sin(\theta_{o})] \\ +h_{3} [\sin(\theta_{d3})\cos(\theta_{o}) + \cos(\theta_{d3})\sin(\theta_{o})] \\ +h_{4} [\sin(\theta_{d4})\cos(\theta_{o}) + \cos(\theta_{d4})\sin(\theta_{o})]\}$$
(B.13)

$$y_{2}(t) = x_{\vartheta_{p}}(t) \{h_{1} [\cos(\theta_{d1}) \sin(\theta_{o}) + \sin(\theta_{d1}) \cos(\theta_{o})] \\ +h_{2} [\cos(\theta_{d2}) \sin(\theta_{o}) + \sin(\theta_{d2}) \cos(\theta_{o})] \\ +h_{3} [-\sin(\theta_{d3}) \sin(\theta_{o}) + \cos(\theta_{d3}) \cos(\theta_{o})] \\ +h_{4} [-\sin(\theta_{d4}) \sin(\theta_{o}) + \cos(\theta_{d4}) \cos(\theta_{o})]\}$$
(B.14)

On the other hand, if $\theta_a = \pi/2$, then $y_1(t)$ and $y_2(t)$ become

$$y_{1}(t) = x_{\vartheta_{p}}(t) \{h_{1} [\cos(\theta_{d_{1}})\cos(\theta_{o}) + \sin(\theta_{d_{1}})\sin(\theta_{o})] \\ +h_{2} [\cos(\theta_{d_{2}})\cos(\theta_{o}) + \sin(\theta_{d_{2}})\sin(\theta_{o})] \\ +h_{3} [\cos(\theta_{d_{3}})\cos(\theta_{o}) - \sin(\theta_{d_{3}})\sin(\theta_{o})] \\ +h_{4} [\cos(\theta_{d_{4}})\cos(\theta_{o}) - \sin(\theta_{d_{4}})\sin(\theta_{o})]\}$$
(B.15)

$$y_{2}(t) = x_{\vartheta_{p}}(t) \{h_{1} [\cos(\theta_{d1}) \sin(\theta_{o}) + \sin(\theta_{d1}) \cos(\theta_{o})] \\ +h_{2} [\cos(\theta_{d2}) \sin(\theta_{o}) + \sin(\theta_{d2}) \cos(\theta_{o})] \\ +h_{3} [-\sin(\theta_{d3}) \cos(\theta_{o}) - \cos(\theta_{d3}) \sin(\theta_{o})] \\ +h_{4} [-\sin(\theta_{d4}) \cos(\theta_{o}) - \cos(\theta_{d4}) \sin(\theta_{o})] \}$$
(B.16)

As can be clearly seen from Equation B.13 until Equation B.16, the phase offset within one pair, θ_a , only randomises further the already random channel path magnitude. Furthermore, setting θ_o of Equation 3.35 and Equation 3.36 to zero will simply eliminate the sin (θ_o) giving the following:

$$y_{1}(t) = x_{\vartheta_{p}}(t) \{h_{1}\cos(\theta_{d1}) + h_{2}\cos(\theta_{d2}) + h_{3}\sin(\theta_{a} + \theta_{d3}) + h_{4}\sin(\theta_{a} + \theta_{d4})\}$$
(B.17)
$$y_{2}(t) = x_{\vartheta_{p}}(t) \{h_{1}\sin(\theta_{d1}) + h_{2}\sin(\theta_{d2}) + h_{3}\cos(\theta_{a} + \theta_{d3}) + h_{4}\cos(\theta_{a} + \theta_{d4})\}.$$
(B.18)

In contrast, setting θ_o to $\pi/2$ will simply eliminate the $\cos(\theta_o)$ giving the following:

$$y_{1}(t) = x_{\vartheta_{p}}(t) \{h_{1}\sin(\theta_{d1}) + h_{2}\sin(\theta_{d2}) + h_{3}\cos(\theta_{a} + \theta_{d3}) + h_{4}\cos(\theta_{a} + \theta_{d4})\}$$
(B.19)
$$y_{2}(t) = x_{\vartheta_{p}}(t) \{h_{1}\cos(\theta_{d1}) + h_{2}\cos(\theta_{d2}) - h_{3}\sin(\theta_{a} + \theta_{d3}) - h_{4}\sin(\theta_{a} + \theta_{d4})\}.$$
(B.20)

