Interference Mitigation in Cognitive Small Cell Networks

Diky Siswanto

Submitted in accordance with the requirements for the degree of

Doctor of Philosophy

The University of Leeds

School of Electronic and Electrical Engineering

July 2017

Intellectual Property and Publication Statements

The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Publications

Chapter 4 is based on work published in:

Siswanto, D.; Zhang, L. & Navaie, K. Spectrum splitting-based cognitive interference management in two-tier LTE networks. 2014 11^{th} International Symposium on Wireless Communications Systems (ISWCS), pp. 613-617. 26-29 Aug. 2014, Barcelona. DOI: 10.1109/ISWCS.2014.6933427, ISSN: 2154-0217

Chapter 6 is based on work published in:

Siswanto, D.; Zhang, L.; Navaie, K.; & Deepak. Weighted Sum Throughput Maximization in Heterogeneous OFDMA Networks. 2016 IEEE 83^{rd} Vehicular Technology Conference (VTC 2016-Spring), pp. 1-5., 15 –18 May 2016, Nanjing. DOI: 10.1109/VTCSpring.2016.7504531

Zhang, L. & Navaie, K. provided directions, supervisions, and reviews for those works. Author performed modelling, coding, simulating and numerical analysis as well as analysed the results. Deepak G. C. provided the basic concept.

To my parents: (the late) Mr Suatmadi and Mrs Sunartiah that encourage and motivate me achieving the dream.

To my family that accompanies and supports my strive achieving the dream in situations of joy and sorrow: Esti, Iqbal, Alya and Nabila.

To my siblings who accompany, motivate, inspire and strive together achieving the mature of life: Sony, Yuni, Fony, Rony and Ratna.

Acknowledgements

First and foremost, all praises be to Allah the Almighty the Merciful who has been giving me his blessings and guidance throughout my journey in the PhD and my life.

I am grateful to Dr Li Zhang who was my main supervisor during my doctoral studies. Her patient, guidance, motivation, and support were invaluable to my research.

I am grateful to Dr Keivan Navaie who was my co-supervisor during my doctoral studies. His guidance, motivation, support, and exemplary encourage me to pursue my PhD.

I am thankful to Dr Des McLernon who was the Post Graduate Research Tutor at School of Electronic and Electrical Engineering, the University of Leeds during my doctoral studies.

I am grateful to Professor Jaafar Elmirghani who was the Director of the Institute for Integrated Information System (I3S), School of Electronic and Electrical Engineering, the University of Leeds during my doctoral studies. His support and exemplary motivate me to finish my doctoral study.

I appreciate to Professor Mounir Ghogho who oversees researchers at the Laboratory where I worked during my doctoral study at School of Electrical and Electronics Engineering, University of Leeds.

I appreciate to Dr Mohsen Razavi and Dr Daniel Ka Chun So, who were the examiners during the doctoral examination. Their critical and valuable feedbacks encourage and help me to improve and perfect my works.

I am thankful to Directorate General of Higher Education (DIRJEN DIKTI) - the Republic of Indonesia that provided scholarships and opportunities for my doctoral studies at the University of Leeds, Leeds, England.

I thank the University of Widyagama for the support and opportunity that allows me to pursue the PhD at the University of Leeds, Leeds, England.

Finally, I extend my dearest thanks to my friends that I met during my long journey pursuing the PhD. I thank Dr Aseem and Dr Yossif for the motivation and great help. I thank Dr Waleed for his wise advice during my critical times at the beginning phase of the long journey pursuing the PhD. I thank Dr Ali and Dr Bernadi for the spirit, motivations and clues for pursuing my PhD. I thank Dr Taufiq for his valuable discussion that useful in expanding my knowledge and research. Hopefully, we can extend the discussion and conduct further study some day. I thank Deepak that inspiring me to extend my research. I also thank Dr Munajat, Dr Boya, Dr Arif, Dr Andyka and brother Agung for their support and the great help during my journey to finishing my PhD. We have many meaningful times with KIBAR and PPI-Leeds that forge me to be maturer and wiser with life. Last but not least, I thank all friends and colleagues for giving help and support during my tough journey finishing the PhD that I cannot mention each of them. May Allah bless all of you.

Diky Siswanto, Malang.

Abstract

The increasing demand for high-speed data service triggers researchers investigating and developing mobile wireless technology for indoor services. Some types of small cellular networks (small cells) are designed for indoor and random deployment with minimal operator involvement. The random deployment feature raises the probability of both co-tier and cross-tier interference. It enforces the small cells to have a feature of self-organisation. Hence, the research question going to be solved is "*how to mitigate interference in small cells subject to the spectrum scarcity, random deployment, dynamic wireless channel, and complexity of the heterogeneous cellular networks* (HetNet)?"

Considering the complexity problem, researchers consider a concept with a comprehensive approach to addressing those problems, e.g. cognitive small cell or cognitive interference management. To simplify and speed up information exchange among base-stations (BSs) and to consider channel gain for resource allocation, some methods called spectrum splitting based-cognitive interference management (SSCIM) are proposed in this thesis. The methods start with recognising subchannel gain, in which each BS broadcasts pilot signals. Then each user terminal will receive the pilot and transmit back to its serving BS. Base on the pilot, the macro cellular BS (macro-BS) will identify and classify the resource blocks based on an assigned threshold, map and schedule the resource allocation. Subsequently, the macro-BS broadcasts the control channel and followed by data broadcasting. Meanwhile, small-BSs sense and analyse the macro-BS's control channel and then calculate and decide to occupy the idle spectra by using some power allocation techniques. The simulation results show that

SSCIM methods outperform both non-interference management and interfering resource blocking-based-CIM for the allocated subcarriers. Moreover, SSCIM methods have better spectrum efficiency than two others. However, the results are penalised by less macrocell performance. Additionally, the SSCIM's cell capacity is less than two others because of less allocated subchannels.

Furthermore, a sub-optimal spectrum and power allocation (sOSPA) method is also proposed to maximise sum rate in a simple HetNet model. SOSPA combines some techniques, such as local search and penalty function, to solve the nonlinear and nonconvex optimisation problem. sOSPA achieves the near optimum by finding out equilibrium of equal power allocation in each subchannel of the mutual interfering networks and sets either less or no power for violated subchannels. In the high-interference environment, with the proper SINR threshold, sOSPA achieves higher rate than the other methods. Additionally, sOSPA achieves the near optimum by considering both channel gain and inter-cell interference with a high rate of convergence.

Abbreviations

3GPP	Third Generation Partnership Project
5G	Fifth Generation
AMC	Adaptive modulation and coding
AWGN	Additive white Gaussian noise
BER	Bit-error-rate
BS	Base-station
bps	Bits per second
C-CSMA	Cognitive-carrier sense multiple access
C-SON	Centralised self-organising network
CA	Cognitive agent
CCTV	Close-circuit television
CDF	Cumulative Distribution Function
CDMA	Code division multiple access
CIM	Cognitive Interference Management
CIO	Cell individual offset
CoMP	Coordinated multipoint
CR	Cognitive Radio
CSC	Cognitive Small Cell
CSG	Closed (access) subscriber group
CSI	Channel state information
DEM	Dynamic exclusive use model
DSA	Dynamic spectrum access
EPA	Equal (uniform) power allocation
ETSI	European Telecommunications Standards Institute
FBE	Frame-based equipment

FC	Full-cognitive
FCC	Federal Communications Commission
FDMA	Frequency division multiple access
FFR	Fractional frequency reuse
FFT	Fast Fourier transform
FRF	Frequency reuse factor
HAM	Hierarchical access model
HeNB	Home evolved node B
HetNet	Heterogeneous cellular networks
HNB	Home node B
HUS	Home unit server
ICIC	Inter-cell interference coordination
ID	Identity
InH	Indoor hotspot
IP	Internet protocol
IRB-CIM	Interfering-resource-blocking-based CIM
ISM	Industrial, scientific and medical
IWF	Iterative water-filling
kbps	Kilo-bps
LBE	Load-based equipment
LOS	Line-of-sight
LTE	Long-Term Evolution
LTE-A	LTE-Advanced
MLB	Mobility load balancing
MRO	Mobility robustness optimisation
macro-BS	Macrocell BS
macro-UT	Macrocell user-terminal
macrocell	Macro cellular network
NLOS	Non-line-of-sight
NIM	Non-interference management
OFDM	Orthogonal Frequency Division Multiplexing

OFDMA	Orthogonal Frequency Division Multiple Access
OOPA	On-off power allocation
OSM	Open sharing model
PDCCH	Physical Downlink Control CHannel
PDSCH	Physical Downlink Shared CHannel
PF	Proportional fairness
PFR	Partial frequency reuse
PIC	Parallel interference cancellation
PU	Primary user
PUCCH	Physical Uplink Control CHannel
QoS	Quality of Service
RB	Resource-block
RB-map	Resource-block allocation map
RB-matrix	Resource-block allocation matrix
RF	Radio Frequency
RLF	Radio link failure
RS	Reference (pilot) signal
RSRP	Reference signal received power
SC	Semi-cognitive
SDMA	Space-division multiple access
SFR	Soft frequency-reuse
SIC	Successive interference cancellation
SINR	Signal-to-interference-plus-noise-ratio
SNR	Signal-to-noise-ratio
SSA	Split spectrum allocation
SSCIM	Spectrum-spliting-based CIM
SSR	Spectrum splitting and reuse
SU	Secondary user
small-BS	Small cell BS
small cell	Small cellular network
small-UT	Small cell UT

sOSPA	Sub-optimal spectrum and power allocation
TCSN	Temporary cognitive small cell network
TDMA	Time-division multiple access
UMa	Urban macro
UMi	Urban micro
UT	User terminal
VoIP	Voice over IP
VSAT	Very small aperture terminal
WF	Water-filling
Wi-Fi	Wireless-fidelity
WiMAX	Worldwide Interoperability for Microwave Access

Symbols

$\|\| \cdot \|\|$	norm of a vector
$\circ$	Hadamard product operator
$\otimes$	Kronecker product operator
$\mathbf{A}$	step size matrix
B	system bandwidth
B_{sc}	subchannel bandwidth
$\mathbf{C}$	a matrix of constraint functions
C	channel capacity
$\boldsymbol{\chi}$	a vector of estimated channel-to-interference-ratio
$\boldsymbol{\chi}^*$	a vector of selected channel to interference ratio
D	distance between centres of the nearest co-channel cells
$\boldsymbol{d}_{M/S}$	distance vector from BS to UT of the macrocell-M or the small cell-S
$\boldsymbol{d}_{MS/SM}$	distance vector from macro-BS-M to small-UT-S; or from small-BS-S to macro-UT-M
$\boldsymbol{d}_{MS0}$	distance vector between the macrocell centre and the small cell centre
d	transmitter to receiver distance
d_{corr}	decorrelation distance
d_{in}	a perpendicular distance from wall to a user
d_m	duplexing mode
d^M_{min}	minimum distance to macrocell
d^S_{min}	minimum distance to small cell
d_{out}	distance from macro-BS to the wall next to a small-UT
$\Delta(\cdot)$	differential function
Δf	subcarrier spacing
$\boldsymbol{\delta}$	a step size vector of the penalty function

δ	separation distance between two adjacent shadowing channels
e	the Euler's number
ϵ	a small value constant
$F_X(\cdot)$	cumulative distribution function of a random variable X
f_C	centre frequency
f_c	carrier frequency
f_d	fading channel type
$\boldsymbol{G}^{M/S}$	channel gain matrix from BS to UT of the macrocell-M/ the small cell-S
$\boldsymbol{G}^{MS/SM}$	channel gain matrix from macro-BS-M to small-UT-S/ from small-BS-S to macro-UT-M
$\boldsymbol{G}^{MS0}$	channel gain matrix between centres of macro-BS and small-BS
$G_k^{M,n}$	gain of subchannel-n for the macro-BS-M to macro-UT-k
$G_{k'}^{S,n}$	gain of subchannel-n for the small-BS-S to small-UT-k'
$G_{n,k}$	the propagation channel gain on subchannel n of user k
$\boldsymbol{\gamma}$	an estimated SINR vector
$\boldsymbol{\gamma}^*$	an estimated SINR vector of the selected channels
γ	signal-to-(interference-plus)-noise-ratio (SINR or SNR)
γ_0	optimum SNR threshold of the water-filling algorithm
γ_n	SNR of subchannel-n
γ_{in}	indoor path loss exponent
γ_n	an SINR of subchannel-n
γ_{ot}	urban macrocell path loss exponent
γ_{th}^M	macrocell SINR threshold
γ_{th}^S	the small cell SINR threshold
$\gamma(f)$	SNR of subchannel-f
H	Gaussian channel gain
H_f	channel response in frequency domain
H_n	channel gain of subchannel-n
$H_{n,k}$	frequency selective fading with Rayleigh distribution on subchannel-n of user k

$\boldsymbol{h}$	a vector of estimated channel
I	received interference power
$\boldsymbol{i}$	a vector of ones
i_0	number of co-channel interfering cells
$\mathbf{J}$	a matrix of ones
K	number of macro-UTs
K_S	number of small-UTs
L_w	wall penetration loss
$m_{k,n}$	allocation metric for user-k on resource block-n
N	number of total subchannels
N_0	Gaussian noise power spectral density
N_c	cluster size
$N_{collide}$	number of collided frames
N_F	FFT size
N_{frame}	number of total frames
N_{frame}^{sub}	sub-frame number per frame
$\mathcal{N}_k$	number of subchannels allocated to user-k
N_{RB}^{sc}	subcarrier number per RB
N_{sc}	number of subchannels
N_{sc}^*	number of allocated subchannels
N_{sub}^{slot}	slot number per sub-frame
N_{sub}^{RB}	resource-block number per sub-frame
N_{wu}	variant number of weak users per RB
n	path-loss exponent
$\boldsymbol{n}_k^{M/S}$	allocated subchannel set to user-k of macrocell M or small cell S
$\boldsymbol{\nabla}(\cdot)$	gradient function
$\boldsymbol{\Omega}$	penalty function multiplier
P	transmission power
$PF(\cdot)$	proportional fairness function
P_n	transmission power allocated to subchannel-n
P_n^M	allocated power on subchannel-n of the macrocell

P_n^S	allocated power on subchannel-n of the small cell
P_{tot}	total power allocated to a wireless system
P_{tot}^M	macro-BS total power
P_{tot}^S	small-BS total power
PL	propagation path-loss
PL_{B1}	UMi outdoor path-loss
PL_b	basic path-loss
PL_{In}	indoor link propagation loss
PL_{In-In*}	propagation loss for adjacent cells
PL_{In-Ot}	indoor to outdoor link propagation loss
PL_{in}	path loss inside the building
PL_{Ot}	outdoor link propagation loss
PL_{ot}	path loss outside the building
$\boldsymbol{\pi}_k^1$	an allocated power vector for small-UT-k of small-BS(1)
$\boldsymbol{\varphi}_0$	pre-transmitted pilot signal vector
$\boldsymbol{\varphi}_0^k$	pilot signals from macro-BS being received by the macro-UT-k
$\boldsymbol{\varphi}_1$	pilot signals received back from the small-BS(1)
$\boldsymbol{\varphi}_S$	a vector of total sum of pilot signals of all underlaying small-BSs
$\boldsymbol{\varphi}_{S^*}$	a vector of sum of pilot signals of neighbouring small-BSs
$\boldsymbol{\varphi}_s$	a vector of individual pilot signal from the neighbour small-BS-s
φ	resource allocation threshold
φ_M	percentage of allocated spectrum to macrocell
$\boldsymbol{\Psi}$	weak RB-matrix
ψ	shadowing
ψ_{dB}	log-normal shadowing
Q	co-channel reuse ratio
$R(\delta)$	spatial autocorrelation shadow fading
R_k	capacity of user-k
$R_k^{M,n}$	data rate of macro-UT-k on subchannel-n
$R_{k'}^{S,n}$	data rate of small-UT-k' on subchannel-n
$\overline{R_k(t)}$	average data rate of user-k over the transmission period

r	cell radius
$r_k(t)$	instantaneous data rate of user-k at time-t
$r_{kn}(t)$	data-rate of user-k on subchannel-n at time-t
r_M	radius of macrocell
r_S	radius of small cells
$\mathfrak{R}$	RB-matrix
$\boldsymbol{\rho}_k$	RB-map vector of the macro-UT-k
$\boldsymbol{\rho}^*$	a vector of idle subchannels not occupied by macrocell
S	total number of small-BSs
S_r	received signal power
$\sigma_{\psi dB}$	standard deviation of log-normal shadowing
T	signal time duration
t_c	average window size (in time slots)
$\boldsymbol{\theta}$	a vector of weak user number per RB with unique value
$\mathcal{V}(\cdot)$	penalty function
$\mathbf{X}$	a matrix of power allocation at HetNet
X_N	random variable with zero mean and Normal distribution
$x_{kn}(t)$	channel assignment status of user-k on subchannel-n at time-t

Contents

List of Figures

List of Tables

List of Algorithms

Chapter 1

Introduction

Along with the increasing demand on the high-speed data service, especially in indoor areas, the cellular technology has been growing up to *heterogeneous cellular networks* (HetNet) that include the main macro cellular (macrocell) and the underlaying small cellular (small cell) networks. Location, width, and the number of indoor areas can be various. Moreover, the thick and the material of the surrounding walls of indoor areas can be various as well. It will be costly and overload if radio resource allocation in indoor small cells, such as picocell and femtocell, must be arranged and controlled by the network provider. Based on this situation, indoor small cells are designed to enable random deployment without or with least intervention of the network provider. However, this feature of random deployment has a potency of interfering to nearby cellular networks, either macrocells or small cells. Thus the small cells also need a feature of interference mitigation capability to avoid or merely mitigate the harmful interference, either co-tier or cross-tier interference.

This thesis investigates the Interference Mitigation in Cognitive Small Cell Networks. The problems come up due to the random deployment of small cell networks. This situation has a potency of interfering the core macrocell network as well as among nearby small cell networks. It will degrade the performance of the overall system.

Some algorithms have been offered to mitigate the interference in HetNet. Various schemes are offered to solve the problem such as interference cancelation (Lopez-Perez et al., 2009), interference randomisation (Stamatiou and Proakis, 2005), interference avoidance (Rahman and Yanikomeroglu, 2010), co-tier vs cross-tier management (Saquib et al., 2012), coordinated management (Kosta et al., 2013) and distributed management (Chandrasekhar et al., 2009). The benefits of those various schemes as mentioned above were mutually exclusive, in which the combination of those approaches will give more benefits to the system (Rahman and Yanikomeroglu, 2010).

Alternatively, cognitive radio (Mitola, 1999) is considered the smartest radio technology to deal with dynamic and uncertainty of wireless propagation channel. The concept has inspired and motivated some researchers to apply this approach to small cell to enable smart and cognitive small cell dynamically and responsively adapt to the surrounding environment.

In this thesis, the interference management and radio resource allocation in HetNet have been studied. Some methods related to cognitive interference management in *orthogonal frequency division multiple access* (OFDMA)-based HetNet have been proposed. A numerical method to maximise sum rate in HetNet has also been proposed. Finally, conclusions of the research and potential future works are discussed in the last Chapter.

1.1 Motivation

The increasing need for data services, especially in indoor areas (Ericsson, 2014), encourages researchers to develop wireless technology to cover this area. Coexistence between the macrocell and the small cells is termed as HetNet. In which, at least two different network tiers coexist in the same area. Those networks have some remarkably different characteristic, such as transmission power, the radius of coverage areas, number and distribution of users. Thus, each element in these networks has a high probability of interfering each other harmfully.

Small cells are small, low-price, and low-power indoor base stations. These networks are generally consumer deployed and connected to the users' internet backhaul. In these aspects, they are similar to wireless-fidelity (Wi-Fi); but they alternatively utilise one or more commercial cellular standards and licensed spectrum. With the portable size and limited capacity, the deployment cost of small cells becomes more affordable for the users and can be installed in the desired areas subject to provided internet backhaul connected to the main network provider.

Along with the increase in wireless applications, radio spectrum becomes increasingly scarce. Thus, the deployment of HetNet needs to be aware of the spectrum efficiency, for example by applying radio spectrum sharing among coordinated networks. Moreover, as the extended coverage areas of the core macrocell networks, the small cell design must consider not to interfere, or to minimise the negative impact, to the macrocell and guarantees the improvement of the performance and the data rate for indoor users.

The proper selection of resource allocation strategies, such as transmission power control, frequency reuse, and dynamic spectrum access, can help improve the spectrum efficiency as well as reduce interference in HetNet. Resource allocation strategies mentioned above are complementary. It is necessary for the planning, coordination, and implementation appropriately and regular evaluation periodically. So that, it can mitigate interference in a dynamic and complex environment of HetNet.

Furthermore, having the inherent characteristic of awareness and adaptive, the cognitive radio concept gives an expectation in solving the problem of limited resources, dynamic and uncertainty of the wireless environment of the small cell networks.

1.2 Related Works

Some different schemes have been proposed to mitigate the interference in the small cell networks. A brief description of the schemes will be discussed here.

Interference cancellation is an interference mitigation scheme that decodes the received signal, and then use it along with channel estimates to remove the interference from the received signal. However, this scheme is often disregarded due to errors in the cancellation process (Lopez-Perez et al., 2009).

For interference randomisation, this scheme mitigates interference by dynamically and periodically allocating different time or frequency to a user, such as time hopping (Zahir et al., 2013) and frequency hopping (Verhulst et al., 1984). However, there are challenges to implementing these techniques, such as synchronisation between transmitter and receiver, and the overall bandwidth required to provide frequency hopping is much wider than that of one carrier system.

Meanwhile, interference avoidance manages the radio resources to avoid the impact of interference. By having the proper resource allocation techniques, such as transmission power control (Foschini and Miljanic, 1993), frequency reuse (Rappaport, 2002), time-access scheduling (Kong et al., 2009), and beamforming (Van Veen and Buckley, 1988), the system can keep the interference impact as low as possible.

The above schemes are commonly used in single layer networks. Those techniques can be classified as co-tier interference management. In those schemes, the resource allocation techniques are well planned, centrally coordinated and controlled to achieve the required performance of the overall system. However, the conventional static resource allocation techniques are not suitable for fast growing and random deployment of small cells (Saquib et al., 2012). Thus the method should also consider the existence of the small cells. In HetNet, the interference problems will be more complicated than in single layer cellular networks. Thus, the more independent, more distributed and hierarchical methods will be useful to deal with the problems.

For cross-tier interference management, the method should consider the existence of different tiered networks, such as the central macrocell network and its underlaying small cells. Each type of network groups has several unique differences such as maximum transmission power, the radius of coverage areas, the required performance and deployment objectives. In HetNet, the networks with different tiers could share the same radio spectrum, the same geographical space and the same time-access as well as the total allocated power. Under certain conditions, the network provider could assign different service priorities to different tiers of networks. To some extent, these networks need coordination and information exchange among tiers to mitigate interference and to improve the performance and capacity of overall HetNet. For example, to reduce the cross-tier interference, the strongest interferer femtocells should decrease their transmission power till a cellular user obtaining its *signal-to-interference-plus-noise-ratio* (SINR) target (Chandrasekhar et al., 2009). In which, it needs an information exchange among tiers to make a right decision of power allocation.

The coordinated interference management scheme mitigates the interference among networks by performing a coordination among interference sources. Some related nodes exchange inter-cell signalling among each other to understand each node's parameter and then allocate resources accordingly. In which, inter-cell signalling refers to the communication interface between neighbouring cells, and the received measurement message report from the user equipment (Kosta et al., 2013). Recent developments of the coordinated interference management are characterised by its control strategies. *Inter-cell interference coordination* (ICIC) (Kosta et al., 2013), *coordinated multipoint* (CoMP) (Irmer et al., 2011), and clustering small cells (Abdelnasser et al., 2014) can be considered as part of this scheme.

Distributed interference management is designed to enable scalability, reduce signalling overhead, and ease the implementation of small cells. This design will allow small cells to manage their resources with minimum dependency on the core macrocell network. In distributed networks, each node still requires coordination among others. In conventional networks, a backhaul network performs the necessary coordination (Pennanen et al., 2016). On the other hand, for fast-growing small cell deployments, such as picocell or femtocell, inter-network coordination will increase congestion and time delay in backhaul networks. Thus it needs another method to avoid those problems. Chapter 3 provides a detailed discussion of various interference management schemes above.

However, the complexity of interference management in the small cell networks and the dynamic nature of wireless channel need a comprehensive approach to addressing the problem. Rahman and Yanikomeroglu (2010) considered that some benefits of those schemes above were mutually exclusive. Thus, the combination of those approaches will give more benefits to the system.

Alternatively, *cognitive interference management* (CIM) is designed to combine some advantages of different schemes above by adopting the concept of a *cognitive radio* (CR) process. The idea of CIM comes from the CR concept that has a cognitive ability to sense the radio-scene, to identify the idle channels, to analyse and make a decision as well as to adjust the radio resources to use by considering some important aspects such as interference and channel gain (Haykin, 2005; Jouini et al., 2012; Mitola, 2000). CR is considered as the smartest radio technology to deal with dynamic and uncertainty of wireless propagation channel (Mitola, 1999). It is an intelligent wireless communication system that is aware of and learns from the radio environment and adapts to statistical variations in the input stimuli (Haykin, 2005). This concept becomes an answer for small cells that require the self-optimisation feature to adapt to their unpredicted environment. This concept has encouraged some researchers to apply this method to small cell to enable smart and cognitive small cell dynamically and responsively adapt to the surrounding environment.

1.3 Research Objectives

The research objectives of this thesis are:

- To investigate the radio resource allocation strategies that mitigate interference in HetNet.
- To investigate the sum rate maximisation methods in OFDMA-based HetNet.
- To analyse, compare, and evaluate the statistical performance of the proposed methods with some well-known algorithms.

1.4 Research Contributions

In this thesis, the author has:

1. Developed a model of HetNet including their propagation channel models.
2. Developed a simplified model of frame-based downlink transmission Long Term Evolution (LTE) networks.
3. Proposed some novel radio resource allocation techniques to mitigate interference as well as to maximise the overall system performance in HetNet. The proposed methods are spectrum-splitting-based cognitive interference

management (SSCIM1) (Chapter 4), the extended methods of SSCIM1 (SS-CIM: 2, 3 and 4) (Chapter 5), and sub-optimal spectrum and power allocation (sOSPA) (Chapter 6).

4. Analysed and compared the proposed methods with other existing methods. They consist of spectrum-sharing and *equal power allocation* (EPA) of non-interference management (NIM), interfering-resource-blocking-based CIM (IRB-CIM) (Kaimaletu et al., 2011), water-filling power allocation (WF) (Goldsmith, 2005), iterative water-filling (IWF) (Yu et al., 2002), partial orthogonal spectrum-allocation (also called as on-off power allocation: OOPA).

Some contributions are published in the following papers:

1. Siswanto, D.; Zhang, L. & Navaie, K. Spectrum splitting-based cognitive interference management in two-tier LTE networks. Wireless Communications Systems (ISWCS), 2014 11^{th} International Symposium on, 26-29 Aug. 2014, Barcelona, Spain.

2. Siswanto, D.; Zhang, L.; Navaie, K.; & Deepak. Weighted Sum Throughput Maximization in Heterogeneous OFDMA Networks. 2016 IEEE 83^{rd} Vehicular Technology Conference: VTC 2016-Spring, 15 –18 May 2016, Nanjing, China.

1.5 Thesis Outline

Following the Introduction in **Chapter** 1, the thesis is organised as follows:
Chapter 2 will overview the Cognitive Small Cell network including the concept and key requirements of a small cell, indoor deployment scenarios and self-organisation requirements. It also covers the current research of cognitive small cell and the underlying concept of cognitive radio.
Chapter 3 will discuss Interference and Resource Allocation in HetNet including some interference management techniques in small cell networks. This Chapter will also discuss a cognitive radio approach for interference management. In the last part, this Chapter will discuss various radio resource allocation techniques

in HetNet, including their issues such as channel capacity and optimisation problems.

Chapter 4 will propose Spectrum-Splitting-based Cognitive Interference Management (SSCIM1) to mitigate interference in HetNet. The Chapter will also describe the network and radio infrastructure models as well as the propagation channel model to provide a comprehensive understanding of the problem. The Chapter will end with simulation results and the performance analysis of the proposed scheme.

Chapter 5 will discuss the extended work of SSCIM1 (Chapter 4), namely SSCIM2, SSCIM3 and SSCIM4. These proposed schemes combine some resource allocation methods with the objectives of mitigating the interference and maximising sum rate of HetNet.

Chapter 6 will discuss weighted sum rate maximisation in a simplified OFDMA-based HetNet model. The Chapter covers problem formulation and a proposed method and also provides numerical analyses.

Chapter 7 will conclude the thesis with a summary, key findings, and explore the future works that can be extended from the current study.

Chapter 2

Cognitive Small Cells

2.1 Introduction

Cognitive small cell (CSC) brings the idea of small cell technology equipped with the self-adaptive ability of *cognitive radio* (CR). The small cell is designed to provide service with less coverage area than the conventional macrocell network, ranging from few metres to few kilometres, from indoor to outdoor and from urban to rural areas. For the smaller coverage of both outdoor and indoor areas, picocell and femtocell are designed to have self-organising capabilities (Claussen et al., 2008; Zhang and de la Roche, 2011), which includes some features such as self-configuration and self-optimisation. These features allow end users to self-deploy the small cell network with minimal intervention from the mobile operator.

Discussion of the CSC is necessary to know the objectives of small cell deployment and the need for features that support these objectives as well as the architecture required to support the feature to function. This Chapter aims to review the small cell concept, its deployment objective, the concept of self-organisation needed for small cell deployment and the idea of the CSC including deployment scenarios of these networks.

In this Chapter, some aspects of the small cell will be discussed. Section 2.2 will review the small cell concept. Self-Organisation features and concepts required for small cell deployment will be presented in Section 2.3. Section 2.4 will discuss the concept of CSC. Moreover, deployment scenarios will be discussed in

Section 2.5. Finally, Section 2.6 will summarise this Chapter.

2.2 The Concept of Small Cell

2.2.1 A Brief History

The idea of small cells has appeared for more than three decades (Stocker, 1984). Initially, "small cell" was a term for the cell size in a metropolitan area. In which a macrocell having a diameter of some kilometres is split into some smaller cells with reduced transmission power, known today as microcells, and having a radius of around several hundred metres.

At the same time, cellular repeaters or "boosters" were investigated as an alternative to small base stations (Drucker, 1988; Quinn, 1986). These re-radiating devices were intended to improve the signal quality in bad coverage regions as well as to reduce costs because of not requiring a wireline backhaul. However, their reuses of the licensed spectrum for backhaul limit the achievable throughput. Hence, cellular repeaters were not helpful to the system capacity.

In the 1990s, a pioneer to cellular pico cells began to appear (Iyer et al., 1990). Their cell sizes ranged from tens to about one hundred metres. These "traditional" small cells were used for coverage infill and capacity improvement. In which macrocell penetration was insufficient to provide a reliable communication link or where the macrocell was overloaded. However, these types of small cells were a smaller version of the macro base station and required comparable planning, management, and network interfaces.

Meanwhile, in the 1992s, BellSouth developed a small cell that is similar to the current femtocell concept (Brickhouse and Rappaport, 1996). The project developed an indoor femtocell-like solution that re-used the same spectrum as the macrocells and used wired backhaul (T1 or *public switched telephone network*). However, there was a lack of ubiquitous *Internet Protocol* (IP) backhaul at that time, and the integration level had not yet achieved the necessary condition in which the small cell functions as a miniature of a base station. Like the other small cell technologies mentioned above, they were technically a step forward but economically unsuccessful. These were caused by the cost of deploying and operating a large number of small cells outweighed the advantage they provided.

Since the 2000s, the operational and cost features of small cell deployment have become a new concern on the configuration and deployment of cellular networks (Andrews et al., 2012). These concepts have been applied successfully to residential femtocells, especially for cost issues. The femtocell concept is intended to combine fixed-line broadband access with cellular telephony, which uses the deployment of low-cost and low-power home base-stations in the subscribers' homes or premises (Claussen et al., 2008). Fundamentally, a femtocell is different from the traditional small cell. Femtocell needs to be more independent and self-adaptive (Andrews et al., 2012). In July 2007, the Femto Forum was founded to promote femtocell standardisation and deployment worldwide. In 2008, *Home Node B* (HNB) and *Home Evolved Node B* (HeNB) were first introduced in *3rd Generation Partnership Project* (3GPP) Release 8. HNB and HeNB are femtocell standards for *Universal Mobile Telephone System* and *Long Term Evolution* (LTE), respectively. By using second and third-generation chipsets, the higher capacity of femtocells was developed that leads these networks suitable for business with higher traffic throughput and coverage.

The coverage of femtocells was then extended outdoors, to include outdoor urban areas and even rural or remote areas. This increased scope led to an evolution of the term Small Cell. In February 2012, Femto Forum had renamed the Small Cell Forum to preferably reflect its work that includes residential, enterprise, metro and rural small cells, and also to prevent the perception that the small cell arena is fragmented.

Recently, small cells have become a hot topic for research. There is a significant increase in publications in this area, in which small cell technology has advanced a great deal from the uncomplicated cell splitting ideas (3GPP, 2015; Andrews et al., 2012; Nakamura et al., 2013; Stocker, 1984). Furthermore, the European Union has started funding research on femtocells, such as the BeFEMTO project, which concentrates on the analysis and development of LTE/LTE-Advanced (LTE-A) compliant femtocell technologies (BeFEMTO, 2010). Today, auto-configuration and self-optimisation capabilities have enabled small cells to be deployed by the end-user in a plug-and-play manner. Small cells can automatically integrate themselves into existing macrocell networks, which is an essential step to enable large-scale deployments of small cells.

Since LTE Release 10, small cell network densification has been an essential evolution direction in 3GPP to provide the necessary means to accommodate the anticipated huge traffic growth, especially for hotspot areas (Nakamura et al., 2013). Recently, LTE Release 12 has been started with more focus on small cell enhancements; in which, they will be focused on additional functionalities for enhanced performance in indoor and outdoor hotspot areas using low power nodes. In 3GPP-LTE Release 13 (3GPP, 2015), the target scenarios for small cell enhancement are defined as: (1) deployment scenarios, (2) spectrum usage, (3) traffic characteristics.

2.2.2 Types of Small Cells

Small cells are available for a broad range of air interfaces such as GSM, CDMA-2000, TD-SCDMA, W-CDMA, LTE and WiMax. Small cells provide a small radio coverage, which can cover from few metres within urban and indoor locations to few kilometres in rural area. Picocells and microcells can also have a range of a hundred metres to a few kilometres. However, they differ from femtocells in which they do not always have self-organising and self-management capabilities. Figure 2.1 illustrate varying small cells as part of future mobile networks.

Small Cell Forum (2012) has defined some terms about small cells as follows.

- Small Cell: This is an umbrella term for low-powered radio access nodes, which operates in a licensed and unlicensed spectrum and has a range of 10 metres to several hundred metres. It contrasts with a typical mobile macrocell which might have a range of up to some tens kilometres. This term covers femtocells, picocells, microcells and metrocells.

- Femtocell: This term is used for a low-power, short-range, self-contained base station. Initially, the term is used to describe consumer units intended for residential homes. Later, the term has expanded to include higher capacity units for wider areas such as enterprise, rural and metropolitan areas. Key attributes of this network include IP backhaul, self-optimisation, low power consumption and ease of deployment.

- Picocell: This term is typically used for low power compact base stations, which is deployed in enterprises or indoor public areas. The term is sometimes used to include outdoor small cells as well. For indoor use, this network deployment requires of selecting the number and location of these cells. Moreover, the self-optimising features of newer picocells, adopted from femtocell technology, minimise the amount of specialist knowledge required.

- Microcell: This term is typically used to describe an outdoor short-range base station intended for improving coverage area for both indoor and outdoor users, in which macro coverage is insufficient. Occasionally this network is installed indoors to provide coverage and increase the capacity in areas beyond the scope of a picocell.

- Metrocell: This term is used to describe small cellular technologies designed for improving the capacity of metropolitan areas. These devices are typically set on building walls or street furniture such as lampposts and *closed-circuit television* (CCTV) poles. This category can encompass technologies such as femtocells, picocells, and microcells that meet the deployment criteria.

A mix of macrocells and small cells as discussed above, and in some cases including *wireless-fidelity* (Wi-Fi) access points (Small Cell Forum, 2012), is called as heterogeneous networks or heterogeneous cellular network (HetNet). This HetNet is deployed together to provide coverage and improve capacity with handoff capabilities between them.

2.2.3 Deployment Objectives

Small cells can provide both indoor and outdoor wireless services. Mobile operators use them to extend their service coverage or increase network capacity. There is a huge data requirement for indoor areas. Almost 80 % of data traffic happens indoors. Besides, just 10 % of cells handle nearly 90 % of data traffic (Viavi Solution, 2015). This indoor service can be provided by indoor small cells such as picocells or femtocells.

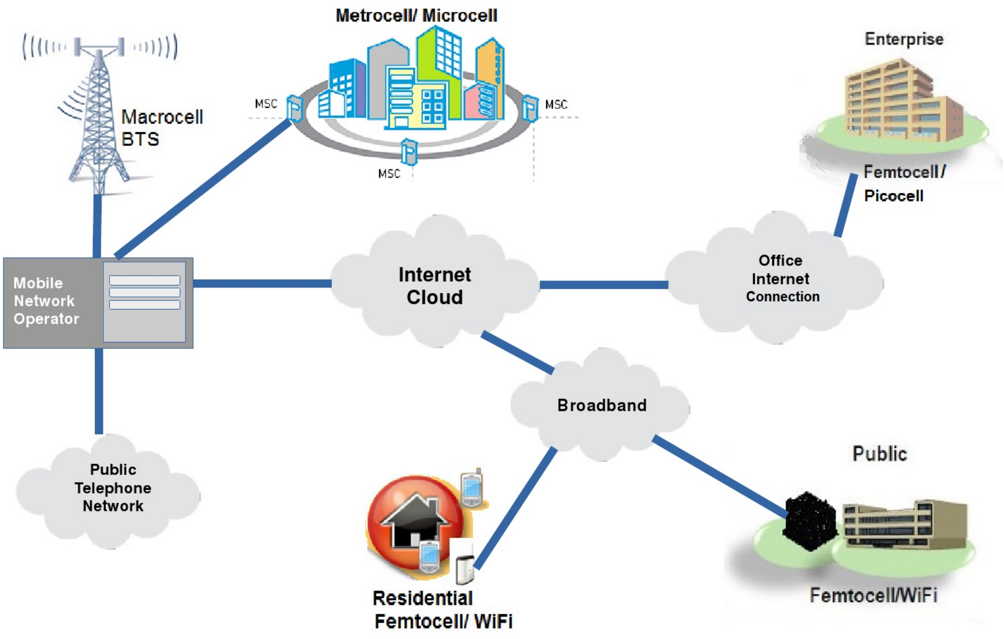


Figure 2.1: Small cells as an integral part of modern mobile networks

An *enterprise small cell* network can also enable service providers to offer services based on location or presence. Network access and applications can be customised based on a device location and employees can manage their accessibility (for example, when in a laboratory or conference room, delivering all communication to voicemail) based on their location or presence (Exact Ventures, 2012).

Rural coverage is also a key market. Mobile operators have started to install metrocell devices in remote and rural areas. Deploying small cells will make economically feasible to provide coverage of much smaller communities - from tens to hundreds of users. Small Cell Forum (2013) has described the technology and business case aspects related to the rural small cell.

Mobile operators have either tested or installed such systems in both developing and developed world countries. SoftBank Mobile, the Japanese mobile operator, has pioneered in providing rural coverage using small cells (Bright and Mavrakis, 2012). It has installed more than 3000 public access small cells on post offices throughout rural Japan. The backhaul requirement in remote locations is deployed using *very small aperture terminal* (VSAT) satellite backhaul to link sites to the core network.

Small cell deployment will reduce the macrocells' load of serving some indoor users, which is also called as offloading. Allocated resources for each indoor small cell user-terminal (small-UT) is equivalent to macrocell's resources that available for serving more than one outdoor macrocell UT (macro-UT), which results in a macrocell offloading gain. The macrocell offloading capacity gain due to indoor small cell deployments has been investigated by Claussen and Calin (2009), which results in up to 30% increase for mean throughput and about 100% gain for cell-edge user throughput. However, this work did not show total sum throughput of the entire HetNet that makes their overall capacity cannot be evaluated.

The objectives of small cell deployment, as investigated by Das et al. (2011), can be classified as follows.

- Maximisation of sum-cell-rate: Sum-cell-rate is the sum-rate of all small-UTs and the outdoor macro-UTs within the same coverage area of the macrocell. The maximum total system capacity can be achieved by allocating the macrocell traffic load optimally (50%) and decreasing the number of macro-UTs, which means offloading macrocell traffic load into small cells. Moreover, the maximum capacity achievement is also supported by enabling all deployed small cells with 100% traffic load and transmission power of 2 dBm, in which the increasing small cells' load have more impact on capacity maximisation than that of increasing the transmission power. Thus, some benefits for this scenario are maximising the total system capacity, offloading macrocell traffic to small cells, increasing small cell's load, and increasing area spectral efficiency when using co-channel for different network tier.

- Maximising the number of active small cells: The number of active small cells is the optimal number of small cells allowed operating at the same time without causing much co-channel interference to macrocell networks. The maximum number of active small cells is achieved by decreasing the number of macro-UTs and finding the optimal value of macrocell traffic load. If compared to the previous result, i.e. sum-cell-rate maximisation, this scenario showed that the 150% increase in the number of active small cells can be achieved against a penalty of 12.8% reduction in the total capacity. Thus, the benefits of this approach are maximising coverage and traffic offloading from macrocells into small cells.

- Combination of the above two objectives, i.e. to find the benefits by combining the above two purposes. This scenario can be achieved by decreasing the number of macro-UTs and finding optimum value of macrocell load. In which, the benefit of this scenario is improving macrocell throughput.

2.3 Self-Organisation

Due to the uncertainty in the number, distributions, and coverage area of small cells, each small cell is required to be able to completely self-organise themselves, especially for picocell or femtocell that are considered as having a user-deployed feature. By having this capability, the small cell needs either no or minimum intervention from the users.

2.3.1 Self-Organisation in Small Cells

From a network management perspective, there are two fundamental differences between the small cell and the conventional macrocell (Fehske et al., 2014).

1. Small cells come in much larger number into wireless networks than macrocells. As a consequence, manual processes for configuration and optimisation are no longer feasible.

2. Small cells are deployed much more dynamically. For macrocell, thoroughly planning is required before network deployments. On the other hand, small cells are often commissioned quickly whenever a capacity need is detected and without a procedural and gradual planning phase.

In general, the impact of small cell deployments on users connected to macrocells must be kept minimal at all times. As a result, small cell networks not only required more adaptations and reconfigurations due to more cells, but also they feature more adaptations and reconfigurations per cell. At a basic conceptual level, small cells do not look different from macrocells, especially from a terminals perspective. Due to the expectedly much large number of small cells, however, their automatic configuration is much more relevant than it is for macrocells. A manual configuration of each small cell would be costly and strongly question its business case.

The self-organisation capability should allow small cells to do some duties as follows (Claussen et al., 2008; Zhang and de la Roche, 2011).

- integrate themselves into the existing networks with minimal human involvement,
- learn about and adapt to their radio environment (neighbourhood and interference),
- tune their parameters accordingly,
- rearrange cell association to offload traffic from one base-station (BS) to another one,
- reconfigure and re-optimise itself when getting a problem.

Based on the scope of network and required time for the process, the self-organisation of small cells can be classified as follows (Fehske et al., 2014).

1. Small-scale short-term self-organisation:
   The reliable and efficient operation of small cells requires proper handovers and cell reselections between adjacent cells, such as between a macrocell and a small cell as well as between two small cells. In particular, the requirements are as follows.

   - Proper mobility: It covers the capability to avoid radio link failures (RLFs) and unnecessary handovers such as ping-pong. The 3GPP standard has defined precise mechanisms to analyse RLFs and exchange corresponding information among BSs which is referred to as Mobility Robustness Optimisation (MRO). Information exchange between BSs is practically achieved via X2 interface (ETSI, 2012), and

MRO can thus readily be applied to small cells as long as an X2 interface is available.

- Proper traffic steering: Appropriate fractions of traffic will be moved toward the small cells and potentially back to the macrocell. The choice of handover time is controlled via a specific parameter called a *cell individual offset* (CIO), which can be set individually for every cell pair. Small procedures for modifying CIOs due to unbalance traffic distribution are called *mobility load balancing* (MLB).

Since both MRO and MLB procedures modify the same parameters, their interaction must be handled with care.

2. Large-scale, long-term self-organisation:
Large-scale, long-term *centralised self-organising network* (C-SON) algorithms optimise certain configuration management parameters of a collection of a neighbouring-cell cluster. Typical C-SON uses for small cell deployments are the so-called *coverage and capacity optimisation* and the *energy saving management*. In particular, MRO and MLB, as discussed above for short-term adaptations, may be addressed by long-term techniques as well.

Based on the scope of duties, self-organisation required by a small cell can be classified as follows.

