QoS-aware Radio Resource Management for Spectrum Sharing Radio Networks

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To all the people I love

Abstract

The trend in multimedia wireless telecommunication is to service diversification with a high Quality of Service (QoS) requirement. However, the types of service that can be offered are severely constrained by the availability of radio resources, especially the spectrum. A proper radio resource management mechanism targeting QoS requirements would undoubtedly be valuable for wireless multimedia transmission.

The work in this thesis investigates the radio resource allocation problem in a cellular Orthogonal Frequency Division Multiple Access (OFDMA) network taking the users' QoS requirement and priority over the resource into consideration. The goal of the research is to investigate QoS satisfaction, user fairness and system throughput through radio resource allocation management. It does this in the context of a Spectrum Sharing Radio (SSR) network where users from different carriers can share spectrum; an extreme example of such a network is Cognitive Radio (CR).

The thesis proposes a QoS-aware and Priority-aware (QP) proportional-fair subcarrier (SC) allocation scheme to achieve QoS satisfaction for the maximum number of users under the premise of a policy that aims to provide a guarantee for priority traffic. The allocation is achieved in a distributed manner making use of non-cooperative game theory. This is unlike most of the work in the literature that aims to maximise the overall capacity.

The thesis further extends the QP algorithm into a three-layer architecture with a reactive behaviour to enable macro adjustment of the system performance to deal with network overload and mobile users. Modularization provides high efficiency and low complexity of design, extension and maintenance. The simulation results show robustness and reliability of the architecture.

Acknowledgement

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List of Abbreviations

AWGN	Addictive White Gaussian Noise
BS	Base Station
BWRC	Berkeley Wireless Research Centre
CPE	Customer Premise Equipment
CQI	Channel Quality Information
CQSR	Combined QoS Satisfaction Ratio
CR	Cognitive Radio
CR-BS	Cognitive Radio Base Station
CR-CPE	Cognitive Radio Customer Premise Equipment
DAB	Digital Audio Broadcasting
DCT	Discrete Cosine Transformation
DFT	Discrete Fourier Transform
DL	Downlink
DRA-NC	Dynamic Resource Allocation with No Coordination
DRA-LC	Dynamic Resource Allocation with Limited Coordination
DRA_FC	Dynamic Resource Allocation with Full Coordination
DSA	Dynamic Spectrum Access
DSO	Digital Switchover
EIRP	Equivalent Isotropic Radiated Power
FCC	Federal Communications Commission
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
FM	Frequency Modulation
GOP	Group of Pictures

HDTV	High-Definition TV
ICI	Inter Cell Interference
IDFT	Inverse Discrete Fourier Transform
ISI	Inter Symbol Interference
ISM	Industrial, Scientific and Medical (frequency band)
IWF	Iterative Water Filling
LTE	Long Term Evolution
MAC	Media Access Control
Max C/I	Maximum Carrier to Interference ratio
MB	MacroBlock
MPEG	Moving Picture Experts Group
MS	Mobile Station
NE	Nash Equilibrium
NO	Network Operator
Ofcom	Office of Communications
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSA	Opportunistic Spectrum Access
PDA	Personal Digital Assistant
P/S	Parallel to Serial converter
PSNR	Peak Signal to Noise Ratio
PU	Primary User
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QP	QoS-aware and Priority-aware
QP-NC	QP algorithm with No user Compromise
QP-C	QP algorithm with user Compromise

QSR	QoS Satisfaction Ratio
QP	Quantisation Parameter
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RR	Round Robin
RRM	Radio Resource Management
SC	Subcarrier
SDR	Software Defined Radio
SINR	Signal to Interference and Noise Ratio
SM	Spectrum Manager
S/P	Serial to Parallel converter
SSR	Spectrum Sharing Radio
SU	Secondary User
TDMA	Time Division Multiple Access
UHF	Ultra High Frequency
UL	Uplink
UNII	Unlicensed National Information Infrastructure
USR	Used SC Ratio
UWB	Ultra Wide Band
VDSL	Very-high-speed Digital Subscriber Line
VHF	Very High Frequency
VLC	Variable Length Coding
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WRAN	Wireless Regional Area Networks

List of Parameters

$\mathbf{A}$	The action space of the game G
A	A factor in the path loss model
A_n	a set of actions of player n
A_{ni}	The number of SCs of user i of player n
a_n	The action of player n
a_c	The autocorrelation of shadow fading
a_{ni}^m	The SC allocation indicator of user i of player n on SC m
B	A factor in the path loss model
B_m	The bandwidth of a SC
β	The upper bound factor for SC release module
C	A factor in the path loss model
C_1	The guard parameter of bitrate
d	The distance between transmitter and receiver
d_{ni}^n	the distance between user i and player n
d_c	The de-correlation distance between two locations
F	The fairness index
f_c	The carrier frequency
G	The game
G_1	The first group of users with the same priority
G_2	The second group of users with the same priority
$h_{ni}^n(m)$	The channel gain between user i of cell n to its BS on SC m
h_b	The height of the BS

h_m	The height of the user device
$\mathbf{I}_{ns}$	The user set of sector s of cell n
$\mathbf{I}_n$	The user set of cell n
$\mathbf{I}_{ns}^u$	unallocated user set of sector s of cell n
$\mathbf{I}_n^Q$	The qualified user set of cell n
$\mathbf{I}_n^{unQ}$	The unqualified user set of cell n
I_n	The number of user in cell n
i	The user ID
j	The user ID
$\overline{L_p}$	The path loss in dB
L_p	The path loss with shadow fading in dB
L_p'	The path loss after movement
$\mathbf{M}$	The SC set of a cell
$\mathbf{M}_{ns}$	The SC set of sector s of cell n
$\mathbf{M}_{ni}$	The SC set of user i of cell n
$\mathbf{M}_n^{unQ}$	The SC set of $\mathbf{I}_n^{unQ}$
$\mathbf{M}_{ns}^{unQ}$	The SC set of $\mathbf{I}_{ns}^{unQ}$
$\mathbf{M}_n^Q$	The SC set of $\mathbf{I}_n^Q$
$\mathbf{M}_{ns}^u$	unassigned SC set of sector s of cell n
m	The SC ID
$\mathbf{N}$	The player set of game G
N	The number of players
N_0^m	The white noise on SC m
n	The player ID
P_{max}	The maximum transmit power

p	The transmit power on one SC
p_{ni}^m	Transmit power of user i of cell n on SC m
R_{th1}	The threshold of QSR of user compromise module
R_{th2}	The threshold of QSR of auto-run module
r	The system overall throughput
r_n	The overall throughput of player n
r_{ni}	The bitrate of a user i of player n
r_{ni}^{grd}	the guard bitrate of a user i of player n
r_{ni}^{req}	the required bitrate of a user i of player n
r_{ni}^{cmp}	The compromised bitrate of a user i of player n
$SINR_n^m$	The SINR of player n on SC m
$SINR_{ni}^m$	The SINR of user i of cell n on SC m
s	The sector ID
T_s	The sample interval/time
T	The timer for SC reallocation
T_{max}	The maximum time
t	The timer for re-run mechanism
τ	The time when algorithm was last run
τ_{max}	The maximum time between two runs of the QP algorithm
$\mathbf{U}$	The utility function of game G
U_n	The utility function of player n
v	Velocity of mobile
X_σ	The shadow fading in dB
θ_{ni}	The correction factor in SC reallocation module
σ	The standard deviation of shadow fading

Chapter 1 Introduction

1.1 Introduction/Motivation

Current situation: spectrum shortage for cellular network due to demand

Nowadays, the spectrum for cellular network is facing significant scarcity because the development of network technologies is not keeping up with the rapid growth in number of users and in new services like multimedia services. According to predictions from the UK Office of Communications (Ofcom), the main applications driving the growth for cellular will be video streaming and downloads and demands for machine-machine communication [1]. As multimedia services gain greater importance, the requirement for QoS is also getting more attention.

Current situation: spectrum shortage due to inefficient utilization

The current static spectrum allocation scheme cannot provide efficient utilization of the spectrum: the unlicensed bands (e.g. ISM and UNII bands) are almost saturated, but the licensed bands (e.g. FM and TV bands – but not mobile bands) held by authorised users are still under less pressure. According to the US Federal Communications Commission's (FCC) report [2] , the utilization rate ranges from 15-85%.

External solution 1: more spectrum

Different approaches have been attempted to alleviate the current shortages: externally, more bands for other services are cleared for the use of mobile broadband. Ofcom has a programme of spectrum awards aiming to make more spectrum available for mobile broadband. The "2.6GHz band" (2500MHz-2690MHz) and 2010MHz-2025MHz have been cleared while the "800MHz band" of 790MHz-862MHz and 550MHz-614MHz band are being released through the UK digital dividend that is mainly due to Digital Switchover (DSO) [3]. However, the approach is becoming more and more difficult.

External solution 2: Cognitive Radio, but sensing as the bottleneck

Cognitive Radio (CR), defined by the FCC as "a radio that can change its transmitter parameters based on interaction with the environment in which it operates [4]", allows unauthorised users to adaptively utilise the "spectrum holes" in authorised spectrum in an opportunistic way. The unused authorised spectrum (commonly called white space) is a potential source of the extra spectrum required according to the regulatory bodies like FCC and Ofcom. They are both expecting further development of the white space reutilization for unlicensed use in [5] and [6]. Mobile operators also have coveted the white space for the use of enhanced services for a long time. Therefore, the IEEE 802.22 working group for the first worldwide standard based on CR was established in October 2004. TV bands are chosen as the operating bands for IEEE 802.22 because of their utilisation stability and low utilisation rate. However, it is crucial to ensure that the intervention of the unauthorised users (also called secondary users, SU) will not degrade the transmission quality of the primary uses of that spectrum. Hence, SUs with CR function should be smart enough to detect the absence of the primary users' (PU) signals, measure and select the "spectrum holes" and use them on the premise of maintaining the quality of PUs' transmission. A geo-location database to monitor the PU's activities on spectrum is still thought to be the most reliable way of realizing spectral awareness but it only can be applied to the situation when spectrum allocation is almost static with slow changes [7]. Reliable sensing information to back up geo-location is necessary to achieve good performance [7].

Although CR has been an active research topic for quite a long time, sensing as the essential and critical technology in CR to identify whether a block of spectrum is available for SUs still faces performance issues and design challenges [8], which makes it the most important bottleneck limiting the development of CR [7].

CR can also be regarded as an extreme form of spectrum sharing, something that network operators and regulators are considering for better spectrum efficiency and higher capacity [71]. The project SAPHYRE in [9] aims to explore the possibility of resource sharing between operators: instead of PUs owning the spectrum exclusively without noticing the SUs occupying spectrum, two operators can share the spectrum by applying a Time Division Muti-Access (TDMA) scheme (orthogonal spectrum sharing) or using beamforming in the transmission (non-orthogonal spectrum sharing).

Alterative solution: resource allocation with QoS-aware and Priority-aware

As sensing is the bottleneck, this research considers whether there is an alternative way to achieve the goal of CR (enabling SUs' transmission with acceptable quality while guaranteeing PUs' transmission) as well as sharing the spectrum. The solution considered is Quality of Service (QoS)-aware and priority-aware radio resource allocation.

1.2 Scope of the research

In this research, radio resource allocation in an OFDMA network to achieve user classification and individual QoS requirement is investigated. This is generic and was originally intended to apply to a CR network, but is more general than that, as will be explained in the thesis.

The spectrum allocation problem in a multi-cell OFDMA network is formulated as a non-cooperative game with each cell acting as a player whose aim is to maximise the number of users who can reach their QoS, subject to the premise that certain user priority guarantees are achieved. Several example cases are studied in this research including one with absolute priority users (just like PUs in CR scenario) but without spectral awareness. This leads to the concept of "Spectrum Sharing Radio (SSR)" that is defined in this thesis.

The difficulties of achieving that goal are:

- how to mitigate the effect of Inter Cell Interference (ICI) in a cellular OFDMA network;
- how to reduce the amount of SCs need to achieve an individual's QoS;
- how to allocate spectrum among users with different priorities;
- how to provide a QoS guarantee to absolute priority users; and
- how to deal with mobile users with changing channel conditions.

1.3 Research contributions

The research described here is novel with the main contributions stated as below,

- *A novel concept: SSR*

  In this thesis, a new concept of "SSR" is defined as a "CR network without sensing" and "an OFDMA network with user priority on spectrum". Instead of using complex sensing and data retrieval techniques in CR, SSR serves the same goal by employing distributed radio resource allocation to provide a new approach of achieving priority awareness and QoS guarantees. In this work, unlike traditional CR, the PUs in SSR are aware of the existence of SUs and when the SUs' transmission affects them, they are able to change their SC allocation strategies to maintain their transmission quality. The concept can be easily applied to more general scenarios of spectrum sharing between operators in existing network framework.

- *A QoS-aware SC allocation algorithm*

  The algorithm is applied to a cellular OFDMA network to allocate the users with the number of SCs necessary to achieve the users' QoS requirements; it does this in a distributed and iterative way to get convergence across all cells in the network. The goal is to satisfy the QoS requirement of as many users as possible. The algorithm eliminates signalling by allowing independent decision-making within a cell to achieve fast convergence so enabling rapid allocation. In the algorithm a SC retrieval mechanism is executed following SC allocation to release the SCs taken by those unqualified users (those with insufficient SCs to achieve their required QoS) to decrease the waste of resources and the ICI. This is necessary because of the varying channel conditions and asynchronous channel information exchange.

- *A priority compensation mechanism*

  The underlying assumption is that this form of CR network can manage the spectrum between PUs and SUs without spectrum sensing leading to the term "SSR network". Based on the QoS-aware SC allocation algorithm, the transmission requirements for PUs are further protected by a priority compensation mechanism to overcome ICI caused by SUs. PUs have the highest priority on the spectrum to give them a QoS guarantee so that the overall system satisfies PUs to the same extent that a conventional CR network would.

- *A layered architecture with reactive behaviours*

  The three layer architecture proposed in this thesis has a clear division of responsibility for each layer and also makes the overall approach more general, including the ability to use it in scenarios with mobile users and network overload.

1.4 Author's publications

[1] Yue Liu and Laurie Cuthbert, *Adaptive Intra Update for H. 264 Video Transmissions over Cognitive Radio Networks*, IASTED WC2011, Jun. 2011

[2] Yue Liu, Laurie Cuthbert, Xu Yang, Yapeng Wang, *QoS-aware resource allocation for multimedia users in a multi-cell spectrum sharing radio network*, ACM MSWiM Workshops PM2HW2N'12, pp.45-52, Oct. 2012

[3] Yue Liu, Laurie Cuthbert, Xu Yang, Yapeng Wang, *QoS-Aware Radio Resource Allocation Game for Multi-Cell OFDMA Network*, pp. 408-412, IEEE ICCS 2012, Nov. 2012

[4] Yue Liu, Laurie Cuthbert, Xu Yang, Yapeng Wang, *Delivering Individualised QoS on Spectrum-Sharing OFDMA Networks*, ACM/IEEE IWQoS 2013, Jun. 2013

1.5 Organisation of this thesis

The remainder of the thesis is organised as follows:

Chapter 2 introduces the relevant background in the field, which includes OFDMA, CR, video transmission, non-cooperative game theory and the wrap-around model.

Chapter 3 introduces the simulator for the radio resource allocation in an OFDMA cellular network. The overall design and the corresponding three layer architecture of the simulation platform are described and followed by the system parameter settings. Then the channel model and interference model in the simulator are analysed in detail. Verification and validation of the simulator are also given in this chapter.

Chapter 4 gives a solution for the radio resource allocation in cellular OFDMA networks taking the individual QoS requirements into account in terms of QoS Satisfaction Ratio (QSR). The relevant literature is summarised and the problem is formulated as a non-cooperative game and an algorithm to fulfil the purpose is proposed with a function description of every module. The validation and the simulation results are analysed at the end of the chapter.

Chapter 5 presents a new network concept of SSR. It then describes enhancements to the algorithm introduced in Chapter 4 in two ways: (i) enabling user priority to suit SSR network; (ii) enabling reactive behaviour to fit it into a wider range of scenarios, including network overload and mobile user activities.

Chapter 6 gives conclusions on this piece of research and points out some directions for further work.

Chapter 2 Background

2.1 OFDM and OFDMA

2.1.1 OFDM

The performance of high data rate telecommunication systems is greatly limited by Inter-Symbol Interference (ISI)[12]. Due to the reflection, diffraction and scattering of wireless channel, multiple wireless propagation paths coexist between transmitter and receiver. The receiver obtains multiple versions of the transmitted signal with different time delays, phases and amplitudes and the composition of those signals will cause multipath fading. Moreover, if a delayed version of a previous signal arrives at the receiver at the same time as the subsequent signal, ISI occurs and introduces errors. Generally speaking if the delay spread is much smaller than the period of the symbol, the effect of ISI can be neglected [10]. However, for high data rate transmission, the period of the symbol is much smaller, so resulting in severe ISI that degrades the system performance greatly.

Traditional single-carrier transmission suffers greatly from ISI and one solution can be using a channel equalizer. However, the complexity of the equalizer increases with the data rate which makes single-carrier transmission less suitable for high data rate transmission.

Unlike single-carrier transmission that uses a single channel to carry high bitrate stream, Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier transmission scheme [11]. It uses a set of orthogonal SCs to transmit data in parallel. The throughput is the sum of the throughput on every single SC so that the throughput required on each individual SC is much lower than the single carrier transmission, which means the period of a symbol can be much bigger than the delay spread and the ISI is eliminated [12]. The orthogonality guarantees no interference between SCs. In this way, high data rate transmission is achieved without complex channel equalization.

The orthogonality of SCs is achieved by applying Discrete Fourier Transform (DFT) and Inverse DFT(IDFT) as shown in Figure 1. However, (Fast Fourier Transform) FFT/Inverse FFT(IFFT) instead of DFT/IDFT is used in real OFDM systems since it is speedy while achieving the same operation [12].

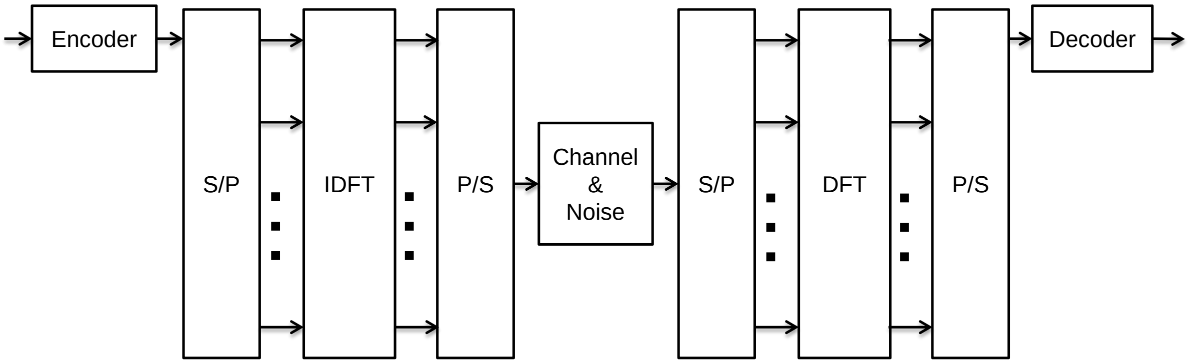

Figure 1 OFDM implemented by using IDFT/DFT[1]

In [13], the advantages of OFDM are stated to include:

- High spectrum efficiency by allowing symbol overlapping compared with Frequency Division Multiplexing (FDM). In OFDM, the spacing between the SCs enables them to be orthogonal to each other. There is no need to have guard bands to separate each SC in the frequency domain like FDM does in Figure 2.
- Resisting frequency-selective fading and narrow band interference by dividing the spectrum into narrowband flat-fading SCs.
- Achieving high system throughput and supporting high bit rate services by eliminating ISI.
- Employing a much simpler channel equalization than the single carrier system.

[1] Figure 1 from reference [12]

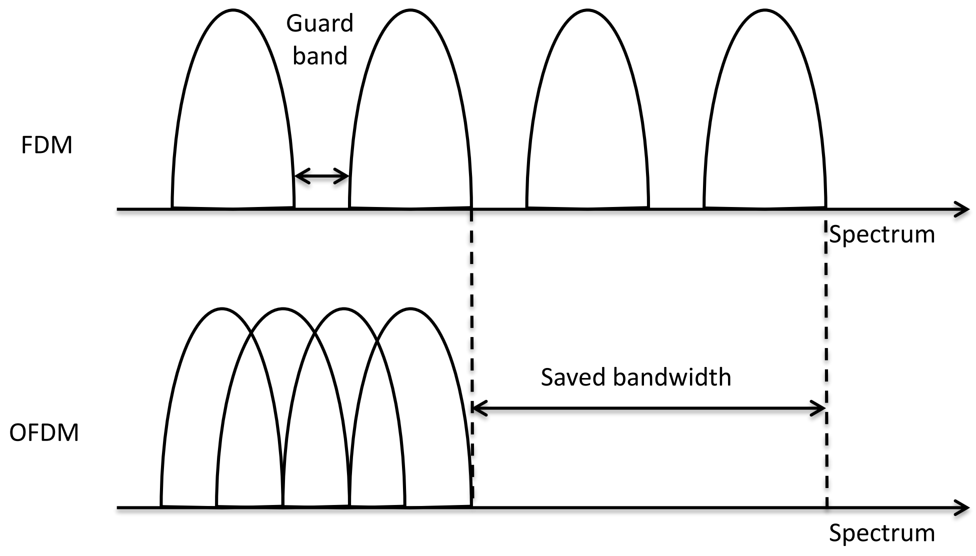

Figure 2 Comparison of FDM and OFDM[2]

Because of those advantages, OFDM is widely applied in wideband data communication systems like Digital Audio Broadcasting (DAB), High-Definition TV (HDTV) and Very-high-speed Digital Subscriber Line (VDSL) [11]. Also it is applied in wireless communication systems like IEEE 802.11a, g (Wireless Local Area Network, WLAN), IEEE 802.16 (Wireless Metropolitan Area Network, WMAN), IEEE 802.22 (Wireless Regional Area Network, WRAN) and Long Term Evolution (LTE) [11].