Equation B.17 until Equation B.20 are evidences that even when the BS's LO phase offset, θ_o , is not perfectly synchronised with that of the transmitters, the receiver will always be able to detect the correct signal from the pair since the inphase and quadrature contain the same baseband signal. In contrast, this is not possible in the case of complex OFDM signal because the inphase and quadrature signals are different and hence the LO imperfections will affect them differently. The worst case scenario of LO imperfection of the complex OFDM signal is when the receiver detects the inphase signal as quadrature signal, which happens when the LO is offset by $\pi/2$.

C. Appendix 3: Proof of Lemma 1

The probability density function (PDF) of the SBS's position across the x or y direction based on the Assumption 1 is given by

$$f_{\mathscr{X}}(\mathsf{x}) = \begin{cases} \frac{1}{l}, & 0 < \mathsf{x} \le l \\ 0, & \text{otherwise} \end{cases}$$
(C.1)

Furthermore, if we assume $(\mathscr{X}_1, \mathscr{Y}_1)$ and $(\mathscr{X}_2, \mathscr{Y}_2)$ are the positions of the first and second random SBSs with PDF of Equation C.1, $\bigtriangleup \mathscr{X}$ and $\bigtriangleup \mathscr{Y}$ are given by $\bigtriangleup \mathscr{X} = \mathscr{X}_1 - \mathscr{X}_2$ and $\bigtriangleup \mathscr{Y} = \mathscr{Y}_1 - \mathscr{Y}_2$ respectively and the distance between the two SBSs, \mathfrak{G} , is given by

$$\mathfrak{G} = \sqrt{\left(\bigtriangleup \mathscr{X}\right)^2 + \left(\bigtriangleup \mathscr{Y}\right)^2}.$$
 (C.2)

 $\Delta \mathscr{X}$ and $\Delta \mathscr{Y}$ can also be written as $\Delta \mathscr{X} = \mathscr{X}_1 + \mathscr{X}_{2^-}$ and $\Delta \mathscr{Y} = \mathscr{Y}_1 + \mathscr{Y}_{2^-}$ where where \mathscr{X}_{2^-} is given by $-\mathscr{X}_2$ and \mathscr{Y}_{2^-} is given by $-\mathscr{Y}_2$. Based on the Assumption 1, then distance between T_c and u_z , d_{cu_z} , is equivalent to \mathfrak{G} and the PDF of d_{mu_z} is given by

$$f_{D_{MU_z}}(d_{mu_z}) = \begin{cases} \frac{1}{d_{MAX}}, & 0 < d_{mu_z} \le d_{MAX} \\ 0, & \text{otherwise} \end{cases}$$
(C.3)

and the relative distance between a UE and its neighboring BS, r_{mc} , is given by

$$r_{mc} = \frac{d_{mu_z}}{\mathfrak{G}}.\tag{C.4}$$

The PDF of \mathscr{X}_{2^-} , $f_{2^-}(\mathsf{x})$ is given by

$$f_{2^{-}}(\mathbf{x}) = \begin{cases} \frac{1}{l} & -l \leq \mathbf{x} < 0\\ 0 & \text{otherwise} \end{cases}$$
(C.5)

and the PDF of X_1 , $f_1(\mathbf{x})$, is equivalent to $f_{\Delta \mathscr{X}}(\mathbf{x})$. Therefore, the PDF of $\Delta \mathscr{X}$, $f_{\Delta \mathscr{X}}(\mathbf{x})$, is given by

$$f_{\Delta \mathscr{X}}(\mathsf{x}) = \int_{-\infty}^{\infty} f_{2^{-}}(\tau) f_1(\mathsf{x} - \tau) d\tau.$$
 (C.6)