1. Self-configuration: A small cell, especially the one that is designed for user-deployed such as picocell and femtocell, needs to adjust its parameters accordingly that regular users do not need to know them in detail. Some critical parameters can affect the network performance if the provider lets low-skilled users tune themselves. It will be safer for overall systems to enable a small cell having self-configuration features from purchase to network integration. On installation steps, it is required the small cell having the ability to select the initial parameters required to commence its operation. Claussen et al. (2008) describes that the initial set up need to include some processes and parameters as follows.

(a) Purchase and Registration: After buying a small cell, the user provides small cell *identity* (ID), registers user's information and the address, preferential access UT for the small cell.

(b) Installation and authentication: the user plugs in power and backhaul connectivity, such as *digital subscriber line*, and switches on the small cell. When an Internet connection is established, the small cell contacts a *home unit server* (HUS) in the operator's network and transmits the identification code, part of user's small cell ID. The HUS then authenticates the small cell.

(c) Autoconfiguration and initial parameters: Some parameters are transmitted to small cells, such as: (i) Operating frequency for uplink and downlink; (ii) Femtocell scrambling code list; (iii) Cell ID; (iv) Location, routing and service area codes; (v) Initial pilot signal and maximum transmission power based on a target range, and (vi) (A) search priority list(s) of the macrocell's neighbour (if information on macrocells is available).

Fehske et al. (2014) considered configuration and optimisation begin with the acquisition of an IP address, downloading the correct software version, and then downloading the correct parameter configuration from an operators database. The process continues with adjusting parameter configuration during operation based on some measurements, such as *key performance indicators*, and customer complaints.

(d) Location check: The physical location of a small cell must be verified to ensure the position of the deployed small cell. It must comply with the operator's terms and conditions as set out in the contract with the end user. It is also not a location where the operator does not own *radio frequency* (RF) spectrum usage rights.

2. Self-optimisation: During operation, the small cell will need to monitor periodically and sense the environment to ensure that it takes into account of any changes required including the channel; pilot and maximum data transmission power; and the neighbour list. It ensures minimal impact on the macrocell network and provides maximum performance in the small cell

under the given constraints. Mitola (1999) develops a CR concept, which is a smart radio system that is aware and adaptive to its environment. This concept is expected to solve the need for self-optimisation features in small cells. Self-optimisation can be achieved through different strategies as follows.

- Distributed self-deployment: Guo and Wang (2012) proposed a distributed self-deployment solution to improve the indoor throughput. The proposed method identifies the direction of the strongest interference source. Then, the algorithm suggests a place to locate an indoor small cell optimally in a multi-room indoor environment. The proposed technique can be viewed as a distributed self-organising solution that does not require *channel state information* (CSI) or inter-cell interfaces. Moreover, the technique does not cause additional interference to the outdoor network that can be used in conjunction with other methods. The benefit of the proposed technique compared to blind placement is that it can achieve a throughput improvement of 20% to 50%.
- Self-optimisation of antenna tilt: Barth and Kuehn (2010) considered that the optimisation target is first to provide continuous coverage; in which connections can be established with acceptable service quality. The second optimisation target is cell capacity because the SINR distribution over the cell area depends again on antenna tilt.
- Self-optimisation of handover performance: Barth and Kuehn (2010) also considered that handover performance is a very critical quality measure for mobile communication systems. On one side, for the mobile user, a seamless mobility support without service interruption or call dropping is an essential feature. On the other hand, the system load generated by handovers has to be kept within reasonable limits to prevent a declining network efficiency.

3. Self-healing: As problems may occur after set-up or when in operation, the small cell will need to be able on solving any problems that may happen.

3GPP (2014) has developed a self-healing concept that consists of several functions and being processed sequentially such as monitoring, diagnosis, recovery actions, evaluation, fallback, and parameter update.

4. Self-decision-making for public access policy: When there is only one macro-cell's resource block available to grant public access to a small cell, the small cell having ability to take over the service for macro UTs of the same operator having a position close to the small cell to prevent excessive interference (Claussen et al., 2008).

2.3.2 Cognitive Radio and Cognitive Cycle

Cognitive radio (CR) is an intelligent wireless communication system that is aware of and learns from the radio environment and adapts to statistical variations in the input stimuli (Haykin, 2005). Two primary objectives of CR are (i) highly reliable communication whenever and wherever needed; (ii) efficient utilisation of the RF spectrum. This concept becomes an answer for small cells that require the self-optimisation feature to adapt to their unpredicted environment.

Cognitive Radio

The concept of CR is proposed as the answer for more RF spectrum needed by the new wireless application and the limitation of RF spectrum availability (Mitola, 1999). Six key words stand out in the definition of CR are awareness, intelligence, learning, adaptivity, reliability, and efciency (Haykin, 2005). The awareness capability of CR includes recognition of the transmitted waveform, RF spectrum, communication network, geography, locally available services, the user needs, language, situation, and security policy (Fette, 2006).

In CR terminology, *primary users* (PUs) have higher priority or legacy rights to occupy a specific RF spectrum. Otherwise, *secondary users* (SUs) have lower priority to exploit the RF spectrum in such a way that they do not interfere with PUs. For enabling to access the RF spectrum, SUs need to have CR capabilities, such as sensing the RF spectrum reliable for finding out the unused RF spectrum and changing the radio parameters to exploit the RF spectrum.

Before accessing the RF spectra, CR needs to sense and analyse which RF spectra are available for SUs. The spectra have been classified as follows (Haykin, 2005).

1. Black spaces: The spectra are occupied by high-power local interferers some of the time.
2. Grey spaces: These are partially occupied by low-power interferers.
3. White spaces: The spectra are free of RF interferers except for the ambient noise, which is made up of natural and man-made of noise.

Among those spectra, white spaces (for sure) and grey spaces (to a lesser opportunity and careful occupation) are obvious candidates for use by SUs.

Cognitive Cycle

The underutilisation of the spectrum has stimulated a confusion in engineering, economics, and regulation communities. They are searching for better spectrum management policies and techniques. Opposite to the static spectrum access, *dynamic spectrum access* (DSA) has broad connotations that encompass various approaches to spectrum reform. DSA strategies can be broadly categorised into three models: dynamic exclusive use model, open sharing model, and hierarchical access model (Zhao and Sadler, 2007). Further discussion about DSA will presented in 3.6.2.

Considering DSA is undoubtedly an essential application of CR; then CR represents a much broader paradigm where numerous aspects of communication systems can be improved via cognition. Self-awareness, user awareness, and machine learning differentiate ideal CR architecture from DSA (Mitola, 2009). CR needs this characteristic to adaptively and correctly responds the surrounding environment. Self-awareness is related to the responsiveness to the stimuli from outside world to recognise the context of its communications tasks. User awareness is related to the sensitivity of user's need such as urgency to respond; bandwidth needs to assure the *quality of service* (QoS). Moreover, machine learning enables the system to develop its capability and intelligence to respond the dynamic environment.

The implementation of CR needs some steps that usually called a cognitive cycle. The cognitive cycle starts from observing the input information both from radio environment and the input terminal, such as a keypad, and then terminates with action, as shown in Figure 2.2.

According to Haykin (2005), fundamental cognitive tasks are:

1. Radio-scene analysis, which encompasses the following:
   - estimation of interference temperature of the radio environment, which is a measure of interference power in a particular frequency band and a geographical area (FCC, 2002).
   - detection of RF spectrum holes, which some RF spectra are assigned to PUs, but, at a particular time or specific geographical area, the RF spectra are not being utilised by those users.
2. Channel-state estimation and prediction, which encompasses the following:
   - CSI estimation;
   - prediction of channel capacity for use by the transmitter.
3. Transmission power control and dynamic spectrum management.

Tasks (1) and (2) are carried out in the receiver, and task (3) is carried out in the transmitter. By interaction with the RF environment, these three tasks form a cognition cycle or cognitive tasks, as described in Figure 2.3.

It is apparent that the cognitive transmitter must work harmoniously with the cognitive receiver. A feedback channel that connects the receiver to the transmitter is needed to maintain this harmony at all times. By using the feedback channel, the receiver can convey information on the performance of the forward link to the transmitter.

From the decision-making perspective, the basic cognitive cycle considers three macro-steps as follows (Jouini et al., 2012):

1. *Observation*: The CR gathers information about its environment through its sensors. Raw data and pre-processed information help the agent to build a knowledge base. In this context, the environment refers to any source of

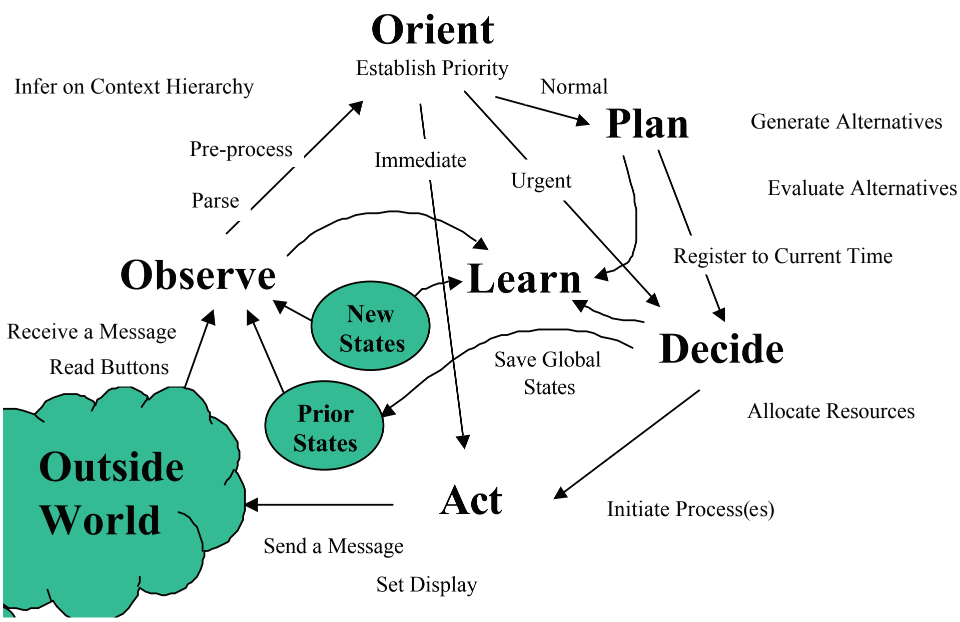


Figure 2.2: Mitola's simplified cognition cycle (Mitola, 2000)

information that could improve the CRs performance (such as internal state, interference level, regulators rules and enforcement policies).

2. *Analysis*: This macro-step includes all needed operations before given specific orders to the actuators (i.e., before reconfiguration in CR contexts). The step can deal with metric analysis, performance optimisation, scheduling, and learning, which depends on the level of sophistication.

3. *Action*: This step reconfigures mainly parameters and transmits waveform. The cognitive cycle should implement a reconfiguration management architecture to ensure efficient and quick reconfigurations.

As illustrated in Figure 2.4, a *cognitive agent* (CA) perceives an environment in a broad sense. The CA repeats the cognitive cycle. It *observes* the environment, *analyzes* the collected information and *decides* the next *action* to take.

A broadly defined CR technology accommodates a scale of differing degrees of cognition. At one end of the scale, the user may only pick an RF spectrum hole and develop its cognitive cycle around the hole (Haykin, 2005). At the other end of the scale, the user may apply multiple implementation technologies to build its

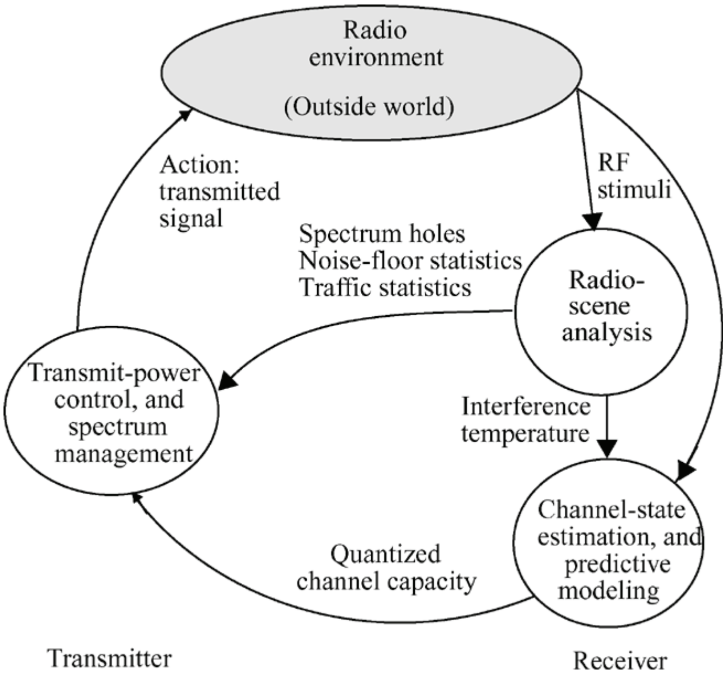


Figure 2.3: Haykin's basic cognitive cycle ©2005 IEEE (Haykin, 2005).

cognitive cycle around a wideband RF spectrum hole or set of narrowband RF spectrum holes to provide the best-expected performance concerning RF spectrum management and transmission power control, and process them in the most highly secure manner possible.

Haykin's DSA gives emphasis that CR needs to be aware of the many occupants of a radio environment by analysing the RF spectrum (Haykin, 2005). This awareness is required to avoid interference, to operate in RF spectrum holes, and to provide channel state information for enhancing the transmission quality.

2.4 Cognitive Small Cell

Cognitive Small Cell is considered as the cognitive radio-enabled small cell that aware and adaptive with the change and the dynamic of surrounding wireless environment. A cognitive network entity such as a small cell BS (small-BS) will be capable of monitoring the surrounding radio environment, adapting its transmis-

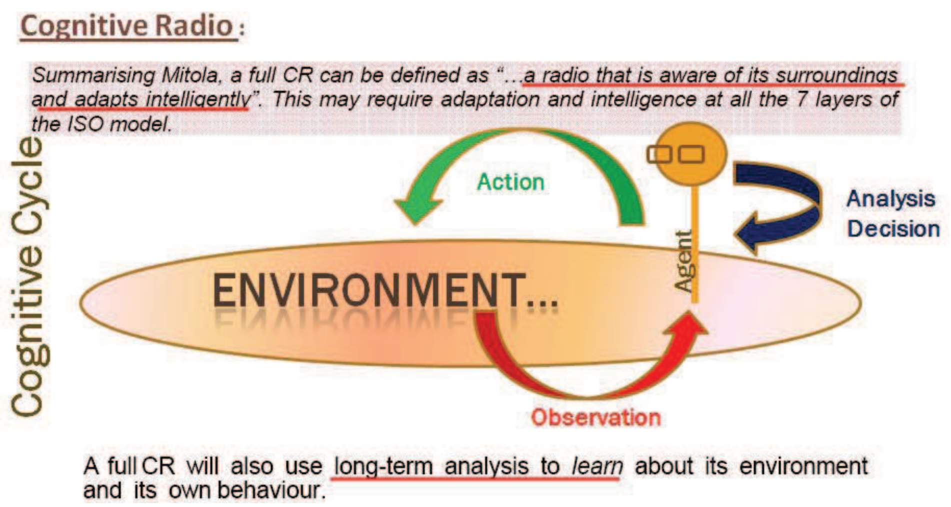


Figure 2.4: Basic cognitive cycle (Jouini et al., 2012).

sion parameters (such as transmission power and beamforming), identifying and locating major interference sources and then avoiding them by opportunistically accessing orthogonal channels (Elsawy et al., 2013). The idea of this concept comes from CR, which is designed to be aware, adaptive and dynamic access to the scarce RF spectrum. By having these characteristics, this concept is expected to be a solution to the complexity of small cell's radio environment.

2.4.1 Objectives

The objectives of the cognitive small cell development, including picocell and femtocell, can be listed as follows.

- to mitigate interference in HetNet (Hossain et al., 2014),
- to improve the network performance (Elsawy et al., 2013),
- to enable ultra-dense small cell deployment for future fifth Generation (5G) cellular technology (Tseng et al., 2015),
- to increase the network capacity in serving indoor users (Gur et al., 2010),
- to allow for higher capacity and intelligent coverage, with guaranteed QoS for future indoor services (Al-Rubaye et al., 2011),
- to improve the energy efficiency in cellular HetNet (Hasan et al., 2011),

- to provide more effective dynamic RF spectrum access and management (Gur et al., 2010),
- for enabling multi-tiered opportunistic access in next-generation wireless systems (Gur et al., 2010),
- to solve the RF spectrum scarcity problems (Al-Rubaye et al., 2011),
- to secure the RF spectrum efficiency in near-future networks (Gur et al., 2010).

Briefly, the objectives of cognitive small cell development above can be summarised as follows.

- to mitigate interference in multi-tier networks that effect to increasing the performance and capacity of HetNet;
- to allocate radio resources of HetNet efficiently or optimally depends on the objective function, such as energy efficiency, RF spectrum efficiency and opportunistic time access.

2.4.2 Requirements

To enable these objectives, a CSC should have capabilities as follows.

1. Being aware of the surrounding wireless environment by sensing the RF spectrum occupation to estimate any free resources (Al-Rubaye et al., 2011). This awareness will also prevent any interference with the macrocell coverage area. Then, transmissions occur wherever the macrocell's user is idle. Awareness of the radio environment is essential for a CSC to obtain available RF spectrum opportunities in macrocell networks. In which RF spectrum opportunities exist in various domains such as frequency, time, geographical space, code, beamforming, and code (Yucek and Arslan, 2009).

2. Having capabilities of learning and adapting to the surrounding environment (Gur et al., 2010). These features will help the small-BS allocates radio resources efficiently and consequently will be able to mitigate interference in HetNet.

3. In addition to cognitive capability, self-configuration capabilities are also the main characteristic of a CSC (Huang et al., 2013). Self-configuration capability helps a cognitive small-BS to coexist in a two-tier network without impact on existing cellular networks. This feature exploits cognitive information in a spectrum state database to optimise parameters of all layers in dynamic surroundings. Self-configuration module enables small cells to adapt to a dynamic environment.

2.4.3 Architecture

CSC should be developed by modifying hardware and firmware modifications in conventional small-BS for providing high-performance spectrum sensing, which can be listed as follows (Gur et al., 2010).

- Protocol stack changes, which provide security and privacy, should also allow access to the cognitive network provider to authorise the SUs and apply the required authentication, authorisation, and accounting functionalities.
- Powerful signal analysis methods for reliable wideband spectrum sensing.
- Hardware requirements such as antennas, more advanced RF front-ends and signal processing circuitry.

On the other hand, for small cells' users, substantial changes are limited to the software domain for wider and easier service penetration (Gur et al., 2010).

Figure 2.5 illustrates the functional architecture of the cognitive small-BS. A cognitive engine synthesises the cognitive and self-configuration modules. The cognitive module provides small cells with radio awareness capability. Any change sensed by the cognitive module automatically triggers an adjustment. Moreover, the self-configuration module enables small cells to adapt to a dynamic wireless environment.

The self-configuration module includes three components: (i) spectrum mobility, (ii) spectrum sharing, and (iii) spectrum configuration. Spectrum mobility management enables small cells to smoothly hand-over, which minimises their performance degradation as much as possible when macro channels are unavailable, or current channel conditions become worse. This scenario enables small

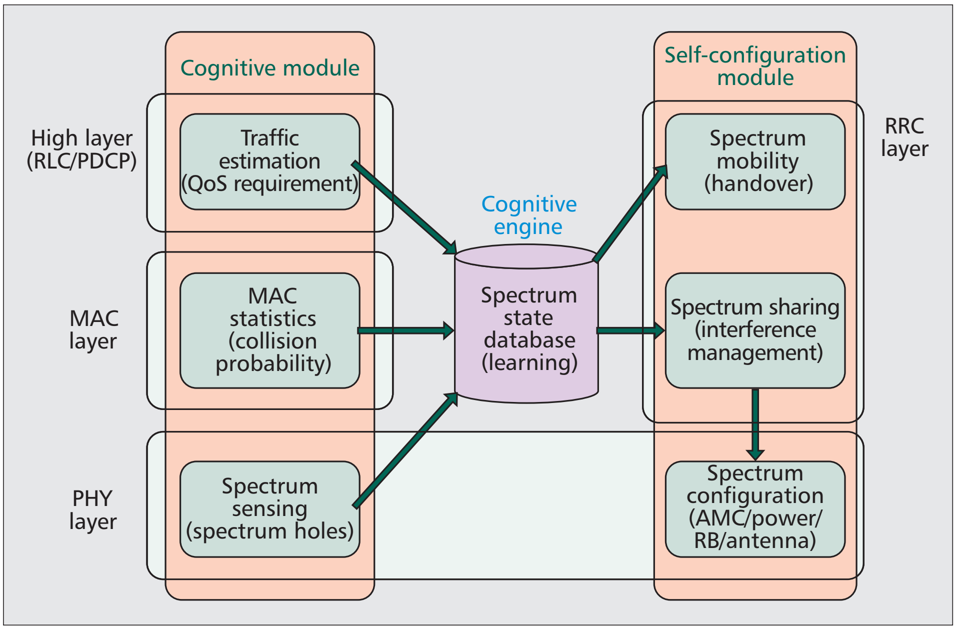


Figure 2.5: Cognitive small cell functional architecture ©2013 IEEE (Huang et al., 2013).

cells to provide open access for external users. Spectrum sharing management avoids co-channel collisions of multiple small cells. The spectrum configuration module ensures that small cells work in the best available channels. Configurable parameters in the physical layer include time-frequency resource blocks of *orthogonal frequency-division multiplexing* (OFDM), modulation and coding schemes, transmission power, and antenna angle/ beamforming.

Briefly, the resource allocation mechanism in a cognitive small cell can be described as follows (Huang et al., 2013). At first, the cognitive module senses the environment and collects specific information of all layers, such as spectrum holes, collision probability, and QoS requirement. Second, the cognitive engine analyses spectrum characteristics and estimates available resources. Also, third, the self-configuration module exploits cognitive information in an RF spectrum state database to optimise parameters of all layers in dynamic environments.

With learning and reasoning capabilities, cognitive small cells keep track of variations and estimate spectrum state from historical data in a dynamic environment. Since cognitive small-BSs have potential to allocate radio resources adaptively and efficiently mitigate co-channel interference in a two-tier network, it is promising to apply CR-enabled small cells to break through the spatial reuse barrier of cellular systems.

2.5 Deployment Scenarios

There are some parameters should be considered when deploying CSCs. It spans from the simple one such as the spectrum sensing threshold to the complicated one such as interference mitigation. This section will discuss deployment scenarios of those kinds of cellular networks.

2.5.1 Spectrum Sensing Threshold and Channel Categories

A spectrum sensing threshold is a border level for received signal on a communication system to determine the good or bad quality of the signal. The obtained information in the term of received power level can represent the channel quality when the signal is transmitted with uniform distribution transmission power for all allocated subchannels such as in pilot signal.

A channel is considered free by a CSC if the received interference power on that channel is smaller than the spectrum sensing threshold. It can be either free channels or semi-occupied channels, depend on the determined level of the spectrum sensing threshold. Otherwise, the channel is considered as occupied by another network.

The spectrum sensing threshold is a very critical design parameter that can be tuned to achieve the desired trade-off between spatially spectral efficiency and interference (which translates to outage probability) (Elsawy et al., 2013). Based on the spectrum sensing threshold, CSCs will avoid using the same channel used by the neighbouring network elements. However, if the spectrum sensing threshold is not carefully tuned, cognition may degrade network performance and increase outage probability (Elsawy et al., 2013).

By using spectrum sensing threshold, channel characteristic can be measured by the possible interference level. Hence, the channels can be classified as follows (Femto Forum, 2010; Li, 2010).

- Free channels (interference free): the channels are 100% free of use because of zero interference. The channels are not reused anywhere in the whole network and thus automatically gain the highest reuse priority. A CSC should always start serving its users by using these perfect channels without causing interference to others.

- Semi-occupied channels (soft-interference): the channels that are only interfered by the majority of far-way small cells. Each of them contributes a low interference to the small cell of interest, and the aggregate effect behaves like a Gaussian distribution due to the Central Limit Theorem. A CSC can opportunistically select the best channels for reuse, which generates the smallest interference to co-channel cells at far distances. The proposed methods in Chapter 4, and Chapter 5, and Chapter 6 apply a threshold to reuse the semi-occupied subchannels.

- Occupied channels (hard-interference): the channels those are not reusable because of strong interference from neighbouring cells. The interference signature of these channels is easily obtainable through either spectrum sensing or channel information exchange between nearby cells. A small cell should assign the lowest priority to reuse these channels or always tries to orthogonalize its occupied local channels to those channel category.

2.5.2 Types of Sensed Information

At least, a communication system uses three types of signals to preserve the quality of the transmitted signal in a downlink wireless system with different functions, namely pilot, control and traffic signal, such as in LTE (Rumney, 2013). The wireless communication system could utilise these signals accordingly to maintain the quality of its transmitted signal.

After getting spectrum information from surrounding environment, subsequently, a CSC will analyse it as well as estimate and predict the following spectrum condition. Then the CSC can decide to deal with the spectrum. This section will discuss some information types having been proposed for complementing the cognitive cycle of the CSC.

Pilot Signal

As discussed by Rumney (2013), the pilot signals hold known amplitude and phase and being allocated in the time and frequency domain. From these pilots, the UT can calculate corrections and thus minimise the probability of demodulation errors. Moreover, the UT can demodulate downlink signals and to report the downlink channel state information on the uplink.

Kaimaletu et al. (2011) proposed a method to mitigate interference in heterogeneous networks. In the proposed method, the pilot signal was used to identify which users were getting significant interference on their resource blocks and to mark them as a victim. Subsequently, those users getting victim status have less priority to access the resource blocks.

Control Signal

As discussed by Pantisano (2013), cognitive small base stations can decode the macrocell control signal and independently identify the transmission opportunities, which is the non-allocated component carriers. Based on this information, the small cells can perform targeted operations for enhancing the QoS or optimising the radio resource usage.

Lopez-Perez et al. (2009) considered that small-BSs must be able to sense the air interface and to tune their parameters accordingly to changes in the network or channel. By decoding the control channels, the small cell can synchronise with the external network, to reselect its *physical cell identity*, and optimise its neighbouring cell list and handoff parameters. Finally, the small-BS adapts its power and selects its subchannels according to the obtained sensing information to ensure that it provides the dominant signal in the desired coverage area. Chapter 4 and Chapter 5 propose cognitive interference management methods by sensing the pilot and control signals to recognise the spectrum occupations.

Traffic Signal

A sensing-based spectrum access strategy for small-BSs was proposed to exploit the activity information of the nearest macrocell BS (macro-BS) (Nguyen and Le, 2014). In particular, upon detecting the interference-plus-noise power, each small-BS decides to opportunistically access the macrocell spectrum by using two different thresholds depending on the presence or absence of the nearest macro-BS. The proposed method in Chapter 6 senses the traffic signal to recognise the spectrum occupations.

2.5.3 Spectrum Sensing Period

In the cognitive cycle, spectrum sensing is a significant aspect. From this activity, relevant information of channel states will be obtained and then will be used by the cognitive system to take action accordingly. In general, the longer the sensing period, the more information will be obtained in the sensing time, but less time will be used to transmit useful signal.

Nguyen and Le (2014) proposed an algorithm to determine the sensing period and access thresholds for throughput maximisation in heterogeneous networks. The results showed that optimal sensing time is obtained by setting an optimum number of samples of the sensed interference plus noise power. It also presented that the total throughput by the access scheme with activity information of the nearest macro-BS is higher than that without this macro-BS. Moreover, the throughput due to the spectrum access scheme without sensing is very poor compared to those schemes with sensing.

2.5.4 Spectrum Sensing Techniques

It is important to have an efficient and accurate spectrum sensing technique, which is mostly influenced by two key metrics such as sensing speed and accuracy (Kpojime and Safdar, 2015). Sensing of the spectrum to find unoccupied spaces enhances the opportunities for CSC users to access the spectrum. CSCs can benefit from various conventional spectrum sensing techniques found in the literature such as energy detection, matched filter, cyclo stationary feature detection, waveform detection, wavelet detection and co-operative sensing. The proposed methods in Chapter 4 and Chapter 5 assume to apply the spectrum sensing technique that can differentiate between the received signal power and the interference plus noise power. Table 2.1 presents various spectrum sensing techniques that can be used in the CSC.

Table 2.1: Spectrum Sensing Techniques ©2015 IEEE (Kpojime and Safdar, 2015)

Sensing Method	Advantages	Limitations
Energy Detection	• Simple to implement when noise power is known at the receiver	• Uncertainty of noise power results in false detection • Noise power estimation error can lead to SNR wall • Unable to detect signals in conditions of low SNR
Matched Filter	• Optimal detection of signals in the channel • Comparatively low Computational cost	• Requires detailed information of the parameters of the primary user's signals • High implementation complexity
Cyclostationary feature detection	• Robust even in low SNR • Able to differentiate noise and signal	• Computation cost is high • Some information about the primary user signal is required • Requires excessive signal processing expertise
Waveform Detection	• Performs well even in low SNR if the known pattern is large	• Susceptible to synchronization errors
Wavelet Detection	• Performs well for wideband signal	• High computation cost • Not very effective in case of spread spectrum signals
Co-operative sensing	• Reduced sensing time • Effective solution for problems such as shadowing and multi-path fading and hidden node terminal	• Requires Development of efficient sensing algorithms and Complex sensing techniques

2.5.5 Cognition Technique

Referring to the discussion of Cognitive Radio and Cognitive Cycle, see Section 2.3.2, cognition technique in CSC could be implemented in various approaches at the same time keeps the basic idea of CR, which is aware of and learn from the surrounding radio environment and adapt to statistical variations in the input stimuli (Haykin, 2005). This following Section is discussing some cognition techniques having been proposed by researchers.

Full vs Semi Cognitive

The performance of two cases of cognitive small-BSs in a multichannel environment, namely the full-cognitive and the semi-cognitive case, has been analysed by Elsawy and Hossain (2013). Both cognitive cases above used two different channel access schemes, namely contention-resolution-based channel access and uncoordinated aggressive channel access, respectively Elsawy et al. (2013).

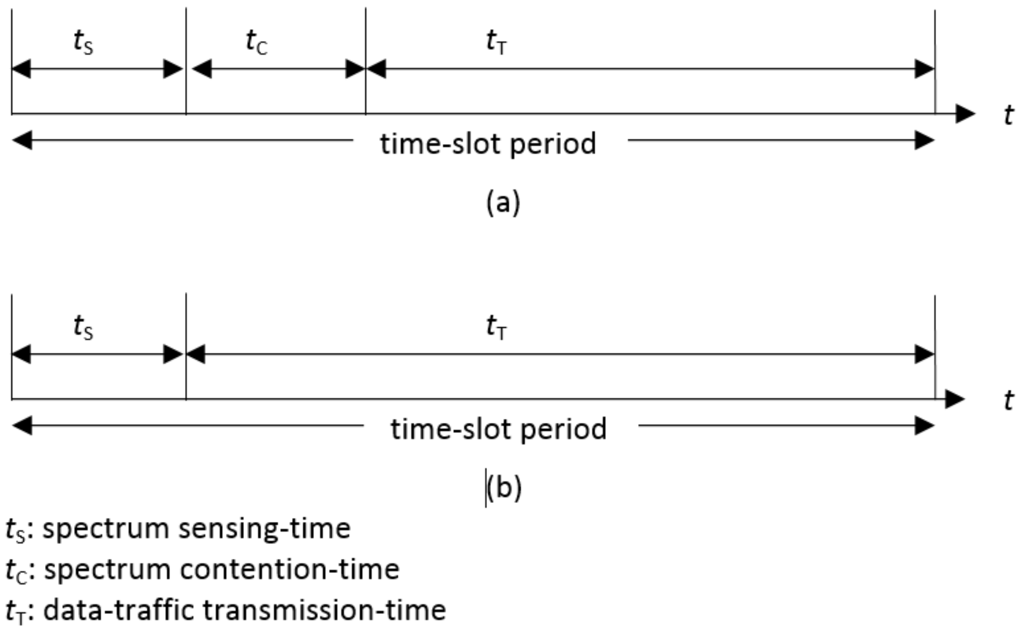


Figure 2.6: Spectrum access in HetNet (a) full-cognitive (b) semi-cognitive.

In the full-cognitive (FC) case, an FC small-BS considers both nearby macro-BSs and nearby small-BSs as major interference sources that should be avoided. The small-BSs access the spectrum via a contention resolution process. Spectrum access for an FC small-BS can be implemented in a way similar to the *cognitive-carrier sense multiple access* (C-CSMA) (Nguyen and Baccelli, 2010), in which, each time slot is divided into three main parts (Figure 2.6(a)). The algorithm of C-CSMA is as follows. At first, each cognitive small-BS senses the available spectrum to detect the channels that are not used by nearby macro-BSs. Second, each cognitive small-BS contends to access one of the available channels (for example by using a random backoff process while persistently sensing the channel). Third, if the sensed channel is free during the entire back off duration (i.e., not used by a nearby small-BS), the cognitive small-BS transmits on that channel for the rest of the time slot. Hence, both the co- and cross-tier interferences are minimised, but at the expense of reduced spectrum access opportunities.

Meanwhile, in the semi-cognitive (SC) case, an SC small-BS considers only nearby macro-BSs as major interference sources that should be avoided. In this scenario, each time slot is divided into two main parts (Figure 2.6(b)). By using this technique, only cross-tier interference is minimised.

The results showed that the outage probability could be significantly decreased for both SC and FC cases. It also indicated that the uncoordinated contention among the FC small-BSs for spectrum access results in SINR outage, in which the SINR falls below the threshold. Thus the obtained gain regarding the SINR outage of the scheme is worthless. Moreover, the result showed that an SC small-BS always outperforms an FC small-BS. The proposed methods in Chapter 4 and Chapter 5 apply the semi-cognitive technique to avoid the strong interference power from the macrocell.

Temporary Cognition

Al-Hourani and Kandeepan (2013) has proposed a temporary cognitive secondary LTE small cell network to improve the coverage of an LTE network for public safety communications. The concept of *temporary cognitive small cell network* (TCSN) is presented as a secondary supplement for the main network, which is referred as the *parent network*. CR networks obtain radio environment maps intelligently using sensing and localisation, which are the key enabler in the proposed solution. TCSN will provide the necessary platform to enable the direct mode (*device-to-device*) in LTE that will allow two devices communicate with each other without the need to route the traffic via the parent network. Using the proposed technique and complemented by interference mitigation techniques, the results showed the coverage enhancement.

Cross-Cognition

Unlike the conventional *primary user* (PU) and *secondary user* (SU) analogy, Hu et al. (2012) has proposed a scheme that recognises a small cell in the same regard as macrocell with the argument that small-BSs could be densely populated with a large amount of data and traffic requiring high priorities like macro-BS. The scheme employed in LTE-A OFDMA Heterogeneous Networks utilises the concept of cross cognition and graph colouring concept technique to mitigate cross-tier and co-tier interference respectively. In cross cognition, all the network elements perform cognition in the system (including small-BSs, small-UTs, macro-BSs and macro-UTs). The spectrum is divided into licensed and unlicensed parts with the macro-BSs and small-BSs having access to both parts. Small-UTs and macro-UTs utilise the licensed spectrum offered by the corresponding serving small-BS and macro-BS but opportunistically utilise the unlicensed spectrum when the licensed spectrum is exhausted.

The results showed that compared with the traditional cognitive schemes, the cross-cognition scheme improves the capacity of small-UTs considerably in dense small cell scenario. Moreover, the interference coordination scheme based on graph colouring increase the SINR and improve the capacity of small-UTs in the cognitive radio small cell network.

2.5.6 Resource Deployment

As discussed by Huang et al. (2013), the resource deployment of indoor small cells, such as femtocells, can be grouped as follows.

Co-Channel Deployment

In this scenario, the wireless system achieves high spectral efficiency as the overall RF spectra are shared among macrocells and small cells. Both network-tiers benefit on occupying overall RF spectra. Moreover, co-channel deployment is more attractive to operators due to low cost and backwards compatibility.

However, it needs effective interference management techniques among macrocells and small cells to get the benefit of shared RF spectrum scenario. Besides, co-channel deployments of closed (access) subscriber group (CSG) small cells create coverage holes in macrocells (Huang et al., 2013). Then, cognitive small cells are developed to solve that problem by sensing their surroundings and flexibly adapt their operations to minimise cross-tier interference.

Dedicated Channel Deployment

In this scheme, a portion of RF spectra allocated to a macrocell is assigned specifically to small cells. Dedicating a portion of the spectra for the exclusive use of small cells eliminates interference with macrocells (Alsohaily and Sousa, 2013). However, small cells should share spectrum with macrocell most of the time due to spectrum scarcity. The proposed methods in Chapter 4 and Chapter 5 apply this technique to deploy the spectrum in HetNet.

Partial-Channel-Sharing Deployment

Using this scenario, overall RF spectra for the system is partitioned into two parts. One part is exclusively assigned to macrocells, and the other one is shared by macrocells and small cells. Macrocells benefit on the particular carrier frequency for universal coverage and shared carrier frequency for partial coverage (outside the small cell coverage). This strategy is efficient without causing much bandwidth loss and mutual interference. However, small cells have to access fewer RF spectra and share them with the macrocell that increases the probability of cross-tier interference and decrease system's performance and capacity.

2.5.7 Network Access

Cognitive small cells are expected to be deployed using one of the following network access modes.

Closed Access

Closed access or also called as closed subscriber group mode restricts the network access to specifically registered users. An indoor small cell, such as a femtocell, can be positioned in closed access network areas, such as homes or offices, which mean that the indoor small-BS provides services to fewer clients, and only registered mobiles can have access to such an indoor small cell. This method has the advantage of decreasing the number of handovers in this particular network and that each user can get a high data rate for being close to the small cell station and because of the limited number of users.

However, this scheme has a disadvantage as well when unregistered macro-UTs stay in a closed-access small cell area and transmit their power strongly to achieve their serving macro-BS. In this situation, the macro-UT became a strong interference source for the uplink-small cell. This thesis investigates the interference mitigation strategies with a closed access policy for all UTs in HetNet.

Open Access

Open access mode allows any user terminal (UT) to access any small cell. This mode enables dynamic cell association for both small cell and macrocell UTs, which UTs can handover from one base station to the other ones based on the strongest received signal or interference potency.

Small-BSs can be deployed in open access modes such as at airports or banks. Any user has the right to access these small-BSs, and there is no need for registration in this case. One benefit of this method is less interference with the macrocellular environment. However, unwanted handover may be increased for many users entering and leaving such small cells, causing a noticeable decline in the QoS.

Shared Access

As discussed by Jo et al. (2012), there is a conflict of interests among of home and cellular users. In which home users prefer closed access; conversely cellular users prefer open access. The paper highlighted that the conflict most noticeable for indoor small cells, such as femtocells, near the cell edge when there are numerous cellular users and fewer small cells. The paper has proposed a shared access strategy to mitigate this conflict, in which small cells allocate a several numbers of time-slots between home and cellular users such that a specified minimum rate for each UT can be achieved. The results showed that for small cells within the outer area, shared access achieves higher throughput than open access while performing the QoS of both home and cellular users. Meanwhile, closed access mode fails for cellular users, and open access mode fails for the home users.

Hybrid Access

Hybrid access mode is similar to CSG, with the exception that an unregistered subscriber may stay for a while and receive some level of service from the small cell (Fan and Sun, 2010). The unregistered subscribers are allowed to access the small-BS only for the limited use of resources (Al-Rubaye et al., 2011). Usually, the indoor small cell operates as a CSG cell. When an incoming unregistered subscriber can potentially cause interference, it will be allowed to access. Thus, the incoming subscriber becomes a member of the small cell and naturally removes all the potential interference to both sides. On the other hand, in the hybrid mode, registered subscribers may potentially get higher priority of access to the local network.

2.6 Summary

In this Chapter, the literature related to the cognitive small cell has been reviewed. From the perspective of mobile operators, the objective of small cell deployment is to extend the service coverage or increase network capacity as well as to infill the blank spot areas. Moreover, deploying small cells will make economically feasible to provide coverage of much smaller communities. By deploying small cells as underlaying networks of macrocells, the macrocell network could get offloading capacity gain and even be higher for cell-edge throughput.

Considering complexity and dynamic of the environment where small cells are deployed, especially for picocells and femtocells, these networks are considered having a capability of self-optimisation. By having this feature, small cells are expected to be able to avoid interference and to increase capacity in HetNet. CR is an intelligent wireless communication system that is aware of and learns from its environment and adapts to statistical variations in the input stimuli. The small cell requirement upon self-optimisation feature encourages the implementation of the CR concept in the small cell, which is also known as the cognitive small cell.

CR proposed the idea of learning and decision making of radio resource management in dynamic and complexity situation such as small cell environment. However, one of the biggest problem obstructing the small cell deployment is interference, especially for co-channel deployments. In Chapter 3, the Interference Problem and Resource Allocation in HetNet will be discussed further.

Chapter 3

Interference and Resource Allocation in HetNet

3.1 Introduction

The small cell has the benefit of the short distance to their served users. It results in less propagation loss of the transmitted signal compared to the macro-cell. However, in densely deployed small cells and randomly users' deployment condition, it will generate interference problem for both co-tier and cross-tier interference. This interference needs to be mitigated to achieve the required *quality of service* (QoS).

In addition to system design and proper choice of technology, radio resource allocation is one of the essential elements contributing to achieving an optimum condition in the wireless system. Proper resource allocation can reduce low interference, improve some performances such as QoS, throughput, and spectrum efficiency. The success of an interference mitigation technique cannot be separated from resource allocation strategies that address interference problem appropriately. Accurate and thorough resource allocation also requires a well-planned and an optimum macro strategy. Hence, many aspects need to be considered in resource allocation span from the physical layer to the network layer or even to the application one, from the smallest element of manageable resources to the global optimisation strategy.

This Chapter will discuss some aspects of interference problems, resource allocation and their issues in HetNet. Section 3.2 will discuss various interference problems in *heterogeneous cellular network* (HetNet). Then various schemes of interference management in these networks will be discussed in Section 3.3. Moreover, Section 3.4 will discuss the development of cognitive radio approach to solving the interference problems in these networks. Some issues in resource allocation will be explored in Section 3.5, including channel capacity and optimisation problem in this area. Section 3.6 will discuss resource allocation techniques in HetNet. Finally, the discussion will be summarised in Section 3.7.

3.2 Interference in Small Cells

When small cells and macrocells are densely deployed in the same area, as expected in the 5G networks, problems may arise by a formation of dead zones in parts of macrocell or small cell areas. The excessive interference from neighbouring small cell base-stations (small-BSs) or macrocell BSs (macro-BSs) would affect the basic connectivity of and service delivery to user-terminals (UTs) in the areas of the serving cellular networks.

The interference scenarios that may arise in HetNet can be classified in the following ways, which can be illustrated as showed in Figure 3.1 and Figure 3.2.

- downlink interference: It comes from a BS to its neighbouring UTs, which are served and controlled by its neighbouring BSs.
- uplink interference: It comes from a UT to its neighbouring BSs.
- same (co-) channel interference: The interference source has the same frequency spectrum with the interfered receiver.
- adjacent-channel interference: The interference comes from the adjacent frequency spectrum.
- benign (not harmful) interference: The interference leads to negligible degraded performance to the receiver end.

- harmful interference: It affects the significantly degraded performance at the receiver end.

- cross-tier interference: The interference source and the interfered receiver comes from different tier networks, such as from macro-BSs to neighbouring small-UTs or from macro-UTs to neighbouring small-BSs.

- co-tier interference: The interference source and the interfered receiver comes from the same tier networks, such as interference among small cells.

As considered in Femto Forum (2010), certain interference scenarios were found to be benign, having negligible performance degradation, and do not seem to require new interference mitigation technique. Moreover, the report also considered that the following scenarios might get advantages from interference mitigation techniques.

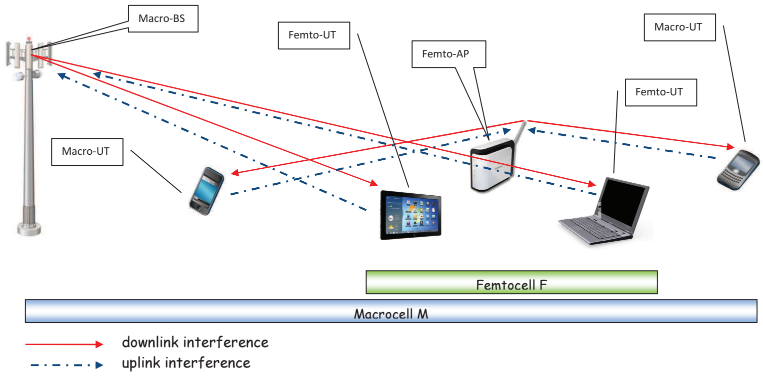
- downlink interference from a small-BS to macro-UTs or another nearby small-UTs on the same carrier;

- uplink interference from a small-UT to a macro-BS or another nearby small-BS on the same carrier.