2.1.2 OFDMA

OFDM is a transmission technique that transmits signals in orthogonal SCs. The corresponding multiple access scheme is Orthogonal Frequency Division Multiple Access (OFDMA); this is a multi-access technique that distributes subsets of orthogonal SCs to multiple users in different domains [12]. Each SC carries a low bit rate sub-signal of a user but the combination of those sub-signals can achieve high bit rate transmission for that user [13]. Figure 3 illustrates the resources are shared by several users in OFDMA system by time, frequency and code respectively [12].

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[2] Figure 2 from reference [11]

SC allocation is an active research topic in OFDMA network. For a cellular OFDMA network the orthogonality ensures SCs give no interference to other SCs so that intra-cell interference is removed. The Inter-Cell Interference (ICI) mitigation becomes crucial. Literature on resource allocation will be introduced in §4.1.

Meanwhile, OFDMA can achieve multiuser diversity: as broadband signals suffer from frequency selective fading, OFDMA distributes different users to transmit over different SCs so that the users are allocated the most suitable SCs, so a deeply faded SC for one user may have much better characteristics for another user [10]. The multiuser diversity can also be exploited in SC allocation.

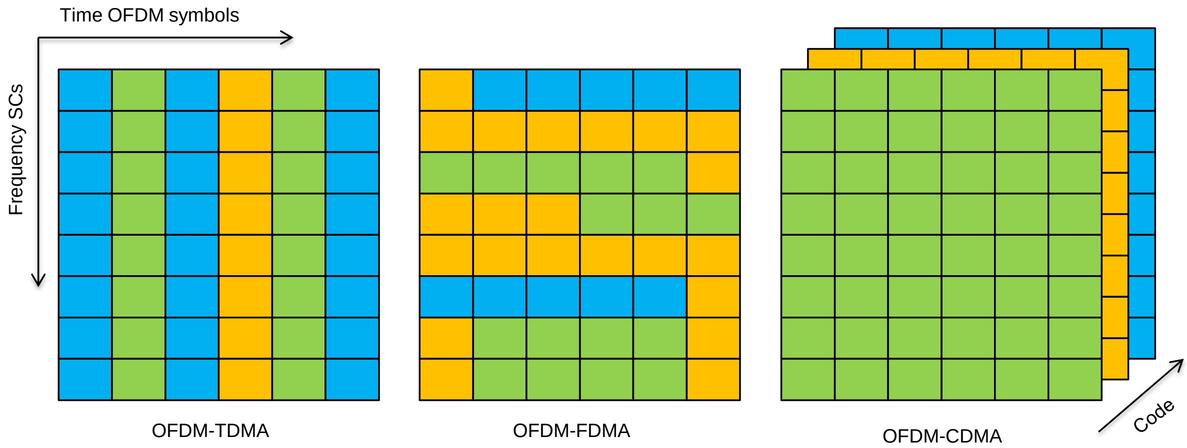

Figure 3 OFDMA illustration[3]

2.2 Cognitive Radio

2.2.1 Introduction

Software Defined Radio (SDR) was first introduced in [14]; it was defined as an open standard hardware platform so that its operating functionalities can be fully or partially realised by software programming, so enabling different telecommunication standards and

[3] Figure 3 from reference [12]

structures to coexist without changing the existing hardware components. Such a platform has better compatibility and flexibility. However SDR still cannot satisfy the requirement of the telecommunications field that a radio device can implement adaptive management of its functionalities which is important when dealing with channel allocation.

In most countries, the government regulatory body, for instance Ofcom in the UK, is in charge of allocating the spectrum to service providers on a long-term and geographical basis with unauthorised users being prohibited from getting access to authorised spectrum, so protecting incumbents' rights at the cost of inefficient usage of spectrum. Figure 4 shows the practical spectrum utilization of 0-6GHz measured at Berkeley Wireless Research Centre (BWRC) [17]. The result illustrates that the spectrum is not fully utilised and most of it is partially utilised or not utilised at all and these areas can be re-utilised.

It is static spectrum allocation which leads to inefficiencies. For example, in the US, the lower Ultra High Frequency (UHF) bands in almost every geographical area have several unused 6 MHz wide TV bands [17]. As an advanced spectrum-access technology, CR offers a new solution to improve the utilization of the authorised spectrum in order to relieve the load on the unauthorised spectrum.

Based on those facts, the concept of CR was introduced in 1999 as an extension of SDR to provide better adaptive management [15]. The biggest difference between CR and SDR is that CR adjusts its transmission parameters based on its own observations from the surrounding environment and from its interaction with other users while SDR is based on programming. Generally speaking, CR is SDR with self-reconfiguring ability [16].

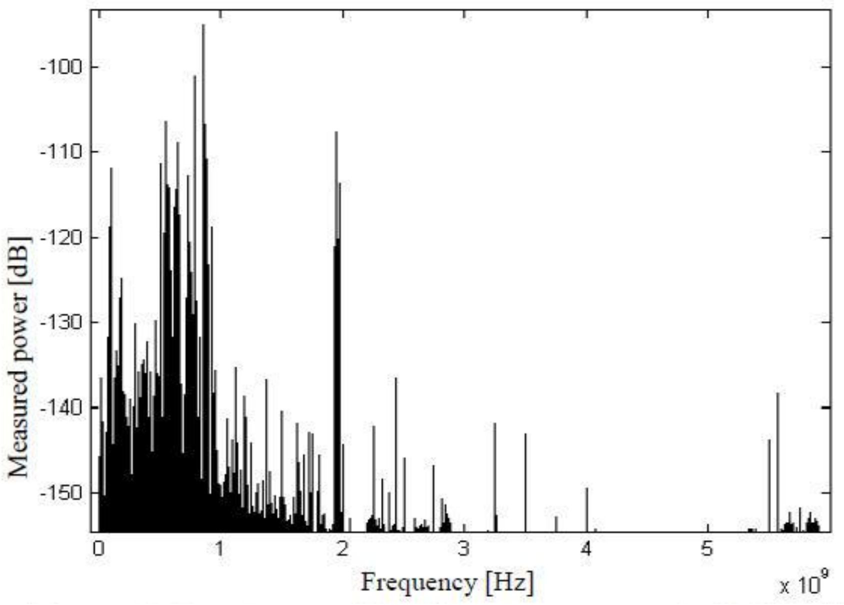

Figure 4 Spectrum utilization measurement at BWRC[4]

2.2.2 *The basics of CR*

The first definition of CR was proposed by Joseph Mitola III in [18]:

> *"The cognitive radio identifies the point at which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent on the subject of radio resources and related computer-to-computer communications to (a) detect user communications needs as a function of use context, and (b) to provide radio resources and wireless services most appropriate to those needs."*

Later, the FCC provided a more practical definition [2]:

> *"A cognitive radio is a radio that can change its transmitter parameters based on the interaction with the environment where it operates."*

According to the FCC's definition, CR should have two capabilities, cognitive capability and re-configurability. Cognitive capability is the ability to sense and detect the surrounding

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[4] Figure 4 from reference [17]

transmission environment. As soon as obtaining these observations, CR analyses the spectrum and then adaptively reconfigures its parameters to suit the surrounding environment without changing the hardware part in order to achieve better transmission performance.

In general, CR allows SUs to sense the "spectrum holes" of the primary spectrum in the time, space and frequency domains in an autonomous manner and then make rational use of them in an opportunistic way on the premise of causing limited and tolerable interference to PUs, as shown in Figure 5. The spectrum hole is a band of frequencies assigned to a PU, but, at a particular time and specific geographic location, the band is not being utilised by that user [4].

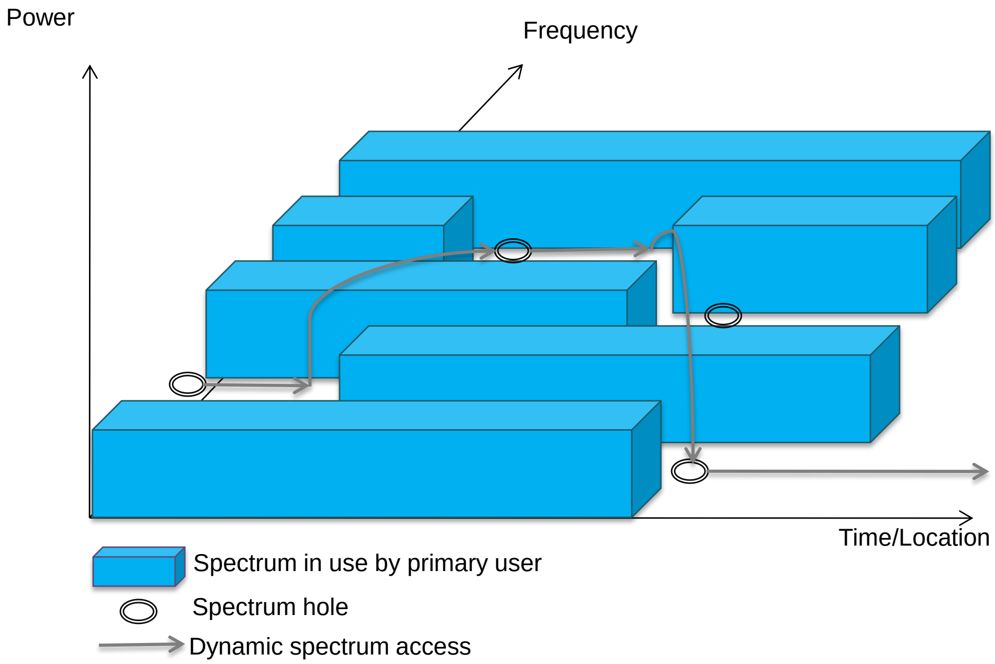

Figure 5 Opportunistic spectrum access[5]

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[5] Figure 5 from reference [13]

2.2.3 *The functions of CR*

2.2.3.1 *Spectrum sensing*

As the foundation of CR, the cognitive capability of CR is achieved by spectrum sensing. It enables the SUs to detect the absence of any PU's signal on a channel and measure the quality of the spectrum holes. Since it is impossible to sense while transmitting, the SU should periodically sense the spectrum. *In-band sensing* [20] is where SUs sense the current spectrum in case the PU returns; *out-of-band sensing* [20] is where SUs sense the other spectrum holes while transmitting in case they need to switch channel. However, there is still a possibility that the PU returns during two sensing points. The collision might cause unavoidable interference to the PU.

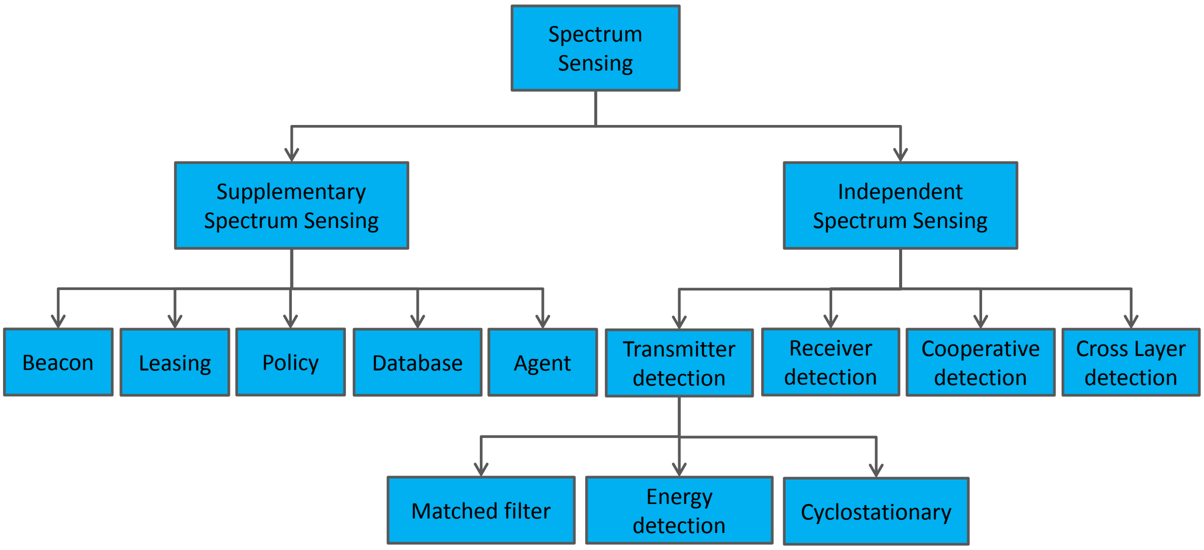

Figure 6 The classification of spectrum sensing[6]

In terms of sensing techniques, they can be classified into *supplementary sensing* and *independent sensing* [13]. Supplementary sensing allows SUs to learn the occupancy information of the primary system via a beacon, by spectrum leasing, by policy, by a PU database access or by a spectrum agent. Independent sensing allows the SUs to use detection

[6] Figure 6 from reference [13]

algorithms and mechanisms to sense the surrounding environment to obtain the occupancy information without the assistance of an entity outside the CR network. One major advantage of independent sensing is that the sensing is processed within the CR network, requiring no information exchange with the primary system or a third party. Hence it requires no modification of the current primary system infrastructure and devices.

The different supplementary sensing mechanisms are:

- *Beacon*: the primary network periodically broadcasts a beacon signal with spectrum availability information [13].

- *Leasing*: the primary network broadcasts the available spectrum and its price. SUs can lease the spectrum via auction. Leasing can increase the spectrum efficiency while bringing profit for the primary network [13].

- *Policy*: the spectrum management body measures and summarises the low-utilised spectrum and instructs the CR network to use that spectrum [13].

- *Database*: the primary system or the spectrum management body constructs and maintains a spectrum occupancy database. The database needs to be updated in real time according to the usage of primary system and CR networks. It should also include the locations of BSs and users and interference range of CR users [13].

- *Agent*: the spectrum agent is a centralised unit that collects spectrum information from different networks and then processes the data and gives spectrum access advice in order to improve the overall system spectrum efficiency. As a third party, the agent will fairly optimise the allocation according to the requirement of the current networks [13].

Supplementary sensing allows the CR network to use the vacant spectrum only with the permission of the primary network and the spectrum management body. It can guarantee the CR network will not cause harmful interference to the primary system. However, the control information cost is huge and it needs the assistance of the primary system and a spectrum management body, which is a big change to the network structure [13].

For these reasons, independent spectrum sensing seems to be the more practical approach [13]. As CR users cannot directly measure the channel condition between the PU's transmitter and receiver, they must continuously sense the whole spectrum. The uncertainties of shadow fading, multipath fading and noise in the wireless communication environment increase the difficulty of rapid and accurate detection.

Transmitter detection is where CR users decide whether there are potential PUs within the interference range by measuring the signals from the PUs' transmitter. The techniques proposed for transmitter detection include *matched filter, energy detection* and *cyclostationary characteristic detection* [13]. These are easy to implement but sensing results are significantly affected by multipath and shadow fading. To get reliable sensing results, the CR user needs to have a high detection sensitivity. A matched filter needs different detectors to distinguish different primary signals. The energy detection detects the energy on a channel and compares it with the threshold to decide whether it is a vacant channel, but as it cannot distinguish the sources of the energy, the sensing results may be unreliable.

In a practical scenario, there can be a "hidden terminal" problem that happens because the PU receiver in the CR user's interference range only receives but does not transmit signals, or it is blocked by obstacles so it is not detected by the CR user. In this situation, the signal from the SU may cause interference to the PU.

Compared with single-node sensing, cooperative detection offers more reliable sensing results through sharing information between multiple CR users. By using cooperative detection, the probability of having a "hidden terminal" is reduced, as are the sensing errors; the sensing time can also be reduced [13].

Cross layer detection [13] can give advice on choosing sensing parameters (e.g. the sensing period) and sensing strategies (e.g. reactive or proactive) based on the Media Access Control

(MAC) and upper-layer QoS requirements of the SUs in order to improve the efficiency of sensing and save energy for the SUs.

However, although a lot of research has been done on CR, sensing is still a problem. To provide rapid and reliable sensing results in all circumstances is difficult and sensing is one of the key factors influencing the development of CR [7]. In [7], problems like low SNR sensing, hidden node problem, QoS guarantee, passive device detection and challenges in wideband spectrum sensing still need to be solved. In [21], the major challenges of sensing are summarised as channel uncertainty, noise uncertainty and aggregate-interference uncertainty.

2.2.3.2 Spectrum sharing[7]

Spectrum sharing is the Radio Resource Management (RRM) problem in CR. Due to the characteristics of CR, it is concerned with how the spectrum is accessed by PUs and SUs on the premise of PU transmission guarantee. According to the current study on spectrum sharing, it can be classified into several categories:

- *Underlay/Overlay spectrum sharing*

  In terms of the spectrum access behaviours of the SUs, there are two approaches: *overlay spectrum sharing* and *underlay spectrum sharing* [22].

  The underlay spectrum sharing in Figure 7 (a) applies spectrum spreading technique on the SU's signal to spread the transmit power over an ultra-wide spectrum so that the transmit power is very low and the interference from the SUs to the PUs does not exceed a certain threshold, for example the short-range communications in Ultra Wide Band (UWB) [7]. This type of sharing relies on close cooperation between the PUs and SUs;

[7] Here spectrum sharing is about allocating spectrum between PUs and SUs. It is different from SSR.

however, it does not match the current network configuration where the PU is not responsible for providing information to SUs.

The core idea of overlay spectrum sharing is to use the spectrum holes opportunistically. It is the main research target in the literature [7]. It is also known as Opportunistic Spectrum Access (OSA) or Dynamic Spectrum Access (DSA). The overlay spectrum sharing in Figure 7 (b) gives PUs the highest priority on occupying the spectrum and SUs are only allowed to use unused spectrum where there is an absence of PUs. Furthermore, SUs have to keep monitoring the PUs' activities to make sure the occupied spectrum should be released at PUs' return.

Both forms of spectrum sharing require PU and spectrum information and in IEEE 802.22 this is provided by a geo-location database, independent spectrum sensing or specially designed beacon [23].

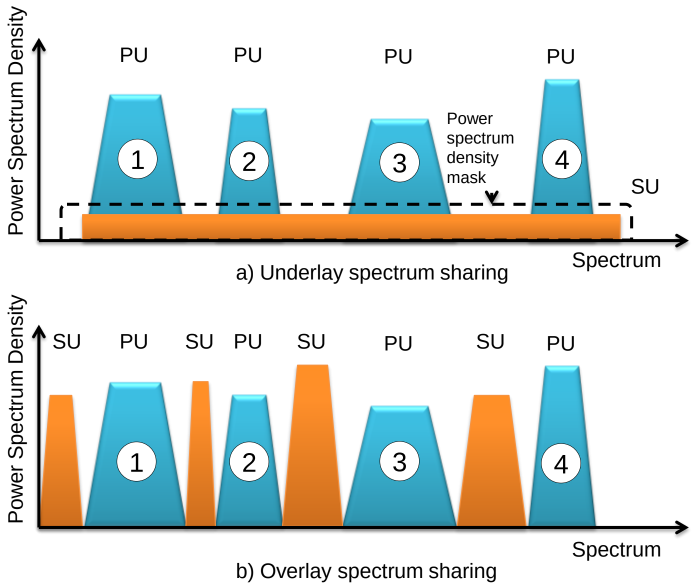

Figure 7 Underlay and overlay spectrum sharing[8]

[8] Figure 7 from reference [22]

- *Cooperative/Non-cooperative spectrum sharing* [22]

  In terms of the sharing behaviour between nodes (e.g. SUs or BSs), *cooperative spectrum sharing* occurs when the nodes accept negotiation and coordination to achieve a common goal; they usually belong to the same service provider. The interference information is shared among the nodes. This sort of arrangement can exist in a centralised network where a centralised unit can promote the cooperation.

  Non-cooperative spectrum sharing allows the nodes to try to gain the most, regardless of the influence of their actions on the others. The nodes are rational and selfish so that they have no concern about the effect of their behaviour on each other. Only a minimal information exchange is required among them. This form of sharing exists on distributed network [22].

- *Centralised/Distributed spectrum sharing*

  In terms of network infrastructure, *centralised spectrum sharing* [22] requires a management centre to coordinate the resource allocation of all nodes. In the IEEE 802.22 network scenario, the spectrum manager (SM) in a Cognitive Radio-Base Station (CR-BS) is in charge of organizing sensing, channel selection and power control management of its Cognitive Radio-Customer Premises Equipments (CR-CPEs).

  Distributed spectrum sharing [22] is applied to distributed networks like *ad-hoc*. In IEEE 802.16 for WiMAX and IEEE 802.11 for WiFi, the nodes should self-determine which channel to use and other parameters based only on their local information and observations.

Game theory is widely used in modelling the spectrum sharing problem. Reference [24] solved a power allocation problem based on an IEEE 802.22 WRAN cell by a *potential game*[9]

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[9] A potential game is a special kind of game that can guarantee the convergence of Nash Equilibrium.

with throughput minus the cost of using the power as the utility function. [25] improved the game efficiency by proposing a price-based iterative water filling algorithm in an *ad-hoc* CR network. [26] proposed a non-cooperative multichannel power allocation game with constraints on the interference temperature set by the primary system. [27] considered a more realistic game with bounded rationality where players gradually adjust their strategies based on their observations. [28] described a repeated power allocation game of two selfish systems with asymmetric capacities and a self-enforcing protocol. [29] took BSs as players and the number of subscribers as the utility function.

No matter how the spectrum sharing problem is classified, the problem should always be solved with the precondition of good transmission for PUs. On that premise, the SU's transmission can be considered.

Table 1 Classification of spectrum sharing

Criterion	**Type1**	**Type2**
Access technology	Overlay: SUs use the spectrum holes.	Underlay: SUs use authorised band continuously subject to power constraints.
Network architecture	Centralised: a central entity controls and coordinates the spectrum access for SUs	Distributed: each SU makes its own decision on spectrum access.
User behaviours	Cooperative: SUs are willing to negotiate to achieve a common goal.	Non-cooperative: SUs have different goals to achieve and are not willing to negotiate.