If we assume that $u(\mathbf{x})$ is a step function across \mathbf{x} given by

$$u(\mathbf{x}) = \begin{cases} 1 & \mathbf{x} > 0\\ 0 & \text{otherwise} \end{cases}$$
(C.7)

Expanding Equation C.6 gives:

$$f_{\Delta \mathscr{X}}(\mathbf{x}) = \frac{1}{l^2} \int_{-\infty}^{\infty} \left[u(\tau+l) - u(\tau) \right] \\ \left[u(\mathbf{x}-\tau) - u(\mathbf{x}-\tau-l) \right] d\tau$$
(C.8)

and therefore

$$f_{\Delta \mathscr{X}}(\mathsf{x}) = \begin{cases} \frac{1}{l^2} (l + \mathsf{x}) & -l \leq \mathsf{x} < 0\\ \frac{1}{l^2} (l - \mathsf{x}) & 0 \leq \mathsf{x} \leq l \\ 0 & \text{otherwise} \end{cases}$$
(C.9)

Since $(\triangle \mathscr{X})^2$ is equivalent to $(|\triangle \mathscr{X}|)^2$, the PDF of $|\triangle \mathscr{X}|$ is given by

$$f_{|\triangle \mathscr{X}|}(\mathsf{x}) = \begin{cases} \frac{2}{l^2}(l-\mathsf{x}) & 0 \le \mathsf{x} \le l \\ 0 & \text{otherwise} \end{cases}$$
(C.10)

and the joint probability of $|\Delta \mathscr{X}|$ and $|\Delta \mathscr{Y}|$, $f_{|\Delta \mathscr{X}|,|\Delta \mathscr{Y}|}(\mathsf{x},\mathsf{y})$, is

$$f_{\mid \triangle \mathscr{X} \mid, \mid \triangle \mathscr{Y} \mid} \left(\mathsf{x}, \mathsf{y} \right) = \begin{cases} \frac{4}{l^4} \left(l - \mathsf{x} \right) \left(l - \mathsf{y} \right) & 0 < \mathsf{x}, \mathsf{y} < l \\ 0 & \text{otherwise} \end{cases} .$$
(C.11)

Using Equation C.11, the PDF of \mathfrak{G} , $f_{\mathfrak{G}}(\mathbf{g})$, is then given by

$$f_{\mathfrak{G}}(\mathbf{g}) = \int_{-\infty}^{\infty} \left| \frac{\mathbf{g}}{\sqrt{\mathbf{g}^2 - \mathbf{x}^2}} \right| f_{|\triangle \mathscr{X}|, |\triangle \mathscr{Y}|} \left(\mathbf{x}, \sqrt{\mathbf{g}^2 - \mathbf{x}^2} \right) d\mathbf{x}$$
(C.12)

It can be easily shown that $f_{\mathfrak{G}}(\mathbf{g})$ has the following solution

$$f_{\mathfrak{G}}(g) = \begin{cases} f_{\mathfrak{G}1}(\mathbf{g}) & 0 < \mathbf{g} < l \\ f_{\mathfrak{G}2}(\mathbf{g}) & l \leq \mathbf{g} \leq \sqrt{2}l \\ 0 & \text{otherwise} \end{cases}$$
(C.13)

where $f_{\mathfrak{G}_{1}}(\mathbf{g})$ and $f_{\mathfrak{G}_{2}}(\mathbf{g})$ are given by

$$f_{\mathfrak{G}1}(\mathbf{g}) = \frac{4\mathbf{g}}{l^4} \left[l^2 \arcsin\left(1\right) + \frac{1}{2}\mathbf{g}^2 - 2l\mathbf{g} \right]$$
(C.14)

$$f_{\mathfrak{G}2}(\mathbf{g}) = \frac{4\mathbf{g}}{l^4} \left[l^2 \arcsin\left(\frac{l}{\mathbf{g}}\right) - \frac{l^2}{2} + 2l\sqrt{\mathbf{g}^2 - l^2} - (C.15) \right]$$
$$2l^2 - l^2 \arcsin\left(\frac{\sqrt{\mathbf{g}^2 - l^2}}{\mathbf{g}}\right) - \frac{1}{2}\left(\mathbf{g}^2 - l^2\right) \right]$$

and it can be proven that

$$\int_{0}^{l} f_{\mathfrak{G}1}\left(\mathbf{g}\right) d\mathbf{g} \gg \int_{l}^{\sqrt{2}l} f_{\mathfrak{G}2}\left(\mathbf{g}\right) d\mathbf{g}.$$
 (C.16)