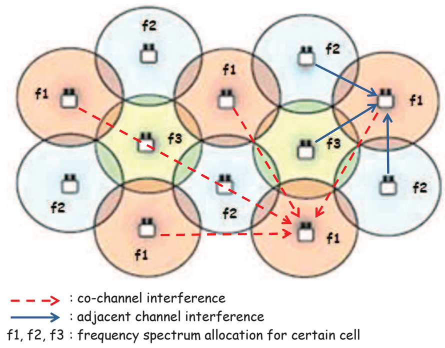
Harmful scenarios will occur as the number of deployed small cells increase and the distances among BSs decrease, either among small-BSs or cross-tier cellular networks.

3.3 Interference Management in Small Cells

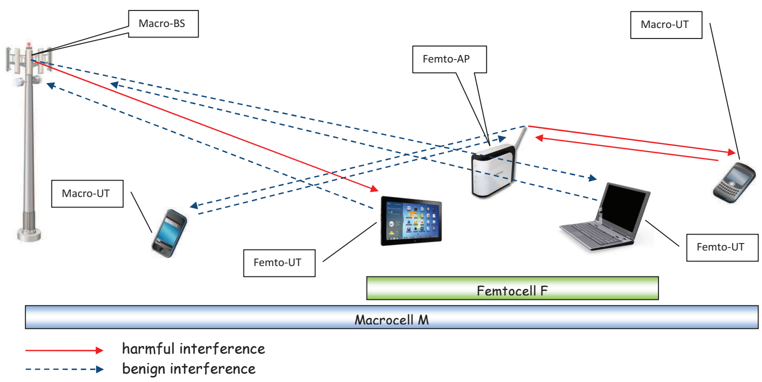
Interference mitigation can be performed either in macrocell side or small cell side to mitigate the impact of harmful interference in either macrocell or small cell networks. Interference mitigation, as a technical approach to interference management, can improve the utilisation of radio resource and network infrastructure, as well as increase the data throughput to end users or other criteria such as QoS or low dropped calls. There are some schemes can be used to mitigate the interference impact that will be discussed in this Section. Figure 3.3 illustrates interference management schemes with various techniques.



(a) Uplink/ downlink interference



(b) Co-/ adjacent channel interference



(c) Benign/ harmful interference

Figure 3.1: Interference scenarios in heterogeneous cellular networks

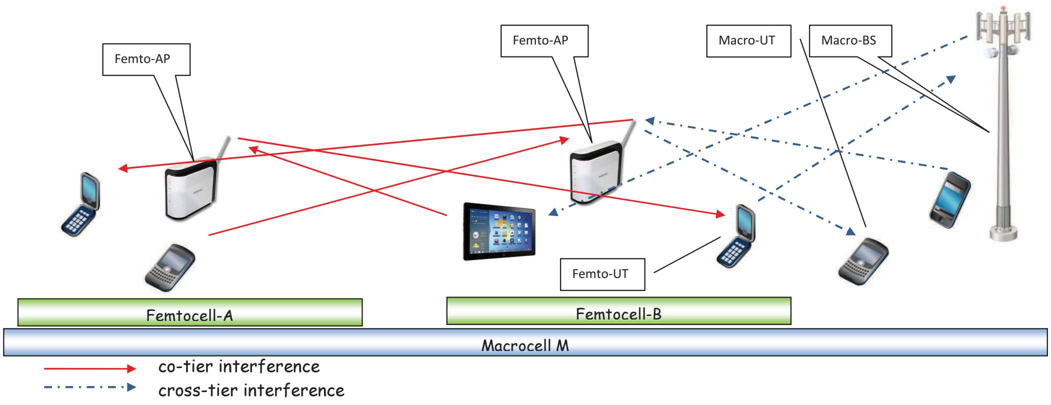


Figure 3.2: Co-/ cross-tier interference in heterogeneous cellular networks

3.3.1 Interference Cancellation

Interference cancellation scheme reduces interference at the receiver end. Hence, interference is cancelled after the signal is received. This scheme demodulates or decodes desired information and then use it along with channel estimates to cancel received interference out from the received signal defined. Two classical techniques in interference cancellation applied in the uplink of CDMA system are successive interference cancellation (SIC) and parallel interference cancellation (PIC) (Andrews, 2005). SIC detects only one user per stage. The strongest received signal is detected first, and then followed by the next strongest, and so

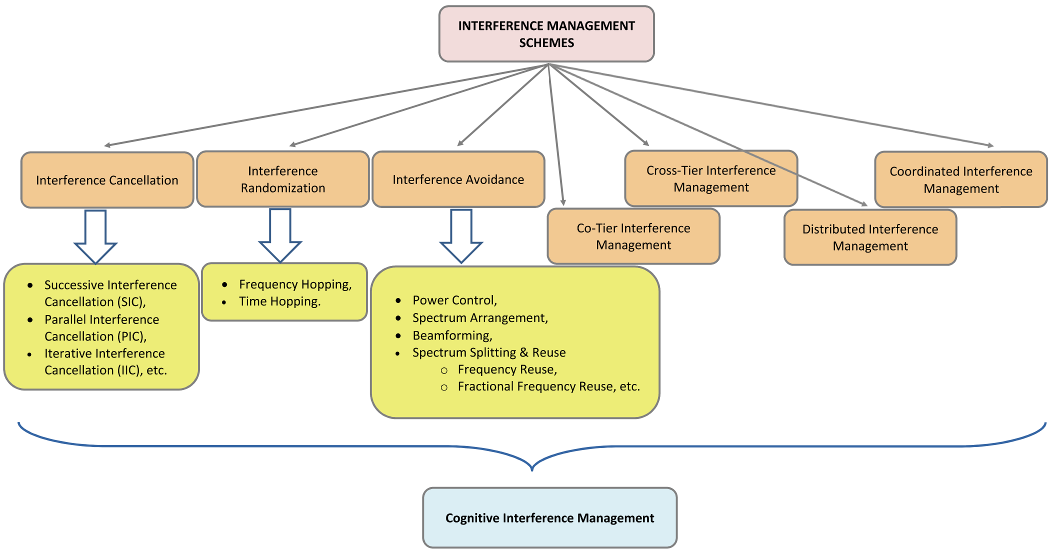


Figure 3.3: Interference management schemes

on. Meanwhile, PIC detects all users simultaneously. The initial estimate can be used to cancel some interference, and then parallel detection can be repeated.

Most of the interference cancellation techniques require information of the characteristics of the interfering signal and antenna arrays at the receiver system to cancel any interference. These requirements make the schemes less suitable for UTs, but more suitable for implementing in base stations. Therefore, the schemes are mostly applied for the uplink interference mitigation.

3.3.2 Interference Randomisation

Interference randomisation mitigates interference by dynamically and periodically allocating different time or frequency to a user. This scheme can be realised by using either time or frequency hopping channel assignment.

In frequency hopping, radio signals are transmitted by rapidly switching a carrier among many frequency channels and using a pseudorandom sequence known to both transmitter and receiver. The advantages of employing frequency hopping in a cellular system are well-known (Olofsson et al., 1995; Verhulst et al., 1984), such as:

- avoiding or reducing interference such as co-channel, adjacent channel, and intermodulation interference,
- increasing the channel capacity, and
- decreasing multipath fading effect by switching the frequency channel periodically.

However, there are challenges to implementing this technique as follows.

- synchronisation between transmitter and receiver, and
- overall bandwidth required to provide frequency hopping is much wider than that needed for transmitting the same information that uses only one carrier frequency.

Moreover, for time hopping, the pulse position of the transmitted signal is varied within the frames. When different time-hopping sequences are assigned to different users, these sequences can be arranged in such a way that pulses collide only in a few ($N_{collide}$) frames, but not the others. This results in a suppression of interference by a factor of $N_{collide}/N_{frame}$, where N_{frame} is the number of frames.

As presented by Zahir et al. (2013), time hopping technique is used to reduce cross-tier uplink interference in HetNet. In this technique, the transmission period is subdivided into small portions; and subsequently, a user transmits and keeps silent for the other portions. When there is no synchronisation in transmission period between two network tiers, then each network tier independently chooses its periods. The advantage of this technique can control interference level among controlled sequences. However, the disadvantage is difficult to design synchronised sequences, especially if it is desired a large number of sequences with small collisions.

3.3.3 Interference Avoidance

Interference avoidance manages radio resource in such a manner to avoid the impact of interference. By having the proper resource allocation, the system can keep the interference impact as low as possible. Therefore, the designed QoS and data rate can be achieved using this scheme.

This scheme is closely related to the proper resource allocation regarding transmitted power, occupied spectrum, time access and spatial location. Some power allocation techniques to avoid interference are iterative water-filling (Yu et al., 2002), limiting the transmission power and dynamically distributed power control (Foschini and Miljanic, 1993). For spectrum allocation, some techniques for this scheme are frequency reuse (Rappaport, 2002), fractional frequency reuse and soft frequency reuse (Rahman and Yanikomeroglu, 2010). Meanwhile, some techniques based on spatial location are beam-forming (Van Veen and Buckley, 1988) and load balancing (Sharma et al., 2012). Moreover, time-access based resource allocation techniques are multiple access (Jamalipour et al., 2005) and scheduling (Kong et al., 2009). Section 3.6 will discuss some techniques being used for radio resource allocation in HetNet, which are mostly related to Interference Avoidance techniques.

3.3.4 Co-Tier Interference Management

Interference management in single layer cellular networks or co-tier interference management has been developed and widely implemented. The characteristics of used techniques are a single layer or co-tier networks and centrally controlled. Moreover, both static and dynamic techniques are used. In which, the static approach is usually used in macrocell networks. While, the dynamic approach is usually used for the smaller networks, such as indoor small cells.

Some above schemes could be applied to single layer cellular networks such some techniques in interference cancellation (Section 3.3.1), randomisation techniques (Section 3.3.2), and interference avoidance (Section 3.3.3) as well as coordinated techniques (Section 3.3.6).

3.3.5 Cross-Tier Interference Management

Nevertheless, for HetNet, the interference problems will be more complicated. Thus, the more independent, more distributed and hierarchical methods will be useful to deal with the problems, such as discussed in Section 3.3.7.

Cellular networks have been developed into many types, such as the macrocell, microcell, metrocell, picocell and femtocell, to serve users with different environment and requirement. Each type of networks has different characteristics such as coverage area and users' mobility; different performance requirement such as transmission power and QoS; and the different objective. In HetNet, some networks with different tiers could share the same frequency, space and time access and could be the total allocated power.

In certain condition, network provider must set the priority of service for different tiers of networks. These kinds of networks need coordination and information exchange among tiers to mitigate interference and improving performance and capacity of overall HetNet. In conventional cellular networks, cross-tier interference management is performed using some approaches such as cell splitting that is followed by reduced transmission power and antenna down-tilting and could be frequency reuse (Rappaport, 2002). However, the conventional static resource allocation techniques are not suitable for fast growing and randomly small cell deployment (Saquib et al., 2012). Thus, dynamic and adaptive approach to resource allocation is required that can match the dynamic change of small cell network deployment.

3.3.6 Coordinated Interference Management

This scheme mitigates the interference among networks by performing a coordination among interference source nodes. Some related nodes exchange inter-cell signalling among each other to understand each node's parameters and then allocate resources accordingly. Inter-cell signalling refers to the communication interface among neighbouring cells and the received measurement message report from the user equipment.

Kosta et al. (2013) surveyed key issues in mitigating interference and gives an overview of the recent developments of an interference avoidance through inter-cell interference coordination. The paper considered that this scheme could be classified based on its characteristics of control strategies. They include fixed, adaptive (semi-static), real-time (dynamic); time-scale: long days, days, minutes, seconds; adaptability: non-adaptive, adaptive on long-term network condition, cell-load adaptive, user-load adaptive, fully synchronised, and adaptive to different cell-type; techniques: particular frequency reuse, selective power reuse, invert selective frequency/ power reuse, self-organising channel reuse for small cells. ICIC (Kosta et al., 2013), CoMP (Irmer et al., 2011), and clustering small cells (Abdelnasser et al., 2014) can be considered as part of this scheme.

3.3.7 Distributed Interference Management

Small cells are designed to have some autonomous functions to enable scalability, to reduce signalling overhead, and to ease implementation. This design will enable small cells to manage their resources with minimum dependency on the main macrocell network.

It is possible to provide sufficient knowledge to the small cells through the backhaul network. However, it would cause much congestion on the backhaul network and additional load on the main network. Furthermore, as the number of small cells grows up and their locations spread out, it is impractical for the main network to provide great information in real time condition to small cells through the backhaul. In those cases, distributed methods get more benefits compared to the centralised ones (Chandrasekhar and Andrews, 2009*a*).

Moreover, in distributed networks, to some extent, coordination among nodes is still required. In conventional networks, this coordination is performed through backhaul networks (Pennanen et al., 2016). Fast growing of small cell deployments, such as picocell or femtocell, will also increase congestion and time delay in backhaul networks. Thus it needs another method to avoid those problems.

3.3.8 Disadvantages of the Conventional Methods

Section 3.3 has discussed some interference management schemes in HetNet. Each scheme above has its advantages for specific interference problem. Thus, there is no guarantee that each method will be suitable and matched the overall requirements of HetNet. This Section will summarise and discuss disadvantageous of schemes as mentioned earlier.

In addition to some advantages, *interference cancellation scheme* (Section 3.3.1) has also some disadvantages. However, this scheme requires the information of characteristics of interfering signals such as modulation techniques, decoding techniques, and channel estimates. These make the schemes less suitable for downlink, in which UTs perform the interference cancellation process. These schemes are mostly suitable for implementing in base stations; that mostly is used for the uplink interference mitigation.

Interference randomisation scheme (Section 3.3.2) has also some disadvantages. It needs synchronisation between the transmitter and the receiver, and additional bandwidth for frequency hopping. There is no guarantee for this scheme that the destination hopping points, such as frequency, time slot, and code, will be the most optimum choice that mitigates the interference problem.

Interference avoidance scheme (Section 3.3.3) is based on natural radio and system parameters such as transmission power, frequency spectrum, time access and spatial locations. It is the simplest way for interference mitigation. However, to accurately and optimally mitigate the problem of potentially mutual-interfering networks, such as cellular and HetNet, it needs to adopt and combine the other techniques accordingly.

Distributed interference management scheme (Section 3.3.7) is more scalable and easier to deploy compared to the centralized one. It is used for one-tier networks such as cellular networks. However, it still needs information of surrounding networks as a reference for decision making of resource allocation so that the scheme will be optimal for overall systems. In which, the required information can be obtained or exchanged through inter-cell signalling that is an additional burden to the system. To some extent, *cross-tier interference management scheme* (Section 3.3.5) has similar methods with the distributed one. However, it is even more complicated. Different tiered-networks usually have less inter-cell signalling that limits the knowledge of different network tiers.

For *coordinated interference management scheme* (Section 3.3.6), it needs some inter-cell signalling to accurately and optimally allocate resources without interfering with adjacent networks. It will be worse when more users need service, or more small cells coexist with the macrocell. Thus it is suitable for limited and specific users, especially on the border of some adjacent networks, e.g. some users in handoff (handover) condition.

Since a small cell is surrounded by varied and complicated environments as well as dynamic wireless channels, implementing one scheme above for interference mitigation does not guarantee to result in optimum performance in a wireless system. Rahman and Yanikomeroglu (2010) argued that the benefits of those schemes are mutually exclusive, and the combination of those approaches is likely to be implemented in the system. However, the combination of those schemes must consider the aspects that make this combination achieves the assigned objectives. Thus, it needs a well-planned, thorough and visionary effort to smartly and wisely select and combine some schemes above and then constructs into a new method that expected has better performance than the conventional ones. Hence, it needs to carry out new research with the aim of interference mitigation in HetNet.

3.4 Cognitive Radio Approach for Interference Management

To combine advantages of different techniques above, recently researchers have integrated cognitive radio into interference management methods, also called as cognitive interference management. Cognitive interference management mitigates the interference impact by implementing cognitive process either on BS side or both BS and UT sides. It could be applied to either small cells or overall HetNet. The idea comes from cognitive radio concept that has a cognitive ability to sense, analyse, make a decision and adjust the radio resources to use by considering some important aspects such as interference and channel gain.

Lopez-Perez et al. (2009) has discussed some guidelines regarding cognitive interference management. Especially on the approach to spectrum allocation and interference mitigation problems, the use of self-configuration and self-optimisation techniques for the interference avoidance. In that paper, it is explained that small-BSs must be able to *sense* the air interface and to *tune* their parameters accordingly to changes in the network or channel. In *sensing phase*, small-BS must be (i) aware of the presence of neighbouring cells and spectrum allocations, (ii) able to learn about the state of the network (e.g. architecture and load) and channel conditions (e.g. interference, fading and shadowing). In *tuning phase*, small-BS should also be able to select and modify parameters in different situations base on its requirement. Self-configuration provides the initial settings of the small-BS when it is turned on; whereas self-optimisation updates the configuration of the small-BS to adapt its parameters to the environment.

Wireless propagation channel conditions can alter rapidly due to shadowing and multipath fading. Moreover, network load and user traffic fluctuate quickly depending on the hierarchical position of the network element, user location and time, and because of the packet nature of the services. OFDMA small cells must dynamically adapt their radio resource to their environments to anticipate the fluctuating conditions and keep optimal the network performance. Information changes can be detected during the sensing phase such as traffic load, power and frequency interference, user mobility/ hand-over, and dropped calls. By taking into account this information, then the small-BSs analyse, decide and tune their parameters (such as power, subchannel, and time access) to mitigate interference across cells.

In Chapter 4 and Chapter 5, we propose interference mitigation methods to deal with interference problem in HetNet. In the proposed methods, a cognitive radio approach is adopted to provide the guidelines of resource allocation procedures.

3.5 Issues in Resource Allocation

This Section will discuss some issues in radio resource allocation. The discussion focuses on multi-users multi-carriers HetNet.

3.5.1 Resource Allocation Issues

In HetNet, various types of cellular networks, i.e. macrocells and small cells, are deployed together in the same area. As discussed in Section 2.2.2, small cells consist of microcells, metrocells, picocells and femtocells. In which the last two types of cellular networks are mainly used to provide indoor coverage and could be explicitly dedicated to closed (access) subscriber groups (CSGs). Resource allocation in *orthogonal frequency division multiple access* (OFDMA)-based heterogeneous networks, such as *Long Term Evolution* (LTE) and *Worlwide Interoperability for Microwave Access* (WiMAX), should consider all their resources regarding multi-carriers, multi-users, and HetNet. They should also consider their inherent radio resources such as transmission power, frequency spectra, time access, and spatial location.

In LTE system, a *resource block* (RB) is the smallest unit that can be scheduled for transmission (Rumney, 2013). Resource allocation for each UT bases on the comparison of per-RB metrics. The n-th RB will be allocated to the k-th user if its metric $m_{k,n}$ is the biggest one that satisfies the following equation.

$$m_{k,n} = \max_{j}\{m_{j,n}\}; \forall j \in \{1, \cdots, K\}. \quad (3.1)$$

These metrics can be interpreted as the transmission priority on a different RB for each user. Based on the desired performance requirements, the computation of these metrics is usually evaluated from the data flow information and affects the decision-making process of the allocation of the following parameters (Capozzi et al., 2013).

- The "status of transmission queues" is considered in minimising packet delivery delays.
- The "channel quality" is considered in allocating resources to users experiencing better channel conditions and improving the system performance and capacity.
- The "resource allocation history" is considered in improving fairness.
- The "receiver-side buffer conditions" is considered in avoiding buffer overflows.
- The "QoS requirements" is considered in driving specific policies with the aim of meeting QoS requirements.

Meanwhile, some key aspects that always should be taken into account before defining an allocation policy for LTE are (Capozzi et al., 2013):

1. Complexity and scalability: An LTE packet scheduler works with a time granularity of 1 ms. It has to take allocation decisions every *transmission time interval*. Low complexity and scalability are fundamental requirements for limiting the processing time and memory usage.
2. Spectral efficiency: This is one of the main goals to be achieved.
3. Fairness: This is a major requirement that should be considered to guarantee minimum performance also for the cell-edge users (in general for users encountering bad channel conditions).
4. QoS provisioning: It may vary depending on the application. They are usually mapped into some parameters, i.e. minimum guaranteed bit rate, maximum delivering delay, and packet loss rate.

Moreover, scheduling strategies for LTE downlink can be classified as follows (Capozzi et al., 2013): (i) channel-unaware; (ii) channel-aware/QoS-unaware;

(iii) channel-aware/QoS-aware; (iv) semi-persistent scheduling for *voice over IP* (VoIP) support; and (v) energy-aware strategies.

3.5.2 Channel Capacity

Channel capacity describes the upper bound of the rate at which information can be reliably transmitted over a communications channel. In wireless communications, channels are characterised by some parameters such as separating distance between/ among communicating devices, random noise power, received interference power, frequency bandwidth, and surrounding obstructed objects. So that, different channels have different relevant parameters that lead to different channel capacities.

Capacity in Gaussian Channel

The capacity C in bits per second (bps) of a discreet-time *additive white Gaussian noise* (AWGN) channel is given by Shannon's well known formula (Goldsmith, 2005).

$$C = B \cdot \log_2(1 + \gamma), \tag{3.2}$$

where B is the channel bandwidth. The *signal to noise ratio* (SNR) is the transmission power P over the noise power $(N_0 B)$, $\gamma = P/(N_0 B)$. N_0 is the Gaussian noise power spectral density.

Therefore, Shannon capacity is an upper bound of the achievable data rates under real system constraints at that time, which predicted speeds of roughly 30 kilo-bps (kbps) over the same telephone lines. When Shannon developed his theory, data rates over standard phone lines were about 300 bps. Currently, investigations of digital electronic, modulation and coding techniques, result in commercial modem close to the speeds predicted by Shannon in the 1950s. Moreover, modems can exceed this 30 kbps Shannon's limit on some telephone channels. That is because of transmission lines today are of better quality than in Shannon's day. Thus, these channels result in a higher received power than that used in Shannon's initial calculation.

Capacity of (Time Invariant) Frequency-Selective Fading Channels

Fading causes the channel gain fluctuates each time. In a block fading channel, the gain is constant over some block length T. Then it changes to a new independent value following certain probability distribution $p(g)$. The capacity of channel fading depends on knowledge of the channel gain $g(i)$ at time i, also called the *channel state information* (CSI), at the transmitter and receiver. Some scenarios regarding this knowledge can be presented as follows (Goldsmith, 2005).

1. *Channel Distribution Information*: In this scenario, the probability distribution $p(g)$ of the channel gain $g(i)$ is known by the transmitter and receiver.

2. Receiver CSI: For this scenario, the value of channel gain $g(i)$ is known at the receiver at time i. Moreover, both transmitter and receiver know the probability distribution $p(g)$.

3. Transmitter and Receiver CSI: Both transmitter and receiver know the value of $g(i)$ at time i and its probability distribution $p(g)$ for this scenario.

Because of fading, broadband channel gain will vary for different spectra that are called as frequency selective fading channel. It can be considered that this channel consists of a set of parallel flat fading channels with SNR equals to $|H_n|^2 P_n/(N_0 B)$ on the subchannel-n. P_n is the power allocated to subchannel-n in this parallel set, subject to the power constraint:

$$\sum_{n}^{N} P_n \leq P_{tot}, \forall n \in \{1, 2, \cdots, N\}, \tag{3.3}$$

where N is the total number of subchannels. P_{tot} is the total power allocated to the wireless system.

Then the capacity of this parallel set of channels is the overall sum of each channel rate with power optimally allocated over all channels.

$$C = \max_{P_n : \sum_n P_n \leq P_{tot}} \sum_{n}^{N} B \cdot \log_2 \left(1 + \frac{|H_n|^2 \cdot P_n}{N_0 \cdot B} \right), \forall n \in \{1, 2, \cdots, N\}, \tag{3.4}$$

where $|H_n|^2$ is the channel power gain of the subchannel-n.

Using the Lagrangian technique, then the optimal power allocation for the frequency selective fading channel can be obtained, which leads to the water-filling over frequency (Goldsmith, 2005):

$$\frac{P_n}{P_{tot}} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma_n}, & \gamma_n \geqslant \gamma_0, \\ 0, & \gamma_n < \gamma_0, \forall n \in \{1, 2, \cdots, N\}, \end{cases} \tag{3.5}$$

where P_{tot} is the total power constraint. $\gamma_n = (|H_n|^2 P_n)/(N_0 B)$ is the SNR associated with the subchannel-n, assuming the entire power budget being allocated. γ_0 is the "cut-off" value. Appendix A.2 explains the mathematical proof of the Equation (3.5).

By substituting the power adaptation formula (3.5) into the power constraint (3.3), then the cut-off value is obtained as follows (Goldsmith, 2005).

$$\sum_{n=1}^{N} \left(\frac{1}{\gamma_0} - \frac{1}{\gamma_n} \right) = 1, \forall n \in \{1, 2, \cdots, N\}. \tag{3.6}$$

Then γ_0 can be obtained as follows.

$$\begin{aligned} \frac{N}{\gamma_0} - \sum_{n=1}^{N} \frac{1}{\gamma_n} &= 1, \\ \gamma_0 &= \frac{N}{1 + \sum\limits_{n=1}^{N} \frac{1}{\gamma_n}}. \end{aligned} \tag{3.7}$$

By having the γ_0 value, then water-filling-based power allocation for subchannel-n (P_n) can be obtained as follows.

$$P_n = P_{tot} \left(\frac{1}{\gamma_0} - \frac{1}{\gamma_n} \right), \forall n \in \{x \in \mathbb{I} : 1 \leq x \leq N\}, \tag{3.8}$$

where $\gamma_n \geq \gamma_0$.

The proposed methods in Chapter 4 and Chapter 5 use this technique to allocate power on each subchannel of either the macrocell or small cells.

Then, the capacity of frequency selective channels becomes (Goldsmith, 2005):

$$C = \int_{f:\gamma(f) \geq \gamma_0} \log_2 \left(\frac{\gamma(f)}{\gamma_0} \right) \mathrm{d}f. \tag{3.9}$$

where $\gamma(f)$ is the SNR on subchannel f.

3.5.3 Optimisation Problems in Resource Allocation

Three optimisation problems in resource allocation for multiuser OFDM systems, which also represents the objectives for resource allocation, have been proposed by researchers as follow: (i). Maximisation sum capacity, (ii). Maximisation minimum user's capacity, and (iii). Maximisation weighted sum capacity. Table 3.1 summarises the optimisation problems in resource allocation for multiuser OFDM system.

In maximisation sum capacity, the capacity is maximised when each subchannel is allocated to the user with the best subchannel gain and then power is distributed by the water-filling algorithm (Jang and Lee, 2003). However, the scheme does not consider fairness in its objective. When user locations are very diverse and have different path losses, most resources, e.g. subchannels and power, will possibly be allocated to users with higher average channel gains for a significant portion of time or frequency. On the contrary, users with lower average channel gains may be unable to receive any data.

In maximisation minimum user's capacity, the objective is maximising the worst user's capacity at the same time ensuring that all users achieve a similar data rate (Shen et al., 2005). Nevertheless, the scheme can only provide maximum fairness among the users. In most wireless systems, it is possible that not all users require the same data rates. It may be provided by allowing users to subscribe to different levels of service.

Table 3.1: Optimisation problems of multiuser OFDM resource allocation

Methods	Objective	Advantage	Disadvantage
Max. sum capacity	$\max \sum_{k=1}^{K} R_k$	Best sum capacity	No proportional capacity being shared among users.
Max - min user's capacity	$\max \min\limits_{k} R_k$	Equal user's capacity	Inflexible capacity distribution.
Max. weighted sum capacity	$\max \sum_{k=1}^{K} w_k R_k$	- Adjustable capacity fairness by modifying weights. - Balances the trade-off between capacity and fairness.	- No guarantee for maximising sum capacity. - No guarantee for equal user capacity.

In maximisation weighted sum capacity, the objective is still the sum capacity, but proportional fairness is assured by the different weighted factor for each capacity (Shen et al., 2005). This scheme balances the tradeoff between capacity and fairness.

3.6 Resource Allocation in HetNet

Based on the types of radio resources, resource allocation techniques in HetNet can be classified as follows: power allocation, spectrum allocation, spatial location-based resource allocation and time-access scheduling. This Section will discuss resource allocation in multiuser OFDM-based HetNet.

3.6.1 Power Allocation

Power allocation is a process of transmission power assignment at the transmitter end with the objective of maximising the end receiver throughput. It should consider some channel characteristics such as channel gain, noise power, fading, received and interference power. For an AWGN channel, power allocation can be obtained from Equation (3.2) (Section 3.5.2) by also considering a channel gain between two communicating points.

Water-filling Power Allocation

In (time-invariant) frequency-selective fading channels, channel gains of overall spectrums are not coherent. In this case, the optimal power allocation is obtained using a water-filling formula in frequency domain (Goldsmith, 2005). Power and data rates are increased when channel conditions are favourable. Power allocation in this formula can be presented as follows.

$$\frac{P_n}{P_{tot}} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma_n}, & \gamma_n \geqslant \gamma_0 \\ 0, & \gamma_n < \gamma_0 \end{cases} \tag{3.10}$$

where P_n is the allocated transmission power on the subchannel-n. P_{tot} is the total power constraint. $\gamma_n = (|H_n|^2 P_n)/(N_0 B)$ is the SNR associated with the subchannel-n, assuming the entire power budget is allocated. γ_0 is the *cut-off* value or the SNR threshold.

Power Control

Power control is needed for systems that the transmitted power interferes to another subsystem with the purpose of adjusting the transmission powers of all communicating nodes (i.e. base stations, user terminals) such that each node achieves the required performance. To avoid users from poor channels and to limit interference caused by neighbouring cells, contemporary wireless systems employ the power control such as in frequency reuse technique. In a frequency reuse technique, which aims to improve system capacity, power control must be adjusted optimally to keep low interference power. The threshold of transmitted power may be different for each node, which depends on its required performance.

However, cross-tier interference might significantly decrease the performance of conventional power control techniques in HetNet. Signal strength based power control employed by macro-UTs results in unacceptable decrease of *signal-to-interference-plus-noise-ratio* SINR in small cell (Chandrasekhar and Andrews, 2009*b*). It is caused by a user on a network's edge transmits to its serving base station with high power to meet the required power target. Then, it will result in cross-tier interference at nearby small cells.

A critical point for efficient channel occupation can be achieved by using limited transmission power, which not exceeding the required power in meeting a minimum SINR constraint per user (Foschini and Miljanic, 1993). It also considered that channel reuse could be maximised by keeping the interference environment as low as possible. Cellular communication systems seek a simple and effective means of power control associated with randomly dispersed users, which are reusing a single channel in different and separate cells.

A dynamic distributed power control for wireless cellular communication systems has been proposed (Foschini and Miljanic, 1993). This technique evolves downlink power levels to achieve required SINR of each user iteratively with channel reuse scenario in different cells based on local measurement, instead of the global one. In this research, the proposed technique adjusts the transmission power iteratively in a static propagation channel model.

Parameters in Power-Control

For downlink transmission, the overall power allocation for all UTs is bounded by the total allocated power to the BS. Moreover, the signal quality at the end user terminals is also influenced by the transmitter amplifiers, interference power from an undesired source, and the channel gains to dedicated UTs. So that, the optimum condition could be achieved by providing CSI to the transmitting BS. It can be performed by transmitting back the downlink CSI from UTs to the BS, which will lead to communication overhead.

In wireless cellular networks, power control should consider some functionalities to optimise the networks' objectives as follows (Chiang et al., 2008).

1. Interference Management: Power control helps ensure efficient frequency reuse and meet user needs.
2. Energy Management: Power control can minimise the overall energy expenditure.
3. Connectivity Management: Power control can maintain the logical link for a given signal processing scheme to the end systems.

Based on the quantity measured to determine the allocated power, power control techniques can be classified as follows (Han and Liu, 2008).

1. Power strength-based: The BS measures the signal strength received from a UT to determine its power is higher or lower than the desired level.
2. SINR-based: In this group, an SINR threshold is considered to determine the received signal or the related channel is good or bad. In our proposed methods (Chapter 4, 5, and 6), an SINR threshold is selected and compared with the SINR of the received signals. The channels with SINR higher than the threshold will be considered having good channel gain, and radio resources will be allocated to these channels.
3. *Bit-error-rate* (BER)-based: If the received signal and the interference power are constant, the value of BER will be a function of the SINR level.

In fact, the SINR is a time varying function. Different digital signal processing techniques, such as channel encoding and modulation scheme, will result in different BER values for the same SINR value.
Modern wireless communication systems have already prepared for link adaptation, or *adaptive modulation and coding* (AMC), a mechanism to anticipate dynamic channel conditions. The implementation of AMC enables to hold the transmission power constant over a frame interval and to change the modulation and coding format to match the currently received signal quality or channel conditions (Shami et al., 2010). When the channel is in good condition, the high possible data rate can be transmitted, e.g. by using larger signal constellation, such as 64-*quadrature amplitude modulation*, and less robust error-correcting codes, such as 3/4 convolutional codes or turbo codes. Otherwise, the lower data rate will be transmitted, e.g. by using smaller signal constellation with robust coding such as *quadrature phase shift keying* with rate 1/2 convolutional or turbo codes.

In Chapter 4, 5, and 6, we propose some methods to mitigate interference in HetNet. The methods use some approaches to power allocation and manage accordingly as well as join with another resource allocation schemes to mitigate interference in the HetNet. Some power allocation schemes used in the proposed methods are equal (uniform) power allocation (EPA), water-filling power allocation and sub-optimal power allocation based on local search and penalty function.

3.6.2 Spectrum Allocation

In cellular networks, spectrum allocation is a process of allocating radio spectra and communication channels of end systems (such as BSs or UTs) to the various, often competing, interests. The objective is to achieve the maximum system spectral efficiency (in bps/Hertz/site) and to assure a particular QoS by avoiding or minimising co-channel, adjacent channel and cross-network interference (in HetNet) among nearby cells that share the radio spectrum. This Section will discuss the basic strategies of spectrum allocation in HetNet.

Spectrum Splitting and Reuse

This method mitigates the interference by splitting the allocated frequency spectra of a wireless system into two or more groups to serve some areas, reusing the spectra on different geographical areas and keeping the interference impact as low as possible. By using different frequency spectra, a serving cellular network will not get interference from nearby cells. Therefore, the QoS and high data rate throughput can be achieved using this method.

The common and frequently used technique in *spectrum splitting and reuse* (SSR) is a frequency reuse technique, which is the common technique used in cellular network dedicated to improving spectrum efficiency. The relationship among signal-to-interference-ratio (S_r/I), a co-channel reuse ratio (Q), and a cluster size (N_c) can be presented as follows (Rappaport, 2002).

$$\frac{S_r}{I} = \frac{(D/r)^n}{i_0} = \frac{(\sqrt{3N_c})^n}{i_0}, \tag{3.11}$$

where $Q = D/r$ is the co-channel reuse ratio. D is the distance between centres of the nearest co-channel cells. r is the cell radius. i_0 is the number of co-channel interfering cells. And n is the path loss exponent.

There are some techniques in SSR to improve capacity and to keep low interference. Figure 3.4 presents radio resource allocation based on SSR. Figure 3.4(a) and 3.4(b) show the frequency reuse 1 and 3 techniques respectively with the total transmission power per sector remains constant in both cases. Reuse 1 uses the same spectrum for all cells without employing any interference coordination among nearby cells, but limit the maximum transmission power. Meanwhile, reuse 3 implements total power but using the different spectra for different sectors. As presented by Stiakogiannakis and Kaklamani (2009), the performance comparison between both techniques shows that WiMAX networks employing per sector frequency reuse with a *frequency reuse factor* (FRF) of 1 are strongly "interference-limited". Whereas, in the case of per cell FRF of 3, the network behaves as "resource-limited".

Slightly different with frequency reuse techniques, the *fractional frequency reuse* (FFR) technique is developed to achieve an effective reuse factor between FRF 1 and FRF 3 (Rahman and Yanikomeroglu, 2010). The *soft frequency reuse*

(SFR) technique, a variation of FFR, employs zone-based reuse factors in the inner-cell and the outer cell areas. Restrictions are imposed regarding frequency and power allocation in the zones that effective reuse of the techniques can be adjusted by the division of powers between the frequencies used in the inner and outer zones.

In Figure 3.4(c), for 3-sector cell sites that implement SFR, $^1/_3$ of the available spectrum is allocated for the cell-edge band (also termed as the major band). This spectrum band is orthogonal to those in the neighbouring cells and forms a structure of cluster size of 3. Meanwhile, the cell centre band (also called minor band) in any sector is comprised of the frequencies used in the inner zone of neighbouring sectors. Each group of spectra is adjusting the transmission power based on the required effective reuse factor while keeping the total transmission power fixed. Higher transmission power is adjusted for the major band as shown on the right side of Figure 3.4(c).

On the contrary, the idea of the *partial frequency reuse* (PFR) is to restrict the part of the resources so that some frequencies are not used in some sectors at all. The effective reuse factor of this technique depends on the fraction of unused frequency. An example of PFR for sites with three sectors is shown in

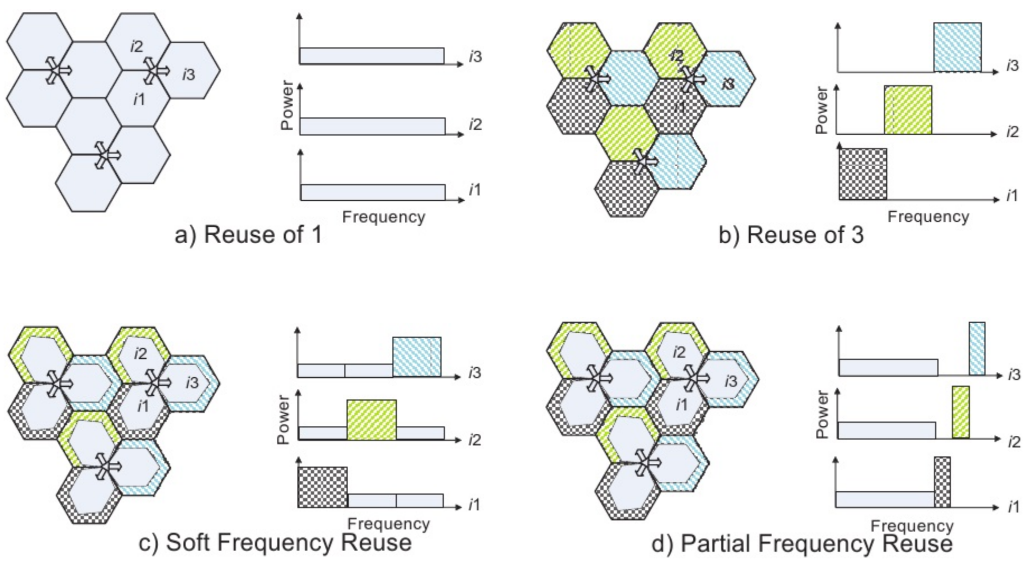


Figure 3.4: Spectrum splitting and reuse methods adapted from Rahman and Yanikomeroglu (2010)

Figure 3.4(d). If it is assumed that the available system bandwidth is B, which is divided into the inner (B_i) and outer (B_o) zones. Band B_i is used with a reuse factor of 1. Whereas, for the tri-sector BSs, the reuse factor for B_o is usually 3 in the outer zone. In this case, the effective frequency reuse factor is given by $B/\left(B_i + ({}^{B_o}/_3)\right)$. Therefore, the effective reuse of PFR technique is always greater than 1. Similar to SFR technique, the power used on frequencies in the outer zone can be amplified as shown in Figure 3.4(d).

Spectrum Splitting vs. Spectrum Sharing

Spectrum sharing allows macrocells and small cells access the same subchannels. Whereas SSR is the other method that allows macrocells and small cells access separate portions of the spectrum. For the cellular system, this approach applies in term of spectrum clustering.

Cheung et al. (2012) have investigated the effect of spectrum allocation in two-tier networks. In this paper, the scenario of closed access policy is applied for macrocells. For the small cells, either open or closed access is applied. The results indicate that with closed access small cells, the optimised shared and split spectrum allocations produce the highest throughput among all schemes in sparse and dense small cell networks, respectively. Whereas, for open access small cells, the optimised shared spectrum allocation provides the highest possible throughput for all small cell densities.

Mehanna (2013) has investigated spectrum allocation in OFDMA HetNet using two different scenarios, i.e. sharing vs splitting spectrum. The paper discovers that, for low small cell interference condition, the performance of spectrum sharing is slightly better than SSR. On the other side, for high small cell interference condition, it is better to split the spectrum between macro and small cells. The analysis shows that it is better to assign separate portions of the spectra to the macro and small cell networks, rather than using the shared spectra.

Unlicensed and Under-Utilised Spectrum Access

The wireless communication industry has purposed to increase the area capacity (in bps per square metre) by three orders of magnitude in the next five to ten years

(Zhou et al., 2016). In addition to densely deploying small cells and improving the spectral efficiency, another easy way is to exploit all available spectra for cellular services (Andrews et al., 2014). In which, future generation cellular networks probably involve multiple radio access technologies over multiple frequency bands.

The prime bands today are the licensed frequency bands under 3 GHz and the 2.4 GHz and 5 GHz unlicensed frequency bands. The industry is currently developing standards for side-by-side deployment of LTE in *licensed* and *unlicensed spectrum*. Recent standardisation developments have started to consider the opportunities for cellular networks to use the unlicensed spectrum bands such as the 2.4 GHz and 5 GHz bands that are currently used by Wi-Fi (Zhang et al., 2015).

Some methods for coexisting those two systems have been investigated (Choi and Park, 2015). They are *duty cycle* method, and two other methods based on *listen-before-talk* method, i.e. *load-based equipment* (LBE) and *frame-based equipment* (FBE) methods. When the wireless system is co-existence and shared spectrum with Wi-Fi, the collisions and latency will be derived. The simulation showed that LBE and FBE have the least effects on collisions and latency of Wi-Fi, respectively. Furthermore, the best performance for total devices in these HetNet is achieved by the co-existing of Wi-Fi and LBE.

Moreover, the Federal Communications Commission (FCC) and the European Telecommunications Standards Institute (ETSI) acknowledged the scarcity of available spectrum. By exploiting the existing wireless spectra opportunistically, CR networks are being developed to answer current wireless network problems resulting from the limited available spectrum and the inefficiency in spectrum usage (Akyildiz et al., 2008).

Thus the idea of Cognitive Radio came as a solution to the limited wireless spectrum that most of the frequency bands are already assigned or in some cases underutilised. Unlicensed spectrum bands such as the Industrial, Scientific and Medical (ISM) (ITU-R, 2011), which is set aside to encourage innovation, is either too congested or heavily underutilised. The FCC released a "NOTICE OF PROPOSED RULE MAKING AND ORDER"for the use of technological capabilities in the exploration of unused bands such as television broadcast bands (FCC, 2003).

Static vs Dynamic Spectrum Access

If spectrum allocation deals with a process of allocating radio spectra and communication channels of end systems to the various interests; then spectrum access deals with the decision of whether an individual user can access certain spectra. In general, there are two typical spectrum access methods in cellular networks, i.e. static and dynamic spectrum access. Static spectrum access, such as frequency reuse, has left spectrum access limited rather than throughput limited. The radio spectrum measurements obtained by the FCC's Spectrum Policy Task Force (FCC, 2002) shows that most spectrum occupation at any given time and location lies idle. This low spectrum occupation has triggered exciting activities in engineering, economics, and regulation societies in looking for better spectrum management policies and techniques.

Opposite to the current static spectrum management policy, the term *dynamic spectrum access* has broad interpretations. The different ideas that were discussed at the first IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks in 2005 (DySPAN 2005) extend this term. Figure 3.5 illustrates the classification of dynamic spectrum access mentioned above. Thus the implementation of dynamic spectrum access can be classified as follows.

1. *Dynamic Exclusive Use Model* (DEM)

This model preserves the basic composition of the current spectrum regulation policy. In which spectrum bands are licensed for exclusive use. The main idea is introducing flexibility for improving spectrum efficiency. Two approaches have been proposed under this model; they are (i) *spectrum property rights* and (ii) *dynamic spectrum allocation* (Zhao and Sadler, 2007). The first approach enables licensees to sell and trade spectrum and to choose technology freely. Then, the second approach aims to improve spectrum efficiency through dynamic spectrum assignment by exploiting its radio spectrum environment, which is the spatial and temporal traffic statistics of different services. In other words, in a certain region and certain time, the spectrum is allocated to services for exclusive use.

2. *Open Sharing Model* (OSM)

This model employs open sharing among some users, which is the basic idea of spectrum management. The approach to this model has been successfully implemented to wireless services in the unlicensed ISM radio bands, such as Wi-Fi. Centralised and distributed spectrum sharing strategies have been investigated to address technological challenges under this spectrum management model (Zhao and Sadler, 2007).

3. *Hierarchical Access Model* (HAM)

This model adopts a hierarchical access structure that classifies users into two groups, i.e. primary and secondary users. The basic idea is to provide licensed spectrum to secondary users while limiting the interference received by primary users (licensees). Spectrum sharing approaches for this model are (i) *spectrum underlay*, and (ii) *spectrum overlay* (Zhao and Sadler, 2007). Spectrum underlay applies severe constraints on the transmission power of secondary users. So the SUs operate below the noise floor of primary users. Different from spectrum underlay, the overlay approach does not necessarily apply severe restrictions on the transmission power of secondary users, but rather on when and where they may transmit. At first, this approach was proposed by Mitola (1999) under the term of *spectrum pooling*; and then investigated further by the DARPA Next Generation programme under the term of *opportunistic spectrum access* (Zhao and Sadler, 2007). It directly targets at spatial and temporal idle spectrum and permitting secondary users to identify and utilise local and instantaneous spectrum availability in a nonintrusive manner. Compared to DEM and OSM, HAM could be the most compatible model with the current spectrum management policies and legacy wireless systems. In which, the secondary system try to access spectra without disrupting to the main system and the spectrum licensee.