2.2.4 *IEEE 802.22*

As introduced in [20], IEEE 802.22 is the first world-wide standard that defines the PHY and MAC wireless air interface for CR networks. The main target of IEEE 802.22 is to provide wireless broadband access to fixed customers such as residences, small and medium businesses in suburban and rural areas.

IEEE 802.22 WRAN cell is a point to multipoint infrastructure network consisting of a CR-BS (service provider) and CR-CPEs (service subscribers). It operates on the Very High Frequency (VHF) and Ultra High Frequency (UHF) TV broadcast bands (54-862MHz in North America, totalling 282 MHz or 47 channels) with channel bandwidth of 6 MHz and allows the CR-CPEs to use the white spaces in the TV spectrum. The IEEE 802.22 work group is trying to establish an international unified CR standard that can apply to worldwide TV channel systems (frequency bands 41-910MHz with bandwidth 6 or 7 or 8 MHz). The IEEE 802.22 draft v3.0 was published in March 2011.

The CR-CPE has two antennas: (i) a directional antenna for signal exchange with the CR-BS, which decreases the interference to other CR-CPEs; (ii) an omni-directional antenna for real-time sensing the surrounding environment.

The downlink (DL) data rate at the edge of coverage is up to 1.5Mbps/user while the uplink (UL) is 384kbps/user. It employs 2K FFT OFDMA for one TV channel. A TV channel is divided into 48 subchannels with modulation schemes: Quadrature Phase-Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (16-QAM), 64-QAM with convolution coding schemes of rate 1/2, 3/4, 2/3 for both UL and DL [20]. The scenario is designed for transmission in suburban and rural areas where the population density is low and coverage is needed over a wide area with large cell radius (17km-100km) and 4W Base Station (BS) equivalent isotropic radiated power (EIRP) limit and 4W Customer Premises Equipment (CPE) EIRP limit in US.

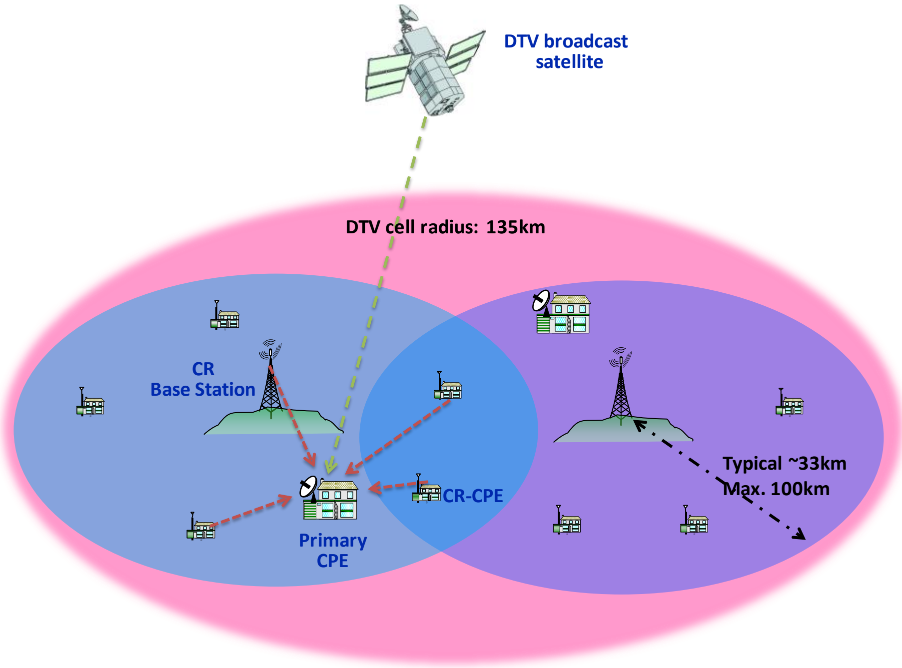

Figure 8 IEEE 802.22 WRAN cell[10]

Figure 8 shows the simplified network configuration of an IEEE 802.22 cell based on [20]. The primary Customer Premises Equipment (CPE) receives the DTV broadcast signal from the satellite. The possible source of interference for the primary CPE is from the surrounding CR-CPEs and the CR-BSs if they transmit using the same frequency at the same time. To avoid the interference, all the CR-CPEs and CR-BSs are not allowed to use the spectrum currently used by the primary CPE (overlay spectrum sharing).

2.3 Video transmission

This section is included to introduce basic theory of video transmission and demonstrate that video signals can be transmitted with different QoS, the coding being able to cope with different transmission characteristics.

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[10] Figure 8 from reference [20]

2.3.1 *Basics of video compression*

The video compression at the encoder includes (i) transform coding (Discrete Cosine Transformation (DCT), quantisation and Variable Length Coding (VLC)) to remove the spatial redundancy within a frame and (ii) motion prediction to remove temporal redundancy between two consecutive frames [30]. The basic functional elements of video compression are Frame and Macroblock (MB). A video stream can be split into a consecutive Group of Pictures (GOP). Generally speaking, these pictures are classified into three types: I frame, P frame and B frame. The order of GOP can be modified according to different requests. A common GOP is IBBPBBPBBI. References [30], [31] and [32] introduce the basics of video compression.

An I frame (the intra frame) is encoded by intra prediction and transform coding to exploit the spatial redundancies without motion compensation taking any previous frame as the reference; it can provide random access and best error resilience. However, the compression ratio is the lowest of all three types. The MB within I frames are all intra-coded [30].

In a P frame (the predicted frame) temporal redundancies are exploited by motion compensation taking the previous nearest I and P frame as its reference and then the predictive residual is encoded by transform coding [30].

B frame (the bi-directional predicted frame) is the one with the highest compression since it does motion prediction in both directions, from previous and future I or P frames. However it brings delay since it can be decoded only after the following reference frame is decoded. This kind of delay is intolerable for real-time video transmission [30].

2.3.2 *The video codec*

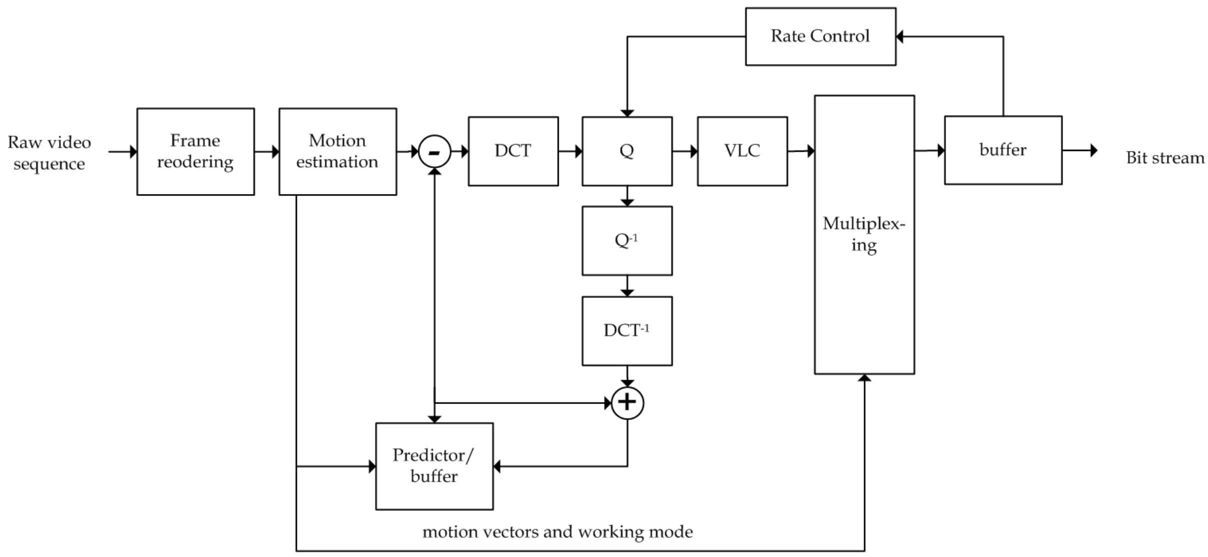

Figure 9 Block diagram of video encoder[11]

The general video encoder and decoder composition is shown in Figure 9 and Figure 11. In the encoder, a raw video sequence splits into frames with GOP IBBPBBPBBI.

The I frame is transformed from the spatial domain into the frequency domain by DCT. The frequency coefficients are quantised by using a Quantisation Parameter (QP), the difference between two adjacent quantisation levels) and VLC is used to further compress the bit stream. One decompressed version of the I frame is stored in the buffer as the reference frame for the next P frames [30].

For the P frame, motion estimation and compensation is used to link each MB in the current P frame with the most similar MB in the reference frame (previous I or P frame) by a motion vector. With the motion vectors and the reference frame in the predictor/buffer, a motion-compensated frame is constructed. The residual between the predicted frame and the actual P frame is encoded by DCT, quantisation and VLC. A decompressed version of the P frame (motion vectors + decompressed residuals) replaces the old one in the

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[11] Figure 9 from reference [30]

predictor/buffer as the reference frame for the next P frames. Motion vectors, working mode and compressed residuals are multiplexed and buffered. Rate control is used to control the source coding rate of the compressed video under a fixed value by modifying the QP. The output is a bit stream consisting of all the information required for the decoder. The bit stream is further packetised for transmission (MPEG transport stream) [30].

A B frame is processed in a similar way as a P frame but with bi-directional motion estimation and compensation.

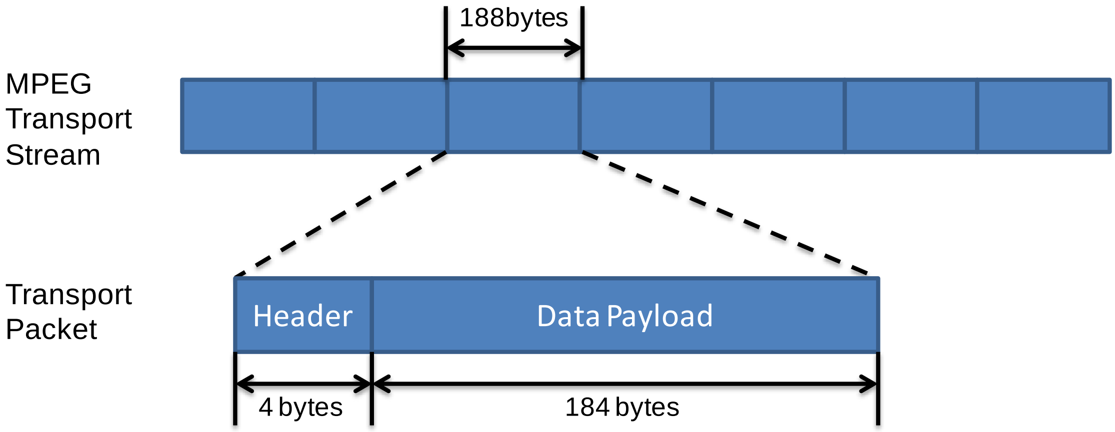

Figure 10 The structure of MPEG transport stream[12]

The Moving Picture Experts Group (MPEG) transport stream as shown in Figure 10 is a standard format for transmission and storage of video and audio data. It consists of a sequence of 188-byte packets with 4 bytes header and 184 bytes data payload. It specifies a container format encapsulating packetised elementary streams, with error correction and stream synchronization features for maintaining transmission integrity when the signal is degraded [34].

After the receiver receives the bit stream, it is buffered and de-multiplexed. The I frame is processed by variable length decoding, de-quantisation and inverse DCT. A version of the decompressed I frame is passed to the predictor/buffer. For a P frame, the de-multiplexed

[12] Figure 10 from reference [34]

part contains the residuals, the motion vectors and working mode. The previous decompressed frame stored in the predictor/buffer works with the working mode and motion vectors to reconstruct the predicted current frame. The residual is processed by variable length decoding, de-quantisation and inverse DCT and then assembled with the predicted current frame to get the P frame. The compressed video is displayed with a fixed frame rate (30 frame/s) to the audience [30].

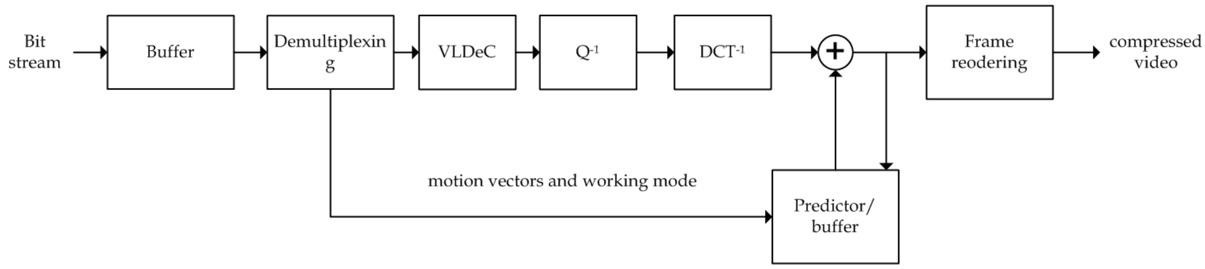

Figure 11 Block diagram of video decoder[13]

2.3.3 *Source distortion*

The simplified process for video streaming between transmitter and receiver is shown in Figure 12. A raw video sequence is passed into the encoder and after compression is converted into MPEG transport stream format then is transmitted via the transmitter. After receiving the stream and decoding, the video sequence is displayed. In both encoding and transmission processes, errors unavoidably occur. The errors in the encoding process due to lossy compression are called source distortion and errors caused in transmission are called channel distortion [30].

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13 Figure 11 in reference [30]

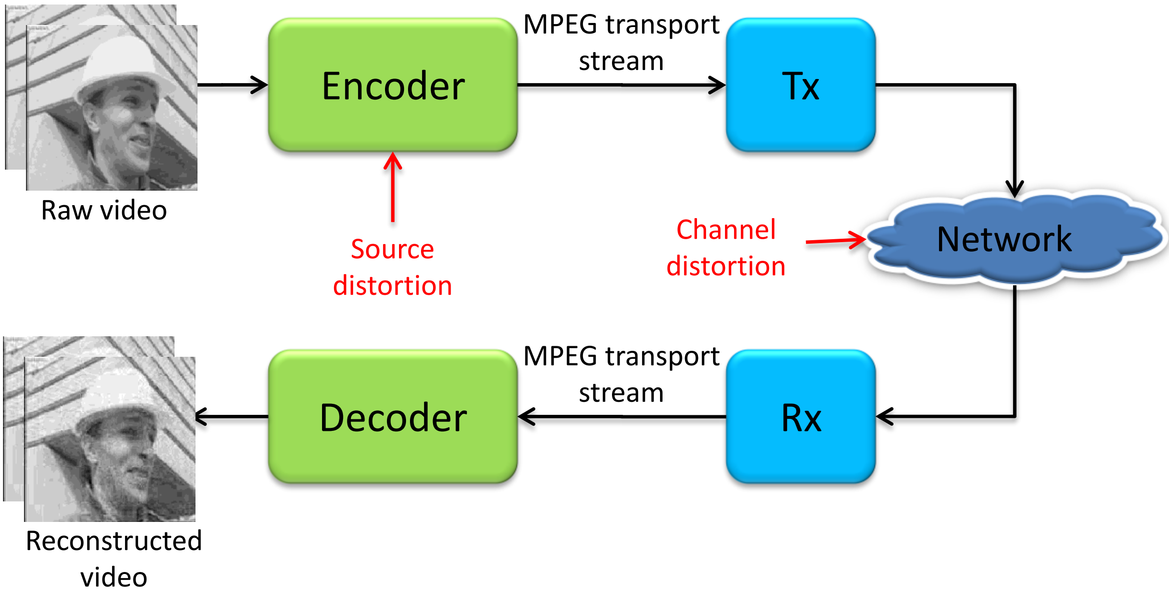

Figure 12 The transmission process for a video service

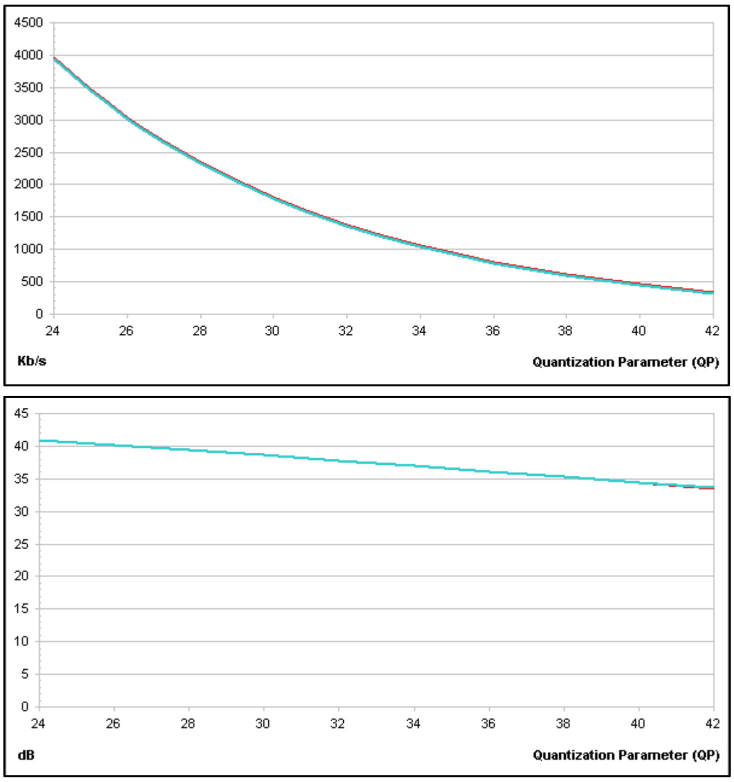

Figure 13 a) bitrate vs. QPs b)PSNR vs. QPs[14]

[14] Figure 13 from [33]

Quantisation in the encoding process is one of important techniques to adjust the encoding rate of a video. Different encoding rates are achieved by setting different QPs [30]. Peak Signal to Noise Ratio (PSNR) is used to measure the quality of a compressed video by using raw video as a benchmark. Figure 13 shows the relationship between video encoding rate, PSNR and QPs. The larger the value of QP is used, the bigger source distortion, the smaller PSNR and the smaller encoding rate will be. Hence, the video quality is greatly determined by the transmission rate as the transmission rate decides which encoding rate and QP can be used. The transmission rate should always be bigger than the encoding rate. (e.g. for interactive video with 384kpbs encoding rate should have 460kbps transmission rate to ensure the quality[68].) Therefore, in this research the QoS requirement for the video streaming user is specialised as the transmission rate.

2.4 Non-cooperative game theory

Non-cooperative game theory is used in this research. As a BS is fully in charge of SC allocation independently in a cellular OFDMA network, it can be regarded as a selfish and independent player trying to gain more profit for itself while competing with other BSs that have the same non-cooperative behaviour. Also it avoids massive signalling between BSs to reduce power and time consumption. Compared with other optimization techniques, for example, genetic algorithm, it can achieve much faster convergence and can be easily applied in practice although it might cause suboptimal solutions. Some basics of non-cooperative game theory are introduced here.

A non-cooperative game has a strategic form, denoted as $G = \langle \mathbf{N}, \mathbf{A}, \mathbf{U} \rangle$.

Where $\mathbf{N} = \{1, 2, \ldots, n, N-1, N\}$ is a finite set of players involved in the game[15]; $\mathbf{A} = \{A_n | n \in \mathbf{N}\}$, is the action space of the game which contains all the players' strategies against the others, A_n is a set of actions for player n with all the possible strategies $A_n = \{a_n | \; n \in$

[15] Equations in Section 2.4 are all from reference [35]

$\mathbf{N}\}$; $\mathbf{U} = \{U_n | \, n \in \mathbf{N}\}$ is a finite set of all the player's utility functions. U_n measures the payoff of player n determined by the strategies chosen by all the players. It has two determining coefficients which are the strategy of player n and the strategies of all players except player n. The detailed game formulation in this research is given in Chapter 4.

- Nash Equilibrium (NE) [35]

Definition An action set $\{a_1^*, a_2^*, \ldots, a_n^*\} \subset \mathbf{A}$ is said to be a Nash Equilibrium (NE) if, for every player,

$$U_n(a_n^*, a_{-n}^*) \geq U_n(a_n, a_{-n}^*), \forall\, a_n \in A_n \qquad \text{Eqn 2.1}$$

Where a_n denotes the strategy of player n and a_{-n} denotes the strategies of all players except player n [35]. The *Nash Equilibrium* is regarded as the solution of a non-cooperative game. A NE consists of every player's *best response* against all others' strategies. In other words, it is a steady-state point that none of the players has incentives to change its strategy since none of them can unilaterally increase his utility function given that the other players stick to their current strategies. The best response function $BR(.)$ of player n is denoted as below,

$$BR_n(a_{-n}) = \{a_n \in A_n \colon U_n(a_{-n}, a_n) \geq U_n(a_{-n}, a_n')\}, \forall a_n' \in A_n \qquad \text{Eqn 2.2}$$

- Existence of NE

Theorem A strategic game $\langle \mathbf{N}, \mathbf{A}, \mathbf{U} \rangle$ has a Nash Equilibrium if, for all $\forall\, n \in \mathbf{N}$, the action set A_n of player n is a non-empty compact convex subset of a Euclidian space, and the payoff function U_n is continuous and quasi-concave on A_n [35].

- Pricing-the method to improve NE efficiency

The selfish and rational behaviour of the players might lead to inefficient NE, which contradicts with the goal (e.g. maximise the system capacity with efficient NE). One widely used NE efficiency improvement method is pricing. Physical meaning of pricing function is usually the cost of using the resources (e.g. how the PU charges for using the spectrum) or the harm the user imposes on other users, in terms of performance degradation, revenue deduction, or interference [35]. By designing the utility function as the payoff minus the cost, it prevents every selfish player from requiring more resources without limit and so leads to an improved efficiency of the system performance. The simplest pricing is linear pricing, where the cost is proportional to the resources consumption of a user (e.g. transmit power, occupied bandwidth). However, it requires global information, which is impractical for some network scenarios.

2.5 **Wrap-around**

To get rid of the "edge effect" in the simulation of cellular networks, wrap-around model is widely used in simulations [36]. Figure 14 shows how the wrap-around works. In this research, one round of interference cells for every cell is considered.