The PDF of the relative distance, r_{mc} , as described in Equation C.4 is given by

$$f_{R_{MC}}(r_{mc}) = \int_{-\infty}^{\infty} |\mathbf{g}| f_{D_{MU_z},\mathfrak{G}}(\mathbf{g}r_{mc},\mathbf{g}) d\mathbf{g}$$
(C.17)

where $f_{D_{MU_z},G}\left(d_{mu_z}, \mathbf{g}\right)$ is the joint PDF of d_{mu_z} and \mathfrak{G} given by

$$f_{D_{MU_z},\mathfrak{G}}\left(d_{mu_z},\mathfrak{g}\right) = \begin{cases} \frac{f_{\mathfrak{G}1}(\mathfrak{g})}{d_{MAX}}, & 0 < d_{mu_z} < d_{MAX}, \ 0 < \mathfrak{g} < l\\ \frac{f_{\mathfrak{G}2}(\mathfrak{g})}{d_{MAX}}, & 0 < d_{mu_z} < d_{MAX}, \ l \le \mathfrak{g} \le \sqrt{2}l \\ 0 & \text{otherwise} \end{cases}$$
(C.18)

Inserting Equation C.18 into Equation C.17 gives

$$f_{R_{MC}}(r_{mc}) = f_{R_{MC}1}(r_{mc}) + f_{R_{MC}2}(r_{mc})$$
(C.19)

where $f_{R_{MC1}}(r_{mc})$ and $f_{R_{MC2}}(r_{mc})$ are given by

$$f_{R_{MC}1}(r_{mc}) = \int_{-\infty}^{\infty} \frac{|\mathbf{g}| f_{\mathfrak{G}_1}(\mathbf{g})}{d_{MAX}} [u(\mathbf{g}) - u(\mathbf{g} - l)] [u(\mathbf{g}r_{mc}) - u(\mathbf{g}r_{mc} - d_{MAX})] d\mathbf{g}$$
(C.20)

$$f_{R_{MC}2}(r_{mc}) = \int_{-\infty}^{\infty} \frac{|\mathbf{g}| f_{\mathfrak{G}2}(\mathbf{g})}{d_{MAX}} \left[u(\mathbf{g}-l) - u(\mathbf{g}-\sqrt{2}l) \right] \\ \left[u(\mathbf{g}r_{mc}) - u(\mathbf{g}r_{mc} - d_{MAX}) \right] d\mathbf{g}.$$
(C.21)

Since the CDF of $f_{\mathfrak{G}1}(\mathbf{g})$ and $f_{\mathfrak{G}2}(\mathbf{g})$ are related based on Equation C.16, it can be shown that

$$f_{R_{MC}}\left(r_{mc}\right) \approx f_{R_{MC}1}\left(r_{mc}\right). \tag{C.22}$$

It can also be easily shown that $f_{R_{MC}1}\left(r_{mc}\right)$ has the following solution

$$f_{R_{MC}1}(r_{mc}) = \begin{cases} \frac{4l}{3d_{MAX}} \operatorname{arcsin}(1) + \frac{4l}{10d_{MAX}} - 2\frac{l}{d_{MAX}}, & 0 < r_{mc} < \frac{d_{MAX}}{l} \\ \frac{4d_{MAX}^2}{3l^2 r_{mc}^3} \operatorname{arcsin}(1) + \frac{4d_{MAX}^4}{10l^4 r_{mc}^5} - \frac{2d_{MAX}^3}{l^3 r_{mc}^4}, & r_{mc} \ge \frac{d_{MAX}}{l} \end{cases}$$
(C.23)