Opportunistic Spectrum Access for Cognitive Radio

To improve the utilisation of the limited radio resources, it needs a method that optimally utilises the current spectrum allocation. Cognitive radio has been proposed to dynamically and opportunistically access the spectra that previously has been allocated to another system. One of the major challenges in system design is to coordinate and cooperate in accessing the spectrum opportunistically among multiple distributive users with only local information (Han and Liu, 2008).

There are similarity and intersection ideas between this CR and HAM of

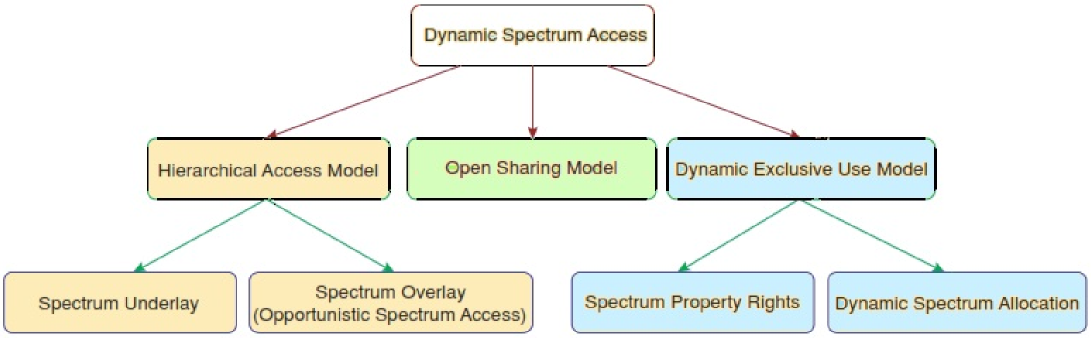


Figure 3.5: Dynamic spectrum access adapted from Zhao and Sadler (2007)

dynamic spectrum access. In which CR performs as a secondary system that accesses the spectrum opportunistically without disrupting the main primary system. Goldsmith et al. (2009) have discussed that there are three main cognitive radio network paradigms; they are underlay and overlay, which are also considered in HAM, and interweave. In the underlay network paradigm, cognitive users are allowed to operate if the interference that effects to non-cognitive users is below a given threshold. In the overlay paradigm, cognitive radio devices use sophisticated signal processing and coding to maintain or improve the performance of communication of non-cognitive radios at the same time to obtain some additional bandwidth for their communication. In the interweave system, the cognitive radios opportunistically exploit spectral holes to communicate without disrupting other transmissions. Figure 3.6 illustrates those cognitive radio network paradigms.

In our proposed method (Chapter 4 and 5), we use an interweave approach for perfect CSI, in which small cells will sense, analyse and occupy spectrum holes that are not occupied by the macrocell. In these methods, small-BSs will be assisted by their small-UTs to identify CSI.

3.6.3 Spatial Location-based Resource Allocation

Spatial location-based resource allocation assigns radio resources to maximise capacity and minimise interference by considering the spatial location of each

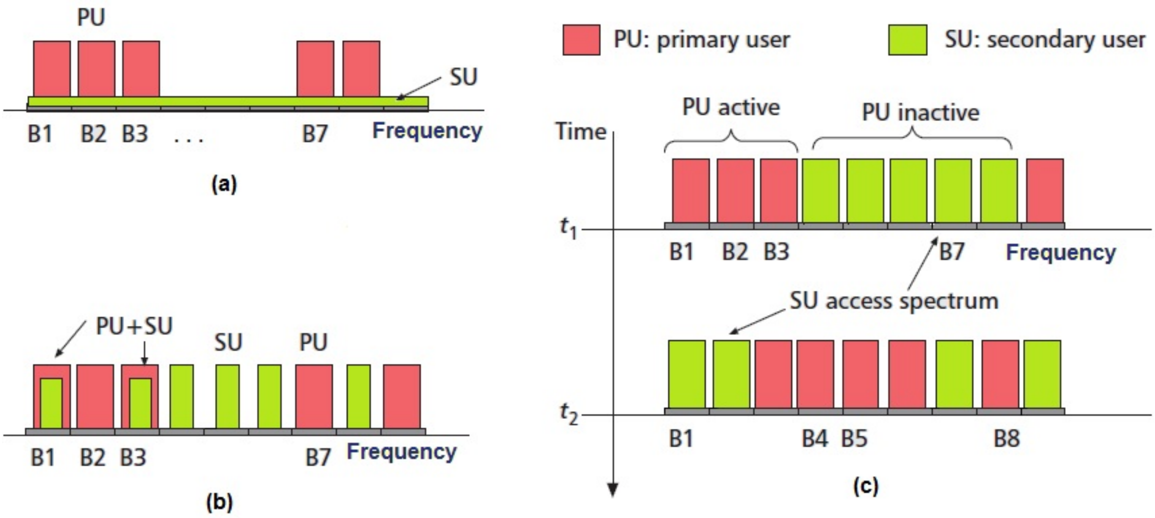


Figure 3.6: Dynamic spectrum access models in cognitive radio: (a) Underlay, (b) Overlay, (c) Interweave; adapted from Song et al. (2012).

node. This type of resource allocation has also been applied inherently in the other method, such as power control and frequency reuse that considering spatial location to minimise interference among adjacent cellular networks.

Based on the way the radio resource is allocated to serve communication nodes, beamforming can be classified into spatial position-based resource allocation. Beamforming is a process of generating a directional beam from an array antenna. It can be used to manage radio resources to maximise power allocation to desired nodes and to minimise interference to/ from unwanted nodes. Beamforming can be applied to achieve spatial selectivity at both the transmitting and receiving ends. The power improvement compared with omnidirectional reception/transmission is known as receive/transmission gain.

As considered by Van Veen and Buckley (1988), beamforming or spatial filtering is a signal processing technique used in antenna/sensor arrays for directional signal transmission or reception. Transmission beamforming uses multiple antennas to control the direction of a wavefront by appropriately weighting the magnitude and phase of individual antenna signals. These array antennas make possible to provide an array gain (also called beamforming gain) and better performance in specific areas along the edges of cells. In our proposed methods (Chapter 4 and 5), we assume using a single monopole antenna for each BS, instead of multiple (array) antennas, with omnidirectional beam pattern.

Meanwhile, to balance the load among different cells, a load balancing method is enabled to transfer the overloaded traffic from overloaded cells to neighbouring less-load ones. Various techniques of load balancing in the cellular network have been reviewed by Sharma et al. (2012). One technique of load balancing that widely known and has been implemented is to use smart base station antennas to change dynamically cellular coverage size and shapes, e.g. cell-breathing as used in *code-division-multiple-access* CDMA system and cell association. Our proposed methods (Chapter 4, 5 and 6), use a CSG approach instead of cell association.

3.6.4 Rate Adaptive-based Resource Allocation

Rate adaptation is one of the essential resource allocation issues, in which the system can adapt the users' data rates so that the limited radio resources can be efficiently utilised. Compared to power control, rate adaptation provides a different dimension of freedom to change the information rate over time, e.g. transmission power maintains the desired link quality whereas rate adaptation adjusts this link utilisation.

Fantacci et al. (2009) proposed the efficient adaptive modulation and coding techniques for WiMAX-based wireless networks, which captures the concept of rate adaptation. The techniques allow improving the network performance in case of non-line-of-sight (NLOS) communications, which are typical in urban areas. The modulation order and coding rate are possible to be switched using these techniques to match the channel conditions better. Hence, the wireless networks will obtain better performance both regarding error probability and data throughput.

In the proposed methods (Chapter 4 and 5), rate adaptation is assumed being implemented in scheduler units to allocate resources by considering proportional fairness among UTs, which will be discussed in detail in Section 3.6.5.

3.6.5 Time-Access Scheduling

In radio resource allocation, scheduling is a technique to distribute subchannels, regarding time and frequency access, to multiple-UTs by considering channel condition and QoS requirements (Capozzi et al., 2013). There are some approaches considered in scheduling techniques that will be discussed in this Section.

Multiuser Systems

In a multiuser system, resources must be divided among multiple users (Goldsmith, 2005). Signals of bandwidth B and time duration T utilise a signal space of dimension $2BT$, which the number 2 represents the forward and the reverse communication links. Signalling dimensions can be allocated to different users in various ways so that multiuser channel capacity is defined by a rate region instead of a single number. This region describes all possible user rates, which can be simultaneously supported by the channel with small error probability.

In a system with multiple users whose channels independently fade, multiuser diversity takes advantage of the fact that some users have better channel gain than others at any given time. System resources are allocated to the users with the best channel gain. It leads to improved system capacity and performance. Multiuser diversity was first proposed by Knopp and Humblet (1995) as a method to reduce error probability and increase throughput in uplink channels, and the same ideas can be implemented to downlink channels. The paper presented that an increase in capacity over a perfectly power-controlled (Gaussian) channel can be achieved, especially for a large number of users.

In multiuser diversity, different users are associated with different channels; and the system typically uses selection-diversity to choose the user with the best channel in any given fading state. The multiuser diversity gain relies on various channels among users. The larger the range of the dynamic fading, the higher the multiuser diversity gain. Moreover, system performance improves with the number of independent channels. Hence, the utilisation of multiuser diversity in a wireless system with a large number of users is so effective that will improve the system capacity when being included in the resource allocation strategy.

Multiple Access

The signal dimensions must be allocated to different users to support multiple users. It is also called as multiple access. The limitation of wireless radio resources and the increasing number of UTs demand communication channels be shared among multiple UTs. Hence the multiple access allocates limited radio resources to multiple UTs.

Because of limited resources, it needs to combine several signals for transmission on a particular shared medium, e.g. a radio spectrum channel. Signals are combined at the transmitter side by a multiplexer and split up at the receiver site by a demultiplexer. Based on the techniques used to share the transmission medium, the multiple-access schemes can be classified as time division (TDMA), frequency division (FDMA), code division (CDMA), space-division (SDMA) and orthogonal-frequency-division (OFDMA). Advantages and disadvantages of those different schemes have been discussed by Jamalipour et al. (2005).

In Chapter 4, 5, and 6, we propose resource allocation schemes to mitigate interference in OFDMA-based HetNet.

Proportional Fairness Scheduling

Multi-users need to get access to network service fairly following the objective of the network deployment. The serving network has a service module dedicated to access scheduling to distribute access to multi-users, which is also called as a scheduler.

A multiuser scheduler with *proportional fairness* (PF) has been proposed to maximise the downlink throughput of an LTE cellular communication system (Kwan et al., 2009). The paper was intended to examine some scheduling schemes, focussing on how the physical resource blocks are assigned. Numerical analyses showed that the proposed technique provides a superior fairness performance with a modest loss in rate relative to the Max-Rate scheduler, as long as the user's average SINRs are relatively uniform.

Besides, Huang et al. (2009) have found that the gradient-based scheduling scheme can reduce the complexity of the optimisation problem of resource allocation in a dynamic channel, in which the problem is solved in each time-slot based.

By using this approach, the scheduling and resource allocation problems involve some processes. They consist of selecting a subset of users for transmission, preparing the assignment of available subcarriers to selected users, and for each subcarrier determining the transmission power as well as the coding and modulation scheme used. Whereas, these duties are processed during each time-slot. By using a dual formulation, the simulation showed that an optimal algorithm was obtained when multiple UTs can share each tone in a time manner.

Moreover, a QoS-aware proportional fairness packet scheduling method has been proposed for the downlink of OFDMA systems (Kong et al., 2009). The proposed method is based on a cross-layer design, in which the scheduler considers both the channel (physical layer) and the queue state (data link layer) information to obtain proportional fairness at the same time to maximise each user's packet-level QoS performance. In this method, a proportional fairness value at time-slot t can be presented as follows.

$$\begin{aligned} PF(t) &= \sum_{k=1}^{K} \log\left(1 + \frac{\sum_{n=1}^{N} x_{kn}(t) \cdot r_{kn}(t)}{(t_c - 1)\overline{R_k(t)}}\right), \\ &= \sum_{k=1}^{K} \log\left(1 + \frac{r_k(t)}{(t_c - 1)\overline{R_k(t)}}\right), \end{aligned} \tag{3.12}$$

where K is total number of UTs. $x_{kn}(t) = \{0, 1\}$ represents the channel assignment status of user-k on subchannel-n at time-t. $r_{kn}(t)$ is the k-th user's data rate on subchannel-n at time-t. $r_k(t)$ is the instantaneous data rate of k-th user. t_c (time slots) is the average window size. $\overline{R_k(t)}$ is the average data rate over the transmission period of user k at time slot t, which can be approximated using a moving average value with average window size t_c time slots (Kong et al., 2009).

$$\overline{R_k(t+1)} = \left(1 - \frac{1}{t_c}\right) \cdot \overline{R_k(t)} + \frac{1}{t_c} \cdot r_k(t). \tag{3.13}$$

Notice that if one subcarrier is allocated to a different user, then the resulting PF value will be different. For example, before the assignment of the nth subchannel the user rate for every user $k \in K$ is $r_k(t)$. Then when the subcarrier is allocated to the k'th user, the new PF value is given by (Kong et al., 2009):

$$PF(t,k') = \log\left(1 + \frac{r_{k'}(t) + r_{k'n}(t)}{(t_c - 1)\overline{R_k(t)}}\right) + \sum_{k \neq k'} \log\left(1 + \frac{r_k(t)}{(t_c - 1)\overline{R_k(t)}}\right). \quad (3.14)$$

The simulation results showed that this algorithm is efficient regarding packet-dropping probability, packet delay, and average system throughput as well as maintaining adequate fairness among users with relatively low scheduling overhead.

In our proposed methods (Chapter 4 and Chapter 5), a PF scheduler as part of a resource allocation system is developed based on this work.

3.7 Summary

Some aspects of interference problems, resource allocation and their issues in HetNet have been presented in this Chapter. Section 3.2 has discussed various types of interference problems in HetNet. The interference can be classified based on transmission direction (downlink or uplink); frequency similarity (same or adjacent channel); destructive power (harmful or benign interference); and hierarchical network level (cross or co-tier). Different characteristics of the interference need a different approach to eliminate its destructive effect.

Then, various interference management schemes in HetNet have been discussed in Section 3.3. In which, the schemes are effective for the specific purpose in where they are specifically designed for. Thus, the benefits of those schemes are mutually exclusive; and a combination of those approaches might be employed in the system (Rahman and Yanikomeroglu, 2010). This situation encourages researchers investigating a new method combining some advantages of the previous ones.

Moreover, a cognitive radio approach for interference management in HetNet has been discussed in Section 3.4. There are some guidelines related to this scheme; in which small-BSs must have capabilities of self-configuration and self-optimisation based on their radio environment with the objective of interference mitigation across cells. By having some features of environmental awareness, radio scene analysis, channel estimation and predictive modelling, as well as radio resource control and allocation, this approach is expected to be able to cope with the complicated, dynamic, and unpredicted interference problem in small cell deployments.

Furthermore, Section 3.5 has discussed some resource allocation issues in OFDMA-based HetNet, such as LTE. In those problems, the resource allocation should consider network characteristics, inherent characteristic of radio resource, moreover, some other relevant parameters as well as their implementation strategies. Two models of channel capacity, which describe the upper bound capacity of certain channels in wireless networks, have also been discussed in Section 3.5.2. This Section ends the discussion with optimisation problems of resource allocation in OFDMA-based cellular networks Section 3.5.3. It describes some strategies to optimise the channel capacity in those type of networks.

Finally, some approaches to resource allocation in OFDMA-based HetNet has been discussed in Section 3.6. These allocation techniques are based on the inherent characteristics of radio resources, including power allocation, spectrum allocation, spatial location-based resource allocation and time-access scheduling. This Section has also discussed the recently proposed strategies for optimising the spectrum utilisation, i.e. opportunistic spectrum access. In which, this method underlays the CR strategies for accessing and sharing the spectra with their licensees and also optimising the spectrum utilisation without disrupting the performance of the main spectrum licensees.

As previously discussed that one of the main problems in small cell deployments is interference, especially for co-channel or shared spectrum allocation, which can be co-tier or cross-tier interference. The problem will be more complicated in the real and dynamic environments of an LTE system that characterised by multi-carrier, multiuser, and heterogeneous networks. Cognitive interference management in LTE heterogeneous cellular networks will be proposed in Chapter 4 to deal with this problem.

Chapter 4

Spectrum Splitting-based CIM

4.1 Introduction

In this Chapter, *spectrum splitting-based cognitive interference management* (SS-CIM1) in *orthogonal frequency division multiple-access* (OFDMA)-based heterogeneous cellular network (HetNet) is proposed. In this work, HetNet consist of a macrocell network and some underlaying indoor small cell networks, i.e. femtocell networks. SSCIM1 in HetNet refers to the resource allocation method that uses cognitive radio concept to mitigate interference by allocating orthogonal spectrum among macro and small cell networks.

Indoor small cells, such as femtocells, are designed to allow consumer deployment of these networks anytime and anywhere with some restrictions from the network provider. It lets network providers get the benefit of extending their service coverage to blank spot areas, low receive-power indoor areas as well as at Cell-Edges. Moreover, network providers could also expect on having the benefit of improving the service performance, increasing the system capacity as well as enhancing the spectrum efficiency. In such a scenario, interference is a critical issue since small cells reuse the same spectrum that is already allocated to the macrocells. Therefore, small cell deployments have a high potency of introducing interference into the main macrocell network as well as adjacent small cell networks.

Interference management can be performed either in the macrocell, small cell layer or even both of them to mitigate the interference impact in HetNet. Section 3.3 has discussed some schemes of interference management with different approaches. However, each scheme as mentioned above has its advantages for specific interference problems. To combine some benefits of different schemes, researchers have integrated the cognitive radio concept into interference management methods (Attar et al., 2011; Kaimaletu et al., 2011). By using this concept, the scheme will be aware of its environment and adaptive to statistical variations in the input stimuli, with two main objectives of highly reliable communication and efficient utilisation of the radio spectrum (Haykin, 2005).

Kaimaletu et al. (2011) have proposed a cognitive interference management scheme in HetNet. By implementing the cognitive process to some extent, the method avoids occupying interfering *resource-blocks* (RBs) to mitigate the downlink interference in these networks. In which, RB is the smallest unit in *Long-Term Evolution* (LTE) system that can be managed for resource allocation. Thus, we call this method as *interfering-resource-blocking-based* CIM (IRB-CIM). To know which RBs are eligible to be occupied, the method proposed a mechanism to exchange the information about the channel occupancy among all active base-stations (BSs). However, along with increasing number of small cell BSs (small-BSs) and *user-terminals* (UTs), system's complexity and its computational load will also increase. These are mainly caused by information exchange process among interfering and interfered BSs. Moreover, to determine which RBs will be occupied or avoided; the method did not consider the quality of selected RBs. Thus, BSs would probably avoid good RBs and occupy the bad ones.

To simplify and speed up the information exchange among BSs as well as to address the above problem, this Chapter proposes SSCIM1 for downlink-channels of LTE HetNet. The method manages RB allocation based on channel state information and spectrum splitting for different network-tiers.

To discussed the proposed method, this Chapter is organised as follows. Section 4.2 will describe system model and its parameters. Section 4.3 will discuss the proposed resource allocation method. Section 4.4 will discuss simulation method, results and performance analyses of the proposed method. Finally, all these works are summarised in Section 4.5.

4.2 System Model

The system model consists of a macrocell network with some overlying small cell networks within the same coverage area. The duplexing mode is frequency division duplex. The simulation utilizes 3GPP-LTE parameters, including bandwidth and a fast-Fourier-transform (FFT) size (Khan, 2009; Lescuyer and Lucidarme, 2008) and physical layer structure (Rumney, 2013). The propagation channel models cover some aspects of wireless channel models such as propagation path losses (3GPP, 2010) and their modification following some standard techniques (Goldsmith, 2005), shadowing (Zhang et al., 2012), the autocorrelation of shadow fading (3GPP, 2010), and frequency selective channel, see Section 4.2.1. Most system parameters follow the model provided by Kaimaletu et al. (2011); and some of them refer to these works (Nguyen et al., 2014; Zhang and de la Roche, 2011).

The macro-BS is split into three sectors. Each sector serves ten macro-UTs that are uniformly distributed in this area. Each macro-UT has a minimum distance of 30 m to the macro-BS. Moreover, ten small cells are uniformly distributed in each sector. Small-UTs are uniformly distributed in a circular area around each small-BS with a radius of 40 m. The total number of users in each small cell is random between 1 to 2 users. The minimum distance between a small-BS and a unit of small-UT is 10 m. The antenna height of the macro-BS is assumed as 25 m (Kaimaletu et al., 2011). The ceiling height is proportional to the size of spaces, e.g. in a range of 2.7 m-2.85 m in large open office area (Yatt, 1998). Thus the height of small-BSs' antennas is assumed as 2.5 m. During the last two millennia, human height, based off of skeletal remains, has stayed fairly steady. It oscillates around 170 cm (Roser, 2017). Thus, it is assumed that the antenna height for UTs is 160 cm.

It is assumed that small cells have a closed-access policy, where only authorised small-UTs can be served. The overall system parameters are presented in Table 4.1 and Table 4.2. Figure 4.1 illustrates the two-tiers wireless network.

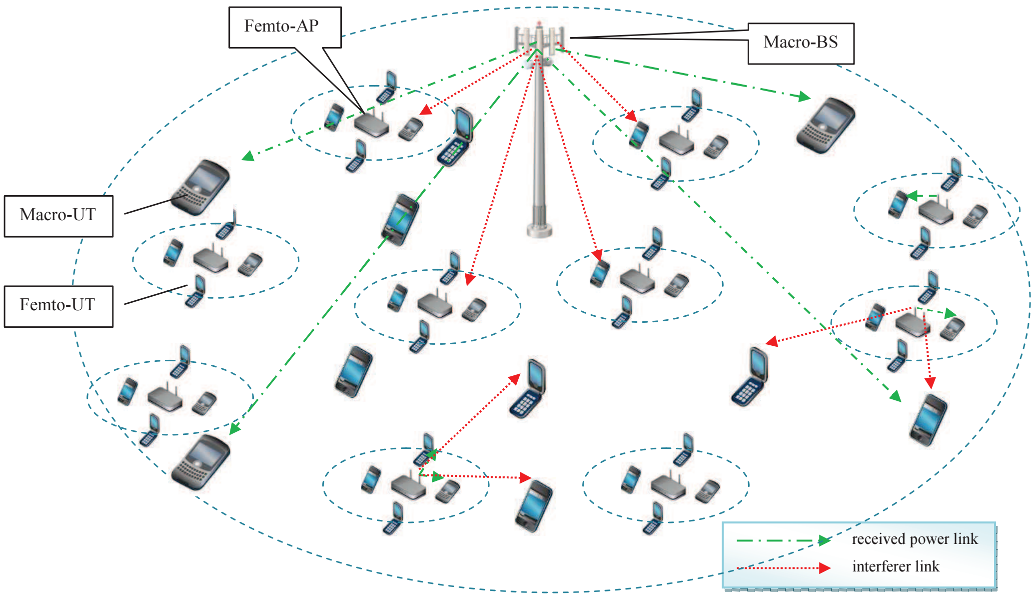


Figure 4.1: Simulation scenario

Table 4.1: Network parameters

Parameters (Unit)	Macrocell	Small Cell	User-Terminal
Number of networks	1	30	-
Distribution of the location	-	Uniform	Uniform
Radius of coverage area (m)	500	40	n/a
Minimum distance (m)	30	3	-
Total transmission power (dBm)	48	30	n/a
Antenna type	directional	omnidirectional	omnidirectional
Antenna gain (dBi)	10	0	0
Antenna height (m)	25 (Kaimaletu et al., 2011)	2.5 (Yatt, 1998)	1.6 (Roser, 2017)
Number of sectors	3	1	1
Number of served users	30	1 to 2 (random)	-

Table 4.2: Wireless channel parameters

Symbol	Parameter (Unit)	Value
f_C	centre frequency (GHz)	2
B	system bandwidth (MHz)	10
N_F	FFT size	512
Δf	subcarrier spacing (kHz)	15
N_{frame}	number of total frames	100 - 400
N_{frame}^{sub}	number of subframes per frame	10
N_{sub}^{slot}	number of time-slots per subframe	2
N_{sub}^{RB}	number of resource blocks per subframe	50
N_{RB}^{sc}	number of subcarriers per RB	12
fd	fading: - each subchannel	Rayleigh flat
	- all bandwidth	Frequency selective
N_0	Gaussian noise power spectral density per RB (dBm)	-120

4.2.1 Propagation Channel Model

Mostly small cells are implemented in heavily built-up urban environments to cover isolated indoor area. The channel models among the macro-BS, small-BSs and user-terminals are dominantly affected by (Lee et al., 2010):

- Outdoor or indoor path losses (PL in dB),
- Log-normal shadowing (ψ_{dB} in dB),
- Multipath fading ($|H_{n,k}|^2$).

The model represents the combination of all channel characteristics and functions as a filter of the transmitted signal. The propagation channel gain of subchannel-n for user k is:

$$G_{n,k} = 10^{-(PL_{n,k}+\psi_{\text{dB}})/10}|H_{n,k}|^2, \tag{4.1}$$

where PL (in dB) is the propagation path-loss. ψ_{dB} (in dB) is the log-normal shadowing with zero mean and standard deviation of $\sigma_{\psi_{\text{dB}}}$ dB. $H_{n,k}$ is the frequency selective channel fading with Rayleigh distribution. This propagation channel (4.1) is generated every two time-slots in the simulation, which is identical to one subframe or 10 times for each frame. Thus, the channel is static for this period. It is assumed that channel is flat fading for one subchannel, i.e. the spectrum width of RB in the frequency domain.

Propagation Path-Loss

In HetNet, the transmitted signal will pass through various types of propagation channels. In this simulation, propagation path loss models are developed based on 3GPP's physical layer models (3GPP, 2010) with several modifications as needed following some well-known techniques (Goldsmith, 2005). Hence, the propagation path losses with the NLOS condition are modelled as follows.

1. The outdoor link propagation loss PL_{Ot} models the channels from the macro-BS to a macro-UT using an *Urban Macro* (UMa) path loss model (3GPP, 2010).

$$\begin{aligned} PL_{Ot}\ (\text{dB}) = \ & 161.04 - 7.1\ log_{10}(W) + 7.5\ log_{10}(h) \\ & - \left(24.37 - 3.7\left(\frac{h}{h_{BS}}\right)^2\right) log_{10}(h_{BS}) \\ & + (43.42 - 3.1 log_{10}(h_{BS}))\,(log_{10}(d) - 3) \\ & + 20 log_{10}(f_c) - \left(3.2(log_{10}(11.75\ h_{UT}))^2 - 4.97\right), \end{aligned} \tag{4.2}$$

   where W is the street width of 20 m. h is the average building height of 20 m. h_{BS} is the macro-BS actual antenna height of 25 m. h_{UT} is the actual user-terminal antenna height of 1.5 m. d is the Tx-Rx distance in metres. f_c is the carrier frequency in GHz.

2. The indoor link propagation loss models the channels from a small-BS to its served small-UT using *Indoor Hotspot* (InH) path loss model (3GPP, 2010).

$$PL_{In}(\text{dB}) = 43.3\ log_{10}(d) + 11.5 + 20\ log_{10}(f_c). \tag{4.3}$$

3. The outdoor-to-indoor link propagation loss is modelled as an equation modification of *Urban Micro* (UMi) for O-to-I loss (3GPP, 2010) as follows.

$$PL_{Ot-In}(\text{dB}) = PL_b + L_w + PL_{in}, \tag{4.4}$$

where PL_b (in dB) is the basic path loss:

$$PL_b(\text{dB}) = PL_{B1}(d_{out}).$$

d_{out} (in metres) is the distance from BS to the wall next to UT location.

$PL_{B1}(\text{dB}) = 36.7\log_{10}(d_{out}) + 22.7 + 26\log_{10}(f_c)$: the loss of UMi Outdoor for NLOS scenario. f_c is the carrier frequency in GHz.

$L_w = 13$ dB: the wall penetration loss (a concrete wall) (Goldsmith, 2005).

The path-loss inside the building in dB (PL_{in}) is:

$$PL_{in}(\text{dB}) = 0.5 \times d_{in},$$

where d_{in} is the perpendicular distance (in metres) from wall to UT, which is 0 m $< d_{in} <$ 25 m. $d_{out} + d_{in}$ is the distance between a transmitter and a receiver or an interfered device, which is 10 m $< d_{out} + d_{in} <$ 1000 m.

4. The indoor-to-outdoor link propagation loss is a modification of the InH path loss model (4.3).

$$PL_{In-Ot}(\text{dB}) = PL_b + L_w + PL_{ot}, \tag{4.5}$$

where $PL_b(\text{dB}) = PL_{In}$: the InH basic path loss (4.3).

The path-loss outside the building uses the *piecewise linear model* (Goldsmith, 2005).

$$PL_{ot}(\text{dB}) = 10\gamma_{ot}log_{10}(d/r_S), \tag{4.6}$$

where $\gamma_{ot} = 3.7$, is the urban macrocell path loss exponent (Goldsmith, 2005). r_S is the radius of the small cell in metres; $d > r_S$.

5. The propagation loss for adjacent small cells is a modification of InH path loss model (4.3).

$$PL_{In-In*}(\text{dB}) = PL_b + L_w + PL_{ot} + L_w + PL_{in*}, \tag{4.7}$$

where $PL_b(\text{dB}) = PL_{In}$: the InH basic path loss, see Equation (4.3). PL_{ot} is the path loss outside the building with $r_S < d < d_1$. d_1 (in metres) is the distance between the interference source small-BS and the border of the neighbour small-BS* which its small-UT* gets interference, see Equation (4.6).

Path loss inside the building of the interfered small cell* (PL_{in*}) (Goldsmith, 2005) is:

$$PL_{in*}(\text{dB}) = 10 \cdot \gamma_{in} \cdot log_{10}(d/d_1),$$

where $\gamma_{in} = 3$, is the indoor path loss exponent (Goldsmith, 2005).

It is assumed that each small cell is covered by a circular concrete wall that surrounds the small-BS, which has a wall penetration loss (L_w) of 13 dB (Goldsmith, 2005). As stated on Table 4.2, thermal noise is -120 dBm/subchannel, in which each subchannel consists of 12 subcarriers of 15 kHz each. Thus, the thermal noise equals to 5.556 $\times 10^{-21}$ W/Hz.

Log-Normal Shadowing

A signal propagated through a wireless channel will typically encounter random variation due to obstruction from objects in the signal path. It will increase random variations of the received power at a given distance. Such variations are also caused by changes in reflecting surfaces and scattering objects. This effect is called shadow fading or shadowing. Shadowing is sensitive to the frequency as well as the location of obstructions concerning the transmitter or receiver. Large-scale variations caused by shadowing of some obstacles are confirmed to follow a log-normal distribution (Chrysanthou and Bertoni, 1990; Greenstein et al., 1997), which means that when measured in decibel they follow a Gaussian distribution.

The distribution of ψ in dB is Gaussian (Normal) with mean $\mu_{\psi_{dB}}$ in dB and standard deviation $\sigma_{\psi_{\text{dB}}}$ in dB as follows (Goldsmith, 2005).

$$p(\psi_{\text{dB}}) = \frac{1}{\sigma_{\psi_{\text{dB}}}\sqrt{2\pi}} \exp\left(-\frac{(\psi_{\text{dB}} - \mu_{\psi_{\text{dB}}})^2}{2\sigma^2_{\psi_{\text{dB}}}}\right), \tag{4.8}$$

The received signal power with the combined effect of path loss (power falls off with distance) and shadowing is given by (Goldsmith, 2005):

$$P_r(\text{dB}) = P_t(\text{dB}) - PL(\text{dB}) - \psi_{\text{dB}}, \tag{4.9}$$

where PL is the propagation path loss as discussed previously, see Section 4.2.1. ψ_{dB} is log-normal shadowing with zero mean and variance of $\sigma^2_{\psi_{\text{dB}}}$,

$$\psi_{\text{dB}} = \sigma_{\psi_{\text{dB}}} \cdot X_N,$$

where X_N is a random variable with zero mean and Normal distribution.

Table 4.3 presents the values of shadow fading standard deviation for the different environment. InH is an indoor hotspot service area. UMi is an urban micro service area. UMa is an urban macro service area. And LOS is a *line-of-sight* condition.

Table 4.3: Shadow fading standard deviation $\sigma_{\psi_{\text{dB}}}$ (in dB); adapted from 3GPP (2010)

InH		UMi			UMa	
LOS	NLOS	LOS	NLOS	O-to-I	LOS	NLOS
3	4	3	4	7	4	6

Spatial Autocorrelation Shadow Fading

Consider two mobile terminals communicate with the same BS, and are separated by a distance of δ. Their shadow fading values have spatial auto-correlation (Zhang et al., 2012):

$$R(\delta) = e^{\frac{\delta}{d_{corr}}}, \tag{4.10}$$

where δ (in metres) is a separation distance between two adjacent fading channels. d_{corr} (in metres) is a decorrelation distance, which is determined by the size of the blocking objects in the environment around the mobile station as presented in Table 4.4. $e \approx 2.71828$ is the Euler's number.

Table 4.4: Decorrelation distances d_{corr} of shadow fading (in metres); adapted from 3GPP (2010)

InH		UMi			UMa	
LOS	NLOS	LOS	NLOS	O-to-I	LOS	NLOS
10	6	10	13	7	37	50

Frequency-Selective Fading

In general, the heights of a mobile antenna are far below the surrounding objects. It is difficult to find an LOS propagation path between the BS and the UT. Hence, the transmitted signal will experience reflection, diffraction and scatter when propagates in this kind of wireless channel. The combination of multipath components with randomly distributed amplitudes, phases and angles of arrival cause distortion of the received signal. Combining vectorially at the receive antenna cause the received signal to distort or fade. Thus, fading is rapid fluctuations of the radio wave in the amplitude, phase and the multipath delays over a short period. The channel power response in frequency domain can be represented as:

$$|\boldsymbol{H}_f|^2 = \text{FFT}(\boldsymbol{\sigma}_h^2), \tag{4.11}$$

where $\text{FFT}(\cdot)$ is the discrete Fourier transform function. $\boldsymbol{\sigma}_h^2$ is the channel power gain. The generation steps of the frequency selective fading channel model will be described in Appendix B. Equation (4.1) represents the overall channel model for a transmission link, including this fading channel model.

Figure 4.2 illustrates the downlink signalling procedure for the even slot of each subframe. Physical layer model such as frame structure and the overall signalling model used in the simulation will be described in Appendix C.

4.3 Proposed Resource Allocation Technique

In this Section, a new dynamic resource allocation method to mitigate interference in HetNet is proposed. In this method, the macrocell allocates RBs by considering the SINR level of the *reference signal received power* (RSRP), which is received

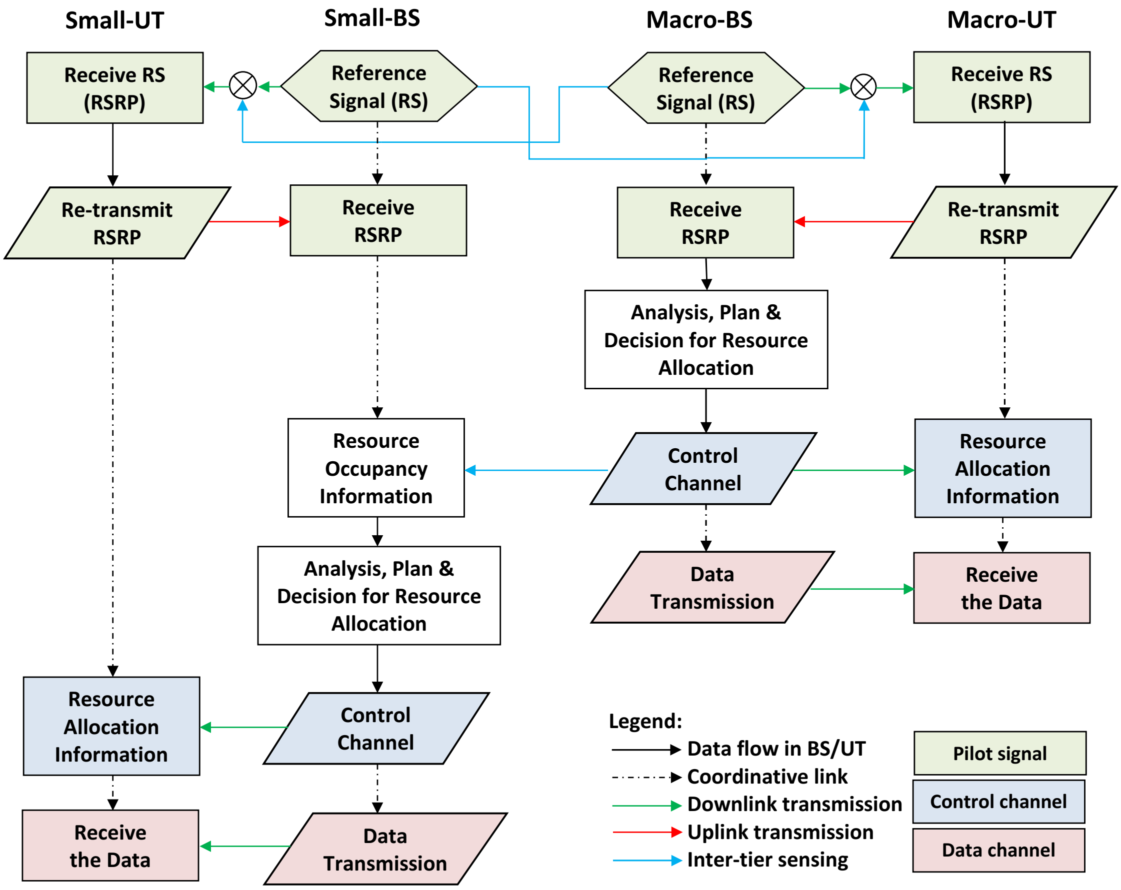


Figure 4.2: Downlink signalling procedure for the even slot of each subframe

back from its served UTs. Hence, *reference signal* (RS) functions as a pilot signal that can be used to estimate the channel state information. It is assumed that each UT can identify the pilot signal from each BS. By blocking some RBs having SINR of RSRP lower than an assigned threshold, the macro-BS allocates good RBs for macro-UTs. Subsequently, a scheduler distributes the RBs to each user at different times. In small cells, by utilising control-channel information received from the macro-BS, small-BSs allocate RBs that are not occupied by the macrocell to serve its users.

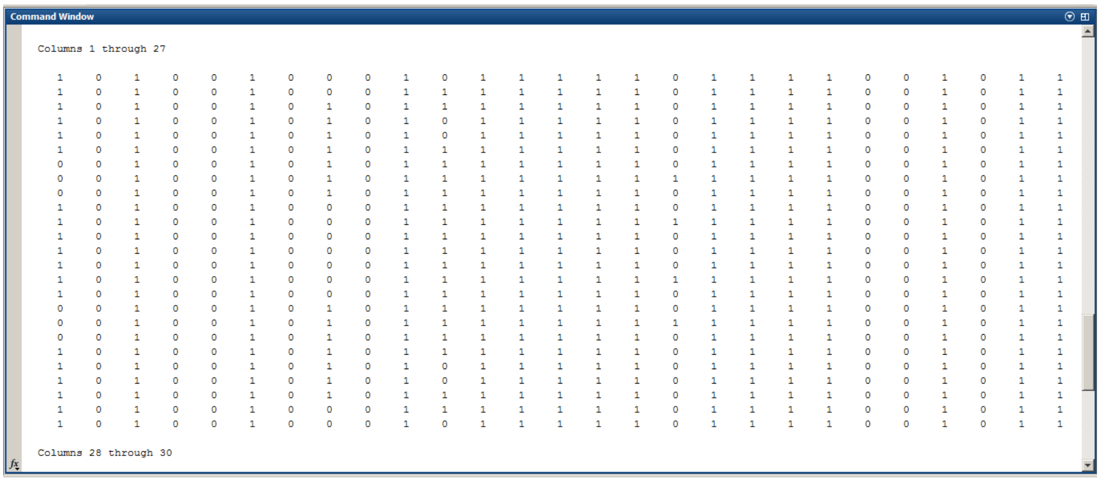
Either on macrocell or small cells, the resource allocation is updated for each subframe following the change period of the dynamic channel. It is assumed no delay between the macro-BS and small-BSs for some signalling processes except for control-channel signalling in small cells having one OFDM-symbol delay over the macrocell's process. This delay is implemented as the small cells need to completely obtain all control-channel information from the macro-BS before determining the resource allocation for their served users. The proposed algorithm has some characteristics of being adaptive to its environment, planning, making a decision and taking an action that commonly used in cognitive radio (Siswanto et al., 2014).

SINR Level Identification and Spectrum Splitting

After all macro and small-BSs transmit their pilot signals at the same time, then each UT receives and identifies the pilot signal from each BS above. Subsequently, the UT retransmit all these pilot signals to its serving BS. After that, the macro-BS identifies these pilot signals being received from all macro-UTs and calculate them to find the SINR.

The macro-BS then marks RBs with SINR lower than a preassigned threshold γ_{th}^{M} as '1'. This value is chosen to allow in counting the number of *weak UTs* in each RB, which are the macro-UTs having SINR lower than a threshold. Then, the macro-BS uses this value as a reference for determining which RBs will be occupied or avoided after compared to the threshold. Next, macro-BS generates a 'weak-RB matrix' (Figure 4.3) to save this information. The matrix represents SINR condition of RSRP signals that are received by all macro-UTs on all sub-channels compared to the threshold. Based on this Table, the macro-BS counts the number of UTs with low SINR (weak UTs) in each RB. It then orders the number of weak UTs of each RB and chooses a resource allocation threshold φ, which is the ratio of a predetermined value n over the variant number of weak UTs N_{wu}, see Algorithm 1: Step 7. When an RB has some weak UTs above the threshold φ, it will be blocked. Finally, the macro-BS blocks some RBs with a high number of weak UTs and lets small-BSs to utilise these RBs. Meanwhile, the unblocked RBs will be occupied by the macro-BS.

All processes above will result in an RB allocation map (RB-map) as shown in Table 4.5. Flag '1' represents an RB being allocated to the macrocell. Algorithm 1 summarises all processes above.



1	0	1	0	0	1	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	1	0	1	0	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	1	0	1	0	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
0	0	1	0	0	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
0	0	1	0	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	1	1
0	0	1	0	0	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
0	0	1	0	0	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
0	0	1	0	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	1	1
0	0	1	0	0	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	1	0	1	0	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	1	0	1	0	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1
1	0	1	0	0	1	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1

Figure 4.3: Part of weak-RB matrix for SSCIM1 (φ 17% and γ_{th}^{M} 10 dB)

Control-Channel Information Sensing

In this step, all small-BSs simultaneously sense the control-channel information, i.e. *physical downlink control channel* (PDCCH), from the macro-BS. These channels hold information of RB allocation for all macro-UTs in one subframe, which are two time-slots. Small-BSs use this information to observe RBs occupied by the macro-BS, find out unoccupied ones and allocate them to their served users. Based on this, each small-BS generates its RB-map (Table 4.5).

Frame-Based Scheduling and Transmission

Based on the RB-map (Table 4.5), the scheduler in each BS (both macro and small cells) then allocates RBs to its served UTs for downlink transmission. By using a *quality-of-service* (QoS)-aware multi-carrier *proportional fairness* (PF) scheduler (Section 3.6.5), the distribution of RBs among users in time and frequency domain can be maintained fairly. Equal power allocation over the entire bandwidth is then implemented for all cells in the system.

4.3.1 Algorithm for Macrocell

In general, the resource allocation procedure for macrocell can be presented as follows.

Broadcasting the Pilot Signals:

1. Broadcasting the pilot: The macro-BS, along with all small-BSs, broadcasts the reference (pilot) signal (RS) to its UTs.

2. Sensing the pilot: Each macro-UT, along with each small-UT, senses and identifies RS signal from the macro-BS as well as from the small-BSs. Thus each UT, either in the macrocell or small cells, has all RSRP information from all transmitting BSs.

3. Retransmitting-back the pilot: Each macro-UT transmits back all of its RSRP signals through the uplink control channel, such as *physical uplink control channel* (PUCCH) of the LTE system, to its serving macro-BS. At the same time, each small-UT also retransmit its RSRP to its serving small-BS.

4. Readmission the pilot: The macro-BS receives RSRP signals from its served macro-UTs. In which, RSRP signals contain information of pilot signals from all transmitting BSs.

Broadcasting the Control-Channel Information:

5. Identifying the weak RBs: The macro-BS identifies RSRP from all of its served macro-UTs, calculates its SINR based on RSRP data, compares the

Table 4.5: RB allocation map (RB-map)

RB index	Allocation flag
1	0
2	1
3	0
⋮	⋮
N_{RB}	1

SINR with the preassigned SINR threshold, and then develops a *weak-RB matrix* (Figure 4.3). The macro-BS then duplicates the matrix for two time-slots, which are the total time-slot number for each LTE subframe. As the channel gain will change for one subframe, thus the resource allocation plan and update are performed for each subframe, for both macro and small cells.