The real cells are shown as the blue cells in Figure 14 - where users and BSs are located. The virtual cells are shown as the white cells with blue outline, which are clones of certain real cells. The number is the corresponding cell ID. By "stamping" the 7 blue-cell set around the real cells, the matching between real and virtual cells is shown in Figure 14. The only aim of generating the virtual cells is providing full interference sources to those edge real cells. For example, for real cell 7, the ICI will come from cell 1, 3 and 5, which are the real cells and also from cell 8, 9 and 19, which are clones of cell 6, 4 and 2 respectively. All the 7 real cells have interference coming from all directions.

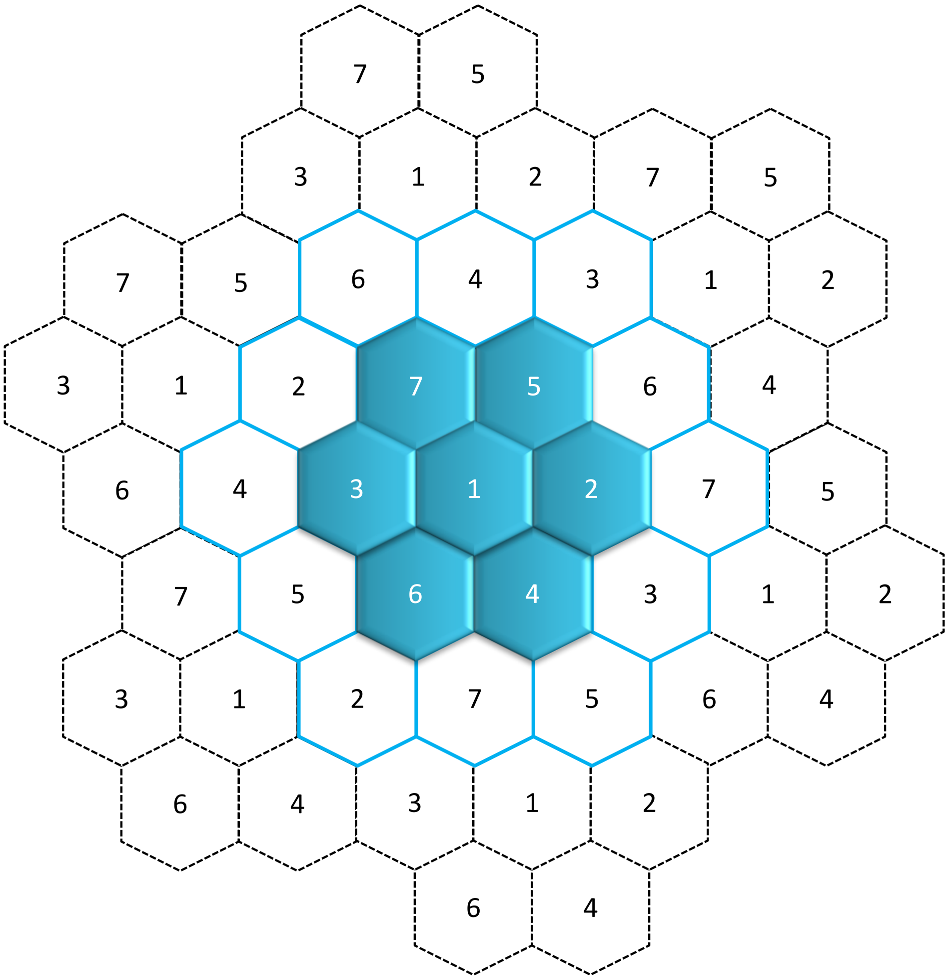

Figure 14 The wrap-around layout

2.6 Summary

From the literature review, several points emerge:

- Because of the advantages of OFDMA, it is a widely applied multi-access technique in cellular networks as the orthogonality of the SCs eliminates the intra-cell interference. However, *the ICI from co-SC users in adjacent cells is the biggest concern for cellular OFDMA network*.

- Even after a lot of research on CR, there are still challenges to have rapid and accurate sensing for industrial use and this is hence a major limitation on CR.

- The quality of a video is, to a large extent, determined by its encoding rate. The transmission rate limits the encoding rate that can be used for the video, and hence the quality. In this case, by having different transmission rates, different QoS can be achieved for video streaming.

- Non-cooperative game theory has been used for SC allocation in mobile networks, and in this research it is extended to multi-cell SSR networks in a spectrum-sharing scenario. As every BS is rational and selfish and as there is no centralised unit to control the behaviour of those BSs, non-cooperative game theory is the most suitable.

- Wrap-around model is used to eliminate the "edge effect" for the multi-cell model in this research and the need for its use is shown in the validation in § 4.4.1.

Chapter 3 Simulator of SC Allocation in OFDMA Networks

During the course of this research a complete simulation platform was written by the author to implement the algorithms and to test their performance since it is a new form of network scenario (SSR network) considered in this research. Rather than break up the description of the simulator into sections within the description of the research, the overall simulator platform is described here with forward references to those sections of the thesis that use those aspects.

3.1 Overview design of simulation platform

The main modules included in the simulation platform are:

1. **Initialisation module** (§3.2.1): generate network topology (e.g. cell and sector); generate the positions of BSs and Mobile Stations (MSs), where the BS is located at the centre of every cell and the MSs are distributed in "uniform" or "hotspot" mode; mark the priority and required QoS of users; do wrap-around matching up virtual cells with real cells.

2. **Channel creation module** (§3.2.2): generate channels by adding large scale path loss, shadow fading.

3. **CQI feedback module** (§3.3.1): Channel Quality Information (CQI) is delivered in the beginning of every round of SC allocation during the decision making process and is updated immediately afterwards. For UL, CQI of MS to BS is measured at the BS and is sent back to the MS by a pilot signal; for DL, the CQI of BS to MS is measured at MS and is sent back to the BS by a pilot signal.

4. Resource allocation module (§3.3.2): The SCs are allocated to MSs in such a way that the system can have as many MSs getting their required QoS as possible. During the allocation, each MS has its own priority for (i) getting resources and (ii) its QoS requirement in terms of bitrate. The power on each SC is fixed and equal and the constraint of a defined total power is applied. The transmit power for a MS is decided by the number of SCs it has and the fixed power value on a SC.

5. Capacity measurement module: according to the resource allocation results, the user's transmission rate is calculated.

6. System performance measurement module (§3.3.3): the overall performance measures (QSR, fairness index, system capacity) are calculated.

7. Systematic adjustment module: (§3.4.1) aiming to improve the system performance by adjusting settings. This only applies when some trigger is met. The trigger criterion is defined in terms of system performance and reaching this criterion will cause the system to macro adjust to enhance the system performance.

These modules fit into a three-layer architecture shown as the overall flowchart in Figure 15 to separate functions that will be performed over different timescales:

- the *Management Layer* corresponds to management functions that take place over a longer timescale, including the initialisation;
- the *Local Planning Layer* is responsible for executing the resource allocation at a particular time (snapshot) and measuring the system performance; and
- the *Reactive Layer* monitors the performance, adapts to external changes and enhances the performance by triggering the system adjustment module if Trigger1 is met. Each simulation result is based on a static snapshot so the allocation result is for a specific time point. To get results that vary with time Trigger2 is used to rerun the

whole simulation in response to user-defined changes, for example, time, user location change.

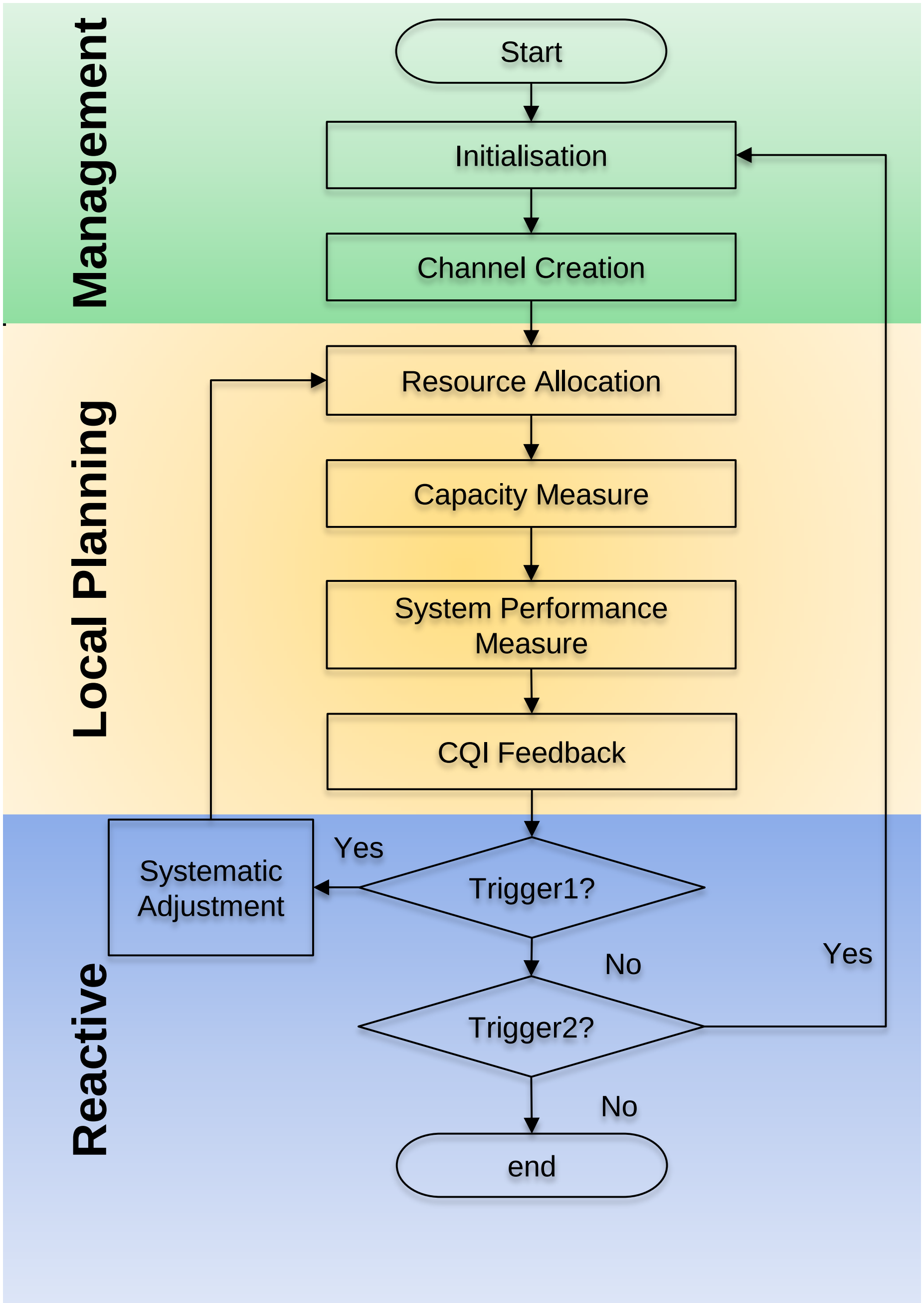

Figure 15 The architecture and flow chart of the simulator

3.2 **Management layer**

The function of this layer is to identify (i) the radio environment, (ii) the user types, (iii) to define the cases and (iv) generate channels.

3.2.1 Initialisation module

Figure 16 is the flow chart of the initialisation module. At first, a 7-cell, 3-sector OFDMA network topology is constructed and wrap-around model as explained in §2.5 is applied. The BS with a 3-directional antenna is located at the centre of every cell and users are distributed in "uniform" or "hotspot" mode within the coverage area. Uniform distribution is a most likely scenario and is used as a benchmark to represent the randomness in user locations and hotspot user distribution to represent unbalanced user distribution in cells is modelled by randomly setting the ratio of user numbers between sectors and the uniform distribution is used in each sector.

Each user has three basic attributes: (i) its location, (ii) its priority and (iii) the required bitrate. The location decides which BS and sector the user belongs and the distance to the BSs therefore greatly determines its channel condition. The attributes (ii) and (iii) are decided by the type of service that the user requests, the tariff the user is on and the operator that serves it. The priority is used to control how resources are shared among users. For example, in a CR scenario, a PU has absolute highest priority over a SU. The required bitrate is the bitrate that determines which kind of service quality the user will receive. In this thesis, for simplification, typical bitrates for video streaming are used. They are 128kbps, 384kbps, 500kbps and 1Mbps.

A *case* includes a set of attributes and parameters passed to the local planning layer to affect how the resource allocation is managed. The case has the following components:

- Topology & wrap-around information

- User attributes

- The trigger conditions for the reactive layer

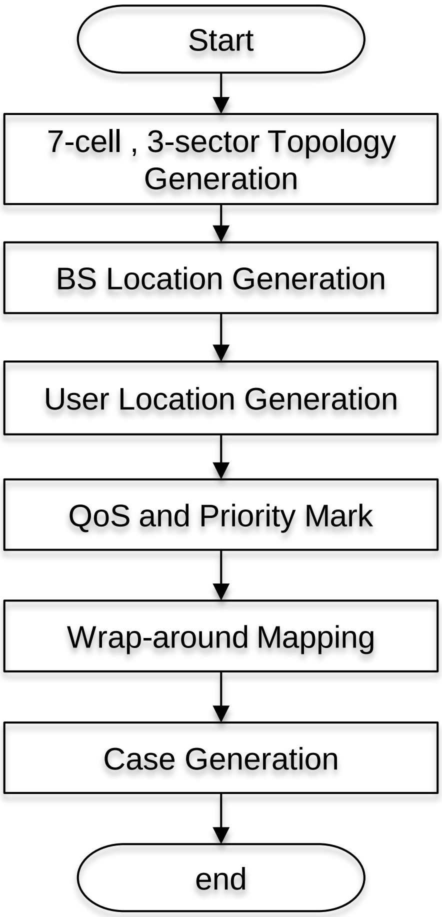

Figure 16 The flow chart of the initialisation module

3.2.2 Channel creation module

The channel creation module generates channels by adding large scale fading including path loss and shadow fading. The thesis focuses on system capacity investigation, which is only related to the average signal condition, so small scale fading is not considered here [39]. The channel gain, the ratio of received power to transmit power, represents the quality of the channel and hence the quality of the transmission. Figure 17 is the flow chart of this module.

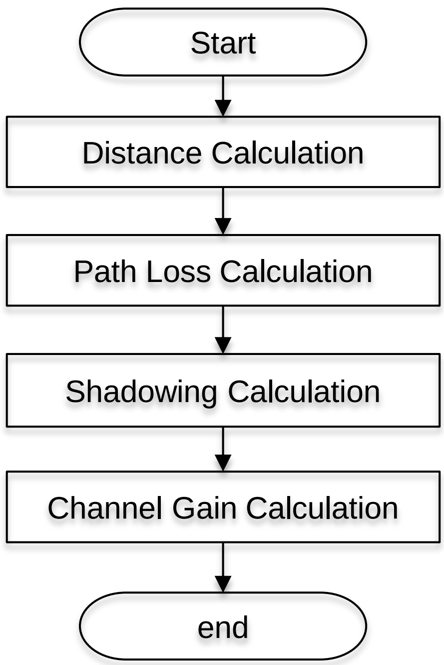

Figure 17 The flow chart of channel creation module

3.3 Local planning layer

The local planning layer is the core part of the simulator. It is responsible to analyse the case and execute a one shot resource allocation algorithm and measure the system performance.

3.3.1 CQI feedback module

Figure 18 shows the road map of the CQI feedback module. The CQI information is the Signal and Interference and Noise Ratio (SINR) of users of a BS on all SCs. By knowing the received signal power, inter-cell interference from co-channel users and white noise, the SINR can be calculated.

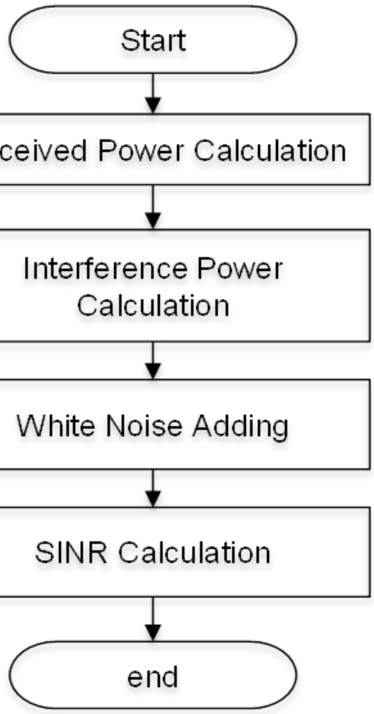

Figure 18 The flow chart of CQI feedback module

3.3.2 *Resource allocation module*[16]

This is where the cases are implemented in terms of channel allocation. Here it is assumed that each BS knows the conditions of its own channels and each BS runs the algorithm by itself without co-operation between BSs. All users in each BS in turn get the resources they require, subject to constraints on such aspects as priority.

The main functional modules of the allocation algorithm are briefly described below:

- **Initial prioritised SC allocation**: the sectors in every cell allocate their SCs to their users in an order that is intended to reduce ICI. As no interference information can be obtained beforehand, the number of SCs is roughly calculated by the user's required bitrate, the noise and a predefined constant value to estimate the ICI.

[16] The flow chart of this module is given in section 4.3.4.

- **SC release**: releases the SCs of users who cannot achieve their required bitrates (so-called unqualified users).

- **SC reallocation:** reallocates the available SCs to those unqualified users.

- **Priority compensation**: this module is only activated when PUs exist and must get their required bitrate. It determines the unqualified PUs in the system and compensates those PUs with additional SCs to reduce the ICI so they can achieve their required bitrates. If insufficient vacant SCs are available, the SCs from SUs are reclaimed.

3.3.3 System performance measurement module

The QoS satisfaction, overall throughput and fairness index are calculated. QoS satisfaction represents users' satisfaction on the quality of the service delivered by the system and is measured by the proportion of qualified users in the system. The overall throughput is the sum of bitrates obtained by all the users in the system. The fairness index measures how evenly the users share the system throughput.

3.4 **Reactive layer**

3.4.1 Systematic adjustment module

It only applies when the trigger criterion (shown as Trigger1 in Figure 15) is met. The trigger indicates certain types of changes have happened so that the system is no longer adequate to reach the required level of performance, in particular poor QSR. At that time the system will adjust the parameters to improve the system performance in the new environment. However, some individual benefits might be sacrificed after the adjustments in order to achieve the overall system-level goal.

3.5 Simulator system parameters

An OFDMA cellular network is considered here according to IEEE 802.22 [37] and LTE [38]. The research topic is derived from CR networks but it is more generalized than CR which enables it to be applicable in general OFDMA network. To have a comprehensive investigation of the proposed algorithm with different systematic settings, two sets of parameters are used as listed in Table 2: one is IEEE 802.22 for CR and the other one is based on DL LTE. A massive amount of simulation tests has been done based on both parameter sets. Due to space limitations, every simulation test is shown with one of two parameter sets.

Table 2 Table of transmission parameters

Parameter	Set 1 (CR)	Set 2 (LTE)
Bandwidth	6MHz	10.24MHz
Frequency	300MHz	2GHz
Total number of SCs	2048	1024
Number of data SCs	1440	960
SC bandwidth	3kHz	10kHz
Cell radius	30km	1km

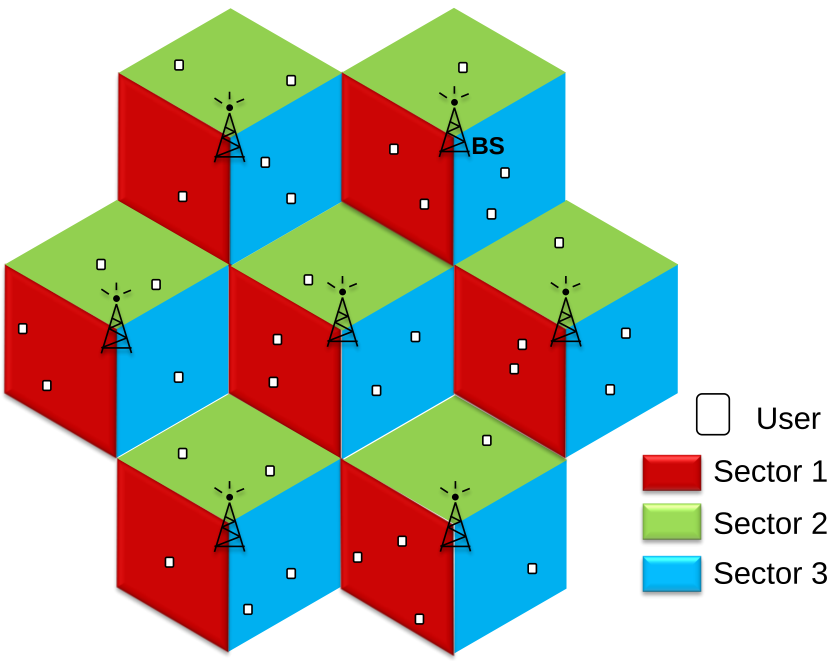

Figure 19 The system scenario

As listed in Table 3, the scenario represents a suburban area that consists of an OFDMA network with 7 hexagonal cells as shown in Figure 19. For Set 1, the cell radius is 30 km and 1 km for Set 2. Wrap-around is applied to fully represent the ICI conditions of the outer cells. The BS adopts a 3-directional transmit and receiving antenna that splits a cell into three equal sectors and each user has an omni-directional transmit and receiving antenna.

Table 3 Table of system parameters

Parameter	Set 1 (CR)	Set 2 (LTE)
Network layout	hexagonal grid, 7-cell sites	
Scenario environment	Suburban	
BS height	75m	
User antenna type	Omni-directional	
BS antenna type	3-directional	
BS antenna gain	12dBi	18dBi
User antenna gain	10dBi	18dBi
Thermal noise density	-106.22 dBm/Hz	

3.6 Channel model

The quality of the radio channel plays an important role in the quality of communications. It is mainly affected by several factors [39]:

- *path loss* represents the transmission loss of the wave travelling through air; this is shown as the black line in Figure 20. It is mainly determined by the distance and the surrounding environment.