6. Identifying the weak UTs: Based on the *weak-RB matrix* (Figure 4.3), then the macro-BS counts the number of the weak macro-UTs on each RB, whose SINR or SNR is lower than the preassigned threshold.

7. Assigning the resource allocation threshold φ, which is the threshold of RBs having some weak UTs will be blocked (see Algorithm 1: Step 7).

8. Generating the RB-map: In this step, some RBs with the high number of weak UTs are avoided. Then, the RB occupation state is used for generating an RB-map (Table 4.5). Flag '1' represents the allocated resource for next transmission.

   Algorithm 1 presents some steps above. $\boldsymbol{\rho}$ is the RB-map, see Table 4.5. N_{RB} is the total number of RBs. N_{wu} is the variant number of weak UTs in each RB. γ_{ik} is the SINR received by user-k on RB-i. γ_{th}^{M} is a macrocell SINR threshold. $\boldsymbol{\Psi}$ is the weak-RB matrix, see Figure 4.3. $n(\cdot)$ is the element number of the set. φ is the resource allocation threshold, which is the ratio of a predetermined value n over N_{wu}. This value determines which RBs having a certain number of weak UTs will be blocked.

9. Resource scheduling: Table 4.5 is then used by the scheduler to allocate resources to certain UTs in different time-slots by considering proportional fairness among users. It demands the scheduler considering some relevant parameters, including channel assignment status (Table 4.5), SINR of allocated user on certain RB at time t, the instantaneous data rate of allocated user, and the average data rate of user-k at time-t as discussed in Section 3.6.5.

   - Proportional fair multi-user multi-carrier resource scheduling: Macro-BS performs a QoS-aware multi-carrier resource scheduling (frequency and time) by considering proportional fairness for all users based on the algorithm proposed by Kong et al. (2009). The scheduler runs the scheduling process based on the RB-map (Table 4.5) from the previous step and the other parameters as presented in Section 4.3.1.

- In general, this PF scheduler is used as follows, see Algorithm 2.
  (a) To generate an (n by k) matrix of weak-RB (Figure 4.3). k is the number of users, and n is the number of subchannels.
  (b) To develop a vector of RB-map (Table 4.5), which represents the best channel among all users in each subchannel.
  (c) The RB-map is used as a reference in scheduling and resource allocation in this formula.
- Algorithm 2 describes the scheduling process. K is the total number of macro-UTs. M is the total number of subchannels. $r_k(t)$ is the k-th user's data rate. $r_{k,m}(t)$ is the $r_k(t)$ for subchannel-m. RB(k, m) is the resource block of the user-k on subchannel-m. $\tilde{k}$ is the selected user. C_k is the subchannel set of the user k.

10. Broadcasting the control-channel information: The macro-BS sets and broadcasts PDCCH channel to all its served macro-UTs based on the results of resource scheduling. The PDCCH channel is then used by each macro-UT to determine which subchannel and time-slot that can be accessed for the next two time-slot periods of downlink transmission. In LTE, the number of OFDM-symbol allocated for the PDCCH is given by the *control format indicator*, which can take the values 1, 2 and 3, and depend on the bandwidth transmission (Rumney, 2013). This physical channel is transmitted on the first order (i.e. even slot) of a period of two time-slots or one sub-frame.
Broadcasting the Data-Channel:
11. Broadcasting data-channel: The macro-BS then broadcasts data via some allocated subchannels using *physical downlink shared channel* (PDSCH) channel to the preassigned macro-UTs by referring to Table 4.5. Transmission power is distributed equally to each subchannel.

Algorithm 1 RB-map vector generation in the macrocell

$\boldsymbol{\rho} = \text{ones}(N_{RB},1)$. $\leftarrow$ setting the initial values of RB-map;
find$(\gamma_{ik} < \gamma_{th}^{M}) \leftarrow$ finding weak RBs;
if $\gamma_{ik} < \gamma_{th}^{M}$ then $\psi_{ik} = 1$, else $\psi_{ik} = 0 \mid \psi_{ik} \in \{\boldsymbol{\Psi}\}$. $\leftarrow$ generating a weak-RB matrix $(\boldsymbol{\Psi})$(Figure 4.3);
$\boldsymbol{\psi} = \sum_{k \in K} \psi_{ik},\ \boldsymbol{\psi} \in \{\boldsymbol{\Psi}\}, \forall i \in \{0, 1, \cdots, N_{RB}\}$. $\leftarrow$ identifying the number of weak macro-UTs per subchannel;
find$(\boldsymbol{\theta})$, $\boldsymbol{\theta} \in \{\boldsymbol{\psi}\}, \boldsymbol{\psi} \in \{\boldsymbol{\Psi}\}, \psi_i \in \{\boldsymbol{\psi}\}, \psi_i \neq 0, \psi_i \neq \psi_j$ for $i \neq j$. $\leftarrow$ finding the unique number of weak UTs per RB;
$\boldsymbol{\theta}_{sorted} = \text{sort}(\boldsymbol{\theta}, \text{'descend'})$. $\leftarrow$ shorting the unique number of weak UTs;
$\varphi = \frac{n}{N_{wu}},\ n \in \{a \in \mathbb{N} : a < N_{wu}\}$. $\leftarrow$ assigning the resource allocation threshold;
$\lambda = \lfloor\ \varphi \times n(\boldsymbol{\theta}_{sorted})\ \rfloor$;
for $k \leftarrow 1, \lambda$ **do**
    find$(i|\psi_i = \boldsymbol{\theta}_{sorted,k}), i \in \{\emptyset, 1, ..., N_{RB}\}$;
    $\boldsymbol{\rho}_i = 0; \leftarrow$ blocking the RBs with many weak UTs.
end for

Algorithm 2 Multi-carrier proportional fairness scheduling, adapted from Kong et al. (2009)

Initialization: $r_k(t) = 0, C_k = 0,\ \forall k \in \{1, \cdots, K\}$;
for $m \leftarrow 1, M$ **do**
    Calculate $r_{k,m}(t), \forall k \in \{1, \cdots, K\}$;
    for $k \leftarrow 1, K$ **do**
        if RB$(k, m) = 1$ **then**
            Calculate PF(t, k), see Equation (3.14);
        end if
    end for
    Assign subchannel m to the user getting the largest PF(t, k): $\tilde{k} \leftarrow \arg\max_k(\text{PF}(t, k))$;
    $r_{\tilde{k}}(t) = r_{\tilde{k}}(t) + r_{\tilde{k},m}(t)$;
    Update the set of subchannels allocated to the user: $C_{\tilde{k}} = C_{\tilde{k}} + \{m\}$;
end for
Update $\overline{R_k(t+1)}, \forall k \in \{1, \cdots, K\}$, see Equation (3.13);
Transmit each user's packets on the assigned subchannels with the corresponding rate.

4.3.2 Algorithm for Small Cell

The general procedures of the downlink resource allocation in small cells have similar steps to the macrocell's procedure, including the broadcasting of pilot signals, control-channel information and data-channel. For pilot signal broadcasting, procedures in small cells are same to the macrocell. Some different procedures in small cells are presented as follows.

Sensing and Broadcasting the Control-Channel Information

1. Sensing the macrocell's control-channel: When the macro-BS broadcasts PDCCH channel to its macro-UTs, see the Algorithm for Macrocell: Step 10 (Section 4.3.1), all small-BSs sense and receive this control channel as well. By decoding this macro-PDCCH, each small-BS is able to identify the unoccupied subchannels and time-slots.

2. Cross-tier spectrum-splitting: On this Step, all small cells identify the idle frequency spectra that are not occupied by the macrocell, generate RB-map (Table 4.5) and then utilize them for their small-UTs. This Step is performed after small cells sense and obtain control-channel information (PDCCH) from the macrocell. The formula for this spectrum allocation (cross-tier spectrum-splitting) can be represented as follows:

$$\begin{aligned} \boldsymbol{\rho}^{m}_{[0,1]} &= \left\lceil \frac{\boldsymbol{\rho}^{m}}{\max(\boldsymbol{\rho}^{m})} \right\rceil, \\ \rho^{f(n)}_{[0,1]} &= \begin{cases} 1, \text{for } \rho^{m(n)}_{[0,1]} = 0, \\ 0, \text{for } \rho^{m(n)}_{[0,1]} > 0, \end{cases} \end{aligned} \tag{4.12}$$

where $\boldsymbol{\rho}$ is the RB-map (Table 4.5). m and f are symbols representing the macro and small cell networks, respectively. [0,1] is the symbol representing the binary elements of the vector $\boldsymbol{\rho}$. N is the total subchannel number. $\boldsymbol{\rho}^{m}_{[0,1]} \in \{\rho^{m(n)}_{[0,1]}\}; \boldsymbol{\rho}^{f}_{[0,1]} \in \{\rho^{f(n)}_{[0,1]}\}; \forall n \in \{i : 1 \leq i \leq N\}$.

3. Broadcasting the control-channel: On the first PDSCH channel of the each even time-slot, when the macro-BS broadcasts its data channel, the small cells broadcast the control channel (PDCCH) for their users.

Broadcasting the Data-Channel:

4. Broadcasting the data channel: After broadcasting the control channel, then the small cells broadcast their data channel for the rest PDSCH transmission phase for 2 time-slots.

4.4 Simulation Results and Analysis

This Section will present simulation method, results and analysis regarding multi-user OFDM resource allocation of the downlink channel. The simulation uses system-level approach, in which the physical layer is abstracted by simplified models that capture its essential characteristics with high accuracy and low complexity (Ikuno et al., 2010). In this simulation, resource allocation for the downlink channels is performed in both macrocell and small cell networks.

4.4.1 Simulation Method

The physical signal and physical channels being considered in the simulation are the only ones that closely related to downlink resource allocation, i.e. RS signal, PDCCH as a control channel and PDSCH as data transmission channel, see Appendix C. The RS signal performs as a pilot signal. PDCCH provides control-channel information and distributes it to all served terminals. By having this information, each UT knows its turn to receive the transmitted data by the macro-BS/small-BS. PDSCH provides data transmission channel for allocated users.

Channel generation, as presented on Equation (4.1), is independently generated once in each subframe. Hence, there is one channel generation for two time-slots or 10-times of channel generations for each frame. When each BS or each UT transmits its signal, then the transmitter signal will propagate through the channel where its characteristics are suitable for the location of each BS and UT, appropriately. As a result, pilot and data transmission will experience power attenuation in the receiver side end, which help each BS recognises the channel state information and determine appropriate resource allocation at that time.

To avoid errors in channel recognising that results in inappropriate resource allocation, it is assumed that transmission processes of control channels are perfect. They are simplified by duplicating the control-channel information from macro-BS/small-BS to its served UTs, and vice versa. Hence, there are no channel distortions as well as data errors in these processes that result in the accuracy of the received control-channel information.

If a small-BS is in the blind spot with respect to the macro-BS, it can still use the back-haul to synchronise the signalling steps. As the small-BS cannot sense the pilot signal and control channel from the macro-BS in this area, then it assumes that there is no interference and no occupied spectrum. In this condition, the small-BS can occupy all allocated spectrum. However, the simulation does not cover this scenario.

The simulation focuses on the downlink resource allocation. The only additional uplink physical channel is used for reporting the channel state information from UTs, which for an LTE system is represented by the uplink control channel (PUCCH) for periodic CSI reporting in an LTE system. Figure 4.2 shows downlink signalling procedures being used in the simulation.

The simulation uses system-level approach and focuses on resource allocation to mitigate the interference in HetNet. Moreover, the simulation considers some channel models as presented in Section 4.2.1. Physical layer model in the simulation uses LTE physical layer structures (see Appendix C). The simulation assumes all users in the system are active. Simulation parameters are presented in Table 4.1 and Table 4.2. The Monte Carlo simulation is performed for each OFDM symbol and repeated to achieve the number of the data channel (PDSCH) $\geq$ 10,000.

4.4.2 Analysis Method

As described in Figure 4.2, there is a period of signalling in the proposed HetNet model that control channel is transmitted asynchronously to different network tiers. Hence, when the macrocell transmits its data (PDSCH), then parallelly the small cells transmit their control channel (PDCCH). Because of the complexity of the modelling and simulation, this period is not included in the evaluation.

Thus, not all measures of the simulation process can be covered in analysis and evaluation.

System performances are evaluated regarding average SINR per occupied subcarrier; average rate per occupied subcarrier; and average sum-rate per cell. The received SINR γ by UT-k at subcarrier-n is:

$$\gamma_k^n = \frac{Pr_k^n}{N_0 B + I_k^n}, \tag{4.13}$$

where Pr is the received power (Watt). N_0 is the Gaussian noise power spectral density (Watt/Hz). B is the subcarrier bandwidth. I is total interference power (Watt).

Then the data-rate per subcarrier of UT-k on subcarrier-n is:

$$C_k^n = B \log_2(1 + \gamma_k^n), \tag{4.14}$$

And the sum-rate (in bps) of a downlink cellular network is obtained by using Shannon's capacity formula as follows:

$$C_{M/S} = \sum_{k=1}^{K} \sum_{n \in \mathcal{N}_k} B \log_2(1 + \gamma_k^n), \tag{4.15}$$

where M and S indicate symbols for macro and small cell networks. K is total number of UTs. $\mathcal{N}_k$ is the number of subchannels allocated to user-k.

The Cell-Edge performance of the proposed method is estimated by finding the 5^{th} percentile of the related SINR and its data-rate.

The cumulative distributive function (CDF) $F(x)$ of system's SINR and its data-rate over the simulation period is obtained as follows.

$$F_X(x) = P(X \leq x) \tag{4.16}$$

where X is a random variable representing the user's SNR/ SINR or data-rate. x is the certain value that the CDF wants to obtained. $P(\cdot)$ is the probability value that the CDF can be obtained.

To evaluate the performance of the proposed method, various parameters of the resource allocation threshold φ and the SNR/ SINR threshold γ_{th}^M are first evaluated. Based on the best trial, then the performance of the proposed method is analysed and compared with the following methods:

- NIM: It is a *non-interference management* method for resource allocation. This method shares the overall allocated spectrum among the macrocell and small cells. The transmission power for each cell is distributed into all subcarriers and allocated uniformly for each of them.

- IRB-CIM: This method avoids occupying interfering *resource-blocks* (RBs) to mitigate the downlink interference in HetNet by implementing the cognitive process to some extent (Kaimaletu et al., 2011). Briefly, the proposed method consists of the following steps. First, each *base-station* (BS), either macro or small BS, identifies its served users with low SINR and exchanges this information with the neighbouring cell(s). Second, based on its neighbour-BS information, each BS blocks some RBs that interfere to the neighbouring cell(s). In opposite, the BS will occupy some RBs being interfered by neighbouring cell(s).

4.4.3 Results and Performance Analysis

The simulation is run with various parameters of φ and γ_{th}^{M}. After running the simulation, then the generated data is averaged up based on sum-rate per cell and Figure 4.4 is obtained. From these results, we decide to pick γ_{th}^{M} = 13 dB and φ = 84 % as selected parameters for further analysis and comparison with different methods, which is considered as the best result compared to φ 80% and 90 %. In which the last two configurations have similar performance with φ 84 %, see Figure 4.4. In general, by using these parameters, SSCIM1 allocates a fraction of entire spectrum exclusively for the macrocell and leaves the rest spectrum for small cells. Likewise, IRB-CIM blocks some interferer RBs to reduce interferer sources. Whereas NIM shares overall spectrum for both HetNet.

Figure 4.5 shows SNR/ SINR distribution function of the SSCIM1 method compared to NIM and IRB-CIM for HetNet. All figures of the CIM methods do not occupy the overall range of the cumulative distribution. These are caused by the methods have the only portion of data compared to the NIM method. The data can also represent the average portion of the allocated spectrum, in which the rest spectra are allocated to the other network tier.

In these figures, parameters of γ_{th}^{M} = 13 dB and φ = 84% for SSCIM1 method are assigned. Figure 4.5(a) shows that SSCIM1 results in the highest performance (i.e. SNR) for allocated RBs compared to others. In which split spectrum approach can avoid interference from small cells. However, SSCIM1 only occupies around 20% of the overall probability distribution, and the rest resources (i.e. subchannels and time-slots) (around 80%) are left by the macrocell, in which, 80% of resources has performance less than the selection criteria. As presented in Table 4.6, the proposed method has average SNR improvements of more than 60 dB for Cell-Edges (the 5^{th} percentile) and more than 30 dB for the allocated spectrum to the macrocell over the other methods. Interestingly, there is no SNR

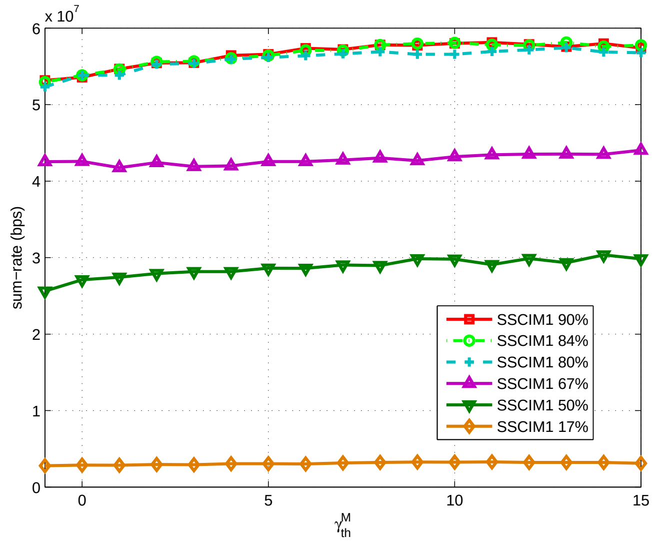
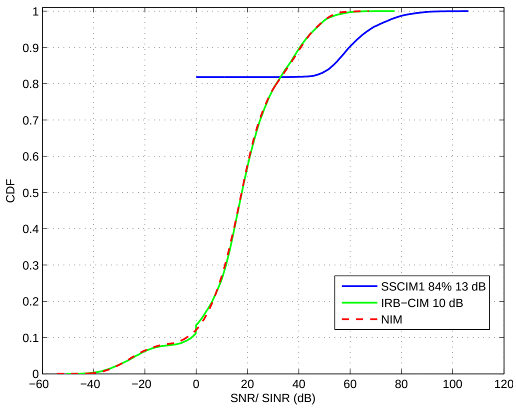


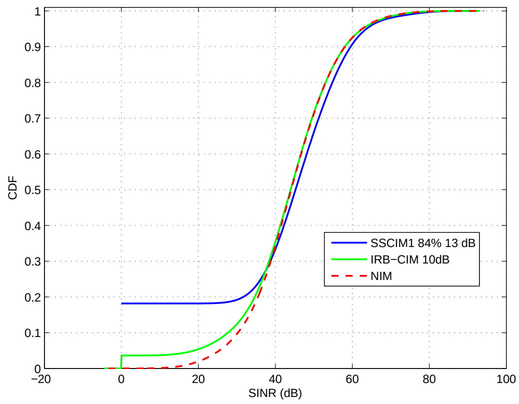
Figure 4.4: Average sum-rate per cell of the overall HetNet with various parameters of γ_{th}^{M} and φ.

Table 4.6: Average SNR/SINR (in dB) for each allocated subcarrier

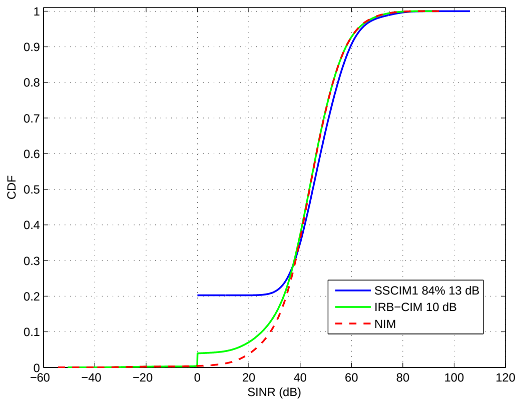
	NIM	IRB-CIM(10 dB)	SSCIM1(84%,13 dB)
Cell-Edge (5^{th}-percentile)			
Macro-UT	-23.7444	-23.5988	48.2941
Small-UT	25.4679	25.8251	34.3407
All Users	22.3424	22.6877	34.3660
Overall Areas			
Macro-UT	40.6546	42.4333	78.2775
Small-UT	59.5977	59.8703	62.8990
All Users	59.4571	59.7286	63.8546



(a) Macrocell



(b) Small Cells



(c) Overall Networks

Figure 4.5: Distribution function of SNR/ SINR for different schemes.

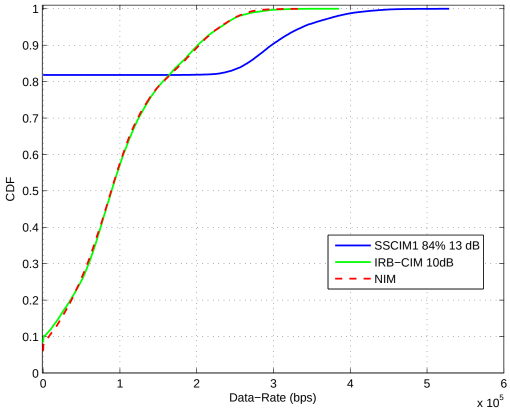
less than or equal to zero decibels for this method. The exclusive spectrum allocation for different tier networks results in no interference from different tier networks that affects to allocated spectrum in each tier. However, this high SNR does not represent high rate since the allocated RBs for the macrocell are only a small fraction of overall spectrum allocated to HetNet.

Figure 4.5(b) shows SINR CDF for small-UTs, which occupies 82 % of the overall probability distribution. The proposed method provides SINR improvement for the allocated spectrum if compared to the others, see Table 4.6. The method has an average improvement of around 3 dB over the other methods for Overall Areas. For Cell-Edge area, this method results in an SINR improvement of around 8 dB over the other methods, which is higher than the improvement in the overall spectrum allocation. The improvement of the subcarrier performance is caused by the exclusive spectrum allocation for small cells that reduces strong interference from the macrocell significantly, particularly in the Cell-Edge areas.

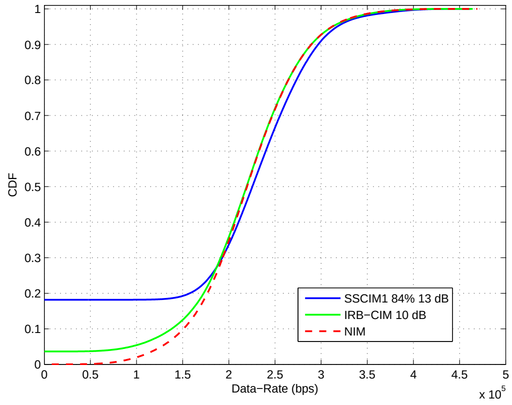
Figure 4.5(c) provides SINR CDF for all systems. In which SSCIM1 occupies 80% of the overall probability distribution. It shows that not all resources, i.e. resource blocks (RBs), is occupied for this scheme. There is significant SINR improvement at Cell-Edges (around 12 dB) and less improvement for all spectrum (around 4 dB), see Table 4.6. It shows that exclusive spectrum allocation for different tier networks can mitigate interference among tiered networks significantly.

Figure 4.6 shows the data-rate distribution function of three different schemes for HetNet. Figure 4.6(a) shows the macrocell section of this distribution function; which SSCIM1 outperforms the other methods. Table 4.7 shows the average subcarrier data-rate of HetNet, which is the mean value of the data-rate of each allocated subcarrier over the simulation period. The macrocell section of this Table shows that the proposed method results in more than 250 times of data-rate at Cell-Edge area compare to others and more than three times of data-rate for Overall Areas compared to others. Since SSCIM1 allocates only around 20% of the total resources to the macrocell if compared to the other schemes, this rate does not represent the highest result in the overall performance. Table 4.8 shows the average sum-rate of HetNet for three methods, which is the mean value of sum data-rate per symbol per cell of all subcarriers over the simulation period. The macrocell section of this Table confirms that the average sum-rate of the macrocell using SSCIM1 is less than others. The result shows that a small number of the allocated resources for the macrocell results in small data-rate.

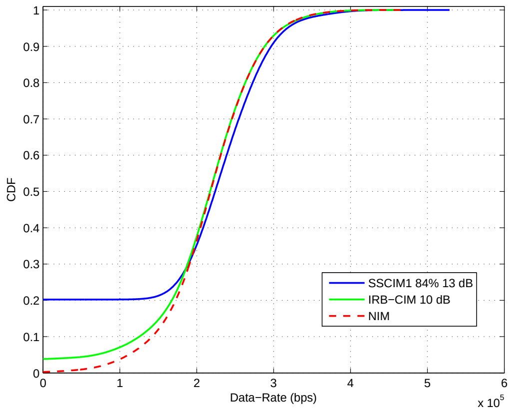
Figure 4.6(b) displays the data-rate distribution function for small cells. SSCIM1 shows a small improvement over the others. The Figure also shows higher improvement at the Cell-Edges (5^{th}-percentile). Table 4.7 on the "Overall Areas" section shows the data-rate improvement of 1.09 times over the other schemes. Whereas for the "Cell-Edge" section, it confirms that the proposed method has around 1.34 times of average subcarrier rate increase over the others. However, the result shows the contradiction for the average sum-rate per cell. Table 4.8 confirms that the proposed method decrease the average sum-rate for the small



(a) Macrocell



(b) Small Cells



(c) Overall networks

Figure 4.6: Distribution function of data-rate for different schemes.

Table 4.7: Average data-rate for each allocated subcarrier (in kbps)

	NIM	IRB-CIM(10 dB)	SSCIM1(84%,13 dB)
Cell-Edge (5^{th}-percentile)			
Macro-UT	0.091	0.094	240.64
Small-UT	126.96	128.74	171.12
All Users	111.46	113.17	171.25
Overall Areas			
Macro-UT	98.23	100.63	312.64
Small-UT	220.42	222.12	242.39
All Users	216.48	218.15	242.91

Table 4.8: Average sum-rate per cell (in Mbps)

	NIM	IRB-CIM 10 dB	SSCIM1 84%,13 dB
Macrocell	29.468	29.502	17.047
Small Cells	66.126	64.219	59.500
All Networks	64.943	63.099	58.130

cell section. It can be concluded that by using SSCIM1, orthogonal spectrum allocation among a macrocell and some small cells can increase the average subcarrier rate of small cells and more significantly in the Cell-Edges. However, the average sum-rate is determined by the number of the allocated resources.

Figure 4.6(c) illustrates the data-rate distribution function for all UTs, either macro or small cells. Following the previous result trends for each network tier that SSCIM1 shows higher average subcarrier data-rate compared to others and the more significant data-rate increase in the Cell-Edges. Table 4.7 confirms that the average data-rate of the allocated subcarriers when using SSCIM1 outperforms the other methods. It shows that the proposed method can efficiently mitigate interference in HetNet, which SSCIM1 carefully plans and selectively chooses the allocated subcarriers. However, the sum-rate per cell (or the cell capacity) is determined by the data rate summation of all subcarriers in a cellular network. Thus the subcarrier performance does not represent the overall performance of the system. Since the proposed method occupies less spectrum than the others, it affects to the system capacity. Table 4.8 confirms that the overall sum-rate of SSCIM1 falls behind the other schemes.

Interestingly, if using the same spectrum number, SSCIM1 has better capacity than others. Table 4.9 confirms that SSCIM1 outperforms to others when the same spectrum number is allocated to small cells. However, these results are penalised by less performance in the macrocell.

4.5 Conclusions

This Chapter has presented the proposed method related to interference mitigation in HetNet. The methods seek to solve the interference problems in these

Table 4.9: Average sum-rate per cell (in Mbps) with portion spectrum

	NIM	SSCIM1		IRB-CIM
Network & portion spectrum		100 %	84%,13dB	28 dB
Macrocell	29.468	0	17.047	31.792
Small cells	66.126	72.633	59.500	55.741
All networks	64.943	70.290	58.130	54.968
Portion spectrum for small cells	100%	100%	81.824%	81.737 %

networks through smart resource allocation, i.e. cognitive interference management. As cognitive radio needs some characteristics to adaptively and correctly responds to the surrounding dynamic environment, the proposed method implements the cognitive concept through some coordinated, structured and managed processes either in BSs sides or UTs sides.

As presented in Section 2.3.2, there are fundamental cognitive tasks in cognitive radio that being classified as (i) radio-scene analysis, (ii) channel-state estimation, (iii) transmission power control and dynamic spectrum management. To some extent, these cognitive tasks have been implemented in the proposed methods. First of all, pilot sensing in all UTs and macro's control-channel information sensing by small-BSs are some efforts to identify the surrounding channel. Transmitting back the reference signal from UTs to their serving BSs and collecting macro's control-channel information by small-BSs will provide information for the systems for radio-scene analysis. Secondly, channel-state estimation is conducted in each BS by estimating channels and evaluating SINR of the RSRP, which are then used to identify spectrum holes and to arrange time-access scheduling. Thirdly, all of the processes above will support the system in making the final decisions on the subchannel and power allocation as well as time-access scheduling.

Overall, there is an average subcarrier performance increase for all HetNet when using the proposed method with Cell-Edges having higher increase than other regions. However, the increasing performance per occupied subcarrier when using SSCIM1 is not followed by the improvement of the cell performance because of the less number of the allocated subchannels using this method. Interestingly, when using the same spectrum number, SSCIM1 has better capacity than others. Table 4.9 confirms that SSCIM1 outperforms two other methods when the same spectrum number is allocated to small cells. However, these results are penalised by less performance in the macrocell.

However, there are still more resources need to be managed dynamically using the cognitive radio approach while expecting better system performance, such as the usage of RSRP in small-BS that support in the decision making of resource allocation, power and spectrum allocation on the related channel characteristics instead of uniform power allocation. To further identify the system performance when allocating these resources in HetNet using cognitive radio technique, Chapter 5 will present Spectrum Splitting and Power Allocation-based Cognitive Interference Management.

Chapter 5

Spectrum Splitting and Power Allocation-based CIM

5.1 Introduction

5.1.1 Motivation

In this Chapter, *cognitive interference management* (CIM) methods based on spectrum-splitting and power allocation in an OFDMA-based heterogeneous cellular network (HetNet) are proposed. The proposed methods are the extension of the SSCIM1 method in Chapter 4. By using the cognitive radio approach, SSCIM1 mitigates the interference in the downlink HetNet through orthogonal spectrum allocation for different network-tiers, proportional fairness scheduling for the access opportunity distribution of multi-users, and equal power allocation for the occupied subcarriers of each network. Nevertheless, there are still more aspects of resource allocation techniques in the SSCIM1 method able to be improved while expecting better system performance of HetNet. Thus, the newly proposed methods are dedicated to mitigating the interference of the downlink HetNet based on the improvement of the SSCIM1 method.

5.1.2 Related Works

As discussed by Jouini et al. (2012), there are some concepts have been proposed for the complete cycle of *cognitive radio* (CR). One of them which was widely known and cited by researchers was proposed by Haykin (2005). As discussed in Chapter 2, Haykin's CR covers some processes that can be classified as follows: (i) radio scene analysis, (ii) channel-state estimation and prediction, and (iii) transmission power control and spectrum management, see Figure 2.3. Moreover, Chapter 2 has also discussed the idea of Cognitive Small Cells (CSCs), which are small cells with the capability of CR functions. It is considered that a CSC system has the ability of self-configuration, self-healing, self-optimisation and smart decision-making to deal with its dynamic, complicated and interfering radio environment in HetNet.

In Chapter 4, SSCIM1 offers dynamic and intelligent ways to mitigate interference in the downlink HetNet. To some extent, this method adopts cognitive radio functions to allocate radio (and system) resources dynamically and adaptively to mitigate interference more efficiently in these networks. The results showed the better performance compared to two other conventional methods, i.e. *interfering-resource-blocking*-based CIM (IRB-CIM) (Kaimaletu et al., 2011) and spectrum-sharing and the EPA technique of non-interference management (NIM).

In that method, spectrum allocation on the macrocell considers the macro-UTs that occupying good subchannels. Then the macro-BS schedules the network access to its macro-UTs using the proportional fairness scheduler (Kong et al., 2009). Moreover, the transmission power is allocated uniformly to all allocated subchannels, which is also called as *equal power allocation* (EPA). Meanwhile, the small-BSs allocate the idle subchannels that are not occupied by the macrocell to their small-UTs and then share the same frequency spectrum among all small-BSs. Following the macrocell, the small-BSs also schedules the network access to their small-UTs using the same technique of scheduler. Then, the transmission power is allocated uniformly to the selected subchannels for the small-UTs.

However, time-access scheduling can be simply optimised by performing time-slot-based resource allocation, and each subchannel can be time-shared by multiple users (Huang et al., 2009). These findings show that the *resource block*

(RB)-map vector generation technique (Algorithm 1) needs an improvement to obtain all information of all good subchannels of all macro-UTs. In which, the RB-map are subsequently fed to the scheduler to schedule the resources for particular macro-UTs.

Moreover, the *equal power allocation* (EPA) for the occupied subcarriers at the macrocell of the SSCIM1 method will allocate the transmission power uniformly either to the good subchannels or the bad ones. This technique will result in less optimal power allocation. Meanwhile, the resource allocation strategies of shared-spectrum among small cells and the EPA technique for all occupied subcarriers have a potency of inter-cell interference among these network-tiers. These results also show that the resource allocation techniques of SSCIM1 need to be improved as well.

5.1.3 Proposal and Contribution

In Chapter 4, SSCIM1 method has been proposed to mitigate interference in HetNet. However, some findings indicate that this method can still be improved to achieve a better system performance. The research purpose of this Chapter is to improve some findings on SSCIM1.

In SSCIM1, some good subchannels may be not selected because the subchannel blocking process considers the number of weak-UTs instead of the quality of subchannel perceived by the assigned macro-UT(s). Huang et al. (2009) believes that scheduling method must be solved in each time-slot and each subchannel can be allocated to different users for different time-accesses. It inspires us to propose a scheduling method based on all pilot signals received by the UTs. By selecting the only best subchannels, it is predicted the system performance will be improved.

Moreover, the SSCIM1 method uses EPA to allocate transmission power in the macrocell. Goldsmith (2005) presented that water-filling algorithm (WF) could optimally allocate transmission power and spectrum as well as assign the optimal SINR threshold γ_0 to a Gaussian channel multi-carrier system. By implementing WF in the macrocell, it is predicted to have better performance for that network.

For the small cell tier, after selecting the spectrum orthogonally over the macrocell, SSCIM1 applies the EPA technique and spectrum sharing for this network tier. As discussed above, the EPA technique allocates the transmission power for each subcarrier uniformly. This strategy, however, is less optimal, in which the power allocation does not consider the channel gain quality. The other techniques could be implemented for multiple channel resource allocation are on-off (OOPA) and water-filling (WF) power allocation. By applying these two methods, the performance of small cells is expected to get improved.

5.1.4 Outline

This Chapter will present our research work related to CIM methods in HetNet. Section 5.2 describes the system model and its parameters, which includes channel models and physical layer models. Section 5.3 presents the proposed resource allocation techniques, i.e. Spectrum-Splitting and Power-Allocation-based Cognitive Interference Management. Section 5.4 presents comparative analyses of proposed methods. Finally, all these works are summarised in Section 5.5.

5.2 System Model

The system model of HetNet consists of a macro-BS that serves 30 macro-UTs. These macro-UTs are uniformly distributed in 3 sectors of the macrocell's coverage. The macro-BS is also surrounded by 30 small-BSs that uniformly distributed in the same area and share the same frequency spectrum. Each small-BS serves one to two users that uniformly distributed in its coverage area. Closed access mode is applied for all users, which means that only the authorised UTs can be associated with serving BSs. The system model has been detailed in Section 4.2.

Physical layer model follows LTE standard that allocates radio resources based on RB units. In the LTE standard, an RB consists of 12 subcarriers in the frequency domain, which is also called as a subchannel, and 7 OFDM symbols in the time domain (Rumney, 2013). The physical layers being considered in this simulation are closely related to resource allocation, i.e. RS signal, PDCCH, PUCCH and PDSCH (see Appendix C). It is considered that control channel (PDCCH) of the macrocell is sent in different (OFDM) symbol periods over the small cell's control channel transmission periods. Small cells need this scenario, i.e. asynchronous transmission of the control channel to their served users, to provide enough time for channel state identification and resource allocation arrangement to their users.

The propagation channel models adopt 3GPP's model (3GPP, 2010) and their modifications follow some standard techniques (Goldsmith, 2005), see Section 4.2.1. In general, channel models consist of propagation path losses, shadow fading and its distance-based correlated channel, and small-scale frequency selective fading.

This simulation uses Monte Carlo method, see Section 4.4.1. A huge number of downlink frames are broadcasted from the serving BSs to its served UTs through random and dynamic propagation channels. Subsequently, the results are averaged up.

The study uses a system level approach and focuses on the resource allocation to mitigate the interference in HetNet. The physical layers, such as modulation, transmission, and network signalling, are abstracted by simplified models that capture its essential characteristics with high accuracy and low complexity. In the simulation, 3GPP-LTE parameters are used. The total number of subcarriers is 300, which are grouped into 25 subchannels or 25 RBs in the frequency domain, see Table 4.2.

5.3 Proposed Resource Allocation Techniques

This Section will present a CIM based on spectrum splitting and power allocation for downlink HetNet. The proposed methods are the extension of the previous one, i.e. SSCIM1 (Chapter 4), to mitigate interference in HetNet.

The main strategy to solve the problems above is characterised by the objective function of the optimisation problem. In general, there are three types of the objective functions of resource allocation in multi-user multi-channel HetNet, see Section 3.5.3. Each objective function has the different strategy to solve its problem. The objective function of the proposed methods in this Chapter is to maximise the capacity of the downlink HetNet.

Principally, the differences among the proposed methods and SSCIM1 (see Chapter 4) are power allocation techniques for both macrocell and small cell networks, spectrum allocation strategy for small cells, and subchannel selection strategy for all networks.

5.3.1 Approaches and Assumptions

It is considered that all networks run in a synchronised way including pilot transmission. It is also assumed that each UT can identify each pilot from different BS. Using these assumptions, it will make easy for BS to estimate the channel based on received pilot signals by UTs. For control channel, it is assumed that macrocell and small cells broadcast this information asynchronously. It demands the control channel being transmitted in different OFDM symbols or even in different time slots for different network-tiers. These approaches enable small cells identifying, analysing and determining resources before allocating them appropriately to their users.

To focus on development processes and to make detailed analyses, three different approaches are proposed in this Chapter, characterised by different power allocation. Table 5.1 presents the key parameters of the proposed methods. The first approach, i.e. SSCIM2, allocates orthogonal spectrum (spectrum-splitting) for different network-tiers and then allocates power using WF for the macrocell. For small cells, the total power of each cell is distributed uniformly into subchannels. The second one, which is called SSCIM3, allocates the transmission power for small cells using on-off power allocation (OOPA) by considering an SINR threshold. Moreover, the third method, i.e. SSCIM4, the proposed method allocates power for small cells using WF.

5.3.2 SSCIM2

If compared to SSCIM1 (Chapter 4), the basic idea of SSCIM2 is to apply water-filling power allocation for the macrocell. This method underlies all methods proposed in this Chapter. Moreover, the other differences between SSCIM1 and SSCIM2 are in the threshold determination and the RB-map generation, which are both processed in the macrocell. Meanwhile, the small cell section uses the

Table 5.1: Key parameters of SSCIM algorithms

Parameters	SSCIM1	SSCIM2	SSCIM3	SSCIM4
Macro-Cell				
Power allocation	EPA	WF	WF	WF
Spectrum allocation over small cells	orthogonal	orthogonal	orthogonal	orthogonal
RRA threshold	portion of weak RBs	SINR	SINR	SINR
RB-map	vector	matrix	matrix	matrix
Small Cells				
Power allocation	EPA	EPA	OOPA	WF
Spectrum allocation among small cells	shared	shared	partial-orthogonal	partial-orthogonal
RRA threshold	-	-	SINR	optimal threshold

same algorithm as the SSCIM1 does, see Section 4.3.2. In which shared-spectrum and equal power allocation among allocated subchannels of small cells are applied.

In SSCIM1, an assigned threshold φ represents the resource allocation threshold, see Algorithm 1. It is the ratio of n over N_{wu}. n is a predetermined value, $n \in \{a \in \mathbb{N} : a < N_{wu}\}$. N_{wu} is the variant number of the weak UTs in each RB. This value determines which RBs having a certain number of weak UTs will be blocked. In the other hand, for SSCIM2, a threshold value represents directly an assigned SINR threshold, which is the ratio of the received signal power over the received interference plus noise power. So that SSCIM2 provides a more accurate approach for quality subchannel selection.

An RB-map in SSCIM1 represents a vector consisting the RBs which can be occupied by macro-UTs. For SSCIM2, an RB-matrix represents all possible RBs can be accessed by certain UTs having SINR higher than a threshold value. So that SSCIM2 provides a wider choice of subchannels that enable a scheduler to allocate resources to the right user, the right time access and the other considerations such as proportional fairness.

Algorithm for the Macrocell

In general, the algorithm has the same procedures as the SSCIM1 has. Some different parts of the algorithm will be presented below.

Split-spectrum percentage and SINR threshold: For the macrocell section, the algorithm is started by setting the percentage of the allocated spectra ($\varphi_M\%$) and the SINR threshold (γ_{th}^M) for the macrocell. Referring to the principles of resource allocation in a multi-user and multi-channel system, the optimal spectrum allocation for HetNet must take into account some network parameters (Goldsmith, 2005). These parameters are the number and the position of active BSs, the total number of active UTs, the assigned SINR threshold, the received and the inter-cell interference power, the subchannel number, and the objective function of the optimisation problem. However, it needs more investigations to prove it.

For a single wireless system, an assigned SNR will determine the quality of received signal power and gain of allocated subchannels. For a cellular wireless system, in addition to received power and subchannel gain factors, the assigned SINR will also determine the allowable received interference power. As applied to the percentage determination of the allocated spectra, we suggest that the selection of the SINR threshold value must take into account some important factors as explained above.

After having an SINR threshold value γ_{th}^M and the allocated spectrum percentage $\varphi_M\%$, then the next steps of the macrocell section of SSCIM2's algorithm follow the downlink transmission procedures of the LTE system. They are (i) pilot broadcasting, (ii) control-channel information broadcasting and (iii) data transmission for certain UTs.

RB-allocation matrix: After receiving pilot signals (RSRP) from all BSs, then each (macro/small) UT transmits RSRP back to its serving BS. Subsequently, the macro-BS calculates the SINR for each subchannel of each UT, compares to SINR threshold, determines the strong/weak subchannels, and generates an RB-allocation matrix (RB-matrix). So that the allocated RBs are those with SINR $\geq \gamma_{th}^M$.

Algorithm 3 presents the RB-matrix generation for the macrocell. K is the total macro-UT number. $\boldsymbol{\varphi}_S$ and $\boldsymbol{\varphi}_s$ are the total sum of and the individual pilot signal received power (RSRP) vectors, respectively, from underlaying small-BSs. $\boldsymbol{\varphi}_0^k$ is the RSRP vector received by the macro-UT-k. S is the total number of underlaying small-BSs. $\boldsymbol{\gamma}$ is an estimated SINR vector. N_{sc} is the total number of subchannels. $\boldsymbol{\rho}_k$ is the RB-allocation vector of the macro-UT-k. $\mathfrak{R}$ is the RB-matrix representing the channel quality perceived by each macro-UT. diag($\boldsymbol{v}$) is a function to create matrix with the elements of vector $\boldsymbol{v}$ on the main diagonal. $(\cdot)^{-1}$ is the inverse matrix notation. $(\cdot)^T$ is the matrix transpose notation.

Algorithm 3 RB-matrix generation for the macrocell

1: **for** $k \leftarrow 1, K$ **do**
2: $\boldsymbol{\varphi}_S = \sum_{s=1}^{S} \boldsymbol{\varphi}_s$.% The sum of received pilot signal power from underlaying small-BSs.
3: $\boldsymbol{\varphi}_0^k \leftarrow$ self pilot vector. % pilot signals received by the macro-UT-k.
4: $\boldsymbol{\gamma} = \text{diag}^{-1}(\boldsymbol{\varphi}_S)\boldsymbol{\varphi}_0^k$; % an estimated SINR vector.
$\boldsymbol{\gamma} = \{\gamma_1\gamma_2 \dots \gamma_{N_{sc}}\}^T$;
5: $\boldsymbol{\rho}_k = \{\rho_{k1}, \rho_{k2}, \dots, \rho_{kN_{rb}}\}^T$;
$$\rho_{k(n)} = \begin{cases} 1, & \gamma_n \geq \gamma_{th}^M; \\ 0, & \gamma_n < \gamma_{th}^M, \ \gamma_n \in \{\boldsymbol{\gamma}\}, n \in \{j : j \in \mathbb{N}^+, j \leq N_{rb}\}. \end{cases}$$
6: **end for**
7: $\mathfrak{R} = (\boldsymbol{\rho}_1, \boldsymbol{\rho}_2, \dots, \boldsymbol{\rho}_K), \mathfrak{R} \in \{0, 1\}$.