- *shadow fading* (also called *slow fading*) occurs when big obstacles like hills and buildings block the main path of the radio transmission. The channel variation caused by shadow fading is normally modelled as a log-normal distribution. The superposition of path loss and shadow fading is shown as the red dashed line.

- *multipath fading* (also *small scale fading*) is caused by the diffraction and reflection combining signal components with different phases, fading levels and delays, in-phase combination enhances the signal strength and out-of-phase weakens the signal.

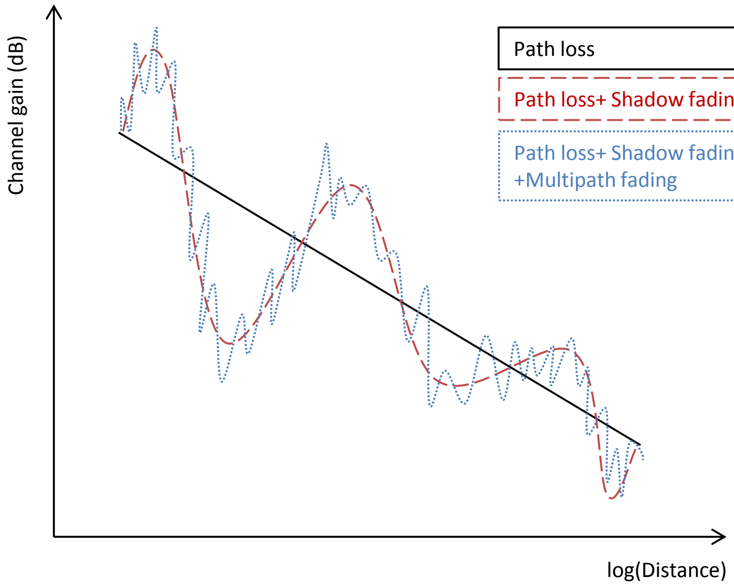

Figure 20 Attenuation types[17]

As small scale fading causes the signal strength to change rapidly and generally by a small amount, it does not have much effect on the average strength of the signal [39]. As this research only involves a system-level simulation concerning the average performance, small scale fading is not considered in this simulator.

3.6.1 Path loss model

The path loss model describes the average power of the received signal. The COST231-Hata model [41] for 1.5 GHz -2GHz and Okumura-Hata model [40] for 150MHz-1.5GHz are used in the simulator. The relevant equations extracted are listed below.

$$\overline{L_p} = A + B\log(d) + C \qquad \text{Eqn 3.1}$$

[17] Figure 20 from reference [39]

where $\overline{L_p}$ is the path loss in dB, A, B, and C are factors that depend on frequency and antenna height. d is the distance between transmitter and receiver in km.

For 150MHz-1.5GHz (Okumura-Hata)

$$A = 69.55 + 26.16\log(f_c) - 13.82\log(h_b) - a(h_m) \quad \text{Eqn 3.2}$$

For 1.5GHz-2GHz (COST321-Hata)

$$A = 46.3 + 33.9\log(f_c) - 13.82\log(h_b) - a(h_m) \quad \text{Eqn 3.3}$$

$$B = 44.9 - 6.55\log(h_b) \quad \text{Eqn 3.4}$$

Where f_c is given in MHz and the function $a(h_m)$ and the factor C depends on the environment. For a suburban environment [40]:

$$a(h_m) = 0 \quad \text{Eqn 3.5}$$

$$C = -2\left[\log\left(\frac{f_c}{28}\right)\right]^2 - 5.4 \quad \text{Eqn 3.6}$$

3.6.2 *Shadow fading*

3.6.2.1 Shadow fading model

Shadow fading causes additional signal attenuation caused by blocking objects such as buildings between the transmitter and receiver. It is usually described as a random variable, which causes the received signal power to obey a log-normal distribution. A standard log-normal shadow fading model from [12] is employed:

$$L_p = \overline{L_p} + X_\sigma \quad \text{Eqn 3.7}$$

Where $X_\sigma \sim N(0, \sigma^2)$ and the standard deviation σ is set to be 10 dB for suburban environment [42].

3.6.2.2 Correlation of shadow fading at different locations

Since mobile users whose locations change slightly during consecutive sample times are considered, the correlated shadow fading experienced between these two locations needs to be calculated. An auto-correlation function in [42] is used here.

$$a_c = e^{-\frac{vT_s}{|d_c|}\ln 2} \qquad \text{Eqn 3.8}$$

Where a_c is the autocorrelation between two positions of a single mobile, separated by some time interval. v is the velocity of the mobile, T_s is the sampling interval, d_c is the de-correlation distance which depends on the environment. In a vehicular test environment d_c is 20m [42]. Therefore, the log-normal path loss L'_p after movement is normally distributed in dB with mean $a_c L_p$ and variance $(1 - a_c^2)\sigma^2$, denoted by $L'_p \sim N(a_c L_p, \sigma^2 (1 - a_c^2)\sigma^2)$ [43].

3.7 Inter cell interference model

Radio resource management aims to control co-channel interference at a system level. However, in cellular OFDMA network, intra cell interference does not exist because of the orthogonality between SCs within a cell, which makes inter cell interference the only target to mitigate. In this section, ICI is considered in more detail to give a better understanding of the core of the optimization; both UL and DL transmission are considered.

The following UL case is considered: a user i is transmitting to its BS using SC m in C1 while 6 other users in neighbouring cells are transmitting using SC m. The BS will get ICI on SC m from the 6 neighbouring users. However, since in the scenario here, the BSs use 3-directional antennas and users have omni-directional antennas, the ICI that the BS receives only comes from one of the three 120-degree angles. The location of the user determines the direction where ICI comes from.

Figure 21 illustrates where the potential ICI comes from for user *i* in C1. For the UL, BS will receive ICI from C4 and C6; for the DL, a user will receive ICI from all directions but only from those BSs that are transmitting towards the user shown as red areas. Table 4 shows the ICI sources for different locations. Cell x Sector y is denoted by Cx Sy.

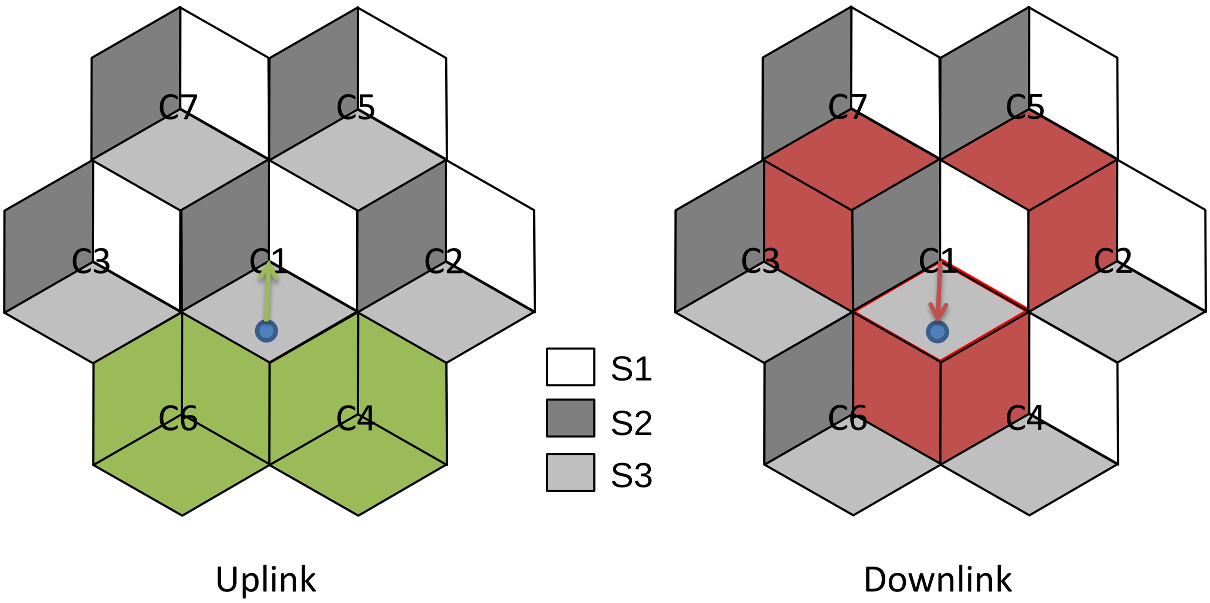

Figure 21 Illustration of ICI source

Table 4 Table of ICI source

Uplink		**Downlink**	
Location of user	ICI source	Location of user	ICI source
C1 S1	C2,C5	C1	C3 S1, C6 S1, C2 S2, C4 S2, C5 S3, C7 S3
C1 S2	C3,C7		
C1 S3	C4,C6		
C2 S1	C6,C7	C2	C1 S1, C4 S1, C5 S3, C6 S3, C7 S2, C3 S2
C2 S2	C1,C5		
C2 S3	C4,C3		
C3 S1	C1,C7	C3	C5 S1, C4 S1, C1 S2, C6 S2, C7 S3, C2 S3
C3 S2	C2,C4		
C3 S3	C6,C5		
C4 S1	C2,C3	C4	C6 S1, C7 S1, C3 S2,

<table>
<tr><th colspan="2">Uplink</th><th colspan="2">Downlink</th></tr>
<tr><td>Location of user</td><td>ICI source</td><td>Location of user</td><td>ICI source</td></tr>
<tr><td>C4 S2</td><td>C1,C6</td><td rowspan="2"></td><td rowspan="2">C5 S2, C1 S3, C2 S3</td></tr>
<tr><td>C4 S3</td><td>C5,C7</td></tr>
<tr><td>C5 S1</td><td>C3,C6</td><td rowspan="2">C5</td><td rowspan="2">C1 S1, C7 S1, C2 S2, C6 S2, C4 S3, C3 S3</td></tr>
<tr><td>C5 S2</td><td>C7,C4</td></tr>
<tr><td>C5 S3</td><td>C1,C2</td><td rowspan="3">C6</td><td rowspan="3">C2 S1, C5 S1, C4 S2, C7 S2, C1 S3, C3 S3</td></tr>
<tr><td>C6 S1</td><td>C1,C4</td></tr>
<tr><td>C6 S2</td><td>C3,C5</td></tr>
<tr><td>C6 S3</td><td>C2,C7</td><td rowspan="3">C7</td><td rowspan="3">C3 S1, C2 S1, C1 S2, C5 S2, C6 S3, C4 S3</td></tr>
<tr><td>C7 S1</td><td>C5,C4</td></tr>
<tr><td>C7 S2</td><td>C6,C2</td></tr>
<tr><td>C7 S3</td><td>C1,C3</td><td colspan="2"></td></tr>
</table>

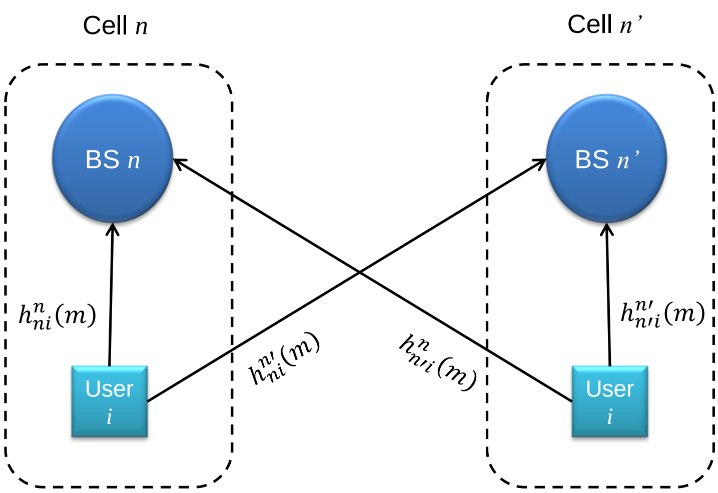

Figure 22 two-cell ICI model for UL transmission

Figure 22 shows the ICI model of a 2-cell case. $h_{ni}^{n}(m)$ is the channel gain between user i in cell n to the BS n on SC m. p_{ni}^{m} is the transmit power of user i in cell n on SC m. N_0^m is white noise on SC m.

The SINR on SC m is calculated as follows:

$$SINR_{ni}^{m} = \frac{h_{ni}^{n}(m)p_{ni}^{m}}{N_0^m + h_{n'i}^{n}(m)p_{n'i}^{m}} \qquad \text{Eqn 3.9}$$

3.8 Verification and validation

Verification is to demonstrate that the simulation platform functions correctly and validation aims to guarantee the results are valid and correct. This section shows simulation results to demonstrate the simulation platform works correctly and the performance comparison with [44] (applying their layout and parameter setting) shows that the simulation results in the proposed simulation platform is valid and convincing.

3.8.1 Verification of system layout

The first stage is to check that the initialisation module is putting entities in the correct place – and this is done by displaying the layout as shown in Figure 23 (for uniform distribution). The outer ring of cells (with users identified in black) forms the wrap-around virtual cells which is completely copied from corresponding real cells to ensure that the outer cells in the 7-cell cluster under investigation receive ICI properly. The BS is marked as a black triangle and the users in different sectors are marked as red, green and blue dots respectively. The users' locations are random with uniform distribution so the probability of a user being in an area should be linearly related to the size of area. Figure 24 shows the relationship between distance to BS and the probability of a user being in an area. The red line is the normalized size of area and the blue bars shows the probability increases linearly until the distance reaches the radius of the inscribed circle of the cell (≈ 0.866) and then decreases linearly. They have a matching pattern so that the user distribution is random as expected.

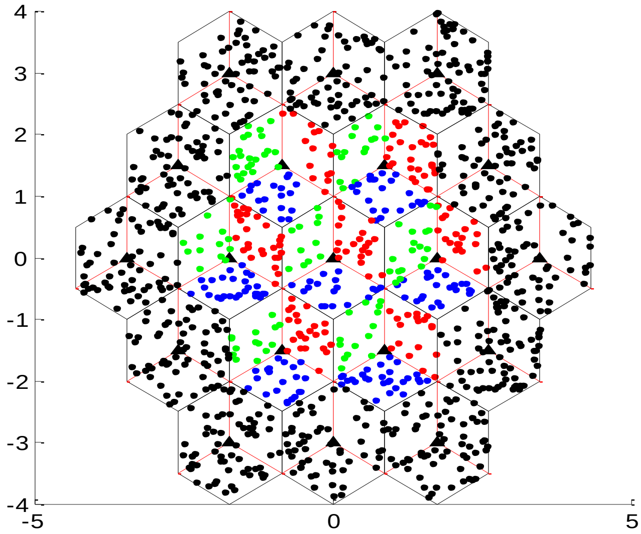

Figure 23 Scenario with uniform user distribution

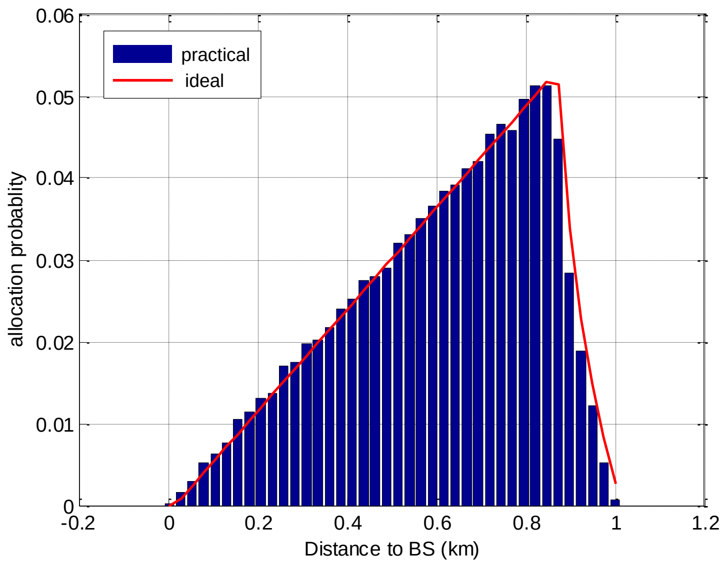

Figure 24 Uniform distribution probability vs. distance to BS

3.8.2 Verification of channel states

Figure 25 shows the large scale path loss (in dB) in blue line and log-normal path loss in red line. Parameter Set 2 and COST321-Hata model are used. The shadow fading loss is a normal distribution with mean 0 and standard deviation 10 dB. The blue lines give a performance similar to that in Figure 6 in [45] with the path loss between 40dB-120dB for distance 0-1km. Figure 26 compares the practical and ideal probability density function of shadow fading loss. The ideal one is derived from the normal distribution equation while the practical values are from the simulation results. It shows the shadow fading in the simulator matches the ideal one.

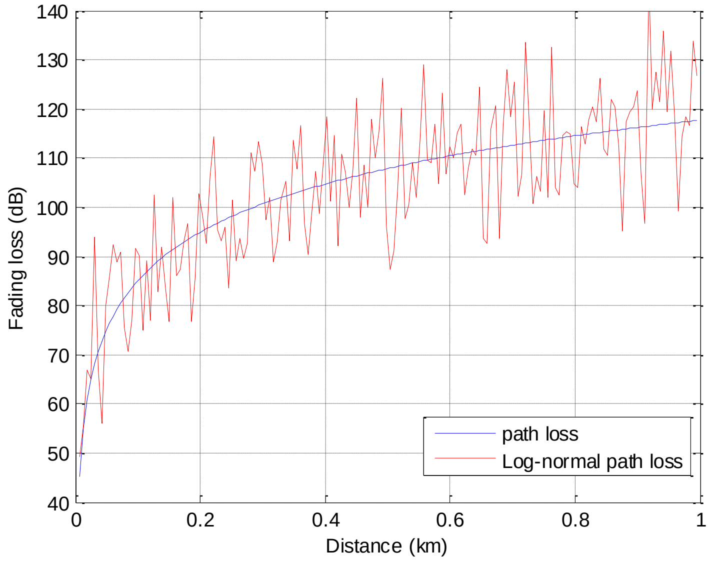

Figure 25 The path loss

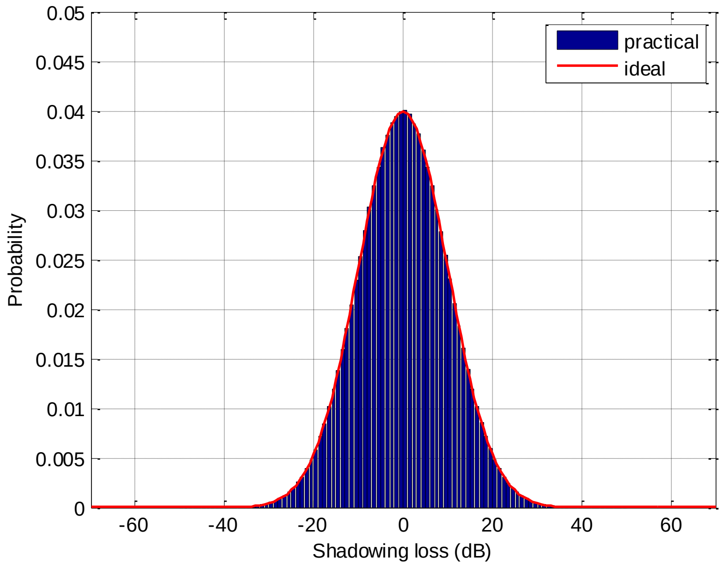

Figure 26 The shadow fading loss

3.8.3 *Platform comparison*

The platform is compared with the proposed algorithm and with those proposed in [44] applying their parameter set completely. [44] adjusts the frequency reuse factor of every sub-channel to minimise the maximum QoS violation ratio in pseudo-cells formed by strong interfering sectors in neighbouring cells. Three algorithms are proposed: DRA-NC is without coordination in a pseudo-cell; DRA-LC is with low coordination and DRA-FC is with full coordination. However, in [44] it is not clear whether there is consideration of the impact of edge cells on the whole system so the performance of the algorithm proposed here is shown with and without wrap-around in Figure 27.

Figure 27 compares the QoS violation ratio (the performance indicator in [44]) for the proposed algorithm with the results published in [44] as the total number of users per cell varies from 30 to 54. Although the results from the algorithm here are shown with and without wrap-around (to match that in [44]) the more accurate comparison is with wrap-around. The results clearly show that the algorithm described in this thesis can more efficiently allocate the SCs while there are sufficient resources. With wrap-around, the QoS violation ratio increases to the level of the DRA-FC algorithm from [44] at 50 users.

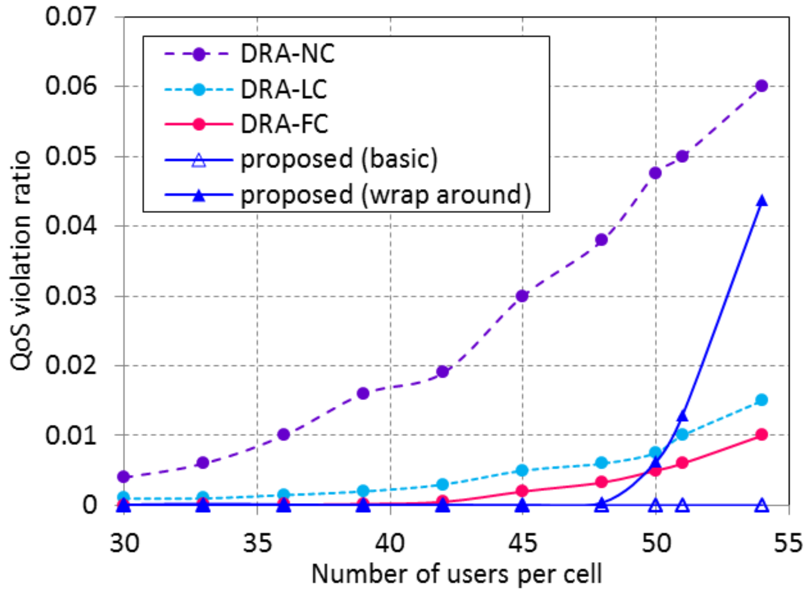

Figure 27 QoS violation ratio vs. the number of users per cell

3.9 Summary

In this chapter, the simulation platform built to implement the algorithm is described. The simulation platform is integrated in a three-layer architecture:

i) The management layer is in charge of long timescale activities including the initialisation, basic setting and channel creation. The relevant content is introduced in depth in this chapter.

ii) The local planning layer executes the proposed resource allocation algorithm on a snapshot and is embedded in the BS to do local decision making.

iii) The reactive layer is responsible for the most flexible functions of the system. It increases the feasibility and adaptability of the local planning layer to deal with more scenarios.