Resource Scheduling: For resource scheduling, SSCIM2 uses the same algorithm as used in SSCIM1 but uses RB-matrix $\mathfrak{R}$ as an input reference. Based on the scheduler's output, the macro-BS evaluates and ensures the percentage of the allocated spectra (φ_M %) and updates the RB-matrix $\mathfrak{R}$ appropriately.

Power Allocation: Power allocation for the macrocell uses the water-filling algorithm. The power allocation process covers some procedures below.

- To estimate the channel based on received back RS signal from its served macro-UTs.
- To estimate the channel to interference ratio.
- To allocate power for each subcarrier using the water-filling algorithm.

Algorithm 4 presents water-filling power allocation for the macrocell. $\boldsymbol{\varphi}_0$ is an original pre-transmitted pilot signal vector. $\boldsymbol{h}$ is a vector of the least square channel estimator. $\boldsymbol{\chi}$ is a vector of the subchannel gain to interference ratio, which is used to count the power allocated to each subchannel in the water-filling algorithm. $\boldsymbol{\gamma}$ is a vector of the carrier to interference ratio. γ_0 is the SINR threshold. γ_n is the carrier to interference ratio for subchannel-n. P_n^M is the allocated power for subchannel-n of the macrocell. P_{tot}^{M} is the total power allocated to the macrocell. N_{sc}^{*} is the number of allocated subchannels. The other variables and notations have been explained in Algorithm 3.

Algorithm 4 Water-filling power allocation in the macrocell

1: $\boldsymbol{\varphi}_S = \sum_{s=1}^{S} \boldsymbol{\varphi}_s$; % total sum of pilot signals from neighbour small-BSs.
2: $\boldsymbol{\varphi}_0 \leftarrow$ to generate pilot signal.
3: $\boldsymbol{h} = \mathrm{diag}^{-1}(\boldsymbol{\varphi_0})\boldsymbol{\varphi}_0^k$; % Least square channel estimator.
4: $\boldsymbol{\chi} = \mathrm{diag}^{-1}(\boldsymbol{\varphi}_S)\boldsymbol{h}$; % a vector of the estimated channel-to-interference ratio.
5: $\boldsymbol{\gamma} = \frac{P_{tot}^{M}}{N_{sc}^{*}} \cdot \boldsymbol{\chi}$; % an estimated SINR vector.
$\boldsymbol{\gamma} \in \{\gamma_n\} : \forall n \in \{1, 2, \cdots, N_{sc}^{*}\}$.
6: $\sum_{n}^{N_{sc}^{*}} \left(\frac{1}{\gamma_0} - \frac{1}{\gamma_n}\right) = 1$; (Goldsmith, 2005).
$\gamma_0 = \frac{N_{sc}^{*}}{1+\sum_{n} \frac{1}{\gamma_n}}$; % to find the threshold.
7: $P_n^M = P_{tot}^{M} \cdot \left(\frac{1}{\gamma_0} - \frac{1}{\gamma_n}\right), \forall n \in \{1, 2, \cdots, N_{sc}^{*}\}$.

5.3.3 SSCIM3

The basic method for SSCIM3 is to implement partial split-spectrum allocation among small cells by considering the small cell SINR threshold γ_{th}^{S} while maintaining the previously proposed method for the rest processes. At the macrocell section, SSCIM3 also applies WF as implemented in SSCIM2 (see Section 5.3.2).

In this method, small cells perform partially orthogonal spectrum/ subchannel allocation against their interfering small cells, which is also called as on-off power allocation (OOPA). The different parts of the algorithm will be presented below.

Algorithm for the Small Cells

Split-spectrum percentage and SINR threshold: To determine which spectra will be allocated, the method considers SINR threshold, either for the macrocell (γ_{th}^{M}) or small cells (γ_{th}^{S}). In this method, a BS calculates the SINR of the received pilot signals of its UTs. Then the BS selects subchannels having SINR higher than a threshold and leaves the lower ones. As discussed in Section 5.3.2, the assignment of a threshold value should consider some factors, such as the inter-cell interference power.

On-Off Power Allocation: Each small-BS allocates the transmission power for each subchannel to its served small-UTs. After the scheduling process, then each small-BS shares and allocates resources to its small-UT(s). This resource allocation considers the unused subchannels that are not occupied by the macrocell and subchannels having SINR higher than the small cell SINR threshold γ_{th}^{S}. Then, this method distributes the transmission power uniformly to the rest subchannels.

Algorithm 5 provides the detail of power allocation. $\boldsymbol{\rho}^*$ is the idle spectrum information that not occupied by the macrocell and obtained from spectrum sensing process. S is the total number of neighbour small-BSs. $\boldsymbol{\varphi}_{S^*}$ is the total sum of RSRP signal vectors from (S-1) neighbour small-BSs. $\boldsymbol{\varphi}_s$ is a pilot signal vector received from the neighbour small-BS-s. $\boldsymbol{\varphi}_1$ is the RSRP vector obtained from the served small-UT. $\boldsymbol{\gamma}$ is the SINR vector. $\boldsymbol{\rho}_1$ is a *binary-value* vector of the RB-map (see Table 4.5) of the small-BS(1) for the active time-slot. γ_{th}^{S} is the pre-assigned small cell SINR threshold. $\boldsymbol{\pi}_k^1$ is the allocated power vector for the user-k of the small-BS(1). $\circ$ is the Hadamard product notation. P_{tot}^{S} is the total power allocated to each small-BS. N_{sc^*} is the number of allocated subchannels. The other variables and notations have been explained in Algorithm 3.

Algorithm 5 On-Off power allocation in each small cell

1: $\boldsymbol{\rho}^*$; % To get information of idle subchannels that not occupied by the macrocell.
2: $\boldsymbol{\varphi}_{S^*} = \sum_{s=2}^{S} \boldsymbol{\varphi}_s$; % The sum of pilot signal vectors from the neighbour small-BSs.
3: $\boldsymbol{\varphi}_1 \leftarrow$ self pilot vector; % Pilot signals received-back from the serving small-BS(1).
4: $\boldsymbol{\gamma} = \mathrm{diag}^{-1}(\boldsymbol{\varphi}_{S^*})\boldsymbol{\varphi}_1$; % an estimated SINR vector.
$\boldsymbol{\gamma} = \{\gamma_n\}^T, n \in \{a \in \mathbb{N} : 0 < a < N_{sc}\}$;
5: $\rho_n = \begin{cases} 1, & \gamma_n \geq \gamma_{th}^{S}; \\ 0, & \gamma_n < \gamma_{th}^{S}, \boldsymbol{\rho}_1 \in \{\rho_n\}^T, \forall n \in \{a \in \mathbb{N} : 0 < a < N_{sc}\}; \end{cases}$
6: $\boldsymbol{\pi}_k^1 = \frac{P_{tot}^{S}}{N_{sc^*}} \cdot (\boldsymbol{\rho}^* \circ \boldsymbol{\rho}_1)$. % Allocated power vector for the small-UT-k of the small-BS(1).

5.3.4 SSCIM4

The basic idea of SSCIM4 is to implement water-filling power allocation algorithm in small cells while keeping the rest processes following the previously proposed method in SSCIM2 (Section 5.3.2). In this method, each small cell allocates the transmission power for the selected subchannels using the water-filling algorithm.

The water-filling algorithm is designed for Gaussian channel (Goldsmith, 2005). On the other hand, the power allocation problem gets interference in addition to Gaussian noise in HetNet. Thus the algorithm must consider interference power as part of the noise.

Algorithm for the Small Cells

To determine which spectra and how much power will be allocated for small cells, SSCIM4 uses WF algorithm. By using this technique, SSCIM4 determines the number of subchannels, which part of subchannels will be occupied, and the optimal threshold. Having those parameters, then WF algorithm can determine how much transmission power will be allocated for each subcarrier.

Commonly the algorithm for this part is same as the previous one (Algorithm 4). The difference is in determining the main RSRP signal, which is the transmitted pilot from the small-BS and then transmitted back by its served UTs.

Algorithm 6 presents the procedure of water-filling power allocation in the small cell. $\boldsymbol{\varphi}_{S^*}$ is the sum of RSRP signal vectors from neighbour small-BSs and the macro-BS. $\boldsymbol{\varphi}_1$ is an RSRP vector from the serving small-BS(1). $\boldsymbol{\chi}^*$ is the selected channel to interference ratio. $\boldsymbol{\gamma}$ is the selected carrier-to-interference ratio. $\circ$ is the Hadamard product notation. P^S_{tot} is total power allocated to a small

Algorithm 6 Water-filling power allocation for the small cell

1: $\boldsymbol{\rho}^*$; % To get information of idle subchannels that not occupied by the macrocell.

2: $\boldsymbol{\varphi}_{S^*} = \sum_{s=2}^{S} \boldsymbol{\varphi}_s$; % The sum of RSRP signal vectors from neighbour small-BSs.

3: $\boldsymbol{\varphi}_0 \leftarrow$ to generate pilot signal;

4: $\boldsymbol{h} = \text{diag}^{-1}(\boldsymbol{\varphi}_{\mathbf{0}})\boldsymbol{\varphi}_1$; % Least square channel estimator.

5: $\boldsymbol{\chi} = \text{diag}^{-1}(\boldsymbol{\varphi}_{S^*})\boldsymbol{h}$; % Estimated channel-to-interference ratio.

6: $\boldsymbol{\chi}^* = \boldsymbol{\chi} \circ \boldsymbol{\rho}^*$; % Selected channel to interference ratio.

7: $\boldsymbol{\gamma}^* = \frac{P^M_{tot}}{N^*_{sc}} \cdot \boldsymbol{\chi}^*$; % an estimated SINR vector of the selected subchannels.
$\boldsymbol{\gamma}^* = \{\gamma_n\}^T, \forall n \in \{1, 2, \ldots, N^*_{sc}\}$;

8: $\sum_{n}^{N^*_{sc}} \left(\frac{1}{\gamma_0} - \frac{1}{\gamma_n}\right) = 1$; (Goldsmith, 2005).
$\gamma_0 = \frac{N^*_{sc}}{1+\sum_n \frac{1}{\gamma_n}}$; % to find the threshold.

9: $P^S_n = \begin{cases} P^S_{tot}\left(\frac{1}{\gamma_0} - \frac{1}{\gamma_n}\right), & \text{if } \gamma_n \geq \gamma_0; \\ 0, & \text{if } \gamma_n < \gamma_0, \forall n \in \{1, 2, \cdots, N^*_{sc}\}. \end{cases}$

cell. P_n^S is transmission power allocated to subchannel-n of a small cell. The other variables and notations have been explained in Algorithm 3 and Algorithm 4.

5.4 Results and Performance Analysis

5.4.1 Analysis Method

In this section, the performance of four SSCIM methods is evaluated. Some dimensions of the performance of the downlink HetNet will be evaluated as having been done in Section 4.4.2, including SNR/ SINR, user data rate, the distribution function of both performance above, and the network capacity. To make a fair comparison of the performances of the proposed methods, some parameters are assigned to result in the same or similar macrocell capacity, which SSCIM1 achieves 17.047 Mbs as presented in Table 5.5. For SSCIM3, after assigning the macrocell capacity, then finding the optimal scenario among the best trials. Then compare and analyse all SSCIM methods' data output from the simulation of each method using scenario mentioned above.

As described in Figure 4.2 and Section 5.3.1, there is a period of signalling in the proposed HetNet model that control channel is transmitted asynchronously to different network tiers. Hence, when the macrocell transmits its data (PDSCH), then parallelly the small cells transmit their control channel (PDCCH). Because of the complexity of simulation and modelling, this period is not included in the evaluation. Thus, not all measures of the simulation process can be covered in analysis and evaluation.

Two common measures to finding the average value of distribution are the mean and the median. The mean is the average of the numbers, a calculated central value of a set of numbers. If a distribution has a density function $p(x)$, then the mean value $\bar{x}$ can be define as follows.

$$\bar{x} = \int_{-\infty}^{\infty} x \; p(x) \mathrm{d}x. \tag{5.1}$$

The median is the middle value in the list of numbers, in which half population has a lower value and half of them has a higher value. The median $x_{1/2}$ of the distribution function is a value such that (Primak; et al., 2004):

$$P(x_{1/2}) = \int_{-\infty}^{x_{1/2}} p(x)\mathrm{d}x = \int_{x_{1/2}}^{\infty} p(x)\mathrm{d}x = \tfrac{1}{2}. \tag{5.2}$$

The median $x_{1/2}$ can be used to estimate mean $\hat{x}$ when the sample size is fairly large using simple approximation (Hozo et al., 2005):

$$\bar{x} \approx \hat{x} = \frac{a + 2x_{1/2} + b}{4}, \tag{5.3}$$

where a is the smallest data value. b is the largest data value. The median is used to estimate the mean value based on CDF figures. Both above measures will be used to analyse and evaluate the performance of the different proposed methods above.

5.4.2 SNR/ SINR Analysis

For three new methods, the frequency spectra are orthogonally allocated to different network-tiers. As much as 17% of total spectrum (φ_M) is assigned to the macrocell, and the rest spectrum is allocated for small cells. Then, different resource allocation strategies are applied to small cells. As the HetNet allocates spectrum orthogonally between tiers, different power allocation strategies in small cells will not affect the macrocell's performance.

Moreover, the macrocell SNR threshold γ_{th}^{M} is assigned as much as 19 dB. Then, the macrocell allocates its power for the selected subchannels using the water-filling algorithm. These configurations result in the macrocell capacity as much as 17.036 Mbps, which has a small difference as much as 6.453×10^{-4} less than in SSCIM1, see Table 5.5.

Figure 5.1 provides the average capacity per symbol period of the SSCIM3 algorithm. The Figure shows that the average capacity of HetNet is stable for the small cell SINR threshold γ_{th}^{S} from 10dB to 16dB and then followed by a bit decrease. Based on these results, it is considered to select γ_{th}^{S} as much as 16 dB for SSCIM3. Whereas the other parameters, i.e. φ_M and γ_{th}^{M}, follow the previously assigned values.

Figure 5.2 provides the cumulative distribution function of SNR/ SINR of the downlink HetNet using SSCIM algorithms. Figure 5.2(a) provides the SNR distribution function of the downlink macrocell network. The horizontal axis of the Figure presents the median of three new methods has higher SNR than in SSCIM1, which show better average SNR than in SSCIM1. Table 5.2 confirms the same results that the new methods have higher average SNR than SSCIM1.

Moreover, the vertical axis of the same Figure represents SNR distribution function of the macrocell network. It also represents the average portion of sub-channels occupied by the macrocell. The Figure shows the new methods occupy narrower distribution than SSCIM1, which means occupying less spectrum than SSCIM1 as confirmed by Table 5.3. However, having higher SNR to occupy the number of spectrum less than SSCIM1, the new methods result in the similar capacity with SSCIM1 for the macrocell section (see Table 5.5).

Figure 5.2(b) provides the SINR distribution function of the downlink small cell networks. In this scenario, each small-BS is surrounded by a wall with a penetration loss PL_{tw} of 13 dB. Thus, interference power between two small-BSs will decrease at least as much as 26 dB (i.e. two times of PL_{tw}) after passing through those two separating walls of both small cells. After splitting

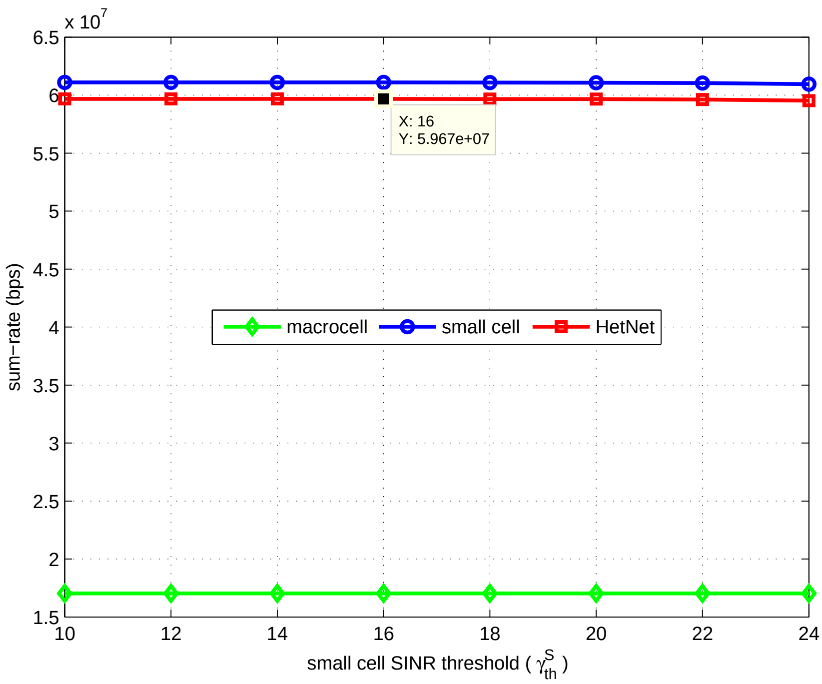
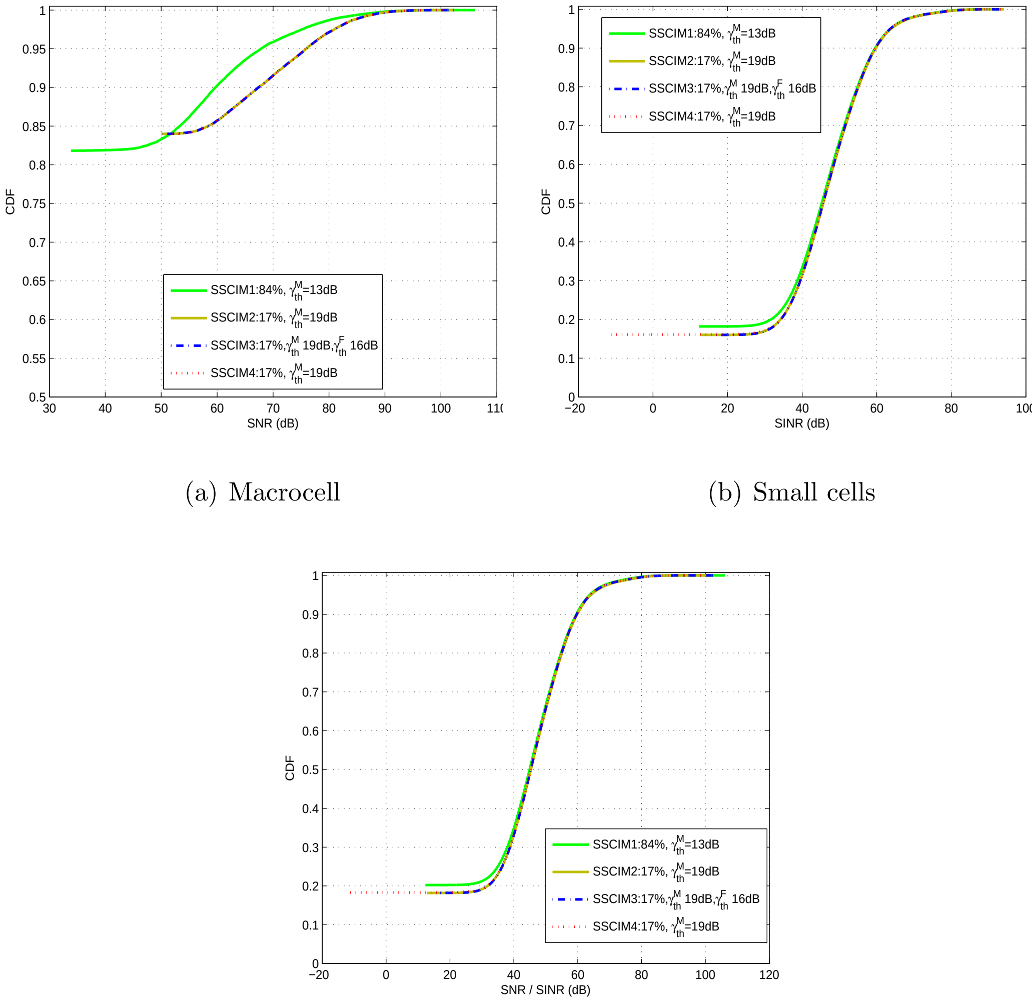


Figure 5.1: Average capacity per symbol period of SSCIM3: φ_M 17%, γ_{th}^M 19dB.



(a) Macrocell

(b) Small cells

(c) HetNet

Figure 5.2: Cumulative distribution function of SNR/ SINR for SSCIM.

17% of spectrum for the macrocell, then the rest spectrum is allocated for small cells. For SSCIM2, power in small cells is distributed equally (uniformly) to the occupied subcarriers using EPA. For the other methods, power allocation is applied for small cells after selecting the best subchannels based on the pilot signal information, in which SSCIM3 uses an on-off method (OOPA) by considering γ_{th}^{S} of 16 dB and SSCIM4 uses water-filling power allocation (WF).

The horizontal axis of Figure 5.2(b) shows that the medians of the new SSCIMs have a bit higher SINR than SSCIM1. It means that the new methods have better SINR than SSCIM1 for the small cells. Table 5.2 confirms the above

Table 5.2: Average (mean) SNR/SINR (in dB) for each occupied subcarrier

	SSCIM1	SSCIM2	SSCIM3	SSCIM4
Cell-Edge (5^{th}-percentile)				
Macro-UT	48.294	**57.770**	**57.770**	**57.770**
Small-UT	34.341	34.428	34.515	**34.542**
HetNet-UT	34.366	34.451	34.536	**34.566**
Overall Areas				
Macro-UT	78.278	**80.191**	**80.191**	**80.191**
Small-UT	62.899	**63.313**	63.132	63.140
HetNet-UT	63.855	**64.456**	64.319	64.326

Table 5.3: Average portion of allocated subchannels for each network tier

Method	Macro-cell	Small cells
SSCIM1	18.18%	81.824
SSCIM2	16%	84%
SSCIM3	16%	83.99%
SSCIM4	16%	83.9%

results that the new methods result in higher SINR than SSCIM1 for the small cell section. Moreover, the vertical axis of the Figure presents the new methods occupy wider distribution than SSCIM1 for the small cells, which means occupying more spectrum than SSCIM1 for this network tier as confirmed by Table 5.3. Thus, by having a bit higher SINR to occupy more spectrum than SSCIM1, the new methods result in a higher capacity than SSCIM1 for the small cells (see Table 5.5). Moreover, this Figure also shows that SSCIM3 has the highest SINR at the end Cell-Edge area, but not at the all Cell-Edge areas with 5^{th}-percentile. It is caused by avoiding the subcarriers with SINR less than threshold strategy on this algorithm. This strategy is capable of improving the performance at the Cell-Edge areas if compared to SSCIM1 and SSCIM2 (see Table 5.2).

Figure 5.2(c) shows the SNR/ SINR distribution of overall HetNet consisting of the macrocell and the small cells. This Figure informs that the new SSCIM methods have better performance than SSCIM1. These results are also confirmed by Table 5.2 for HetNet section.

Table 5.2 provides the average performance (SNR/ SINR) of each occupied subcarrier on different network tiers. This Table presents that at Cell-Edge areas SSCIM4 results in the highest SINR for the small cell part. WF in SSCIM4 will allocate less or even no power for the bad subchannels, such as in cell-edge areas. Hence, a bad subchannel means the low gain or the high interfered subchannel. Less allocating power at or avoiding the bad subchannels could reduce the probability of occupying subchannels with low gain or high interference. It leads low interference for that subchannel and improves the performance of cell-edge areas.

For Overall Area group, SSCIM2 shows its performance superiority. By using EPA and wider spectrum than others for all occupied subcarriers, SSCIM2 results in less maximum transmission power at each subcarrier. Moreover, the frequency selective channel with different gain for all spectrum and the wall penetration losses at small cells reduce the effect of inter-cell interference and lead to higher performance at the receivers, see Table 5.2.

Table 5.3 provides the average portion of allocated subchannel per network tier for the different scenario. As explained above, as much as 17% of total spectrum is allocated to the macrocell. However, the portion number of subchannels allocated to the macrocell is 16%, which is less than 17% of the total spectrum. This result can be explained as follows. The number of allocated subcarriers is:

$$17\%(\text{of total spectrum}) \times 300(\text{subcarriers}) = 51(\text{subcarriers}).$$

The smallest unit than can be managed for resource allocation is the RB, which consists of 12 subcarriers per RB in the frequency domain. Then the number of allocated RB is:

$$\frac{51 \text{ subcarriers}}{12 \text{ subcarriers/ RB}} = 4.25 \approx 4 \text{ RBs}.$$

Thus, the portion of allocated RB is:

$$\frac{4 \text{ RBs}}{25 \text{ RBs}} \times 100\% = 16\% \text{ of total RBs per time-slot (in frequency domain).}$$

It is identical to 16% of total subchannels per time-slot.

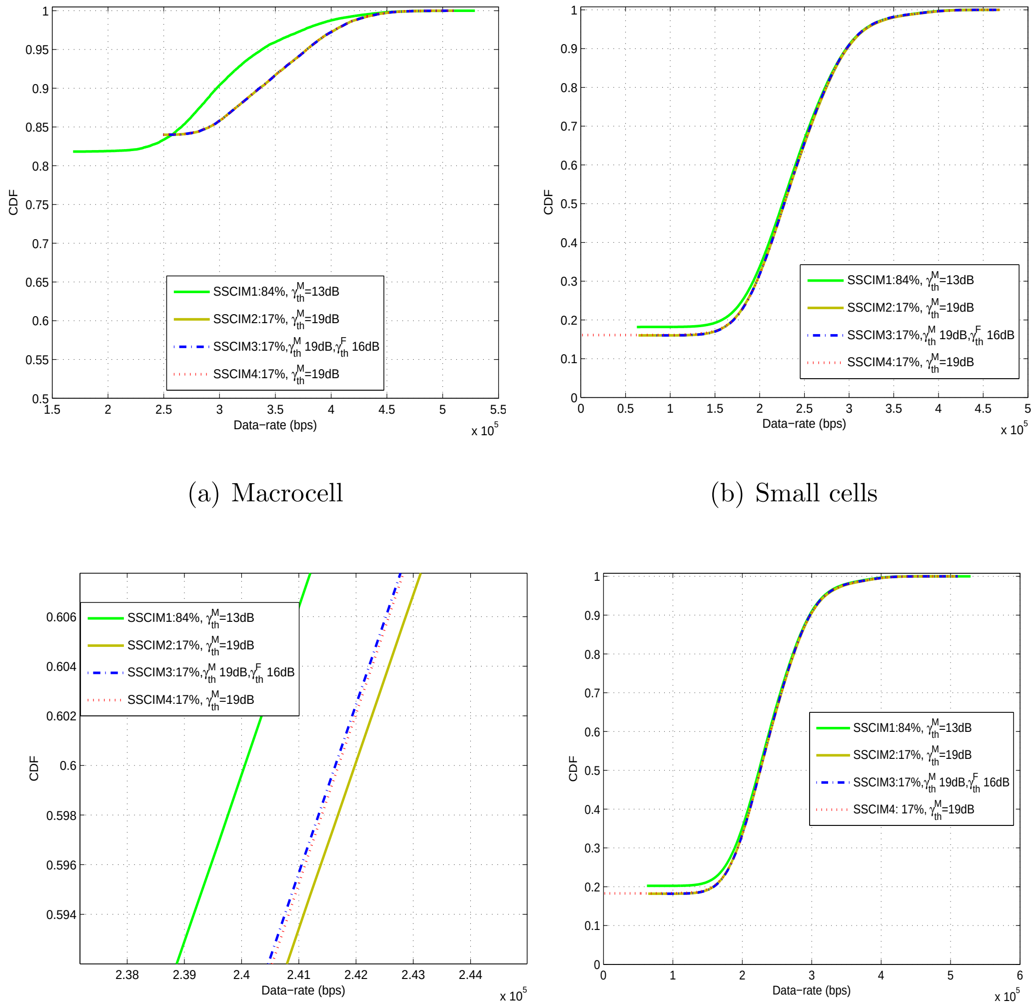
5.4.3 Data-Rate Analysis

Figure 5.3 provides the distribution function of user data-rate of the downlink HetNet using SSCIM algorithms with the same parameters as in Figure 5.2. Figure 5.3(a) presents the macrocell section of the data-rate distribution. This Figure shows that medians of the new methods outperform SSCIM1, which means the new methods have higher average rate than SSCIM1. Table 5.4 confirms the above results.

For the macrocell, the new three methods are set to allocate 17% of the total frequency spectrum. Spectrum-splitting and water-filling power allocation are performed in the macrocell. These methods apply WF algorithm to allocate transmission power for the downlink macrocell network, in which WF can optimally allocate spectrum and transmission power for a system with multiple Gaussian subchannels as well as assigns the optimal SINR threshold γ_0. Refer to the vertical axis of Figure 5.3(a), the new methods occupy the spectrum narrower than SSCIM1 for the macrocell section, see Table 5.3. However, by occupying less spectrum but having average data-rate per each subcarrier higher than SSCIM1, this condition makes the new methods achieve the similar macrocell capacity with SSCIM1, see Table 5.5.

Figure 5.3(b) provides the data-rate distribution of the downlink small cell networks, in which the enlarged version is provided in Figure 5.3(c). As discussed above, the new methods allocate the rest spectrum to small cells after the macrocell takes some good subchannels, in which each method allocates different spectrum portions depend on the algorithm they use.

The vertical axis of Figure 5.3(b) provides that the new methods occupy the wider distribution than SSCIM1, which means occupying wider spectrum for small cells than SSCIM1. The Figure also provides that the median of the new methods slightly outperform SSCIM1, which means having the better rate than SSCIM1. By achieving both results above the new methods have better capacity than SSCIM1 for small cells as presented in Table 5.5. For Cell-Edge areas, the new methods have better improvement than rest areas. By having wider spectrum and higher rate per occupied subcarrier, the new methods achieve higher sum rate than SSCIM1, see Table 5.5.



(a) Macrocell

(b) Small cells

(c) Small cells (enlarged figures)

(d) HetNet

Figure 5.3: Cumulative distribution function of user data-rate for SSCIM.

Figure 5.3(b) shows the new methods have a slightly higher average rate per occupied subcarrier for small cells. As presented in Table 5.1, three methods of the new SSCIM use three different strategies of resource allocation for small cells. They are equal (uniform), on-off and water-filling power allocation, which are implemented in small cells for SSCIM2, SSCIM3 and SSCIM4, respectively. Figure 5.3(c) shows that SSCIM2 achieves the best rate among the others. Hence, SSCIM2 allocates the transmission power for small cells using EPA, in which total transmission power is uniformly distributed to each occupied subcarrier.

Table 5.4: Average (mean) data-rate (kbps) per allocated subcarrier

	SSCIM1	SSCIM2	SSCIM3	SSCIM4
Cell-Edge (5^{th}-percentile)				
Macro-UT	240.640	**287.862**	**287.862**	**287.862**
Small-UT	171.120	171.560	171.994	**172.127**
HetNet-UT	171.250	171.672	172.097	**172.245**
Overall Areas				
Macro-UT	312.640	**354.913**	**354.913**	**354.913**
Small-UT	242.390	**242.752**	242.437	242.539
HetNet-UT	242.910	**243.459**	243.146	243.249

As SSCIM2 allocates more spectrum for small cells than others, EPA strategy decreases the maximum transmission power per subcarrier. Moreover, as the wall penetration losses among small-BSs are high, this EPA method effects to low inter-cell interference. Thus, SSCIM2 achieves the highest data-rate among the others. Small Cells section of Table 5.4 at Overall Areas group and Table 5.5 at small cell part confirm the above results.

For SSCIM3 (on-off) and SSCIM4 (water-filling), they select the best subchannels based on the pilot signal information. Both methods occupy fewer subcarriers than SSCIM2 and allocate more power for each subcarrier. Table 5.3 shows that SSCIM3 and SSCIM4 do not occupy overall of the rest spectrum. Instead of 84% as happens to SSCIM2, SSCIM3 and SSCIM4 allocate the average portion of the whole spectrum as much as 83.99% and 83.9%, respectively. Thus, both methods have stronger inter-cell interference power among small-BSs than SSCIM2 that decreases the average rate in small cells. However, by using these approaches, both methods avoid subchannels with the gain less than the pre-assigned requirement. These strategies improve the performance at Cell-Edge areas, in which SSCIM3 and SSCIM4 outperform SSCIM1 and SSCIM2, see Table 5.4 on Cell-Edge group for the Small-UT part.

Figure 5.3(d) provides the data-rate distribution functions of HetNet, consisting of the macrocell and the underlaying small cells. The Figure is dominantly influenced by 30 small cells instead of one macrocell. Thus, it is reasonable that Figure 5.3(d) has the similar pattern with the small cells' Figure 5.3(b), but over-

Table 5.5: Average (mean) sum-rate (Mbps) / symbol period

	SSCIM1	SSCIM2	SSCIM3	SSCIM4
Macrocell	17.047	**17.036**	**17.036**	**17.036**
Small cells	59.500	**61.173**	61.088	61.051
HetNet	58.130	**59.750**	59.667	59.631

all networks have the better rate than the one of small cells section. Table 5.4 confirms these results, in which overall networks have higher average sum rate than other sections.

In general, Figure 5.3(d) provides that the median value of the new methods be slightly higher than SSCIM1, which means having an average rate higher than SSCIM1. HetNet sections of Table 5.4 confirm that the new methods result in the average (mean) rate higher than SSCIM1. At the vertical axis, the Figure also shows that the new methods occupy a wider distribution than SSCIM1. It indicates these methods occupying wider spectrum for HetNet than SSCIM1. Both achievements above, i.e. a bit higher average rate per occupied subcarrier and wider occupied spectrum, lead the new methods to achieve higher average (mean) sum rate for HetNet.

5.5 Conclusions

This Chapter has presented the proposed methods related to interference mitigation in HetNet. These methods are the extension of SSCIM1 (see Chapter 4). The HetNet model consists of one macrocell and thirty underlaying small cells. These methods are also called as spectrum-splitting-based cognitive interference management (SSCIM) algorithm, consisting of SSCIM2, SSCIM3 and SSCIM4.

For the macrocell section, the proposed methods split the spectrum over the small cells and then apply the water-filling algorithm (WF). They also consider two parameters before determining the occupied resources, including the SINR threshold γ_{th}^{M} and the spectrum allocation percentage $\varphi_M\%$. The results show that by occupying less spectrum but having a higher rate per occupied subcarrier than SSCIM1, the new methods achieve the similar capacity to SSCIM1 that uses

EPA. It shows that WF outperforms EPA for multiple Gaussian subchannels as in the macrocell network.

For the small cells, the methods apply three different techniques for the downlink HetNet. SSCIM2 applies EPA and spectrum-sharing among small cells as used on SSCIM1. Meanwhile, SSCIM3 applies OOPA and partial spectrum-splitting for the same network tier, in which it assigns γ_{th}^{S} for the selected subcarriers. Whereas, SSCIM4 implements WF that consequently allocates the optimal spectrum and power allocation as well as assigns the optimal SINR threshold γ_0 for the small cells. The results show that the new methods occupy wider spectrum and achieve a bit higher performance than SSCIM1. As SSCIM1 and SSCIM2 use the same strategy for small cells, both methods should have the same performance for this network tier. Thus, the higher performance in SSCIM2 is caused by wider spectrum allocated in this method that decreases the power allocation for each subcarrier. It results in less inter-cell interference and improves the small cells' performance.

For the three proposed methods at Overall Areas of small cells, SSCIM2 that applies EPA and spectrum-sharing outperforms two others, which three methods occupy similar spectrum portion. Hence, EPA achieves the best performance for frequency reuse scenario in the low interference environment if compared to OOPA (SSCIM3) and WF (SSCIM4) techniques. The effect of inter-cell interference in the small cells decreases because of the wall penetration losses. Moreover, by occupying the widest spectrum on small cells, EPA will also reduce the maximum transmission power per occupied subcarrier that leads to inter-cell interference decrease. To conclude, applying EPA while limiting the maximum transmission power on the occupied subcarrier can reduce the inter-cell interference of cellular system with low interference environment.

However, the Cell-Edge areas of small cells provide the different results. In which SSCIM4 that uses WF achieves the best average performance per allocated subcarrier. To conclude, WF can improve the cell-edge performance of the cellular networks with low inter-cell interference.

The assignment of SINR threshold, either for the macrocell (γ_{th}^{M}) or small cells (γ_{th}^{S}), helps to select the good subchannels. The macrocell results show that by assigning a threshold γ_{th}^{M} for subchannel selection, and then followed by

WF, leads to significant improvement in the network performance with multiple Gaussian subchannels. Additionally, SSCIM3 that applying OOPA also assigns a threshold γ_{th}^{S} for the selected subcarriers for small cells. The results show that SSCIM3 achieves the highest performance for the end cell-edge areas. To conclude, the proper threshold assignment can avoid the interference and improve the performance of HetNet.

However, all the above results above are not obtained fully using automatic and self-optimisation approaches. Some parameters are set based on the best trials, instead of automatically update. To have these features, it needs coordination among small cells, which will increase the network load. Moreover, it is considered that the performance of the proposed methods can still be improved further by applying the cognitive radio concepts proposed by Haykin (2005) more comprehensively, such as by taking into account the interference temperature recognising, channel-state predictive modelling, noise-floor statistics and traffic statistics. Thus the methods still need an improvement to find the optimal parameters automatically and reduce the network load. These features can provide small cells available for self-deployment and self-optimisation.

To further investigate the optimal resource allocation in HetNet, Chapter 6 will present our works related to Sum Rate Maximisation in a Simplified HetNet Model.

Chapter 6

Sum Rate Maximisation in a Simplified HetNet Model

6.1 Introduction

6.1.1 Motivation

Heterogeneous cellular networks (HetNet) serve their user terminals by sharing the same RF spectrum with different radio parameters, such as transmission power and coverage area. Regarding radio resource allocation, the system capacity of Gaussian channel is determined by the channel bandwidth (in Hertz), signal and noise power (in Watts) as proposed by Claude Shannon in 1940s (Goldsmith, 2005). However, for a multi-user system, the maximum data rate of an OFDMA system is achieved when each subchannel is allocated to a single user terminal having the best channel gain on that subchannel (Jang and Lee, 2003). In this case, radio resources must be assigned to the best channel gain of each subchannel to maximise the data rate. Besides, to maximise the capacity of a multi-channel system, more transmission power must be allocated to higher gain channels and even no power assigned to channels with the *signal-to-interference-plus-noise ratio* SINR lower than a threshold (Goldsmith, 2005). This concept is called as water-filling power allocation.

For HetNet, in addition to some resource allocation parameters mentioned above, maximising the transmission power does not guarantee for maximising the system capacity; because increasing the transmission power in one cell will increase interference to other ones as found in Chapter 4 and Chapter 5. Thus, power control must be considered in power allocation to maximise the system capacity for these networks.

For multi-user multi-channel HetNet, e.g. 3GPP-LTE system, in addition to parameters as mentioned earlier, resource allocation must also consider frequency spectrum allocation for each network. Moreover, because of inter-cell interference, the sum rate optimisation problem in multi-cells is a nonconvex problem (Andargoli and Mohamed-pour, 2012).

This Chapter proposes a new method to optimise the capacity of downlink multi-user multi-channel HetNet. The method is developed based on the combination of local search and penalty function methods by considering critical point escape procedure that considers the objective function.

6.1.2 Related Works

Because of the inter-cell interference, the sum rate maximisation problem in HetNet is nonlinear and nonconvex in (P_n^M, P_n^S) (Andargoli and Mohamed-pour, 2012), which are the transmission power on subchannel-n of the macrocell base-station (macro-BS) M and of the small cell BS (small-BS) S, respectively. This problem cannot be solved using the standard convex optimisation method (Boyd and Vandenberghe, 2004).

Nonlinear optimisation (or nonlinear programming) is the term used to describe an optimisation problem when the objective function or the constraint function is not linear, without known to be convex (Boyd and Vandenberghe, 2004). This nonlinear optimisation problem can be solved using different approaches that involve some compromises, such as local optimisation method, the global optimisation method, and reducing the problem to the convex optimisation problem.

Khoshkholgh et al. (2010*b*) proposed a mixed access strategy for spectrum sharing based on the overlay and underlay strategies to maximise the capacity of the secondary service for cellular HetNet. In cognitive radio, the secondary service is provided for users with less priority for spectrum access. By using an approach of Jensen's inequality (Boyd and Vandenberghe, 2004) to simplify the problem and then solve it using Lagrange dual function, this proposed method is simple. It also achieves the capacity that is approaching the maximum achievable capacity of the secondary system. However, this work (Khoshkholgh et al., 2010*b*) is focused on the secondary network. It does not maximise the total capacity of HetNet.

To optimise the data rate in digital subscriber line systems, a distributed power control method based on an iterative water-filling technique was developed (Yu et al., 2002). In this paper, interference channel is modelled as a non-cooperative game. The method can be implemented distributively without centralised control. It results in competitive optimal power allocation by offering an opportunity to negotiate the best utilisation of frequency and power between two edges of the system. This method is one of some methods that will be evaluated and compared with our proposed method.

For maximising the data rate of HetNet, a spectrum splitting-based cognitive interference management in two-tier LTE networks was proposed, see Chapter 4. The proposed method allocates the transmission power, frequency spectra and time slot based on the received pilot signals from a macro-BS and small-BSs and also control channel information. Transmission power is distributed to each subchannel uniformly. For each BS, subchannels are allocated separately to different tier networks by considering the best channel gain and the best trial number, not the optimal one. So that, the method is still away from the optimal result. This method, with some simplifications to adapt to the network models and configurations, will also be evaluated and compared to the proposed method.

To improve the global search efficiency, Strekalovsky and Yanulevich (2008) proposed the usage of a local search at each iteration. Moreover, Strekalovsky and Yanulevich (2013) described the usage of a mathematical apparatus to make possible to escape a local solution. These approaches help to find the global solution in game equilibrium problems, hierarchical optimisation problems, and other nonconvex optimisation problems. This Chapter proposes a method based on the idea of Strekalovsky and Yanulevich (2008, 2013) to solve the sum rate optimisation problem in downlink multi-user multi-channel HetNet.

6.1.3 Proposal and Contribution

In general, the problem being investigated in this Chapter is the same as that of Chapter 4 and Chapter 5, which is *Interference Mitigation in Small Cell Networks*. However, in this Chapter, the problem is simplified into one sector of the downlink cellular HetNet. It consists of a macrocell and a small cell. These approaches are taken into account to ease identification, analysis and solving of the problem.

When a spectrum is accessed simultaneously by two adjacent cells, by ignoring a hybrid multisystem spectrum sharing (Khoshkholgh et al., 2010*a*) and CDMA (Buehrer, 2006) techniques, interference avoidance on a cellular system using an omnidirectional antenna can only be done through the power control and the spectrum allocation. It also excludes the differentiation of the resource access time. To determine how far the spectrum can be shared or should be split orthogonally to one of the two adjacent cells, the method proposed in this Chapter explores the issue by simplifying the structure of HetNet into only two nearby cells, which represent a macrocell and a small cell. Simplification of the issue through a network modelling in one dimension aims to ease the identification, analysis and problem-solving (Andargoli and Mohamed-pour, 2012).

In this Chapter, a new suboptimal resource allocation method for downlink OFDMA-based HetNet is proposed to maximise the capacity of HetNet. The maximum transmission power and quality of service (QoS) constraints are considered to maximise the sum rate of HetNet. Moreover, subchannel allocation constraint is also considered, in which each subchannel will be allocated only for one user terminal in the one-tier network.

In this situation, the optimisation problem is nonlinear and nonconvex, which cannot be solved using the standard convex method. To deal with the problem, an approximation using a *local search* strategy is proposed in this Chapter. However, this method is suitable for an unconstrained optimisation problem (Boyd and Vandenberghe, 2004). Thus, it needs modification to solve the constrained optimisation problem. Moreover, optimal power allocation at fading channel assumes average power constraint (Goldsmith, 2005). So that, the problem solving is approximated by using a local search method by finding the greatest lower bound of the objective function and assuming average power allocation for each subchannel and vanishing the violated subchannels using a *penalty function*. Hence, the penalty function is used to approximate the constrained optimisation problem as an unconstrained one, as discussed in (Ruszczyński, 2006). To approximate the maximum achievable capacity of the HetNet, some constraint functions are included in escaping procedure from the critical point. It results in spectrum and power allocation scenarios for each BS in HetNet, i.e. a hybrid of split and shared spectrum allocation between the networks.

6.1.4 Outline

This Chapter is organised as follows. Section 6.2 will describe the Problem Formulation. Section 6.3 will explain the Proposed Method, i.e. SubOptimal Spectrum and Power Allocation (sOSPA) for downlink OFDMA-based heterogeneous cellular networks. Subsequently, Numerical Results and Discussion will be discussed in Section 6.4. Finally, Section 6.5 will summarise and conclude this Chapter.

6.2 Problem Formulation

6.2.1 System Model and Parameters

The investigated system is downlink sectorised OFDMA-based HetNet. As proposed by Andargoli and Mohamed-pour (2012), networks are modelled in one dimension to ease identification, analysis and solving of the problem. However, the model still grasps important aspects of the real problem in HetNet.

The simplified model consists of one macrocell and one underlaying small cell, which represent heterogeneous cellular networks. Same numbers of user terminals (UTs) ($k_M = k_S$), k_M for macrocell and k_S for the small cell, are uniformly distributed in each cell. These two-tier networks share the same spectrum.