In the end, the comparisons here indicate that the simulation platform is designed and implemented correctly and the simulation results are valid.

Chapter 4 QoS-Aware Radio Resource Allocation

4.1 Introduction

Much research has been done on radio resource allocation in multi-cell OFDMA network to achieve different purposes. In a single cell OFDMA network, the importance of ICI is not considered, so the focus of resource allocation is mainly on multi-cell OFDMA network. To summarize, the objectives are mainly: i) system throughput optimization [46]-[57] and ii) transmit power minimisation [51] [58]-[62].

Much of the literature ([46][47][51][52][54][56]) considers highly efficient algorithms (illustrated by the Max C/I used for comparison in Chapter 4) that maximise the throughput for a given spectrum under some power constraints – this gives rise to the extreme case of "some users get much more capacity than they need while others can barely transmit". The system allocates those users with the best channel conditions with more spectrum than they need, leading to those with worse conditions not being able to achieve their QoS requirement at all.

To avoid this, the fairness should be considered. So the opposite extreme case (illustrated by the Round Robin (RR) approach in Chapter 4) is that "users share the resources fairly so, when there are insufficient resources, none of the users gets the desired QoS".

Both of the cases are poor in terms of user satisfaction and this is even more important in video transmission as the encoding rate of the video is determined before transmission when the raw video source is encoded. Having a larger transmission rate will not improve the quality of the video, but if the transmission rate is lower than the encoding rate, the viewer will experience a degraded service.

Therefore, QoS requirement should be given sufficient attention. It can be regarded as a criterion to balance the fairness and system level consideration. Trade-off between system demand and user requirement should be carefully balanced. It is essential to note that users will have a capacity requirement to achieve the QoS that will allow them to access the service they desire. Hence, it is essential to avoid cases like (i) "a few users get more capacity than they need while others can barely transmit" and (ii) "users share the resources fairly so none of the users gets the desired QoS".

The importance of QoS is also because of the need for high quality transmission with the rapidly increasing multimedia services. The other reason is the fierce competition within the telecom industry: better service quality attracts more users so making the operator more competitive. Now operators are not only concerned about their capacity but also the customer's individual satisfaction with the services provided.

As the importance of QoS is gradually being realized, it has been addressed in resource allocation problem in the form of constraints. Reference [58]-[64] aimed to minimise the power consumption subject to individual user transmission rates and/or bit error rate while [48]-[50], [53] and [55] maximised the system throughput or the weighted sum of user bitrates under individual QoS constraints: [48]-[50] set minimum QoS requirement for every user to reach; however, [53] and [55] only block a minimum amount of spectrum for every user to achieve fairness to some extent but no QoS guarantee for users. However, what if the QoS requirement can be regarded as the goal of a static resource allocation problem rather than constraints? It can link the system performance with the individual performance directly so that the operator can have a straight-forward look at the system performance in terms of user satisfaction. Reference [44] took a further step towards QoS provisioning with some limitations, presenting a low-overhead resource allocation algorithm with load balancing in a "pseudo cell" structure to minimise the maximum value of QoS violation ratios in a multi-cell OFDMA system. To achieve that goal, the frequency reuse factor of every SC in neighbouring cells is dynamically determined. The problems with that approach are that it needs a large amount of signalling exchange between pseudo cells and it is only applied with light load which is unrealistic in real network.

In this thesis, QoS is considered as the goal of the optimization. The QoS satisfaction ratio (QSR), which is the ratio of the number of users having their requirement reached to the total number of users served, is regarded as the indicator of measuring the system performance. It addresses more the individual QoS requirements and gives a direct measure of system performance based on user satisfaction with their services.

Here the SC allocation is formulated as a non-cooperative game with a distributed QoS-aware SC allocation algorithm to get the Nash Equilibrium. As there is no centralised SC allocation unit for the multi-cell system, every cell acts like a rational individual trying to maximise its payoff so this constitutes a non-cooperative game.

Moreover, because it is intended to be applicable in a CR scenario, the algorithm also needs to be fast because the radio environment can change as users move and primary users come and go.

4.2 Game formulation for spectrum allocation

In this research, a static scenario is considered: multiple users request spectrum (thus, SCs) from BSs to transmit in a multi-cell OFDMA network. Based on all gathered information, each BSs runs an algorithm and assigns the SCs to the users within its coverage. To avoid excessive signalling between BSs, non-cooperative game theory is suitable for modelling this kind of multi-person problem characterised by strategic interdependency [65]. However, that might cause a suboptimal solution [35]. In this game, every BS aims to decide the SC allocation scheme to maximise its number of qualified users, competing against other cells that are playing the same game at the same time. However, the utility of each cell depends not only on its own decision but also the decisions of the other players. By observing the channel conditions from round to round, the cells change their decisions accordingly until all the cells choose to stick to their current decisions. At that point, they have reached an agreement where no one can unilaterally increase its utility when others are sticking to their decisions. Everyone benefits the most from this decision making. This point of the stable decision set is called the Nash Equilibrium.

The game G is formed by three essential elements: the players $\mathbf{N}$, the action space $\mathbf{A}$ and the utility function $\mathbf{U}$.

- Players $\mathbf{N}$

  The BSs, where each BS is denoted by $n \in \mathbf{N} = \{1, .., N\}$

- Action space $\mathbf{A}$

  It is the SC allocation scheme of player n, denoted by $\mathbf{A} = \{a_{ni}^m\}, \forall i \in \mathbf{I}_n$. $\mathbf{I}_n = \{1,2, \dots, i, \dots, I_n\}$ is the user set of player n. a_{ni}^m is the SC allocation indicator of user i of BS n on SC m. If SC m is occupied by the user, $a_{ni}^m = 1$, otherwise 0.

- Utility function $\mathbf{U}$

  The utility of a player is its QSR, which is the ratio of users whose bitrate is at least the required bitrate within the coverage of player n. A user who satisfies this criterion is called a qualified user.

$$U_n = \frac{1}{I_n} \sum_{i \in \mathbf{I}_n} 1\left(r_{ni} \geq r_{ni}^{req}\right) \quad \text{Eqn 4.1}$$

  Where $1(x)$ is an indicator function that has value 1 if condition x is met and value 0 if not. r_{ni} and r_{ni}^{req} are the actual and required bitrate of a user i of player n.

There are 3 constraints arising from the network conditions:

i) The total transmit power of a single user cannot exceed the maximum transmit power P_{max}. The transmit power on a single SC is fixed to be p.

$$\sum_{m\in\mathbf{M}_{ni}} a_{ni}^{m} p \le P_{max}, \forall n \in \mathbf{N}, i \in \mathbf{I}_n \qquad \text{Eqn 4.2}$$

ii) In a cell, a particular SC can only be allocated to one user as this is the way OFDMA operates.

$$\sum_{i\in\mathbf{I}_n} a_{ni}^{m} = 1, \forall n \in \mathbf{N} \qquad \text{Eqn 4.3}$$

iii) To avoid users being greedy and taking an excessive number of SCs, an upper bound is set to a user's bitrate.

$$r_{ni} \le \beta r_{ni}^{req} \ where\ \beta \ge 1 \qquad \text{Eqn 4.4}$$

Apart from the ultimate goal of the game-QSR, two other performance indicators are measured as well:

i) the system throughput:

$$r = \sum_{n\in\mathbf{N}} r_n = \sum_{n\in\mathbf{N}} \sum_{m\in\mathbf{M}} B_m \log_2(1 + SINR_n^m) \qquad \text{Eqn 4.5}$$

Where $SINR_n^m$ is the SINR on SC m in cell n. B_m is the SC bandwidth. r_n is the sum of users' bitrates of cell n.

ii) Fairness on user bitrate from [66]:

$$F(r_{ni}) = \frac{(\sum_{n\in\mathbf{N}} r_{ni})^2}{N\left(\sum_{n\in\mathbf{N}} r_{ni}^2\right)} \qquad \text{Eqn 4.6}$$

where $r_{ni} = B_m \sum_{m\in\mathbf{M}_{ni}} \log_2(1 + SINR_{ni}^m)$

4.3 The QoS-aware SC allocation algorithm

The SC allocation is simplified into the problem of choosing the *number* of SCs and *the particular SCs* (their IDs). The main constraint is the ICI generated by the co-SCs in adjacent cells. The ICI mitigation is done by two approaches: i) applying directional antennas; ii) ICI mitigation embedded in the proposed algorithm which will be explained later. The power allocation is done together with the SC allocation with a fixed transmit power assigned on each SC. It would be possible to adjust the power of transmission, but here maximising QSR is the main concern rather than minimising the consumed power to serve a fixed number of users.

The proposed algorithm has three basic modules: (i) the initial prioritised SC allocation, (ii) the release of SCs occupied by unqualified users and (iii) the reallocation of those released resources.

4.3.1 Initial prioritised SC allocation

For the initial SC allocation, a prioritised scheme is employed rather than a random allocation. For the 3-sector 7-cell network: in BS n, the three sectors start allocating SCs to their users simultaneously from a separate block of SCs for each sector chosen to minimise the inter-cell co-channel interference. As shown in Figure 28, the spectrum for a player is equally split into 3 parts and each sector is allocated with one part. Then the users are served in the order of increasing distance from the centre of the cell and the SCs are allocated in turn. Increasing distance is used as a proxy for reducing SINR, but the allocation uses the actual SINR to determine the number of SCs required. Distance-based allocation and spectrum sectoring is to mitigate the effect of ICI. At this stage, a sector can only use the spectrum assigned to it. Later (§4.3.3) it will be seen that a sector can borrow SCs from a different sector in the same cell.

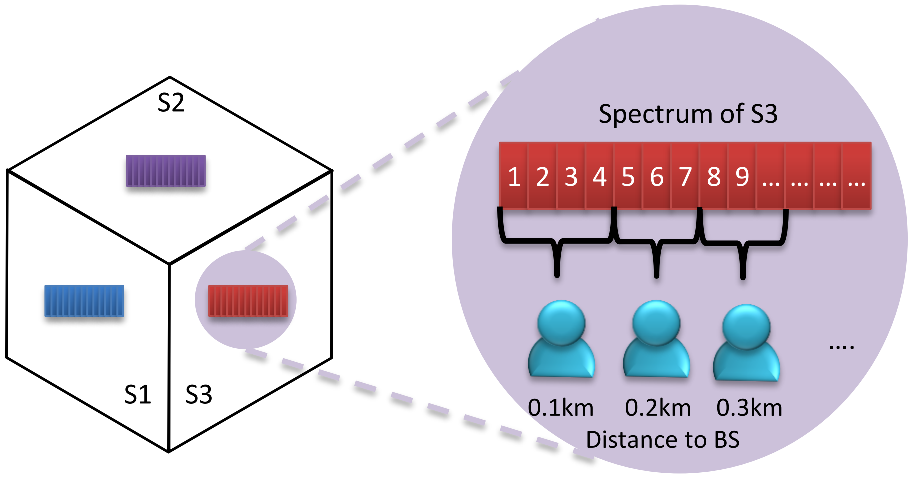

Figure 28 Initial prioritised SC allocation

The amount of SCs allocated to a user should be able to reach its required bitrate under the current interference condition. Since there is no ICI information available beforehand, it is assumed initially that every SC only has Additive White Gaussian Noise (AWGN) and the SINR on an SC is much greater than 1 ($SINR_{ni}^{m} \gg 1$). According to a well-known Shannon approximation in [67], the required bitrate can be calculated as below,

$$r_{ni}^{req} \approx \frac{B_m}{3.01} \sum_{m \in \mathbf{M}_{ni}} (SINR_{ni}^{m})_{\text{in dB}} \qquad \text{Eqn 4.7}$$

This approximation is used to ease the calculation of the required number of SCs during the game. However, it should be noted that the approximation gives a pessimistic view of the capacity available for a given SINR as shown in Figure 29 so that the allocation algorithm will over-allocate SCs. However, in the evaluation of the capacity after the game the exact form is used.

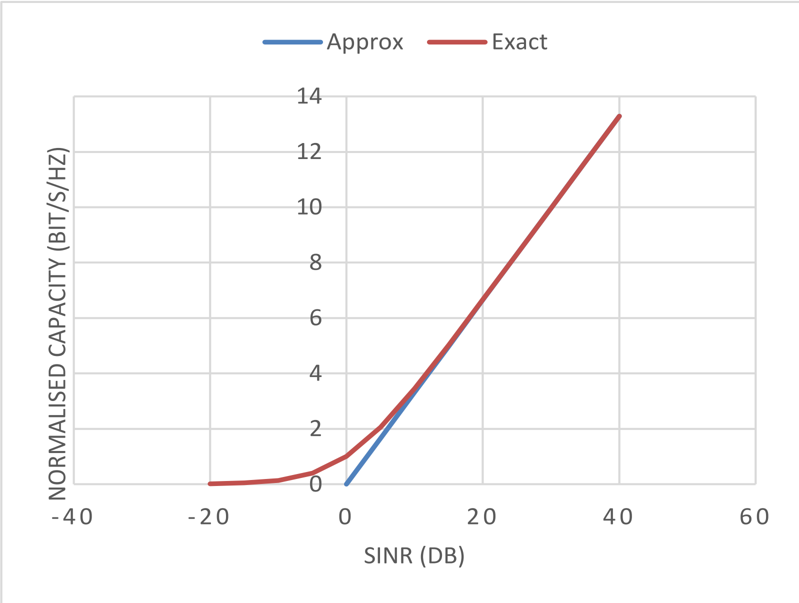

Figure 29 Comparison of Shannon theorem and the approximation

By using Eqn 4.7, the required bitrate in dB is further transformed:

$$r_{ni}^{req} = \frac{B_m}{3.01} \sum_{m \in \mathbf{M}_{ni}} 10\log_{10}\left(\frac{h_{ni}^{n}(m) a_{ni}^{m} p}{N_0^m}\right) \qquad \text{Eqn 4.8}$$

$$= \frac{10B_m}{3.01} \sum_{m \in \mathbf{M}_{ni}} \log_{10}\left(\frac{h_{ni}^{n}(m) a_{ni}^{m} p}{N_0^m}\right) \qquad \text{Eqn 4.9}$$

The number of SCs for user i in cell n is denoted by A_{ni}. As $h_{ni}^{n}(m)$, N_0^m and p are fixed currently, Eqn 4.9 is transformed:

$$r_{ni}^{req} = \frac{10B_m}{3.01} A_{ni} \log_{10}\left(\frac{h_{ni}^{n}(m) p}{N_0^m}\right) \qquad \text{Eqn 4.10}$$

Therefore, the number of SCs a user needs can be calculated by the following equation,

$$A_{ni} = \left\lceil \frac{3.01 r_{ni}^{req}}{10B_m \log_{10}\left(\frac{h_{ni}^{n}(m) p}{N_0^m}\right)} \right\rceil \qquad \text{Eqn 4.11}$$

In the *initial* allocation using Eqn 4.11, the SCs are assumed to only have noise with no ICI present. However, after the first round allocation, ICI is generated and can be calculated. In this case, A_{ni} normally cannot ensure the required bitrate because of the interference reducing the perceived SINR. A user is likely to need more SCs than A_{ni}. To predict the effect of ICI and to allow more users to get their required bitrate, a guard parameter is used: so instead of r_{ni}^{req}, r_{ni}^{grd} is used in the calculation where:

$$r_{ni}^{grd} = C_1 r_{ni}^{req} \; where \; C_1 > 1 \qquad \text{Eqn 4.12}$$

So that Eqn 4.11 becomes:

$$A_{ni} = \left\lceil \frac{3.01 r_{ni}^{grd}}{10 B_m \log_{10}\left(\frac{h_{ni}^{n}(m)p}{N_0^m}\right)} \right\rceil \qquad \text{Eqn 4.13}$$

The pseudo-code of this module is described below. The block of SCs belonging to sector s is denoted as $\mathbf{M}_{ns}$. The user set located in sector s is denoted as $\mathbf{I}_{ns}$. $\mathbf{I}_{ns}^{u}$ is the subset of $\mathbf{I}_{ns}$ which contains unallocated users and $\mathbf{M}_{ns}^{u}$ is the subset of $\mathbf{M}_{ns}$ which contains unassigned SCs. d_{ni}^{n} is the distance between user i and its BS n.

Pseudo-code 1 Initial prioritised SC allocation

```
FOR cell n ∈ N
    FOR sector s=1:3
        Set I^u_ns = I_ns and M^u_ns = M_ns
        WHILE I^u_ns ≠ ∅
            Select user i* = arg min_{i∈I^u_ns}(d^n_ni);
            Calculate A_ni* using Eqn 4.13;
            Select A_ni* SCs starting from the smallest SC ID;
            Allocate the SCs to user i* and update a^m_ni*
            Remove i* from I^u_ns and update M^u_ns;
        END
    END
END
```

4.3.2 *SC release*

This module takes away the SCs allocated to users that turn out to be unqualified users after one round of all-cell SC allocation so they can be reused for users that could benefit from them. It is important to remember that this research is concerned with *qualified users*, so that a user who is not qualified is simply "hogging" resources that could be used to help qualify another.

After one round of SC allocation of all cells, the actual bitrate of every user r_{ni} is calculated (using the exact form of Shannon) and then compared with r_{ni}^{req}. If $r_{ni} \geq r_{ni}^{req}$, user i is put into the qualified user pool of cell n; otherwise, into the unqualified user pool, denoted by $\mathbf{I}_n^{unQ}$. The SCs occupied by the unqualified users will be released and put into the unqualified SC pool of cell n, denoted as $\mathbf{M}_n^{unQ}$ while the SCs occupied by qualified users are in the qualified SC pool, denoted as $\mathbf{M}_n^{Q}$.

Having unqualified users occupying resources that are actually not sufficient to allow those users to meet their required QoS is a waste. Rather than giving some users this resource that does not meet their requirement, the resource is taken back and distributed to those who are likely to meet their requirement if they were given the released SCs.

On the other hand, if a qualified user takes too many SCs so that its bitrate exceeds an upper bound as stated in Eqn 4.4, the SC release module releases the extra SCs in order of increasing SINR until the user's bitrate is below the bound. β in Eqn 4.4 defines the upper bound of the maximum bitrate. Those released SCs are also put into $\mathbf{M}_n^{unQ}$ and ready for reallocation. This is shown in the pseudo-code below.

Pseudo-code 2 SC release

```
FOR cell n ∈ N
    FOR i ∈ I_n
        Calculate r_ni;
        IF r_ni ≥ r_ni^req    %for users whose bit rate is no less than required bitrate
            i ∈ I_n^Q ;
            IF r_ni ≤ βr_ni^req
                M_ni ⊂ M_n^Q ;
            ELSE
                WHILE M_ni ≠ ∅  %release extra SCs from overqualified users
                    m* = arg min_{m∈M_ni}(SINR_ni^m) ;
                    Remove m* from M_ni and add m* to M_n^unQ;
                    Update r_ni and a_ni^m;
                    IF r_ni ≤ βr_ni^req
                        Break;
                    END
                END
                M_ni ⊂ M_n^Q;
            END
        ELSE %for unqualified users
            i ∈ I_n^unQ;
            M_ni ⊂ M_n^unQ;
            Set M_ni = ∅ and update a_ni^m  %release all SCs from unqualified users
        END
    END
END
```

4.3.3 SC reallocation for unqualified users

Following the release of SCs, the status is that (i) qualified users occupy enough SCs to keep them qualified while (ii) unqualified users have no SCs as the SC release module has taken them all back into the pool. Then the cells start a process of reallocating $\mathbf{M}_n^{unQ}$ to $\mathbf{I}_n^{unQ}$ within each sector.

If necessary, SC borrowing will occur between sectors within a cell. Of course the reallocation of SCs will add ICI and the borrowing between sectors will exacerbate that effect since the borrowed SC will be nearer its neighbouring co-channels. The consequence will be some users especially at the edge of cells that were qualified with the previous interference map will become unqualified after this round of allocation. Therefore, this process must be carried out iteratively with the SC release module after each round.

In one cell, the unqualified users from $\mathbf{I}_n^{unQ}$ (in order of increasing distance from the BS) choose SCs from the vacant SC pool $\mathbf{M}_n^{unQ}$; they choose SCs in order based on (i) those SCs allocated to the same sector and (ii) the best SCs in terms of SINR perceived by that user taking into account the ICI. The received bitrate will be calculated whenever a new SC is assigned to the user. The assignment stops when r_{ni}^{req} is reached.

After each round each BS will have a table that saves information including the interference on each SC. With the directional 3-sector antenna, the interference received on a specific SC depends on the location of the user that uses it and particularly which sector the user belongs to as explained in §3.7. Also when the user chooses SCs, it gives priority to SCs belonging to its own sector until that sector has no vacant SCs; it then starts borrowing vacant SCs from the other two sectors in the same cell.