For propagation path losses, 3GPP TR 36.814 V9.0.0 models (3GPP, 2010) are used, i.e. outdoor and indoor path-loss models. The channel model is the same as that used in Equation (4.1), but without shadowing for simplification. Figure 6.1 illustrates the investigated system model. Table 6.1 presents the parameters of the system model.

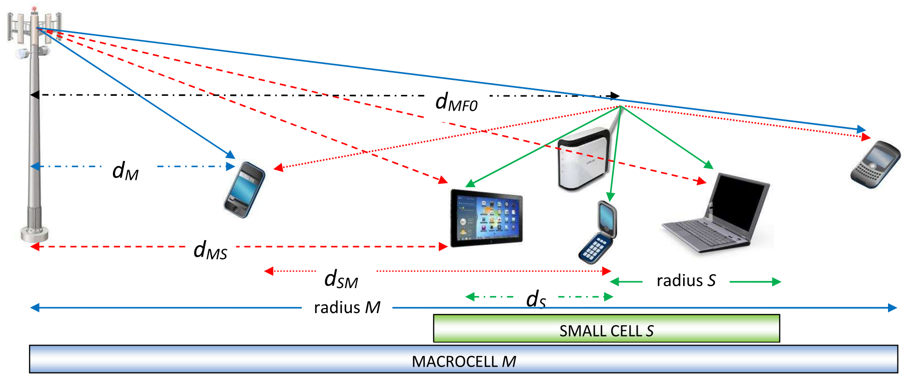


Figure 6.1: System Model (Siswanto et al., 2016)

Table 6.1: System Parameters (Siswanto et al., 2016)

Symbol	Parameter (Unit)	Value
f_c	carrier frequency (GHz)	2
B_{sc}	freq. bandwidth per subchannel (kHz)	180
N_{sc}	number of subchannels	25
N_0	thermal noise density (W/Hz)	$5.556 \cdot 10^{-21}$
fd	channel fading	frequency selective Rayleigh fading
L_w	wall penetration loss (dB)	13
P^M_{tot}	macro base-station (BS) total power (dBm)	48
P^S_{tot}	small-BS total power (dBm)	30
r_M	radius of macrocell's coverage area (m)	500
r_S	radius of small cell's coverage area (m)	40
d^M_{min}	minimum distance to macro-BS (m)	30
d^S_{min}	minimum distance to small-BS (m)	3
K	number of macro-UTs	varying, same with K_S
K_S	number of small-UTs	varying, same with K
	user distribution/ cell	Uniform

6.2.2 Problem Formulation

In this Section, the optimisation problem of the sum rate maximisation of OFDMA-based heterogeneous cellular networks is investigated. Solving this problem is equivalent to finding the upper bound capacity of these networks. The optimisation variables are the set of allocated power at each subchannel and occupied subchannels of each BS.

Jang and Lee (2003) has shown that the maximum data rate of an OFDMA system is obtained when each subchannel is allocated to the user terminal with the best channel gain. However, in heterogeneous cellular networks, performing only the same approach above for each network may not result in the best capacity because of the interference. To optimise the capacity of these networks, in addition to the best channels of allocated users, resource allocation also needs to consider the channels among adjacent interfering networks. Thus, power allocation in HetNet must take into account properly both high transmission power for high capacity optimisation and interference avoidance to nearby interfered networks caused by this resource allocation.

Consider that the data rate (in bps) on a subchannel-n of the macro-UT-k is:

$$R_k^{M,n} = B_{sc} \log_2 \left(1 + \frac{P_n^M G_k^{M,n}}{N_0 B_{sc} + P_n^S G_k^{S,n}} \right), \tag{6.1}$$

where P_n^M is the power transmitted by the macro-BS M on subchannel-n whereas P_n^S is transmitted by the small-BS S. $G_k^{M,n}$ denotes the channel gain from the serving macro-BS M to the macro-UT-k on subchannel n; and $G_k^{S,n}$ is the channel gain from the interfering small cell-S. $B_{sc} = 180$ kHz is the subchannel bandwidth. N_0 is the Gaussian noise power spectral density.

Using the same approach as in (6.1), the data rate (in bps) of the subchannel-n of the small-UT-k' being served by the small cell-S is:

$$R_{k'}^{S,n} = B_{sc} \log_2 \left(1 + \frac{P_n^S G_{k'}^{S,n}}{N_0 B_{sc} + P_n^M G_{k'}^{M,n}} \right), \tag{6.2}$$

where $G_{k'}^{S,n}$ denotes the channel gain on subchannel n from the serving small-BS S to the small-UT k'; and $G_{k'}^{M,n}$ is the channel gain from the interfering macrocell-M.

The objective of the optimisation problem is to maximise the sum rate of downlink heterogeneous wireless OFDMA networks (6.3) under a number of constraints, i.e. Equation (6.4) to (6.7). The constrained optimisation problem can be stated as follows:

$$f(P_n^M, P_n^S) = \max_{P_n^M, P_n^S, \boldsymbol{n}_k, \boldsymbol{n}_{k'}} \left(\sum_{k}^{K} \sum_{n \in \{\boldsymbol{n}_k\}} w_k^{M,n} R_k^{M,n} + \sum_{k'}^{K'} \sum_{n \in \boldsymbol{n}_{k'}} w_{k'}^{S,n} R_{k'}^{S,n} \right), \quad (6.3)$$

where n is the subchannel index, $\forall n \in \{1, \cdots, N\}$. N is the total number of subchannels. $f(\cdot)$ is the objective function with the input arguments of P_n^M and P_n^S. M and S are symbols indicating macro and small cells, respectively. P_n^M and P_n^S are the allocated power on subchannel n for the macrocell-M and small cell-S, respectively. $\boldsymbol{n}_k$ and $\boldsymbol{n}_{k'}$ are the sets of the allocated subchannels to macro-UT-k and small-UT-k', respectively. K and K' are the total number of macro-UTs and small-UTs, respectively. $w_k^{M,n}$, $w_{k'}^{S,n} \in [0, 1]$: are the weight on subchannel-n of the macro-UT-k and the small-UT-k' respectively, which represent subchannel allocation.

The power constraints for the optimisation problem are:

$$C_1 : \sum_{k}^{K} \sum_{n \in \boldsymbol{n}_k} P_n^M \leq P_{tot}^M, \quad (6.4)$$
$$\sum_{k'}^{K'} \sum_{n \in \boldsymbol{n}_{k'}} P_n^S \leq P_{tot}^S,$$

$$C_2 : \quad P_n^M \geq 0, P_n^S \geq 0, \quad \forall n \in \{1, \ldots, N\}, \quad (6.5)$$

where P_{tot}^M and P_{tot}^S is the total transmission power of the macro-BS M and the small-BS S, respectively. N is the subchannel number.

Then, the quality (QoS) constraints are as follows.

$$C_3 : \quad \frac{P_n^M G_k^{M,n}}{N_0 B + P_n^S G_k^{S,n}} - \gamma_{th} \geq 0, \quad \forall n \in \{1, \ldots, N\}, \quad (6.6)$$
$$\frac{P_n^S G_{k'}^{S,n}}{N_0 B + P_n^M G_{k'}^{M,n}} - \gamma_{th} \geq 0, \quad \forall n \in \{1, \ldots, N\},$$

where γ_{th} is the SINR threshold, which is the input parameter being imposed by the desired QoS level. It states the minimum QoS level of a subchannel will be allocated for both network-tiers of the HetNet.

And the subchannel allocation constraints are as follows.

$$C_4: \quad \boldsymbol{n}_k^M \cap \boldsymbol{n}_{k'}^M = \varnothing; \boldsymbol{n}_k^S \cap \boldsymbol{n}_{k'}^S = \varnothing; \quad \forall k \neq k', \tag{6.7}$$

where $\boldsymbol{n}_k^M$ and $\boldsymbol{n}_{k'}^M$ are the sets of the allocated subchannels to different macro-UTs k and k'. $\boldsymbol{n}_k^S$ and $\boldsymbol{n}_{k'}^S$ are the allocated subchannels to different small-UTs k and k'. At the same time, each subchannel is assigned only to one user of each cellular network. The allocated subchannels $(\boldsymbol{n}_k, \boldsymbol{n}_{k'})$ are part of the optimisation problem (6.3) and having dynamic values following to the desired QoS level (6.6).

6.3 Proposed Spectrum and Power Allocation Technique

6.3.1 Proposed Method

The optimisation problem is considered as a weighted sum rate maximisation problem subject to some constraints. Hence, the constraints become weighted factors for each radio resource element to determine certain resources being allocated or not. It is assumed that channel information has been known before resource allocation. Radio resources are allocated to the best gain of channels among all UTs' for each subchannel of each cell.

The optimisation problem of radio resource allocation in HetNet is non-convex. The proposed method approximates the maximum achievable points by using a local search algorithm, i.e. gradient descent method, and set critical point escaping procedure based on some constraint functions. However, this local search algorithm is suitable for unconstrained optimisation problem (Boyd and Vandenberghe, 2004). The penalty function is added to that algorithm to address the constrained optimisation problem.

Local Search Algorithm

The local search algorithm is used to find the power allocation for each subchannel. First of all, total power is distributed uniformly to each subchannel. Then iteratively, this allocated power is adjusted by a step size matrix $\mathbf{A}$ multiplied by the gradient of the objective function $\boldsymbol{\nabla} f$ (6.3), which is the Jacobian matrix. By setting the proper step size matrix $\mathbf{A}$, an equation for variable updating for the local search algorithm is obtained.

$$\mathbf{X}_{(new)} = \mathbf{X}_{(old)} - \mathbf{A} \circ \boldsymbol{\nabla} f(\mathbf{X}_{(old)}) \tag{6.8}$$

where $\mathbf{X}_{N\times 2}$ is a matrix of the power allocation of 2 cellular networks, i.e. macro and small cells. N is the total number of subchannels on each cell. $[\boldsymbol{\nabla} f]_{N\times 2}$ is a matrix of the objective function gradient, not the variable updating function. This gradient is used as deduction elements of iterative searching of the allocated power $\mathbf{X}$. $\circ$ is the Hadamard product operator.

The step size matrix $\mathbf{A}_{N\times 2}$ is:

$$\mathbf{A} = \begin{cases} \epsilon \cdot \mathbf{J} \div \boldsymbol{\nabla} f, & \text{if } \boldsymbol{\nabla} f > 0. \\ 0, & \text{otherwise.} \end{cases} \tag{6.9}$$

where ϵ is a small value constant. $\mathbf{J}_{N\times 2}$ is a matrix of ones. $\div$ is an element-wise matrix division notation.

Penalty Function

The idea of penalty methods is to approximate a constrained optimisation problem by an unconstrained optimisation problem or by a problem with a simple constraints (Ruszczyński, 2006). Their solutions ideally converge to the solution of the original problem, which is the constrained optimisation problem. The unconstrained problems are developed by appending a penalty function to the objective function. When the solutions violate the constraints, this function will penalise the unconstrained problems. Otherwise, the function will set to zero when there is no violated constraint.

In this case, the constrained optimisation problem (6.3) is approximated by the unconstrained optimisation problem, which uses the local search algorithm (6.8) as suggested by Strekalovsky and Yanulevich (2008). Then the penalty function $[\mathcal{V}(\mathbf{X})]_{N\times 2}$ is added to relieve the impact of inter-cell interference due to power allocation on subchannel-n of the macrocell or the small cell whose constraints are violated. This function will reduce the transmission power of each cell at each subchannel when at least one constraint is violated, either the transmission power (6.4 or 6.5) or the QoS constraint (6.6).

This function is developed based on constraint formulas (6.4 - 6.7) as follows.

$$c_{n,1}^{A} = \frac{P_{tot}^{A}}{N} - P_{n}^{A}, \quad \forall n \in \{1, \cdots, N\}, \tag{6.10}$$

$$c_{n,2}^{A} = \frac{P_{n}^{A} \cdot G_{kA}^{A,n}}{N_0 B + P_{n}^{B} \cdot G_{kA}^{B,n}} - \gamma_{th}, \quad \forall n \in \{1, \cdots, N\}, \tag{6.11}$$

$$\mathbf{C} = \left\{ \boldsymbol{c}_1^M, \boldsymbol{c}_1^S, \boldsymbol{c}_2^M, \boldsymbol{c}_2^S \right\} \tag{6.12}$$

where $c_{n,1}^{A}$ and $c_{n,2}^{A}$ are the values of constraint functions of cell A on subchannel n above, i.e. (6.10) and (6.11). $A \in \{M, S\}$, in which M and S are indexes for the macro and small cells. $\boldsymbol{c}_m^A = [\{c_{1,m}^A, c_{2,m}^A, \cdots c_{N,m}^A\}^T]_{N\times 1}$ is an N-element column-vector of constraint function values of cell A. $m \in \{1, 2\}$ is the index of above constraint function values . $\mathbf{C}_{N\times 4}$ is a matrix of constraint function values. N is the number of total subchannels.

Step size vector $\boldsymbol{\delta}$ of the penalty function is set to gradually vanish the power allocation on subchannels whose constraints are violated; so the rate of convergence is set higher than $\mathbf{A}$ (6.9). The step size $\boldsymbol{\delta}_{1\times 4}$ is a row-vector obtained as follows.

$$\boldsymbol{\delta} = \left| \overline{\mathbf{C}}_0 \right| / N, \tag{6.13}$$

where $|\ .\ |$ is an absolute function. N is the number of total subchannels.

$$c_0^{np} = \begin{cases} c^{np}, & c^{np} < 0, c_0^{np} \in \mathbf{C}_0, c^{np} \in \mathbf{C}; \\ 0, & \text{otherwise}, n \in (q \in \mathbb{N} | 0 < q < N), p \in (r \in \mathbb{N} | 0 < r < 4). \end{cases}$$

$[\overline{\mathbf{C}}_0]_{1\times 4}$ is a row-vector containing the mean value of each column of matrix $[\mathbf{C}_0]_{N\times 4}$.

Then the penalty function multiplier $\boldsymbol{\Omega}_{N\times 2}$ is:

$$\boldsymbol{\Omega} = \begin{cases} \beta \cdot \boldsymbol{\Omega}_2^{-1} |\boldsymbol{\nabla} f_{neg}|, & \text{if } \boldsymbol{\nabla} f < 0. \\ 1, & \text{otherwise}. \end{cases} \tag{6.14}$$

where

$$\boldsymbol{\nabla} f_{neg} = \begin{cases} \boldsymbol{\nabla} f, & \text{if } \boldsymbol{\nabla} f < 0, \\ 0, & \text{otherwise}. \end{cases}$$

$$\mathbf{\Omega}_2 = |\min(\boldsymbol{\nabla} f_{neg})| \otimes \boldsymbol{i}.$$

β is set to make the penalty function gradually eliminates power allocation on subchannels whose constraints are violated. $\boldsymbol{i}_{N\times 1}$ is an N-element vector of ones. $\otimes$ is the Kronecker product operator.

And the penalty function is:

$$\mathcal{V}(\mathbf{X}) = \left\{\boldsymbol{\rho}^M + \boldsymbol{\mu}^M, \boldsymbol{\rho}^S + \boldsymbol{\mu}^S\right\}, \tag{6.15}$$

where

$$\boldsymbol{\rho}^A = \begin{cases} -\delta_1^A \cdot \frac{P_{tot}^A}{N} \cdot \boldsymbol{c}_1^A, & \text{if } c_{n,1}^A < 0, \\ 0, & \text{otherwise.} \end{cases}$$
$$\boldsymbol{\mu}^A = \begin{cases} -\delta_2^A \cdot \frac{P_{tot}^A}{N} \cdot \boldsymbol{c}_2^A, & \text{if } c_{n,2}^A < 0, \\ 0, & \text{otherwise.} \end{cases}$$

$A \in \{M, S\}$, in which M and S are indexes for the macro and small cells. $\delta_m^A \in \{\boldsymbol{\delta}\}|\ \delta_m^A$ is a step size variable for cell A, $m \in \{1, 2\}$, see Equation (6.13). The function is developed from two constraint functions, i.e. transmission power (6.4) and QoS (6.6) constraints. If one of two constraints is violated, it will set the penalty function as non-zero and reduce the transmission power of related cell on a certain subchannel. Otherwise, the function will be set as 0. So the transmission power will not be reduced when there is no violated constraint.

Then Equation (6.8) will be rewritten as follows.

$$\mathbf{X}_{(new)} = \mathbf{X}_{(old)} - \mathbf{A} \circ \boldsymbol{\nabla} f(\mathbf{X}_{(old)}) - \mathbf{\Omega} \circ \mathcal{V}(\mathbf{X}_{(old)}). \tag{6.16}$$

Stopping Condition

Stopping conditions are set to approximate the maximum achievable points of the objective function. These conditions take into account constraint functions as follows.

$$0 \le c_{n,1}^M \le \frac{P_{tot}^M}{N}, \quad 0 \le c_{n,1}^S \le \frac{P_{tot}^S}{N}, \tag{6.17}$$

$$c_{n,2}^M \ge -\gamma_{th}, \quad c_{n,2}^S \ge -\gamma_{th}, \tag{6.18}$$

$$\frac{\Delta f}{f} \le \epsilon, \tag{6.19}$$

where $n \in \{1, \ldots, N\}|$ n is the subchannel index. f is the objective function (6.3). ϵ is a small quantity of constant.

Algorithm Summary

In general, the proposed method is summarised as follows.

1. Initially, for each subchannel of each network, the best channel for all users is selected, and power allocation is set equally.

2. Transmission power of each subchannel of each BS is evaluated regarding its constraints. For subchannels having violated constraints, which show the interfered conditions, the allocated power on these subchannels will be iteratively adjusted using the gradient of the objective function (6.8), i.e. the Jacobian matrix, with slight steps, which is dedicated to reducing the interference effect of the nearby cellular network. The iteration is repeated till achieving the equilibrium of power allocation for interfering cells while maximising the objective function.

3. For subchannels with violated constraints, the penalty function (6.15) will penalise the unconstrained problem (6.16).

4. Evaluating the stopping condition to ensure the maximum achievable objective is approached, see Equation (6.17) to (6.19).

At the end of the iteration process, spectrum allocation for these HetNet can be a hybrid of split (orthogonal) and shared spectrum. In general, the algorithm can be presented as Algorithm 7. $\|\cdot\|$ denotes the length of a vector.

6.4 Numerical Results and Discussion

6.4.1 Numerical Method

In this Section, the results of the proposed method using numerical analysis to approximate the maximum achievable sum rate for each iteration cycle is presented. Moreover, then repeat the algorithm for different network configurations to get the final average results. The performance of the proposed algorithm is compared and analysed with the following algorithms:

Algorithm 7 Algorithm Summary (Siswanto et al., 2016)

Initialization: $P_{tot}^{M}, P_{tot}^{S}, P_{n}^{M}, P_{n}^{S}, d_{MS0}, \boldsymbol{n}_{k}^{M}, \boldsymbol{n}_{k'}^{S}, channel\_type$;
$(\boldsymbol{d}_M, \boldsymbol{d}_S, \boldsymbol{d}_{MS}, \boldsymbol{d}_{SM}) \leftarrow$ load *distance_vector*;
$(\boldsymbol{G}^M, \boldsymbol{G}^S, \boldsymbol{G}^{MS}, \boldsymbol{G}^{SM}) \leftarrow$ generate *channel_gain* matrix;
$\boldsymbol{G}^M = \{G_k^{M,n}\}^T; \boldsymbol{G}^S = \{G_k^{S,n}\}^T; \boldsymbol{G}^{MS} = \{G_k^{MS,n}\}^T; \boldsymbol{G}^{SM} = \{G_k^{SM,n}\}^T;$
$\forall k \in \{3, 6, \cdots, 30\}; \forall n \in \{1, 2, \cdots, N\}.$
$\max_k (G_k^{Mn}, G_{k'}^{Sn}, G_k^{MSn}, G_{k'}^{SMn}) \leftarrow$ find the best gain of each downlink subchannel;
$\forall n \in \{1, \cdots, N\}; \forall k \in \{1, \cdots, K\}; \forall k' \in \{1, \cdots, K'\};$
$f(P_n^M, P_n^S) \leftarrow$ set the *objective function* (6.3);
$\boldsymbol{\nabla} f \leftarrow$ set the *gradient function*;
$\mathbf{C} \leftarrow$ set *constraint functions* and their *matrix* (6.10 - 6.12);
while NOT stopping condition **do**
  $\mathbf{A} \leftarrow$ set the step size matrix (6.9);
  Calculate the penalty function: $\boldsymbol{\delta}, \boldsymbol{\Omega}$ and $\mathcal{V}(\mathbf{X})$ (6.13 - 6.15)
  Update $\mathbf{X}_{new}$ (6.16);
  Evaluate variable bounds, e.g. $P_n \geq 0$, $\sum P_n \leq P_{tot}$;
  $\|\{\boldsymbol{n}_k^M\} \neq 0\|$; $\|\{\boldsymbol{n}_{k'}^S\} \neq 0\| \leftarrow$ count the number of occupied subchannels;
  set$(P_{tot}^{M,n}, P_{tot}^{S,n})$
  Evaluate the stopping conditions (6.17 - 6.19)
end while

- Multi-cell iterative water-filling (IWF): This method implements an optimal multi-channel power allocation method based on the water-filling algorithm in a distributed manner (Yu et al., 2002). This approach achieves an optimal resource allocation competitively by offering an opportunity for loops to negotiate the best use of frequency and power within each cell.
- Equal power allocation (EPA): This method selects the best subchannels among all UTs' propagation links. Then the total transmission power of each cell is distributed uniformly into the allocated subchannels of the selected UTs.
- Split spectrum allocation (SSA): Total spectrum is divided as much as certain percentages for each cell. Figure 6.2 presents the average sum rate of each cell when using the SSA method with particular parameters; d_{MS0} is 75 m (outdoor), K and K_S are 6 UTs per cell, and various portions of the allocated spectrum for the macrocell. Refer to Chapter 4 and Figure 6.2, the less spectrum allocated for macrocell and the more spectrum

for small cell lead to the more capacity for HetNet. Based on Figure 6.2, then the allocated spectrum for the macrocell is around 17 %. After having the portion of the allocated spectrum, then the macrocell selects the best subchannels among all UTs' propagation links as much as the number of allocates subchannels and leaves the rest ones for the small cell. Subsequently, the transmission power is distributed uniformly for allocated subchannels on each cell.

3GPP's path loss channel models (3GPP, 2010) for indoor and outdoor small cells are used. The average sum rate is obtained by simulating the method in many repetitions with different configurations, i.e. the random positions of UTs, the inter-cell distances, the channel models and the assigned SINR threshold.

6.4.2 Results and Discussion

Figure 6.3 shows the average sum rate of sOSPA with different scenarios. The differentiate scenarios are separating distances between cells d_{MS0}, i.e. 75 m and

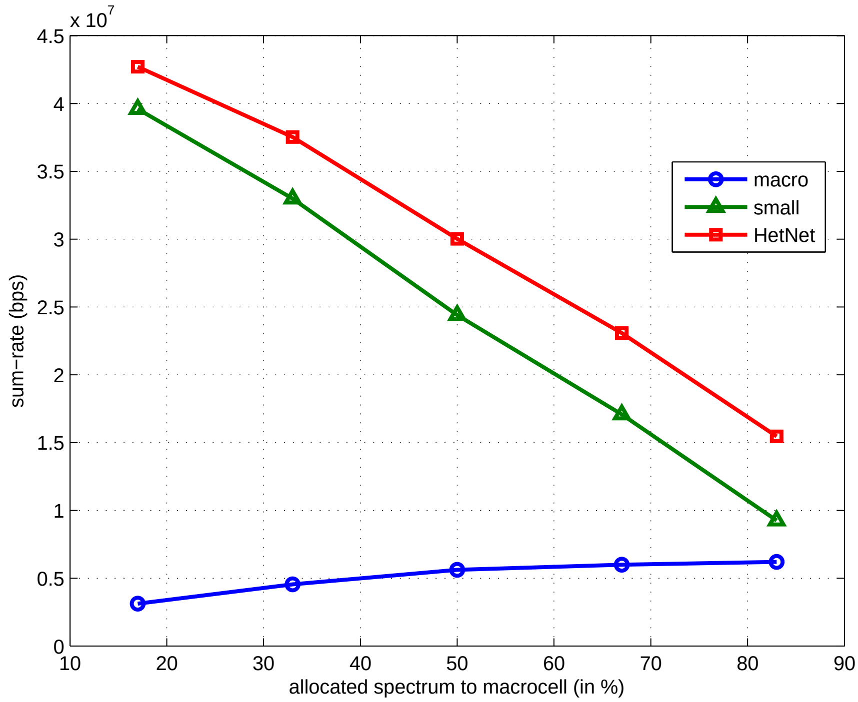


Figure 6.2: Average sum rate of each cell using the SSA method with d_{MS0} 75 m (outdoor), 6 UTs per cell, and portions of the macrocell's spectrum.

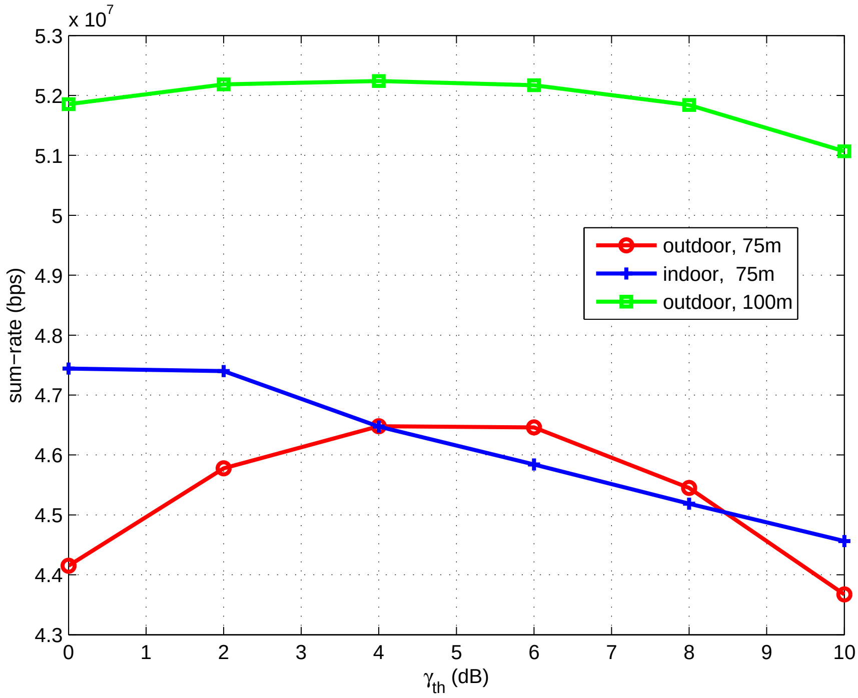


Figure 6.3: Average sum rate of HetNet using sOSPA with different scenarios.

100 m; channel models, i.e. 3GPP's path losses for outdoor and indoor small cells; and the selected SINR threshold γ_{th} ranges from 0 dB to 10 dB with 1 dB steps. K and K_S are 6 UTs for each network. The other parameters are presented in Section 6.2.1 above. The figure shows that the different scenarios affect the differences in average sum rate and average peak rate. For the outdoor small cell scenario, sOSPA with d_{MS0} 100 m reaches a peak rate at γ_{th} 4 dB. Moreover, sOSPA with d_{MS0} 75 m for the same outdoor scenario reaches a peak rate at the same γ_{th} of 4 dB. It shows that sOSPA with the appropriate selection of γ_{th} can optimise the average sum rate of HetNet with high interference scenarios. When applying indoor channel scenario, the wall penetration loss of 13 dB is assigned (3GPP, 2010). This kind of path loss can reduce interference power significantly from outside cells depend on the wall material (3GPP, 2010; Goldsmith, 2005). However, when implemented in the indoor small cell with d_{MS0} 75 m, sOSPA has decreasing trend for the increase of γ_{th}. It confirms that the method is not suitable to optimise the capacity of HetNet in the low interference scenario.

Figure 6.4 shows the average sum rate of HetNet with various numbers of users. d_{MS0} is 75 m. The path loss channel model is outdoor, i.e. a small cell without surrounding wall. In this Figure, the proposed method (sOSPA with γ_{th} 4 dB) is compared with IWF, EPA, and SSA 17 %. In general, the sum rate of all methods increases with increasing number of UTs. The proposed method outperforms all others. The sOSPA allocates the transmission power on each subchannel of each cellular network by iteratively decreasing the power of each cell. This approach proposed to reduce the inter-cell interference and to avoid the violated constraints, see Equation (6.4) to (6.7). By using this method, sOSPA occupies the best subchannels and releases the worse ones, which enables the other BSs to utilise the subchannels. Alternatively, EPA distributes the transmission power uniformly to all allocated subchannels of each cell. Using EPA, high gain inter-cell subchannels will interfere to the close-distance neighbour-BS; whereas the low ones reduce the power efficiency.

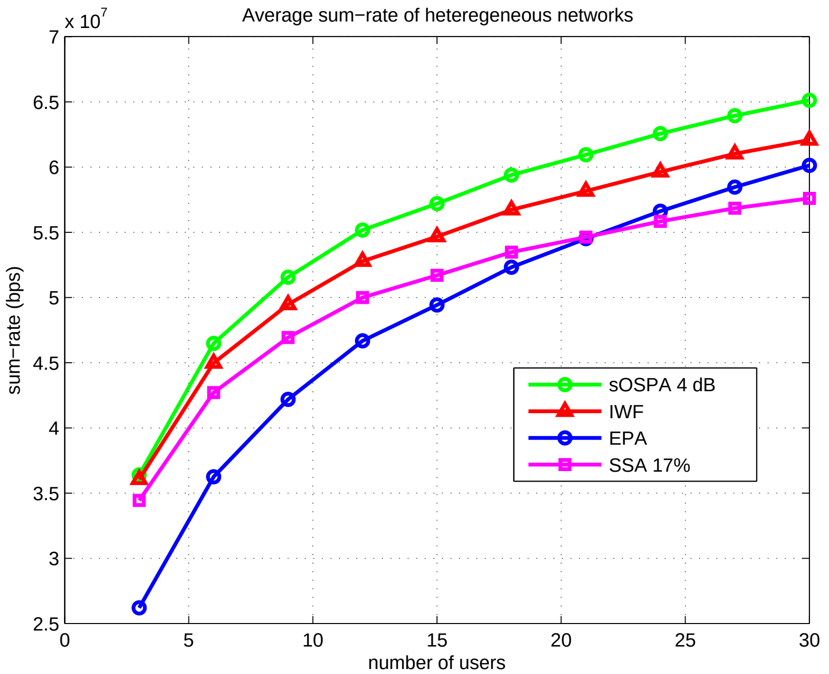


Figure 6.4: Average sum rate of HetNet (outdoor small cells, $d_{MS0} = 75$m) with various numbers of users.

Comparing to IWF, sOSPA has better sum rate of HetNet, see Figure 6.4. The water-filling power allocation method (WF), the core algorithm of IWF, is developed to maximise the power allocation in a Gaussian multi-channel environment without receiving interference power (Goldsmith, 2005). WF allocates more power to the good channels than the bad channels. Moreover, WF will allocate no power to channels with SNR lower than a threshold, see Equation (3.10). In this case, IWF allocates power to each subchannel optimally based on the WF method. When implemented in an interference environment, such as HetNet, IWF will look for optimal equilibrium between all BSs using a competition approach (Yu et al., 2002). The rate of convergence of this method is paid off by the loss of optimal point. Alternatively, sOSPA approximates optimum conditions iteratively, gradually and simultaneously for all subchannels and multicell. This approach makes sOSPA outperforms IWF in multi-channel HetNet.

Comparing to SSA, sOSPA results in higher sum rate of HetNet, see Figure 6.4. SSA selects the best allocated (around 17 %) spectrum for the macrocell and leaves the rest ones (around 83 %) for the small cell. Then the pre-assigned power in each network is distributed uniformly to the allocated spectrum. By using this approach, there is no interference among different network tiers. However, fewer spectra for each network reduce the benefit of frequency diversity in a multi-channel system. Moreover, the transmission power is distributed uniformly on the allocated subchannels regardless of channel conditions. It leads to the high channel gain occupied by the same transmission power as the weak one. So the power allocation on each subchannel is less optimal.

Figure 6.5 shows the portion of average allocated power for each subchannel over the total (maximum) power of each network for each iteration step. d_{MS0} is 75 m. Channel model is 3GPP's outdoor propagation path loss. γ_{th} is 4 dB. The number of UTs is six units. The average allocated power tends to decrease as iteration steps increase. In the small cell, there is a slight decrease allocated power. On the contrary, in the macrocell, the reduction of the transmission power is sharper. It happens because the average distance between the macro UTs and the macro BS is greater than the one of the small-BSs and small-UTs. So the average propagation path losses in the macrocell are more significant than in the small cell. Moreover, the random spread of macro-UTs in HetNet will be

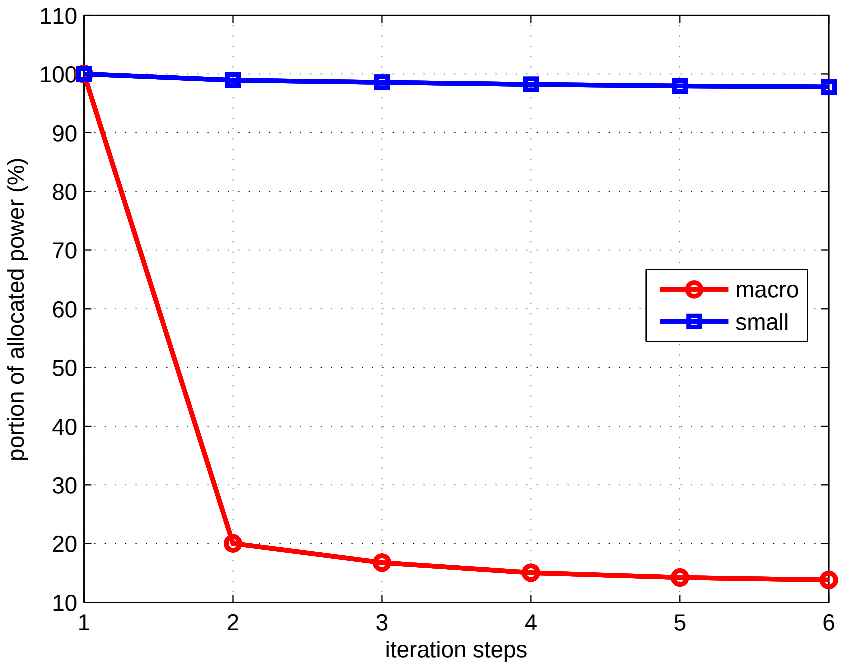


Figure 6.5: The average portion of the allocated power over the maximum power of each cell when using sOSPA 4 dB (outdoor, 75 m, 6 UTs for each cell).

more likely interfered by small cell compared to a limited distribution of small-UTs around the serving small-BS. By assuming the noise power is constant, the determining factor of the channel quality is the channel gain and the received interference power. The combination of high propagation path losses and the high probability of getting interfered in the downlink transmission leads to a worse channel in the macrocell than the one of the small cell.

Figure 6.6 shows the average sum rate of the proposed method for each iteration step when using the same scenario as the previous one. The investigated number of iteration steps is limited to six, which is resulted by around 90.0 % of total various network configurations of numerical iterations, see Figure 6.7.

When compared to Figure 6.6, Figure 6.5 shows that the decreasing allocated power in the macrocell from iteration step 1 to 2 results in the decreasing rate of the macrocell, but increases the data rate of the small cell and entire networks. It shows that by limiting the transmission power in the macrocell can improve the capacity of the nearby small cell and entire networks. For step 2 to 6, the slight

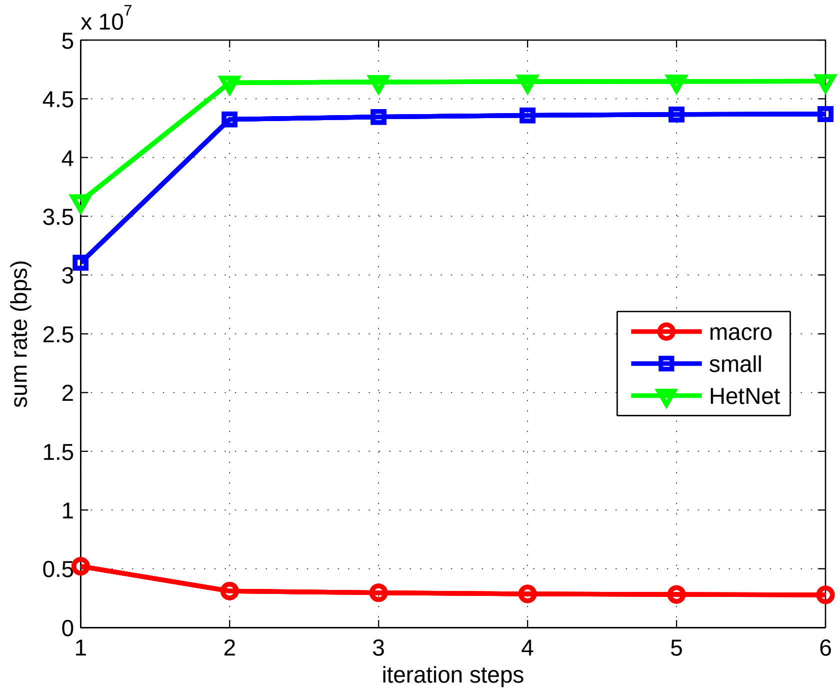


Figure 6.6: Average sum-rate of sOSPA for each iteration steps.

decrease of the allocated power in the macrocell and the small cell leads to slightly decreasing the macrocell's sum rate and followed by slightly increasing sum rate in the small cell and entire networks. It shows that proper power allocation in each subchannel of each cellular network leads to decreasing interference power as well as increasing sum rate of the network. Moreover, it also shows both networks seek out the equilibrium for these steps. For step 5 to 6, the sum rate of HetNet starts to achieve steady state condition. It indicates that the system starts to achieve equilibrium points and also approximates the maximum achievable results of the objective function. To conclude, the proposed method approaches the optimal points of the objective function, i.e. suboptimal power allocation in each network, by considering channel gain and inter-cell interference. Moreover, the proposed method has a fast rate of convergence that shown by the small number of iteration steps to stop.

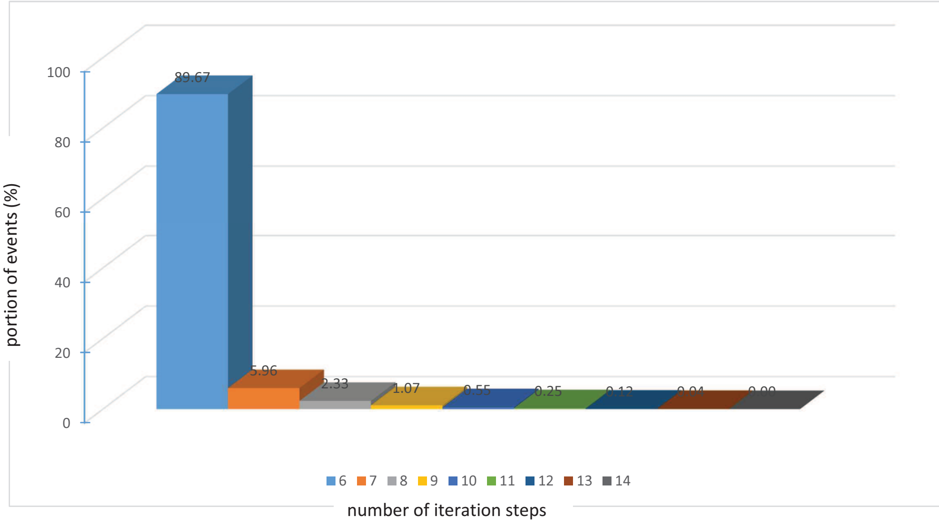


Figure 6.7: Distribution of the iteration step number.

6.5 Conclusions

In this Chapter, the sum rate maximisation in downlink heterogeneous OFDMA networks has been proposed. The proposed method implements a local search algorithm to adjust iteratively and simultaneously the transmission power from interfering to the nearby cell. Then, the penalty function is activated to penalise the subchannels having violated constraints, which can operate in controlling the spectrum allocation. Moreover, the stopping conditions are set to escape from the iteration loops when the objective function achieves steady state conditions, which is considered as approaching the maximum achievable results.

By using the proposed method, near optimum conditions can be achieved by a hybrid of split (orthogonal) and shared spectrum allocation. The proposed method (sOSPA) achieves the near optimum capacity by finding out equilibrium of equal power allocation in each subchannel of each network and set less or even no power for the violated subchannels. In the high-interference conditions, the proposed method with the right selection of SINR threshold γ_{th} achieves higher rate than the other conventional methods. Moreover, the proposed method approximates the maximum achievable capacity of the HetNet by considering both channel gain and inter-cell interference power with a high rate of convergence.

Chapter 7

Conclusions and Future Works

This thesis discusses the state-of-the-art methodologies to mitigate interference in heterogeneous cellular networks (HetNet). The study mainly deals with radio resource allocation strategies in the OFDMA-based heterogeneous cellular network to improve the system performance and capacity. This thesis has investigated the impacts of random deployment of small cells in a macrocell network, dynamic strategies to deal with inter-cell interference problem and maximum achievable capacity in those networks. The study has proposed some novel schemes that adaptively and smartly allocate radio resources to mitigate interference in those networks. Finally, a resource allocation algorithm to approach the maximum system capacity of those networks has also been proposed.

7.1 Summary

To mitigate interference in the downlink HetNet, interference management for two-tier LTE networks has been studied. In this thesis, the radio resources, such as transmission power, frequency spectra, and time-access, are allocated by each BS to its UTs to mitigate inter-cell interference, either co-tier or cross-tier interference. Some resource allocation methods are applied in the proposed scheme, such as equal power allocation (EPA) to all subchannels, split (orthogonal) spectrum allocation (SSA) for different network tiers, and proportional fairness scheduling for all users. The application of those resource-allocation methods is designed with the concept of cognitive radio. Moreover, an SINR threshold is considered before determining the allocated resources.

In the beginning, as a core network, the macro-BS determines radio resources that will be occupied. Then, each small cell senses the control-channel information from the macro-BS, identifies the spectrum being occupied by the macro-BS and then determines the spectra for its users.

The radio resources are allocated to the macro-BS and small-BSs using some strategies based on the current subchannel conditions, which are sensed by the pilot signal. Received SINR on the user side is used to evaluate the capacity of each occupied subcarrier and then used to evaluate the cumulative distribution function of the signal quality and the system capacity by considering some different parameters.

In Chapter 4, the spectrum splitting-based cognitive interference management (SSCIM1) method has been proposed and compared with different interference management methods, such as spectrum-sharing and the EPA technique of non-interference management (NIM), and interfering-resource-blocking-based cognitive interference management (IRB-CIM). These three schemes are then simulated to determine and examine the performance of the HetNet regarding SINR and capacity. The results showed that SSCIM1 achieves a higher SINR and data rate for the occupied subcarriers than NIM and IRB-CIM. However, the results are penalised by the performance loss at the macrocell.

To further investigate the performance of the SSCIM1 method, more resource allocation strategies are added and applied to the interference management scheme. These methods are the water-filling algorithm (WF) for multiple Gaussian subchannels and the interfered environments, on-off power allocation among small cells (OOPA) and the combination of those methods, as explained in Chapter 5. Furthermore, the extended methods are named as SSCIM2, SSCIM3 and SSCIM4. The results showed that for overall networks, SSCIM2 outperforms SSCIM1, SSCIM3, and SSCIM4. SSCIM2 uses the WF method for macrocell and the EPA method for small cells. However, for the cell-edge areas, SSCIM4 that uses the WF method for small cells outperforms the other methods above. Moreover, the SINR threshold assignment at the OOPA method can improve the cell-edge performance of SSCIM3 that leads to the highest lowest bound among the other methods.

In Chapter 6, the sub-optimal spectrum and power allocation (sOSPA) method has also been proposed to maximise the performance of the simplified HetNet. By using a local search algorithm and a penalty function method, the proposed method approximates the maximum achievable capacity through the power allocation for each subchannel, allocating less power at the violated subchannels and avoiding subchannels that have lower SINR than a threshold. Using the numerical iterations and setting the critical point escaping procedure based on some constraint functions, the maximum achievable results are approached by simultaneously considering channel gain and inter-cell interference with a fast rate of convergence. System performance of the proposed method was evaluated by calculating the average sum rate of HetNet with various user numbers. Then this system performance was analysed and compared with the other conventional methods, i.e. EPA, iterative water-filling (IWF) and SSA. The results showed that the sOSPA method outperforms the other methods mentioned above.

7.2 Key Findings

There are some findings obtained in the research. This section will cover some above findings based on the Chapter they are discussed.
SSCIM1: This proposed method has been discussed in Chapter 4. The key findings are:

- For the allocated spectra, the SSCIM1 method with the appropriate selection of the macrocell SINR threshold γ_{th}^{M} and the resource allocation threshold φ can improve the performance of each occupied subcarrier in HetNet if compared to NIM and IRB-CIM. However, these results do not represent the overall performance of HetNet, in which the total spectrum bandwidth can be allocated to SSCIM1 is less than NIM and IRB-CIM. It leads to the total capacity of HetNet using SSCIM1 is less than the NIM and IRB-CIM methods.