However, as the ICI information is calculated from the last round of all-cell allocation to reduce the signalling between BSs and users, it cannot precisely represent the interference for the allocation in the current round. Also the SC release will generate SCs only with noise and that will cause error on the calculation of SC numbers allocated for the following round. For example, the worst case is when all the users are unqualified and all SCs are released when the SC release module runs: this will cause an endless loop as all the SCs have only noise on so the SC assignment for all users are always the same and none are qualified in that case. To prevent such situation from happening, a correction factor θ_{ni} which will be added to the number of assigned SCs is introduced here: this corrects the number of SCs allocated to one unqualified user according to the users' allocation history. At the beginning, all θ_{ni} are initialised to be 0. After one round of all-cell allocation, if a user is unqualified, θ_{ni} is increased by 1, which means during this iteration, the user will be allocated one extra SC. θ_{ni} accumulates through iterations. The value of θ_{ni} determines the speed of the convergence and also the performance. A bigger θ_{ni} can achieve faster convergence but might give more SCs than really needed, so wasting resources. So θ_{ni} is increased by the smallest step, which is 1.

$$\theta_{ni}(t) = \begin{cases} \theta_{ni}(t-1) + 1 \\ \theta_{ni}(t-1) \end{cases} \qquad \text{Eqn 4.14}$$

Pseudo-code 3 SC reallocation

```
FOR cell n ∈ N
    WHILE I_n^{unQ} ≠ ∅
        User i* = arg min_{i∈I_n^{unQ}}(d_ni);
        Calculate r_ni*, Obtain M_ns^{unQ} & θ_ni*;
        % allocate SCs to reach required bitrate
        WHILE r_ni* < r_ni*^{req}  %when the actual bitrate is lower than the required bitrate
            IF M_ns^{unQ} ≠ ∅
                m* = arg max_{m∈M_ns^{unQ}}(SINR_ni*^m);
                Allocate SC m* to user i*
                Update a_ni*^m and M_ns^{unQ}, Calculate r_ni*;
            ELSE %SC borrowing from other sectors
                m* = arg max_{m∈M_ns'^{unQ}}(SINR_ni*^m);
                Allocate SC m* to user i*
                Update a_ni*^m and M_ns'^{unQ}, Calculate r_ni*;
            END
        END
        FOR a = 1: θ_ni*; %allocate θ_ni* SCs to the user for precaution.
            IF M_ns^{unQ} ≠ ∅
                m* = arg max_{m∈M_ns^{unQ}}(SINR_ni*^m);
                Allocate SC m* to user i*
                Update a_ni*^m and M_ns^{unQ};
                Calculate r_ni*;
            ELSE %SC borrowing from other sectors
                m* = arg max_{m∈M_ns'^{unQ}}(SINR_ni*^m);
                Allocate SC m* to user i*
                Update a_ni*^m and M_ns'^{unQ};
                Calculate r_ni*;
            END
        END
    END
END
```

4.3.4 Overall algorithm

The algorithm is as follows and the overall flow chart is shown in Figure 30:

i) **Initial prioritised SC allocation** and initialise the correction factor θ_{ni}

ii) **SC release**: calculate r_{ni} and release the SCs allocated to unqualified users and then increase their θ_{ni} by 1.

iii) **SC reallocation** for those users still unqualified.

iv) SC release and increase their θ_{ni} by 1 for unqualified users.(as in step (ii)).

v) Go back to step (iii) and continue the process until the SC allocation result converges or the maximum iteration value is reached. The condition for determining convergence is the SC allocation scheme of the system remains the same for two consecutive iterations.

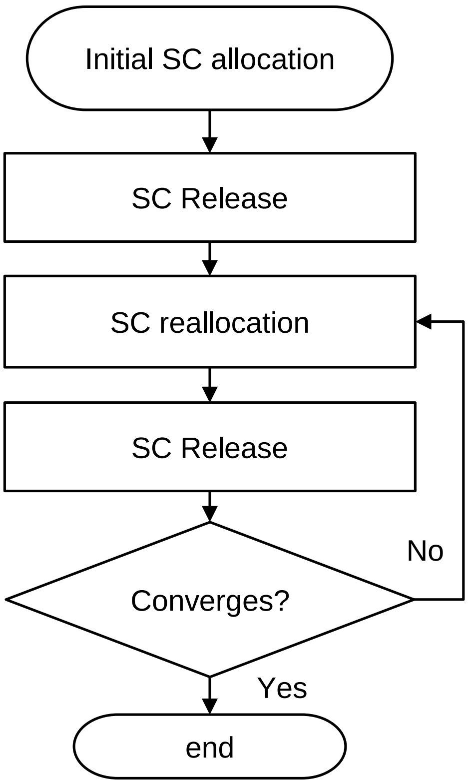

Figure 30 The flow chart of the overall algorithm

4.4 **Validation**

4.4.1 System model evolution

This section explains the reason for using a 7-cell wrap-around model with smaller cell radius. Most work on CR uses a large cell radius (typical 33km) based on concepts from IEEE 802.22 [37] but this is for the sake of coverage over capacity. It assumes suburban and rural environments where fewer people require a relatively small number of services so that system capacity is not a problem. However, prediction shows massive amount of services and higher quality requirements in the future, even in a suburban area [72] Moving towards that scenario here, capacity, especially for high bitrate service traffic, will be more important and a multi-cell network layout is the normal approach to increase the system capacity. However, it is not clear whether this will be a traditional mobile network layout or a small number of cells covering a hotspot area. The former is traditionally modelled as a wrap-around model, but if it is a small cluster then a basic linear layout is more representative as it takes into account edge effects that will really be there – and these can be important as the edge sectors do not suffer from co-channel interference.

However, for this research the first approach is applied as it is a more likely representation. The SC allocation algorithm is tested based on three system models: (i) basic 7-cell without wrap-around, (ii) basic 19-cell without wrap-around and (iii) wrap-around 7-cell. Figure 31 shows the results for the number of qualified users (each requiring 500kbps). The result is the average value of 50 runs. From the figure, the importance of wrap-around is obvious.

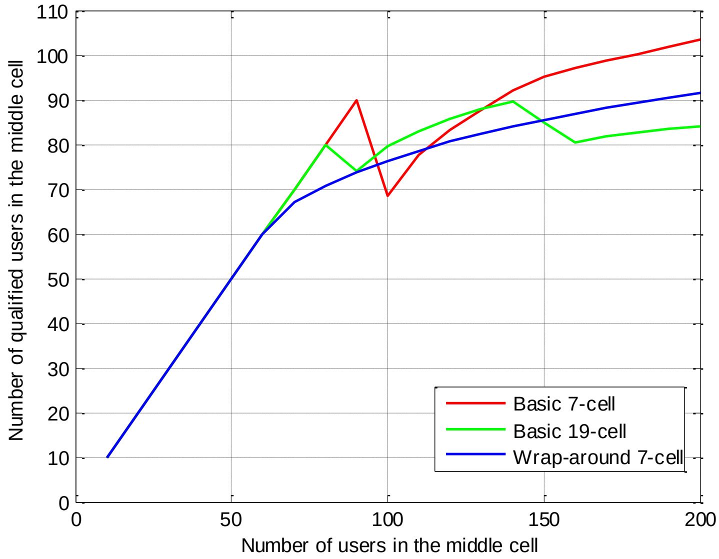

Figure 31 Number of qualified users vs. number of users/cell

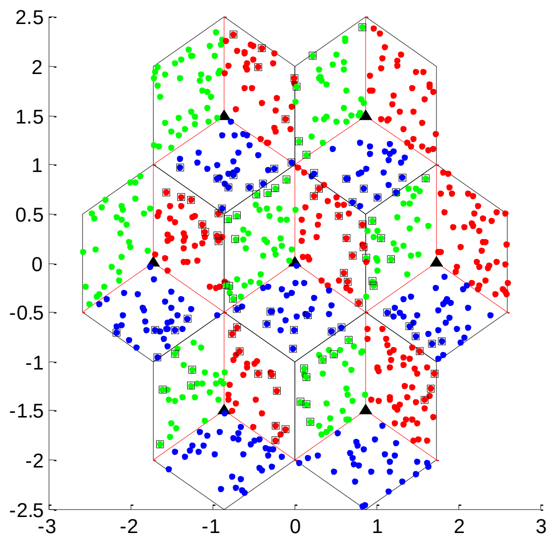

Figure 32 the basic 7-cell system layout when 100 users/cell

In the basic 7-cell system, there are two obvious phases: over-supply and over-demand. In over-supply, all users are qualified with the system still having vacant SCs; as the number of users increases, more demand makes the competition for SCs fiercer. As the demand increases the edge sectors of the outer ring of cells suffer less interference (no adjacent sector) so that all the users in those sectors can become qualified by using a small amount of SCs and a large portion of SCs are still available. Other sectors in those edge cells can easily borrow from those edge sectors to satisfy their unqualified edge users. The borrowing itself brings ICI. Additionally assigning borrowed SCs to edge users in the outer ring of cells exacerbates the effect. Surrounded by this ring of edge cells, the users already qualified in the middle cell experience severe interference and become unqualified; at the same time the edge cells get improved performance. That is why there is a big drop in performance with 90-100 users for the middle cell.

As shown in Figure 31, after 100 users, the situation recovers as the degree of over-demand increases since the number of available SCs reduces and the number of unqualified users grows. This might be thought to make the performance worse, but a greater number of users means there are likely to be more nearer the centre of the cell. As the algorithm will first deal with users closer to the cell centre, the limited number of SCs available means that edge users get less chance to be served and so the interference reduces – there is less chance for borrowing. The user serving order contributes to the increase.

Considering the different amount of interference each cell receives, it is now obvious that the 7 cells can be classified into edge cells that get better performance and the middle cell that is always the one with worst performance (Figure 32 shows an example with 100 users/cell where the unqualified users are marked by squares.). To minimise this impact, the middle cell performance is investigated in a basic 19-cell system. This has two layers of cells surrounding the middle cell and mitigates the effects of ICI on the performance with a smaller drop coming earlier (at 90 users) than the basic 7-cell system. It means the middle cell still gets affected by the 2nd round edge cells, even though the 1st round surrounding cells but the effects are initially lighter. However, as the demand becomes even higher the larger number of edge sectors eventually means there is a second drop in performance as the interference effects and borrowing gets worse.

By employing wrap-around, there are no edge cells and all sectors are subject to full map of ICI. This means there is no impact from the edge interference and the performance of every cell is similar. This model is adopted for the rest of this work as it (i) better represents a cellular OFDMA network over a large area and (ii) avoids the complications of lack of edge-sector interference impacting on the centre cell.

4.4.2 Performance stability check

As is usual with simulation, the results of multiple runs are averaged. Figure 33 and Figure 34 show the maximum, average and minimum values of throughput and QSR for 20 runs, 50 runs and 100 runs. From the figures, different numbers of runs gives similar average results and the difference between maximum and minimum values for every value user density is quite small. For all the average results given in this thesis, the number of runs over which the results are averaged is 50.

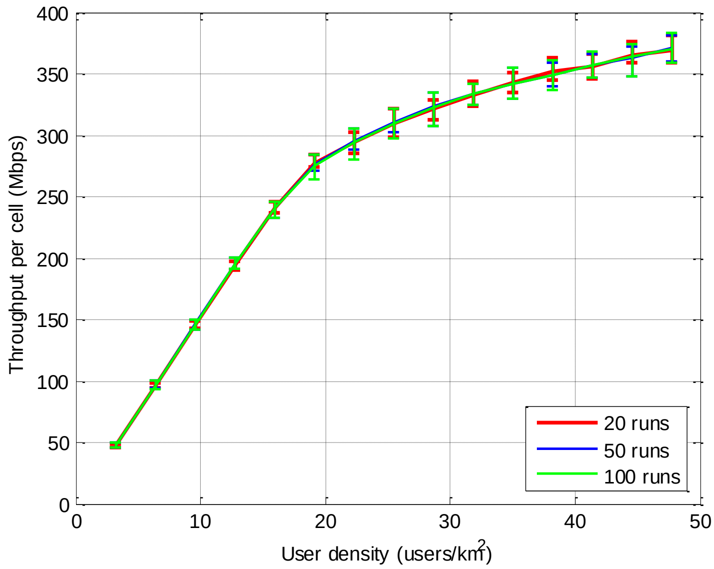

Figure 33 Variation of system throughput

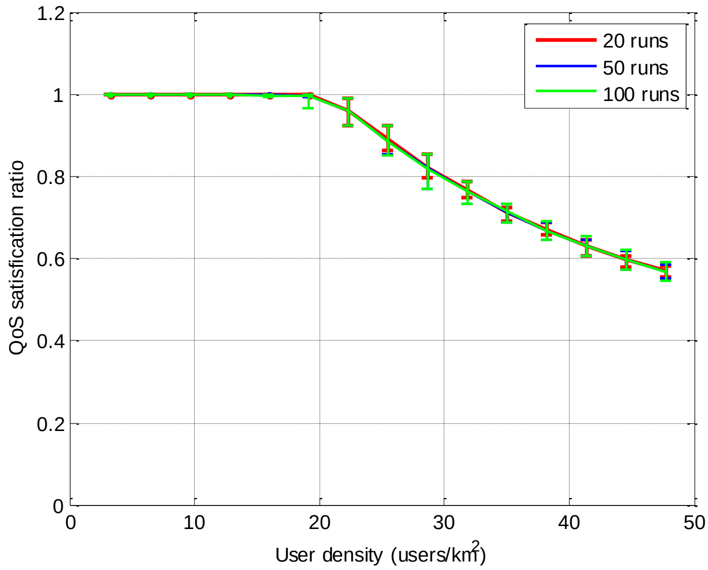

Figure 34 Variation of QSR

4.4.3 Throughput check

The ideal case for this approach is that all qualified users have the exact required bitrate (e.g. 500kbps/user) and all unqualified users have none. The practical case is what the proposed algorithm achieves. In fact, the ideal case cannot be achieved perfectly because the process will allocate a small number of extra SCs because of the way it has to take into account ICI as explained in §4.3.1 and §4.3.3. The practical case is calculated by using Eqn 4.5. The qualified users have a slightly higher bitrate while unqualified users get none.

It is shown in Figure 35 that the overall throughput of practical case is higher than the optimal, so there is some waste in resources. However, this is "safer" than having qualified users with just enough resource as then any marginal change (for example through slight user movement) could cause them to become unqualified. Note that the effect of movement is considered in §5.3.2. The "knee" at user density=20 is because the number of SCs starts to become insufficient to serve all users.

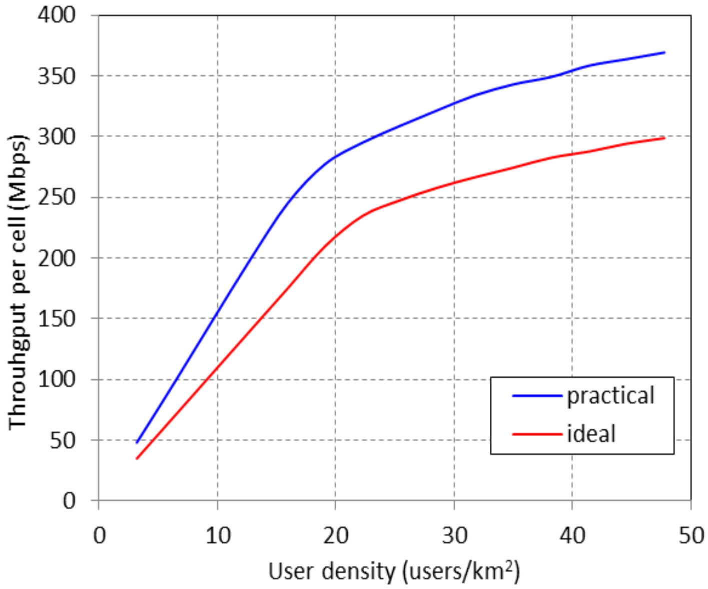

Figure 35 Optimal vs. practical bitrate

4.4.4 *Platform validation*

To validate the algorithm and platform, Iterative Water Filling (IWF) [25] [69] is used as the benchmark. IWF is a typical distributed and iterative algorithm to allocate channel/power that has been widely applied in non-cooperative games [25]. In order to embed IWF into the simulation platform and compare with the proposed algorithm, certain changes are made by the author. As fixed power allocation is used in this research, the modified IWF only does channel allocation. Thus, IWF chooses a fixed number of the best SCs for every user in every sector subject to a maximum power constraint and the users are randomly served. System parameter Set 1 is used. Each user requests 384kbps. Two user distributions are considered here: (i) equal load in each sectors (uniform distribution with the ratio of 1:1:1); and (ii) different loads between sectors with the ratio of 1:2:7.

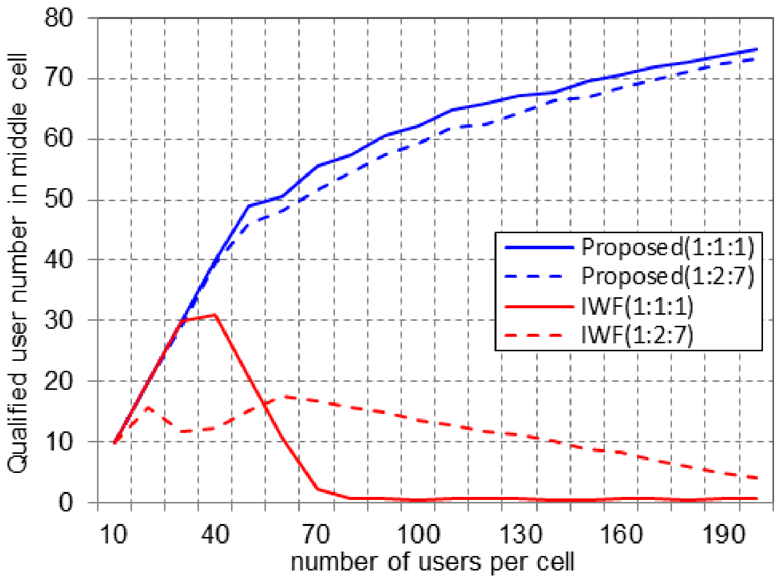

Figure 36 Number of qualified users vs. the number of users per cell

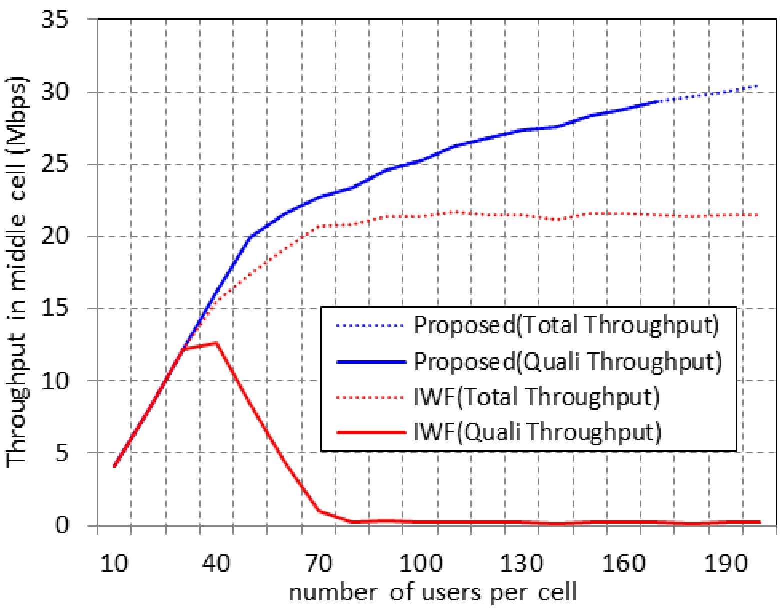

Figure 37 System throughputs vs. the number of users per cell for 1:1:1 case

Figure 36 shows the number of qualified users per cell for both user distributions. For the proposed algorithm, while there are sufficient resources, the increase in qualified users is directly proportional to the load, but then tends to saturate as all the resources are used. The reason for the small slope after saturation is that, as more users are added, the BS selectively serves the users so that more of the qualified users are closer to the cell centre and so have better channel conditions.

On the other hand, the IWF emphasises fairness by serving users the same amount of SCs. It achieves the same performance as the proposed one when there are few users and resources are available. However, when more users appear, more ICI is introduced. Spreading the uneven resources among users will cause some users to have insufficient to meet their QoS requirements so the number of qualified users starts to decrease until a certain point when none are qualified.

When dealing with the 1:2:7 case, the proposed algorithm still has a similar performance, which means it can achieve dynamic resource allocation as well as controlling the ICI. However, the borrowing must cause more ICI, so the total number of qualified users is slightly less than that in the 1:1:1 case. IWF does not cope well with the unbalanced case as the more heavily loaded sectors run out of resource more quickly; however, it does not reduce to zero so rapidly because the lightly loaded sectors still contribute some qualified users.

The throughputs (total and qualified throughput) are shown in Figure 37 for the 1:1:1 case. IWF is implemented in the simulation platform and it achieves a similar performance in system throughput as in [25] when the traffic load increases. The qualified throughput is the sum of the bitrates of all qualified users. For the proposed algorithm the qualified throughput is identical to the total throughput which means all resources are allocated to qualified users – so the algorithm is operating as intended and none of the throughput is wasted on the unqualified users. (The curve for qualified throughput is truncated at 170 users to show that the total throughput is the same and the curves overlap.)

On the other hand, IWF does not consider the QoS requirements so the total throughput is maintained as the number of users becomes high, but the qualified throughput is much less than the total (going down rapidly to zero) as then users cannot achieve their desired bit rates even if the system total throughput is high. Additionally, it is noticeable that the throughputs of the proposed algorithm are higher than even the total throughput of IWF as a mechanism (like Max C/I) to give higher priority to users having better channel conditions is employed.

4.5 Simulation results

This section investigates the proposed algorithm in several aspects. Note that system parameter Set 2 is used and the required bitrates for all users are 500kbps for this section.

4.5.1 Convergence

According to game theory, the sign of convergence is that all players keep the current strategy. In this case, when all the BSs maintain their current SC allocation schemes for the following iteration it means the algorithm has converged. The scheme maintained is the final SC allocation to be used in the transmission.

Figure 38 and Figure 39 show one example of the variation of (i) throughput, (ii) QSR, and (iii) used SC ratio (USR) during the convergence process. The user density is 30 users/km^2. When converged, the throughput is 340Mbps with 0.78 QSR and a USR of almost 1. The convergence can always be achieved within 10 iterations. The processing time is around 15s for a convergence in a desktop with 12G memory and i7 3.33GHz CPU.