- When the same spectrum bandwidth is allocated to small cells, the SSCIM1 method achieves the better capacity than NIM and IRB-CIM methods. However, the results are penalised by the performance loss at the macrocell.

- As the total transmission power is limited, then the wider spectra occupied by the network will result in the less maximum transmission power per occupied subcarrier and the less potency to interfere to the adjacent cellular networks.

SSCIM2, 3, 4: These proposed methods have been discussed in Chapter 5. The key findings are as follows:

- For power allocation at the multiple Gaussian subchannel environments of the macrocell network, the WF technique of the new SSCIM outperforms the EPA technique of SSCIM1. When the channel state information is available, the WF technique can allocate the transmission power and frequency spectrum optimally in multiple Gaussian subchannel environments (Goldsmith, 2005).

- In the low inter-cell interference environment, such as an indoor small cell, the EPA technique outperforms the WF and the OOPA techniques for the overall areas. However, for cell-edge areas, WF outperforms OOPA and EPA.

- The proper selection of the small cell SINR threshold γ_{th}^{S} in the OOPA technique can improve the cell-edge performance of small cells. It results in the highest value of the lowest bound of the indoor small cells performance.

sOSPA: This proposed method has been discussed in Chapter 6. The key findings are:

- For all methods, the higher number of users followed by the highest sub-channel gain selection for the selected users leads to the higher capacity of HetNet. This finding is linear to the concept of multiuser diversity (Knopp and Humblet, 1995). In multiuser diversity, a capacity increase over a perfectly power-controlled (Gaussian) channel can be achieved when the number of users is large with only one user occupies the radio spectrum at a certain time and more power will be allocated to the users when their channels are good.

- In the strong inter-cell interference environment, such as in outdoor and nearby HetNet deployment, the proper SINR threshold of sOSPA can result in increased capacity of HetNet. However, in the low inter-cell interference environment, such as in indoor and far away small cell deployments, the higher SINR threshold leads to the lower capacity of HetNet.

- The sOSPA method with the right SINR threshold achieves a higher capacity of HetNet than IWF, EPA, and SSA methods for the strong interference environment.

- The SSA method, which allocates the best users channel gain for each subcarrier, the portion of 17% of total spectrum for the macrocell and transmission power is uniformly distributed, has a higher capacity of HetNet than the EPA method for a small number of users.

- Near optimum power allocation that leads to near optimum capacity in the strong inter-cell interference condition is achieved by limiting transmission power for spectrum sharing and avoiding low gain subcarriers. The result is linear to the concept of frequency reuse (Rappaport, 2002). In frequency reuse, the same (group of) channels can be reused to cover different areas separated each other. Moreover, that concept keeps interference levels within tolerable limits by limiting the coverage area to within the cell boundaries.

7.3 Future Works

This thesis covers a specified area of interference mitigation in the OFDMA-based heterogeneous cellular network. It has opened some paths for possible extension and future works.

1. This thesis has investigated research questions using an approach to simulation and numerical analysis. Both approaches approximate the optimum capacity and validate the different approach. Mathematical analysis can be done for the investigated research.

2. There is an FCC recommendation for interference temperature that limits the interference power in a particular frequency band and a certain geographical area. Additionally, the cognitive radio concept also considers predictive modelling to predict the future channel condition, noise floor and traffic statistics that is referred to deal with spectrum holes. These methods can be considered to improve the system capacity of HetNet.

3. There are some researches concerning interference modelling as well as network deployments in HetNet environments based on stochastic geometry, which is the study of random spatial patterns. By using the proper approach, the stochastic geometry is expected to be able to represent the HetNet environments better than the current model that uses a uniform distribution.

4. The thesis models the single HetNet consisting of one macrocell and some underlaying small cells. In the real system, the macrocell network-tier consists of multiple macro cellular networks, depending on the width of the area they cover. By covering multiple macro cellulars, the HetNet model is more realistic.

Appendix A

Water-Filling Power Allocation

A.1 Flat-fading channels

Let $s[i]$ be a stationary and ergodic stochastic process representing the channel state at time i, which takes values on a finite set S of discrete memoryless channels. Let C_s denote the capacity of a particular channel $s \in S$. $p(s)$ denotes the probability or fraction of time that the channel is in state s. The capacity of this time-varying channel is

$$C = \sum_{s \in S} C_s p(s). \tag{A.1}$$

The capacity of an AWGN channel with average received SNR γ is:

$$C_\gamma = B \log_2(1 + \gamma).$$

Let $p(\gamma) = p(\gamma[i] = \gamma)$ denote the probability distribution of the received SNR. Refer to (A.1), the capacity of the flat-fading channel with transmitter and receiver side information is:

$$C = \int_0^\infty C_\gamma p(\gamma) d\gamma = \int_0^\infty B \log_2(1 + \gamma) p(\gamma) d\gamma. \tag{A.2}$$

Let us now allow the transmission power $P(\gamma)$ to vary with γ, subject to an average power constraint $\bar{P}$:

$$\int_0^\infty P(\gamma) p(\gamma) d\gamma \leq \bar{P}. \tag{A.3}$$

It is expected that the capacity with this average power constraint $\bar{P}$ will be the average capacity given by (A.2) with the power optimally distributed over time.

Thus the maximum fading channel capacity with average power constraint $\bar{P}$ can be defined as (Goldsmith, 2005):

$$C = \max_{P(\gamma):\int P(\gamma)p(\gamma)=\bar{P}} \int_0^\infty B\log_2\left(1+\gamma\frac{P(\gamma)}{\bar{P}}\right)p(\gamma)d\gamma. \tag{A.4}$$

The optimal power allocation $P(\gamma)$ is obtained using the Lagrangian:

$$J(P(\gamma)) = \int_0^\infty B\log_2\left(1+\gamma\frac{P(\gamma)}{\bar{P}}\right)p(\gamma)d\gamma - \lambda\int_0^\infty P(\gamma)p(\gamma)d\gamma. \tag{A.5}$$

Subsequently, the *extreem* point can be obtained by differentiating the Lagrangian and setting to zero value:

$$\frac{\partial J(P(\lambda))}{\partial P(\lambda)} = \left(\left(\frac{B/\ln(2)}{1+\gamma\frac{P(\gamma)}{\bar{P}}}\right)\frac{\gamma}{\bar{P}} - \lambda\right)p(\gamma) = 0. \tag{A.6}$$

Solving for $P(\gamma)/\bar{P}$ as follows:

$$\begin{aligned}\left(\frac{B/\ln(2)}{1+\gamma\frac{P(\gamma)}{\bar{P}}}\right)\frac{\gamma}{\bar{P}} - \lambda &= 0,\\ \left(\frac{B/\ln(2)}{1+\gamma\frac{P(\gamma)}{\bar{P}}}\right) &= \lambda\frac{\bar{P}}{\gamma},\\ \frac{B/\ln(2)}{\lambda\frac{\bar{P}}{\gamma}} &= 1+\gamma\frac{P(\gamma)}{\bar{P}}.\end{aligned}$$

And $P(\gamma)/\bar{P}$ can be obtained:

$$\begin{aligned}\frac{P(\gamma)}{\bar{P}} &= \left(\frac{B/\ln(2)}{\lambda\frac{\bar{P}}{\gamma}} - 1\right)\frac{1}{\gamma},\\ &= \frac{B/\ln(2)}{\lambda\bar{P}} - \frac{1}{\gamma}.\end{aligned}$$

By replacing $(B/\ln(2))/(\lambda\bar{P})$ with $1/\gamma_0$, the equation will be as follows:

$$\frac{P(\gamma)}{\bar{P}} = \frac{1}{\gamma_0} - \frac{1}{\gamma}. \tag{A.7}$$

With the constraint of $P(\gamma) \geq 0$, Equation (A.7) results in the water-filling power allocation for flat-fading channels that maximises (A.2):

$$\frac{P(\gamma)}{\bar{P}} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma}, & \gamma \geq \gamma_0; \\ 0, & \gamma < \gamma_0, \end{cases} \tag{A.8}$$

where γ_0 is the 'cut-off' value that determining the channel state $\gamma[i]$ at the ith time interval will be occupied or not.

A.2 Time-invariant frequency-selective channels

In frequency-selective fading channels, the frequency spectrum consists of some channels of bandwidth B and has frequency response $H(f)$ at channel f. These channels consist of a set of AWGN channels in parallel with SNR $(|H(j)|^2 P_j)/(N_0 B)$ on the jth channel. P_j is the power allocated to the channel-j, subject to $\sum_j P_j \leq P_{tot}$. P_{tot} is the total transmission power.

The capacity of these channels is the sum-rate of all channels with power optimally allocated over all channels (Goldsmith, 2005):

$$C = \sum_{\max Pj: \sum_j P_j \leq P} B \log_2 \left(1 + \frac{|H_j|^2 P_j}{N_0 B}\right). \tag{A.9}$$

This capacity and optimal power allocation are similar to that of a flat-fading channel, with power and rate changing over frequency in a deterministic way instead of over time in a probabilistic way. The optimal power allocation can be found via the Lagrangian technique in the flat-fading case. It leads to the water-filling power allocation for time-invariant frequency-selective channels:

$$\frac{P_j}{P_{tot}} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma}, & \gamma \geq \gamma_0, \\ 0, & \gamma < \gamma_0. \end{cases} \tag{A.10}$$

Appendix B

Frequency Selective Fading

The following list presents the generation steps of the frequency selective fading channel model. For a subframe period, the static channel is assumed. Thus the Doppler shift is 0 for this period. The MathWorks, Inc. (1994 - 2017) discusses a baseband channel model for multipath propagation scenarios.

1. To generate L multi-tap pulse with different time delay τ and different amplitude α. It represents multipath channel response.

   $$\boldsymbol{\sigma}_h = e^{(-\alpha\tau \cdot l)}, \forall l \in \{1, \cdots, L\};$$

2. To normalise the multipath-channel voltage variance, in which the total variance number equals to one:

   $$\widehat{\boldsymbol{\sigma}} = \frac{\boldsymbol{\sigma}_h}{\|\boldsymbol{\sigma}_h\|},$$

   where $\|\cdot\|$ denotes the norm of a vector, which is a quantity describing the length of a vector.

3. To get the channel voltage response that represents Rayleigh fading:

   $$\boldsymbol{h} = \sqrt{\widehat{\boldsymbol{\sigma}}_h} \cdot (1 + j1);$$

4. To get the channel power gain:
   $\boldsymbol{\sigma}_h^2 = \boldsymbol{h} \cdot \boldsymbol{h}^*;$

   where $\mathbf{h}^*$ is the conjugate of the voltage channel response .

5. To get the channel power response in frequency domain ($|\boldsymbol{H}_f|^2$), see Equation (4.11).

Appendix C

Physical Layer Model

The physical layer model used in this work follows 3GPP-LTE physical layer structures and provides some downlink channels. For simplification, only physical layer elements that are closely related to resource allocation process are considered. Thus, the slot structure consists of only one physical signal and two physical channels. They are Reference Signal (RS) (pilot), control-channel (PDCCH) and shared-channel (PDSCH) (Rumney, 2013) as presented on the green-shadowed-cells of Table C.1

Physical Uplink Control Channel (PUCCH), which is needed for transmitting RS received power (RSRP) back to macro-BS for this scenario, is also considered in the simulation, see the green-shadowed-cell on Table C.2. For simplifying the

Table C.1: List of downlink physical signals and physical channels

Physical signals	Physical channels
Primary synchronization signal	Physical downlink shared channel (PDSCH)
Secondary synchronization signal	Physical broadcast channel (PBCH)
Cell-specific reference signal (CRS)	Physical downlink control channel (PDCCH)
MBSFN reference signal	Physical multicast channel (PMCH)
UE-specific reference signal	Physical control format indicator channel (PCFICH)
Positioning reference signal (PRS)	Physical hybrid automatic request (ARQ) indicator channel (PHICH)
Channel state information (CSI) reference signal (CSI-RS)	

Table C.2: List of uplink physical signals and physical channels

Physical signals	Physical channels
Demodulation reference signal (DMRS) for PUSCH/PUCCH	Physical uplink shared channel (PUSCH)
Sounding reference signal (SRS)	Physical uplink control channel (PUCCH)
	Physical random access channel (PRACH)

process, this control-channel only performs a duplication of pilot received power from macro-UTs or small-UTs to the macro-BS or small-BSs. So that, there is no channel distortion as well as data error in this process that affects the accuracy of the received control-information.

The frame structures used in the simulation follow the 3GPP-LTE structure with some adaptations. A downlink frame consists of 20 sub-frames. One sub-frame consists of two time-slots. Moreover, one slot consists of 7 OFDM symbols. Figure C.1 shows the frame structure used in the simulation.

A resource block (RB) is the smallest unit that can be managed for resource allocation in an LTE system. One RB consists of 12 subcarriers in the frequency domain and 7 OFDM symbols in time domain (ETSI, 2015). Figure C.2 presents the RB structure.

It is considered the synchronised signalling and channelling procedures among small cells and the macrocell. To adopt the concept of a cognitive small cell, it needs a modification of the signal and channel structure. For each sub-frame or two slots, the small cell needs to allocate its resources for channel sensing and control signalling. Figure C.3 presents the modified structure of the sub-frame.

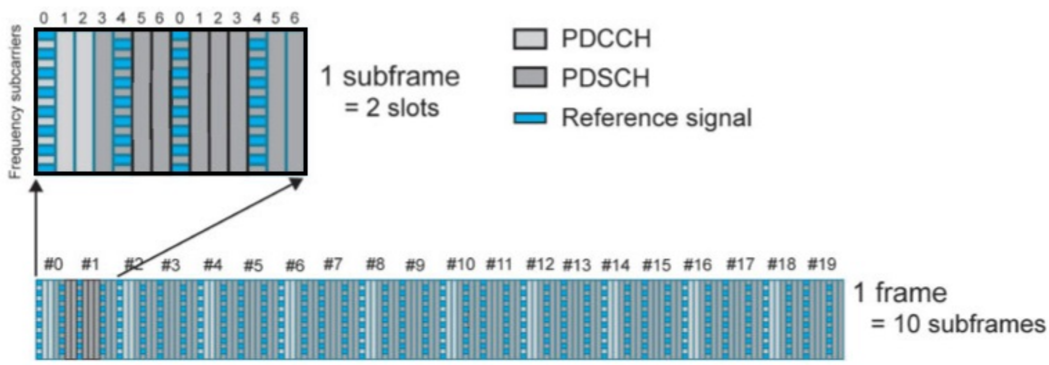


Figure C.1: The simplified LTE frame stucture used in simulation

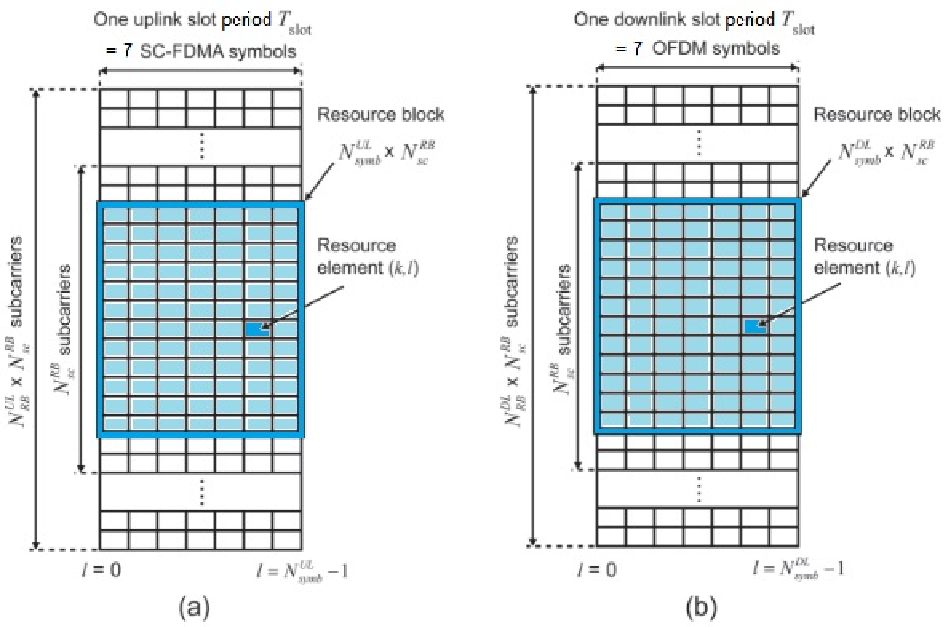


Figure C.2: Resource blocks of 3GPP-LTE for (a) uplink and (b) downlink; adapted from Rumney (2013)

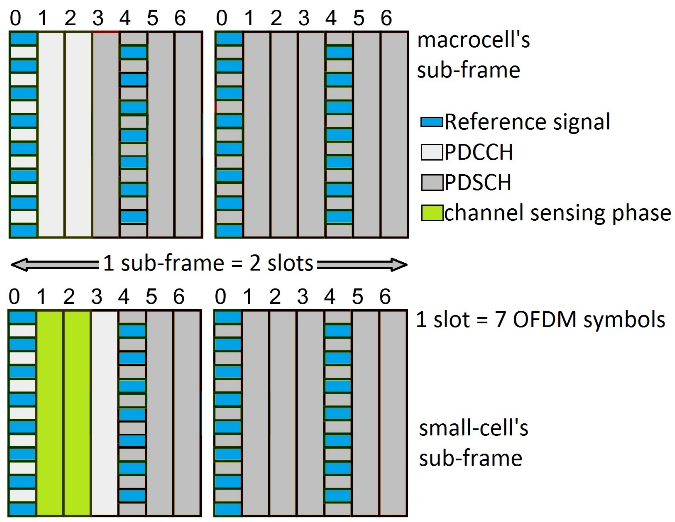


Figure C.3: The model of sub-frames in HetNet used in simulation

There are some assumptions applied to ease the process of the system level simulation as follows. The HetNet system applies frequency duplexing for the downlink and uplink transmission. Then, each UT can differentiate the pilot signal either from the serving BS or from interfering BSs. Thus the UT can calculate the SINR as well as estimate the channel gain of each subcarrier. Moreover, there is no error when each UT send the RSRP back to its serving BS.

For small cells, each small-BS can identify and analyse the control signal from the macro-BS. Thus, the small-BS gets the benefit of obtaining the information of either the idle or the occupied subchannels, which subsequently can be allocated to its users. Then, the small-BS can transmit all required control signal to their UTs for one symbol period, which is a half of the macrocell's period for the same channelling procedure.

References

3GPP (2010), Further advancements for E-UTRA physical layer aspects (Release 9), Technical Report 3GPP TR 36.814 V9.0.0 (2010-03), 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA);, Valbonne - FRANCE.

3GPP (2014), Self-Organizing Networks (SON); Self-healing concepts and requirements (Release 12), Technical Specification 3GPP TS 32.541 V12.0.0 (2014-10), 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Telecommunication management;, Valbonne - FRANCE.

3GPP (2015), Scenarios and requirements for small cell enhancements for E-UTRA and E-UTRAN (Release 13), Technical Report 3GPP TR 36.932 V13.0.0 (2015-12), 3rd Generation Partnership Project; Technical Specification Group Radio Access Network;, Valbonne - FRANCE.

Abdelnasser, A., Hossain, E. and Kim, D. I. (2014), 'Clustering and Resource Allocation for Dense Femtocells in a Two-Tier Cellular OFDMA Network', *Wireless Communications, IEEE Transactions on* **13**(3), 1628–1641.

Akyildiz, I. F., Lee, W.-Y., Vuran, M. C. and Mohanty, S. (2008), 'A Survey on Spectrum Management in Cognitive Radio Networks', *Communications Magazine, IEEE* **46**(4), 40 – 48.

Al-Hourani, A. and Kandeepan, S. (2013), Temporary Cognitive Femtocell Network for Public Safety LTE, *in* 'Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), IEEE 18th International Workshop on', pp. 190 – 195.

Al-Rubaye, S., Al-Dulaimi, A. and Cosmas, J. (2011), 'Cognitive Femtocell', *Vehicular Technology Magazine, IEEE* **6**(1), 44–51.

Alsohaily, A. and Sousa, E. S. (2013), Dynamic Spectrum Access for Small Cells, *in* 'Personal, Indoor and Mobile Radio Communications (PIMRC): Mobile and Wireless Networks, IEEE 24th International Symposium on', pp. 3308 – 3312.

Andargoli, S. and Mohamed-pour, K. (2012), 'Weighted sum throughput maximisation for downlink multicell orthogonal frequency-division multiple access systems by intercell interference limitation', *Communications, IET* **6**(6), 628–637.

Andrews, J. (2005), 'Interference cancellation for cellular systems: a contemporary overview', *Wireless Communications, IEEE* **12**(2), 19–29.

Andrews, J., Claussen, H., Dohler, M., Rangan, S. and Reed, M. (2012), 'Femtocells: Past, present, and future', *Selected Areas in Communications, IEEE Journal on* **30**(3), 497–508.

Andrews, J. G., Buzzi, S., Choi, W., Hanly, S. V., Lozano, A., Soong, A. C. K. and Zhang, J. C. (2014), 'What will 5G be?', *Selected Areas in Communications, IEEE Journal on* **32**(6), 1065 – 1082.

Attar, A., Krishnamurthy, V. and Gharehshiran, O. (2011), 'Interference management using cognitive base-stations for UMTS LTE', *Communications Magazine, IEEE* **49**(8), 152–159.

Barth, U. and Kuehn, E. (2010), 'Self-Organization in 4G Mobile Networks: Motivation and Vision', *Proceedings of the 2010 7th International Symposium on Wireless Communication Systems, ISWCS'10* pp. 731–735.

BeFEMTO (2010), 'BeFEMTO - Broadband Evolved FEMTO Networks', [Online]. [accessed on 03 Nov 2016].
URL: *http://www.ict-befemto.eu/*

Boyd, S. and Vandenberghe, L. (2004), *Convex Optimization*, Berichte über verteilte messysteme, Cambridge University Press, New York, NY.

Brickhouse, R. A. and Rappaport, T. S. (1996), Urban in-building cellular frequency reuse, *in* 'Global Telecommunications Conference, 1996. GLOBECOM '96. 'Communications: The Key to Global Prosperity', Vol. 2, pp. 1192–1196.

Bright, J. and Mavrakis, D. (2012), Satellite backhaul for rural small cells, White Paper, Informa Telecoms & Media, London.

Buehrer, R. M. (2006), *Code Division Multiple Access (CDMA)*, first edn, Morgan & Claypool Publishers, United States.

Capozzi, F., Piro, G., Grieco, L., Boggia, G. and Camarda, P. (2013), 'Downlink Packet Scheduling in LTE Cellular Networks: Key Design Issues and a Survey', *Communications Surveys & Tutorials, IEEE* **15**(2), 678–700.

Chandrasekhar, V. and Andrews, J. (2009*a*), 'Spectrum allocation in tiered cellular networks', *Communications, IEEE Transactions on* **57**(10), 3059–3068.

Chandrasekhar, V. and Andrews, J. (2009*b*), 'Uplink capacity and interference avoidance for two-tier femtocell networks', *Wireless Communications, IEEE Transactions on* **8**(7), 3498–3509.

Chandrasekhar, V., Andrews, J., Muharemovict, T., Shen, Z. and Gatherer, A. (2009), 'Power Control in Two-Tier Femtocell Networks', *Wireless Communications, IEEE Transactions on* **8**(8), 4316–4328.

Cheung, W. C., Quek, T. and Kountouris, M. (2012), 'Throughput Optimization, Spectrum Allocation, and Access Control in Two-Tier Femtocell Networks', *Selected Areas in Communications, IEEE Journal on* **30**(3), 561–574.

Chiang, M., Hande, P., Lan, T. and Tan, C. W. (2008), *Power Control in Wireless Cellular Networks*, now Publishers Inc., Hanover, Massachusetts.

Choi, S. and Park, S. (2015), Performance analysis of various co-existence methods with Wi-Fi in unlicensed bands, *in* 'Information and Communication Technology Convergence (ICTC), 2015 International Conference on', IEEE.

Chrysanthou, C. and Bertoni, H. L. (1990), 'Variability of sector averaged signals for UHF propagation in cities', *Vehicular Technology, IEEE Transactions on* **39**(4), 352–358.

Claussen, H. and Calin, D. (2009), Macrocell offloading benefits in joint macro- and femtocell deployments, *in* 'Personal, Indoor and Mobile Radio Communications (PIMRC), 2009 IEEE 20th International Symposium on', pp. 350–354.

Claussen, H., Ho, L. T. and Samuel, L. G. (2008), 'An overview of the femtocell concept', *Bell Labs Technical Journal* **13**(1), 221–245.

Das, S., Chandhar, P., Mitra, S. and Ghosh, P. (2011), Issues in Femtocell Deployments in Broadband OFDMA Networks: 3GPP-LTE a Case Study, *in* 'Vehicular Technology Conference (VTC Fall), 2011 IEEE', pp. 1–5.

Drucker, E. (1988), Development and application of a cellular repeater, *in* 'Proc. IEEE Vehicular Technology Conference', pp. 321–325.

Elsawy, H. and Hossain, E. (2013), On Cognitive Small Cells in Two-Tier Heterogeneous Networks, *in* '9th International Workshop on Spatial Stochastic Models for Wireless Networks', pp. 75–82.

Elsawy, H., Hossain, E. and Kim, D. (2013), 'HetNets with Cognitive Small Cells: User Offloading and Distributed Channel Access Techniques', *Communications Magazine, IEEE* **51**(6), 28–36.

Ericsson (2014), Ericsson Mobility Report: On the Pulse of the Networked Society, Report June 2014, Ericsson, Stockholm, Sweden.

ETSI (2012), LTE; Evolved Universal Terrestrial Radio Access Network (E-UTRAN); X2 Application Protocol (X2AP) , Technical Specification ETSI TS 136 423 V10.4.0 (2012-01), European Telecommunications Standards Institute, Cedex - FRANCE.

ETSI (2015), LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (3GPP TS 36.211 version 12.5.0 Release 12), Technical Specification ETSI TS 36.211 version 12.5.0, European Telecommunications Standards Institute, Cedex - FRANCE.

Exact Ventures (2012), Rethinking In-building Wireless. The 'Consumerization' of IT and the Emergence of the Mobile Enterprise Enabled by Mobile Operator Managed Services: The Emergence of Enterprise Small Cells Table of Contents, Report October 2012, Exact Ventures, Inc. [Verified 21 July 2016].
URL: *http://www.spidercloud.com/assets/pdfs/ExactVentures0912_0.pdf*

Fan, Z. and Sun, Y. (2010), Access and Handover Management for Femtocell Systems, *in* 'Vehicular Technology Conference (VTC 2010-Spring), 2010 IEEE 71st', pp. 1–5.

Fantacci, R., Marabissi, D., Tarchi, D. and Habib, I. I. (2009), 'Adaptive Modulation and Coding Techniques for OFDMA Systems', *Wireless Communications, IEEE Transactions on* **8**(9).

FCC (2002), Spectrum Policy Task Force, Report ET Docket No. 02- 135, Federal Communications Commission, Spectrum Policy Task Force Working Groups, United States.

FCC (2003), Notice of Proposed Rule Making and Order, Technical Report FCC 03-322, Federal Communications Commission, United States.

Fehske, A. J., Viering, I., Voigt, J., Sartori, C., Redana, S. and Fettweis, G. P. (2014), 'Small-Cell Self-Organizing Wireless Networks', *Proceeding of the IEEE* **102**(3), 334 – 350.

Femto Forum (2010), Interference Management in OFDMA Femtocells, Technical Report March 2010, Femto Forum,, PO Box 23 GL11 5WA UK. [Verified 16 June 2012].
URL: *www.femtoforum.org*

Fette, B. A., ed. (2006), *Cognitive Radio Technology*, First edn, NEWNES, United Kingdom.

Foschini, G. and Miljanic, Z. (1993), 'A simple distributed autonomous power control algorithm and its convergence', *Vehicular Technology, IEEE Transactions on* **42**(4), 641–646.

Goldsmith, A. (2005), *Wireless Communications*, Cambridge University Press, New York, NY.

Goldsmith, A., Jafar, S., Maric, I. and Srinivasa, S. (2009), 'Breaking Spectrum Gridlock With Cognitive Radios: An Information Theoretic Perspective', *Proceedings of the IEEE* **97**(5), 894–914.

Greenstein, L., Erceg, V., Yeh, Y. and Clark, M. (1997), 'A new path-gain/delay-spread propagation model for digital cellular channels', *Vehicular Technology, IEEE Transactions on* **46**(2), 477–485.

Guo, W. and Wang, S. (2012), 'Interference-Aware Self-Deploying Femto-Cell', *Wireless Communications Letters, IEEE* **1**(6), 609–612.

Gur, G., Bayhan, S. and Alagoz, F. (2010), 'Cognitive femtocell networks: an overlay architecture for localized dynamic spectrum access [Dynamic Spectrum Management]', *Wireless Communications, IEEE* **17**(4), 62–70.

Han, Z. and Liu, K. J. R. (2008), *Resource Allocation for Wireless Networks: Basics, Techniques, and Applications*, Cambridge University Press, New York, NY.

Hasan, Z., Boostanimehr, H. and Bhargava, V. K. (2011), 'Green cellular networks: A survey, some research issues and challenges', *Communications Surveys Tutorials, IEEE* **13**(4), 524–540.

Haykin, S. (2005), 'Cognitive Radio: Brain-Empowered Wireless Communications', *Selected Areas in Communications, IEEE Journal on* **23**(2), 201 – 220.

Hossain, E., Rasti, M., Tabassum, H. and Abdelnasser, A. (2014), 'Evolution toward 5G multi-tier cellular wireless networks: An interference management perspective', *Wireless Communications, IEEE* **21**(3), 118–127.

Hozo, S. P., Djulbegovic, B. and Hozo, I. (2005), 'Estimating the mean and variance from the median, range, and the size of a sample', *BMC Medical Research Methodology* **5**(13), 1–10.

Hu, P., Ye, J., Zhang, F., Deng, S., Wang, C. and Wang, W. (2012), Downlink Resource Management Based on Cross-Cognition and Graph Coloring in Cognitive Radio Femtocell Networks, *in* 'Vehicular Technology Conference (VTC Fall), 2012 IEEE', pp. 1 – 5.

Huang, J., Subramanian, V., Agrawal, R. and Berry, R. (2009), 'Downlink scheduling and resource allocation for OFDM systems', *Wireless Communications, IEEE Transactions on* **8**(1), 288–296.

Huang, L., Zhu, G. and Du, X. (2013), 'Cognitive femtocell networks: an opportunistic spectrum access for future indoor wireless coverage', *Wireless Communications, IEEE* **20**(2), 44–51.

Ikuno, J., Wrulich, M. and Rupp, M. (2010), System Level Simulation of LTE Networks, *in* 'Vehicular Technology Conference (VTC 2010-Spring), 2010 IEEE 71st', pp. 1–5.

Irmer, R., Droste, H., Marsch, P., Grieger, M., Fettweis, G., Brueck, S., Mayer, H.-P., Thiele, L. and Jungnickel, V. (2011), 'Coordinated multipoint: Concepts, performance, and field trial results', *Communications Magazine, IEEE* **49**(2), 102–111.

ITU-R (2011), Impact of industrial, scientific and medical (ISM) equipment on radiocommunication services (Spectrum MaManagement Series), Report ITU-R SM.2180, International Telecommunication Union-Radiocommunication Sector, Geneva, Switzerland.

Iyer, R., Parker, J. and Sood, P. (1990), Intelligent networking for digital cellular systems and the wireless world, *in* 'Global Telecommunications Conference, 1990, and Exhibition. 'Communications: Connecting the Future', GLOBECOM '90.', Vol. 1, IEEE, pp. 475–479.

Jamalipour, A., Wada, T. and Yamazato, T. (2005), 'A tutorial on multiple access technologies for beyond 3G mobile networks', *Communications Magazine, IEEE* **43**(2), 110–117.

Jang, J. and Lee, K. B. (2003), 'Transmit power adaptation for multiuser OFDM systems', *Selected Areas in Communications, IEEE Journal on* **21**(2), 171 – 178.

Jo, H.-S., Xia, P. and Andrews, J. G. (2012), 'Open, closed, and shared access femtocells in the downlink', *Wireless Communications and Networking, EURASIP Journal on* **2012**(1).

Jouini, W., Moy, C. and Palicot, J. (2012), 'Decision making for cognitive radio equipment: analysis of the first 10 years of exploration.', *Wireless Communications and Networking, EURASIP Journal on* **26**.

Kaimaletu, S., Krishnan, R., Kalyani, S., Akhtar, N. and Ramamurthi, B. (2011), Cognitive interference management in heterogeneous femto-macro cell networks, *in* 'Communications (ICC), 2011 IEEE International Conference on', pp. 1–6.

Khan, F. (2009), *LTE for 4G Mobile Broadband: Air Interface Technologies and Performance*, Cambridge University Press, New York, NY.

Khoshkholgh, M. G., Navaie, K. and Yanikomeroglu, H. (2010*a*), 'Achievable Capacity in Hybrid DS-CDMA/OFDM Spectrum-Sharing', *Mobile Computing, IEEE Transactions on* **9**(6), 765–777.

Khoshkholgh, M., Navaie, K. and Yanikomeroglu, H. (2010*b*), 'Access Strategies for Spectrum Sharing in Fading Environment: Overlay, Underlay, and Mixed', *Mobile Computing, IEEE Transactions on* **9**(12), 1780–1793.

Knopp, R. and Humblet, P. (1995), Information capacity and power control in single-cell multiuser communications, *in* 'Communications, 1995. ICC '95 Seattle, 'Gateway to Globalization', 1995 IEEE International Conference on', Vol. 1, pp. 331–335 vol.1.

Kong, Z., Kwok, Y.-K. and Wang, J. (2009), 'A Low-Complexity QoS-Aware Proportional Fair Multicarrier Scheduling Algorithm for OFDM Systems', *Vehicular Technology, IEEE Transactions on* **58**(5), 2225–2235.

Kosta, C., Hunt, B., Quddus, A. and Tafazolli, R. (2013), 'On Interference Avoidance Through Inter-Cell Interference Coordination (ICIC) Based on OFDMA Mobile Systems', *Communications Surveys & Tutorials, IEEE* **15**(3), 973–995.

Kpojime, H. O. and Safdar, G. A. (2015), 'Interference Mitigation in Cognitive-Radio-Based Femtocells', *Communications Surveys & Tutorials, IEEE* **17**(3), 1511 – 1534.

Kwan, R., Leung, C. and Zhang, J. (2009), 'Proportional Fair Multiuser Scheduling in LTE', *Signal Processing Letters, IEEE* **16**(6), 461–464.

Lee, T., Yoon, J., Lee, T. and Shin, J. (2010), Resource allocation analysis in OFDMA femtocells using Fractional Frequency Reuse, *in* 'Personal Indoor and Mobile Radio Communications (PIMRC), 2010 IEEE 21st International Symposium on', pp. 1224–1229.

Lescuyer, P. and Lucidarme, T. (2008), *Evolved Packet System (EPS): The LTE and SAE Evolution of 3G UMTS*, John Wiley & Sons, Ltd., Chichester, West Sussex, England.

Li, Y. Y. (2010), Cognitive Interference Management in 4G Autonomous Femtocells, PhD Thesis, Department of Electrical and Computer Engineering, University of Toronto.

Lopez-Perez, D., Valcarce, A., de la Roche, G. and Zhang, J. (2009), 'OFDMA femtocells: A roadmap on interference avoidance', *Communications Magazine, IEEE* **47**(9), 41–48.

Mehanna, O. (2013), Sharing vs. splitting spectrum in OFDMA femtocell networks, *in* 'Acoustics, Speech and Signal Processing (ICASSP), 2013 IEEE International Conference on', pp. 4824–4828.

Mitola, J. (1999), Cognitive radio for flexible mobile multimedia communications, *in* 'Mobile Multimedia Communications, 1999 (MoMuC '99), IEEE International Workshop on', pp. 3–10.

Mitola, J. (2000), Cognitive radio: An integrated agent architecture for software defined radio, PhD Thesis, Royal Inst of Technology (KTH).

Mitola, J. (2009), 'Cognitive Radio Architecture Evolution', *Proceedings of the IEEE* **97**(4), 626–641.

Nakamura, T., Nagata, S., Benjebbour, A., Kishiyama, Y., Hai, T., Xiaodong, S., Ning, Y. and Nan, L. (2013), 'Trends in Small Cell Enhancements in LTE Advanced', *Communications Magazine, IEEE* **51**(2), 98–105.

Nguyen, K. D., Nguyen, H. N., Morino, H. and S Sasase, I. S. (2014), 'Uplink Channel Allocation Scheme and QoS Management Mechanism for Cognitive Cellular- Femtocell Networks', *Communication Networks and Information Security, International Journal of (IJCNIS)* **6**(1), 62–69.

Nguyen, T. M. and Le, L. B. (2014), Cognitive Spectrum Access in Femtocell Networks Exploiting Nearest Interferer Information, *in* 'IEEE Wireless Communications and Networking Conference (WCNC)', pp. 1132 – 1137.

Nguyen, T. V. and Baccelli, F. (2010), A Probabilistic Model of Carrier Sensing Based Cognitive Radio, *in* 'New Frontiers in Dynamic Spectrum Access Networks (DySPAN), IEEE Symposium on', pp. 1 – 12.

Olofsson, H., Naslund, J. and Skold, A. (1995), Interference diversity gain in frequency hopping gsm, *in* 'Vehicular Technology Conference, 1995 IEEE 45th', Vol. 1, pp. 102–106 vol.1.

Pantisano, F. (2013), Cooperative Interference and Radio Resource Management in Self-Organizing Small Cell Networks, PhD Thesis, University of Oulu Graduate School; University of Oulu, Faculty of Technology, Department of Communications Engineering; Centre for Wireless Communications.

Pennanen, H., Christopoulos, D., Chatzinotas, S. and Ottersten, B. (2016), Distributed coordinated beamforming for multi-cell multigroup multicast systems, *in* '2016 IEEE International Conference on Communications (ICC)', pp. 1–7.

Primak;, S., Kontorovich;, V. and Lyandres, V. (2004), *Stochastic Methods and Their Applications to Communications Stochastic Differential Equations Approach*, John Wiley & Sons, Inc., Chichester, West Sussex, England.

Quinn, E. (1986), The cell enhancer, *in* 'Proc. IEEE Vehicular Technology Conference', Vol. 36, pp. 77–83.

Rahman, M. and Yanikomeroglu, H. (2010), 'Enhancing cell-edge performance: a downlink dynamic interference avoidance scheme with inter-cell coordination', *Wireless Communications, IEEE Transactions on* **9**(4), 1414 –1425.

Rappaport, T. (2002), *Wireless Communications: Principles and Practice*, Prentice Hall communications engineering and emerging technologies series, Prentice Hall PTR, Upper Saddle River, New Jersey.

Roser, M. (2017), 'Human Height', Published online at OurWorldInData.org. [accessed on 14 Jan 2017].
URL: *https://ourworldindata.org/human-height/*

Rumney, M. (2013), *LTE and the Evolution to 4G Wireless: Design and Measurement Challenges*, John Wiley & Sons, Ltd., Chichester, West Sussex, England.

Ruszczyński, A. (2006), *Nonlinear Optimization*, number v. 13 *in* 'Nonlinear optimization', Princeton University Press, Princeton, New Jersey.

Saquib, N., Hossain, E., Le, L. B. and Kim, D. I. (2012), 'Interference management in OFDMA femtocell networks: issues and approaches', *Wireless Communications, IEEE* **19**(3), 86–95.

Shami, A., Maier, M. and Assi, C., eds (2010), *Broadband Access Networks: Technologies and Deployments*, Optical Networks, First edn, Springer US.

Sharma, A., Roy, A., Ghosal, S., Chaki, R. and Bhattacharya, U. (2012), Load balancing in cellular network: A review, *in* 'Computing Communication Networking Technologies (ICCCNT), 2012 Third International Conference on', pp. 1–5.

Shen, Z., Andrews, J. and Evans, B. (2005), 'Adaptive resource allocation in multiuser OFDM systems with proportional rate constraints', *Wireless Communications, IEEE Transactions on* **4**(6), 2726 – 2737.

Siswanto, D., Zhang, L. and Navaie, K. (2014), Spectrum splitting-based cognitive interference management in two-tier LTE networks, *in* '2014 11th International Symposium on Wireless Communications Systems (ISWCS)', pp. 613–617.

Siswanto, D., Zhang, L., Navaie, K. and Deepak (2016), Weighted Sum Throughput Maximization in Heterogeneous OFDMA Networks, *in* '2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)', pp. 1–5.

Small Cell Forum (2012), Small cells - what's the big idea? Femtocells are expanding beyond the home, Technical Report February 2012, Small Cell Forum Ltd, PO Box 23, GL11 5WA UK.

Small Cell Forum (2013), Rural small cell market size, business case, challenges & solutions, White Paper 047.07.01 (Release 7.0), Small Cell Forum Ltd, PO Box 23, GL11 5WA UK.

Song, M., Xin, C., Zhao, Y. and Cheng, X. (2012), 'Dynamic spectrum access: from cognitive radio to network radio', *Wireless Communications, IEEE* **19**(1), 23–29.

Stamatiou, K. and Proakis, J. (2005), A performance analysis of coded frequency-hopped OFDMA [cellular system], *in* 'Wireless Communications and Networking Conference (WCNC), 2005 IEEE', Vol. 2, pp. 1132–1137 Vol. 2.

Stiakogiannakis, I. and Kaklamani, D. (2009), IEEE802.16e - WiMAX: Performance Analysis of Partial and Full Usage of Subchannels under Fractional Frequency Reuse, *in* 'Wireless Technology Conference, 2009. EuWIT 2009. European', pp. 41–44.

Stocker, A. C. (1984), 'Small-cell mobile phone systems', *Vehicular Technology, IEEE Transactions on* **33**(4), 269–275.

Strekalovsky, A. S. and Yanulevich, M. V. (2008), 'Global search in the optimal control problem with a terminal objective functional represented as the difference of two convex functions', *Computational Mathematics and Mathematical Physics* **48**(7), 1119–1132.

Strekalovsky, A. S. and Yanulevich, M. V. (2013), 'Global search in a noncovex optimal control problem', *Computer and Systems Sciences, International Journal of* **52**(6), 893–908.

The MathWorks, Inc. (1994 - 2017), 'Fading Channels', [Online]. [accessed on 24 February 2017].
URL: *https://www.mathworks.com*

Tseng, F.-H., Chou, L.-D., Chao, H.-C. and Wang, J. (2015), 'Ultra-Dense Small Cell Planning Using Cognitive Radio Network toward 5G', *Wireless Communications, IEEE* **22**(6), 76–83.

Van Veen, B. and Buckley, K. (1988), 'Beamforming: a versatile approach to spatial filtering', *ASSP Magazine, IEEE* **5**(2), 4–24.

Verhulst, D., Mouly, M. and Szpirglas, J. (1984), 'Slow frequency hopping multiple access for digital cellular radiotelephone', *Selected Areas in Communications, IEEE Journal on* **2**(4), 563–574.

Viavi Solution (2015), Optimizing Small Cells and the Heterogeneous Network (HetNet), White Paper, Viavi Solutions Inc.
URL: *https://www.viavisolutions.com*

Yatt, B. D. (1998), *Cracking the Codes: An Architect's Guide to Building Regulations*, John Wiley & Sons, Inc., Chichester, West Sussex, England.

Yu, W., Ginis, G. and Cioffi, J. (2002), 'Distributed multiuser power control for digital subscriber lines', *Selected Areas in Communications, IEEE Journal on* **20**(5), 1105–1115.

Yucek, T. and Arslan, H. (2009), 'A survey of spectrum sensing algorithms for cognitive radio applications', *Communications Surveys & Tutorials, IEEE* **11**(1), 116–130.

Zahir, T., Arshad, K., Nakata, A. and Moessner, K. (2013), 'Interference Management in Femtocells', *Communications Surveys & Tutorials, IEEE* **15**(1), 293–311.

Zhang, C., Chen, X., Yin, H. and Wei, G. (2012), Two-dimensional shadow fading modeling on system level, *in* 'Personal Indoor and Mobile Radio Communications (PIMRC), 2012 IEEE 23rd International Symposium on', pp. 1671–1676.

Zhang, H., Chu, X., Guo, W. and Wang, S. (2015), 'Coexistence of Wi-Fi and Heterogeneous Small Cell Networks Sharing Unlicensed Spectrum', *Communications Magazine, IEEE* **53**(3), 158 – 164.

Zhang, J. and de la Roche, G. (2011), *Femtocells: Technologies and Deployment.*, Technology & Engineering, John Wiley & Sons, Ltd., Chichester, West Sussex, England.

Zhao, Q. and Sadler, B. M. (2007), 'A Survey of Dynamic Spectrum Access', *Signal Processing Magazine, IEEE* **24**(3), 79–89.

Zhou, Z., Guo, D. and Honig, M. L. (2016), Allocation of licensed and unlicensed spectrum in heterogeneous networks, *in* '2016 Australian Communications Theory Workshop (AusCTW)', pp. 59–64.