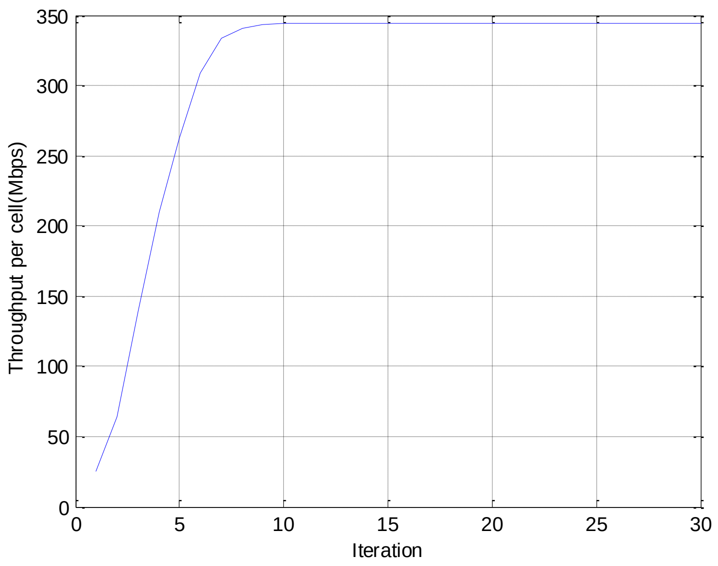

Figure 38 System throughput vs. iteration

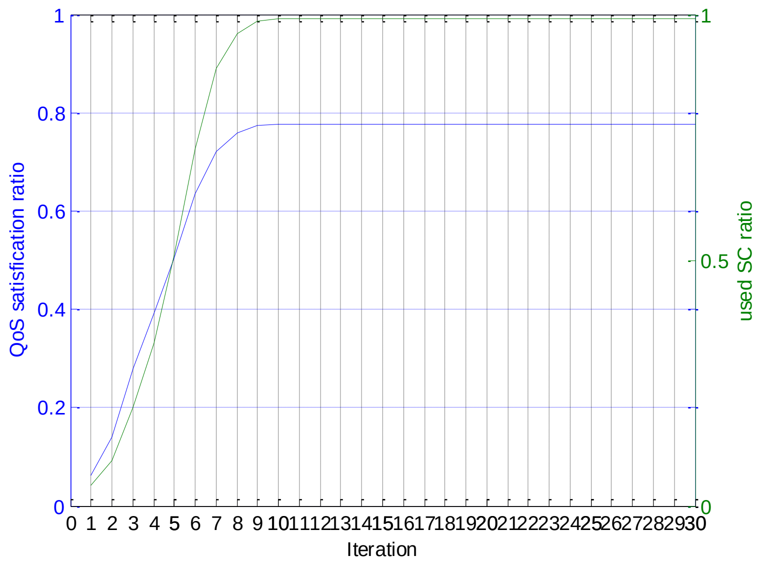

Figure 39 QSR and USR vs. iteration

4.5.2 Comparison

This section compares the proposed algorithm with two benchmarks: (i) RR and (ii) Max C/I.

RR [70][74] allocates an equal amount of SCs to all users in a fair way. The user serving order and the channel selection are both random so that every user has an opportunity to get

SCs with good condition. The fairness is high in this algorithm. However, the system throughput is low because of the ignorance of channel quality.

Max C/I [70][74] is a greedy and extremely unfair algorithm whose ultimate goal is to maximise system throughput. It always selects the best users and allocates them with as many best (in terms of SINR) SCs as possible. It can achieve very high throughput but low fairness and unstable QoS provisioning.

When there are sufficient SCs for users, the three algorithms will have different principles when distributing resources. Max C/I and RR do not consider QoS requirements and use up all SCs while the proposed algorithm does not allocate extra SCs even if there are still some available. So the comparison is done when there are insufficient SCs for all users. The grey areas in the following 3 figures are with light load (user density from 0-20) and are not discussed in detail. In Figure 40, the proposed algorithm achieves the highest QSR followed by the RR and then the Max C/I. As the user density increases all three lines decrease but with different slopes. RR has the sharpest decrement because the SCs are allocated fairly among all users so the bitrate every user can have reduces as the user number grows. In Max C/I, users with best channel conditions occupy more than enough SCs to keep them qualified and are hardly affected by the system load and as they form a major portion of the satisfied users, Max C/I shows the most gradual reduction (albeit from a low base) of all three methods.

Figure 41 shows the throughput vs. user density. Max C/I has the highest throughput by a long way and is followed by the proposed algorithm. Both have increasing throughput with the increasing user density because they can allocate resources to users according to their conditions: as the density increases there will be more users nearer the cell centre so allocating SCs to those users preferentially will increase the overall throughput. RR does not take into account channel conditions so the throughput stays the same.

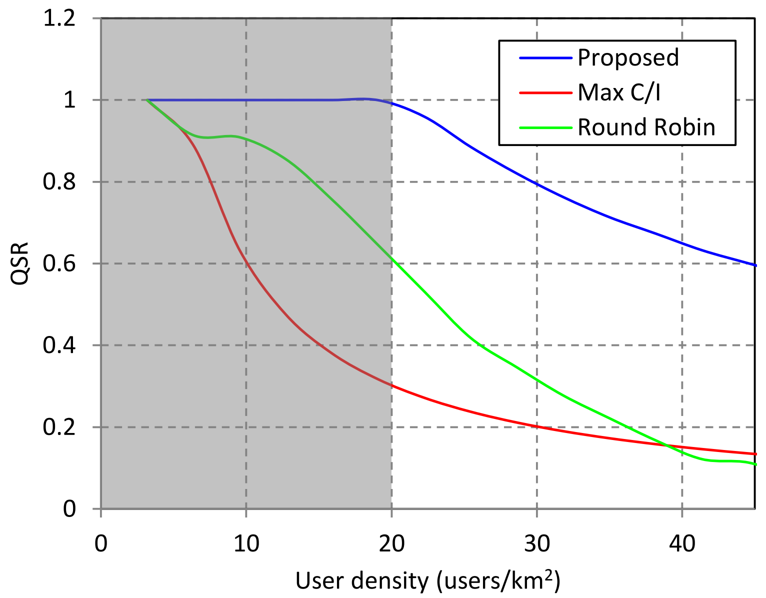

Figure 40 QSR vs. user density

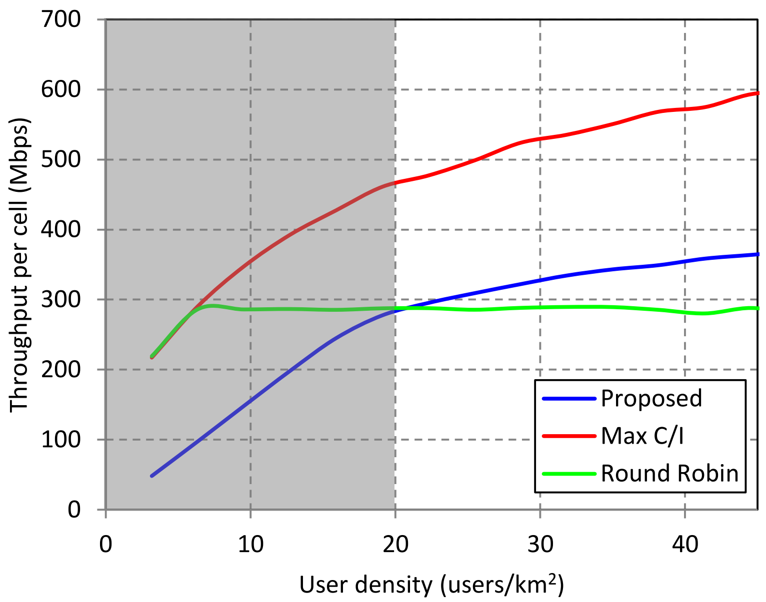

Figure 41 System throughput vs. user density

Fairness in Eqn 4.6 is used to measure the equality of allocation in terms of user bitrate. For example, if all users have the same bitrate, $F(r_{ni})$ =1 means the system is 100% fair.

Figure 42 demonstrates the fairness index for comparison. RR achieves stable high fairness since users are always allocated fairly in amount of SCs and the quality of SCs, so that they all achieve similar but decreased bitrates when user density increases. The proposed algorithm can achieve even higher fairness with light load. However, the proposed algorithm favours users closer to the BSs in order to get more qualified users and as the density of users increases this effect is exacerbated so the fairness on bitrate decreases. The Max C/I always has the lowest fairness indexes due to its extreme bias to "best" users.

Table 5 summarises the comparison:

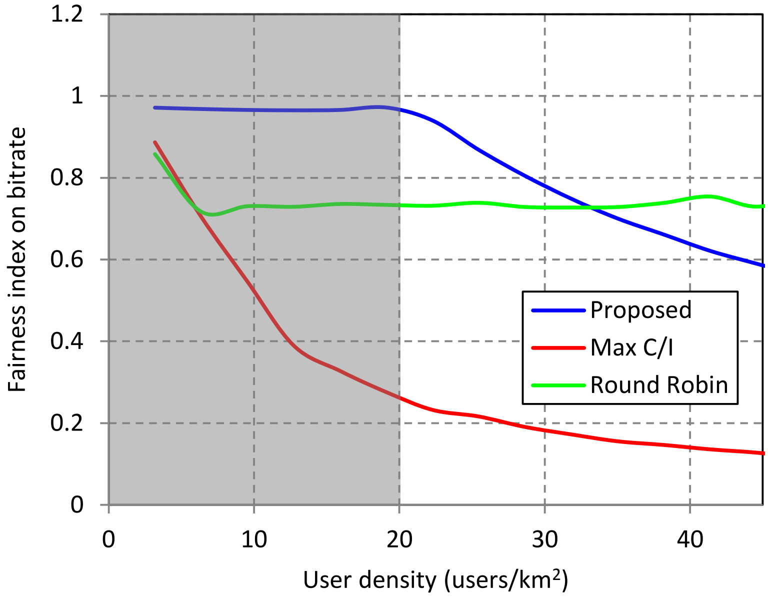

Figure 42 Fairness index on bitrate vs. user density

Table 5 Comparison summary

QSR	Proposed > RR > Max C/I
Throughput	Max C/I> Proposed> RR
Fairness on bitrate	Proposed & RR>Max C/I
Note: > means "better than"; & means "not comparable with"	

4.5.3 SC release test

Figure 43 and Figure 44 show the user bitrate distribution in increasing distance to BS for 400 users and 700 users respectively. DL is used. The proposed algorithm with only SC release (no β constraint) for unqualified users is denoted by blue dots while the red ones are from the proposed algorithm with SC release for unqualified users and overqualified users with β=2. It is clear that there are only two types of bitrates: 0 (unqualified) or above 500kbps (qualified). The 0-bitrate users appear more intensively in areas further from the BS. As red dots show, the bitrate is bounded by 500kbps and 1000kbps, the upper bound stopping users taking SCs. It helps more edge users to be served with QoS guarantee. When the number of users increases to 700 in Figure 44, it still shows the same trend but with more unqualified users. Figure 45 shows the relationships between the probability of user being unqualified and its distance to the BS. It increases as the distance increases.

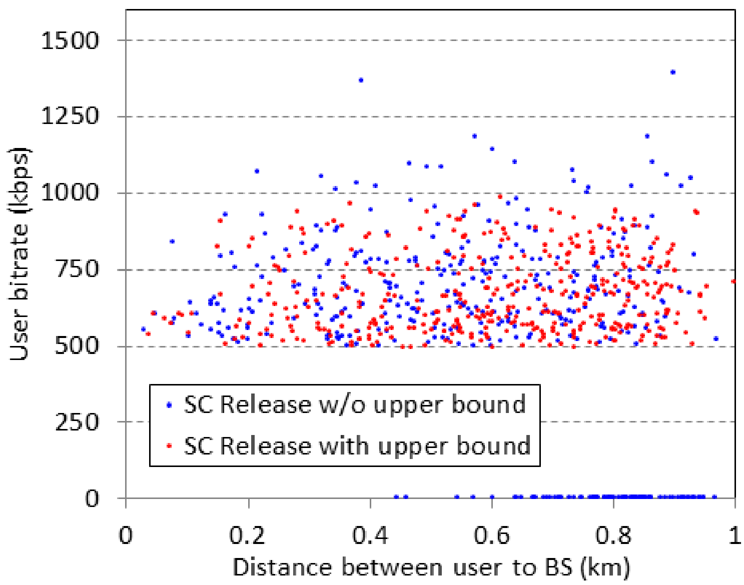

Figure 43 User bitrate distribution based on distance to BS with 400 users

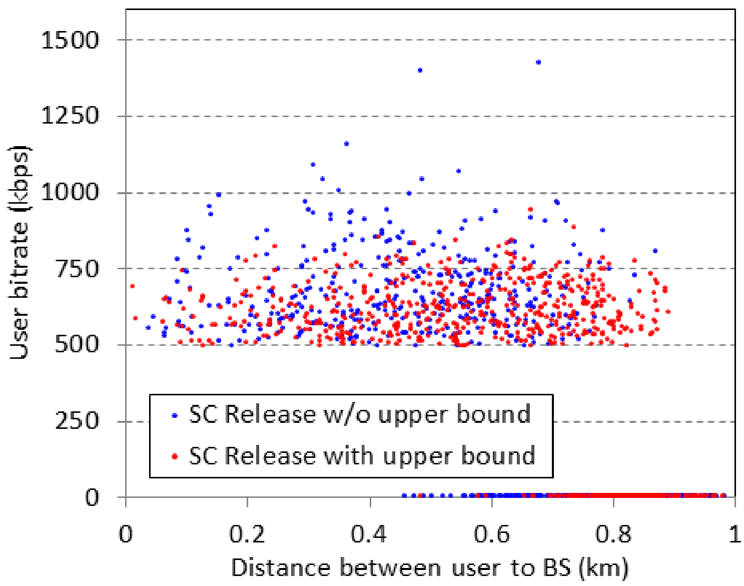

Figure 44 User bitrate distribution based on distance to BS with 700 users

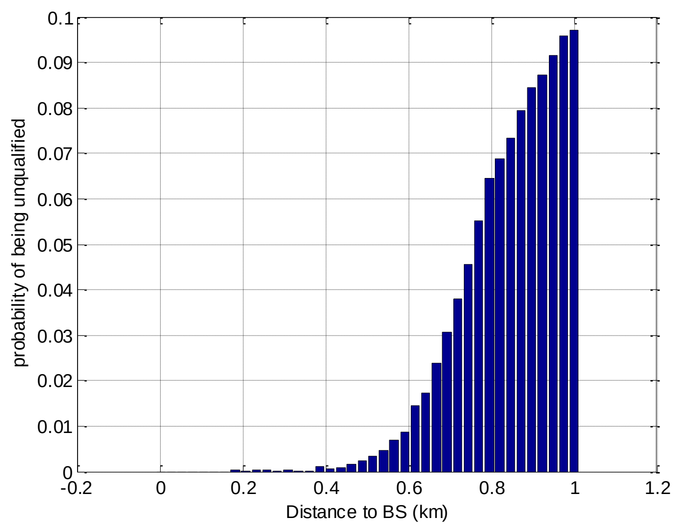

Figure 45 Probability of being unqualified vs. user distance to BS.

4.5.4 Impact of C_1 value

Figure 46 and Figure 47 show the impact of C_1 on QSR and throughput. The blue line is with fixed C_1=1.03 and red line shows the adaptive C_1. For adaptive C1, the way to find the optimal C1 which gives the best performance is to run the algorithm for different C1 values with the range 1.0-0.1 and sampling period 0.1. With adaptive C_1, both performances improve but not greatly. However, to find the best C_1 is time and power consuming. As a trade-off, the fixed C_1 value is used.

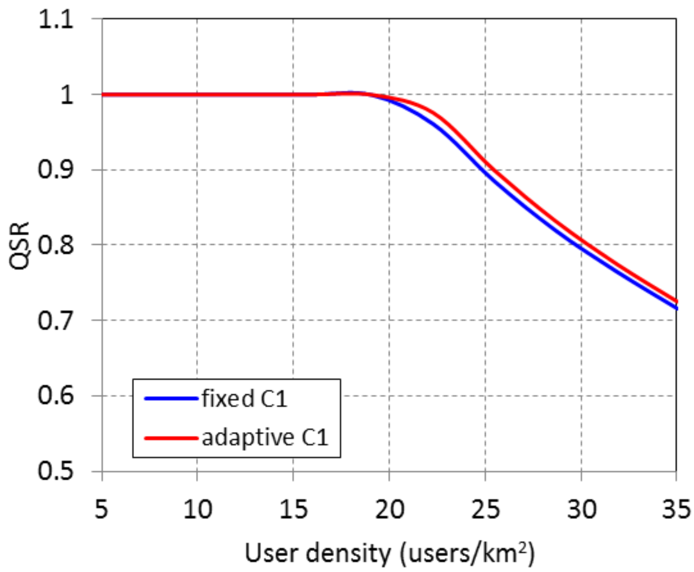

Figure 46 The impact of C_1 on QSR

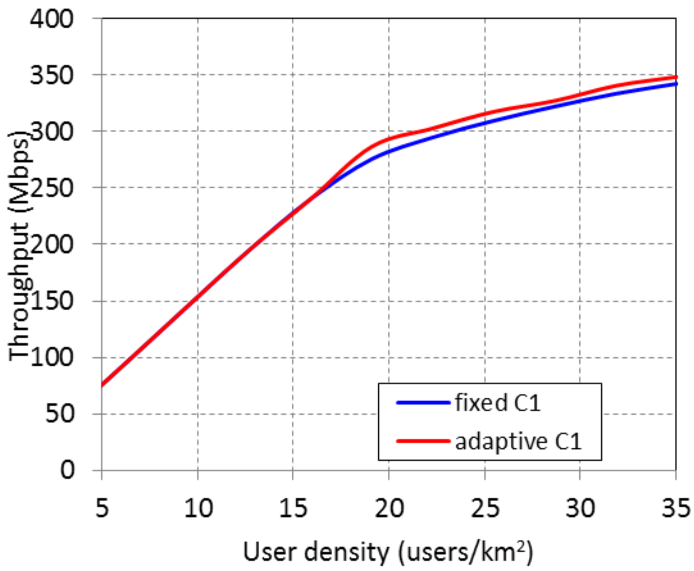

Figure 47 The impact of C_1 on system throughput

4.5.5 *UL vs. DL*

The overall performance of UL and DL are compared in terms of QSR, USR and system throughput in Figure 48 and Figure 49. In order to give a clear comparison and analysis on the effect of ICI, the same parameters are used in both UL and DL. UL and DL follows the similar pattern when the load rises: QSR decreases while USR increases. Ideally, either QSR=1 or USR=1 is the stopping criterion of the proposed algorithm. However, in practice when the system only has SCs with strong interference left, the algorithm will stop since using all remaining SCs cannot make a single unqualified user qualified. That causes the intersection of USR and QSR to be slightly below 1 in Figure 48. Also, the intersection of DL is further from 1 than UL showing that ICI is more severe in DL as explained in §3.7. Due to the same reason, the qualified users of DL are fewer than for the UL while the SCs are used up quicker than with the UL. Figure 49 shows the same pattern on throughput.

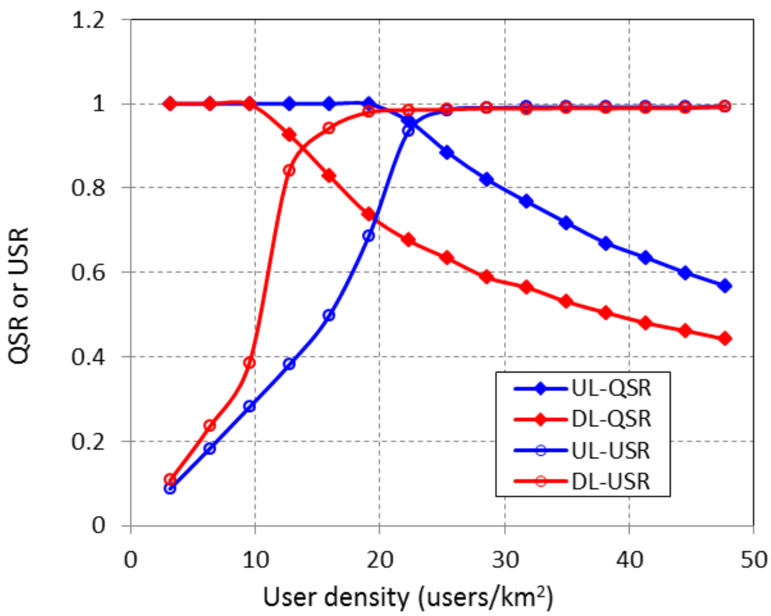

Figure 48 QSR and USR for UL and DL

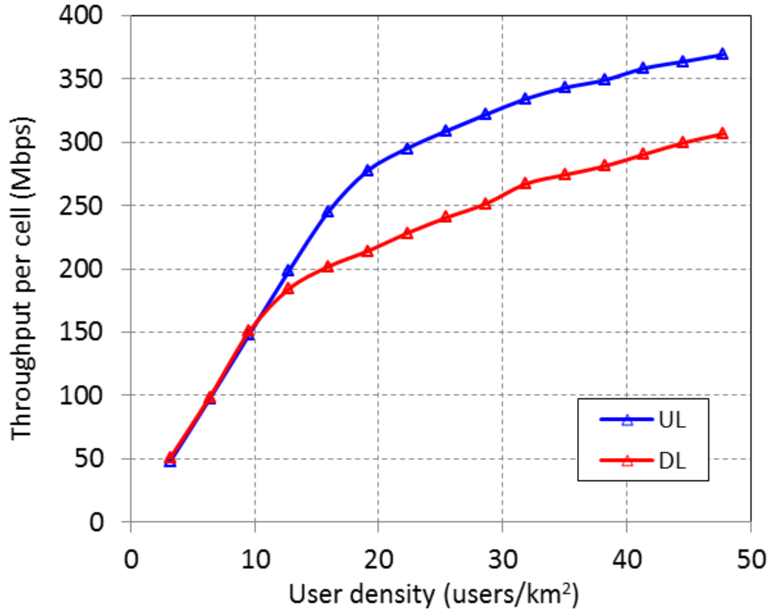

Figure 49 System throughput for UL and DL

4.5.6 The impact of user distribution

Figure 50 and Figure 51 shows the impact of user distribution on the proposed algorithm in terms of QSR and throughput. It is clear the hotspot leads to a lower QSR than the uniform one. That is because hotspot distribution is not as even as uniform distribution so that the unbalanced load in different sectors causes more frequent channel borrowing between sectors and brings more ICI in the system.

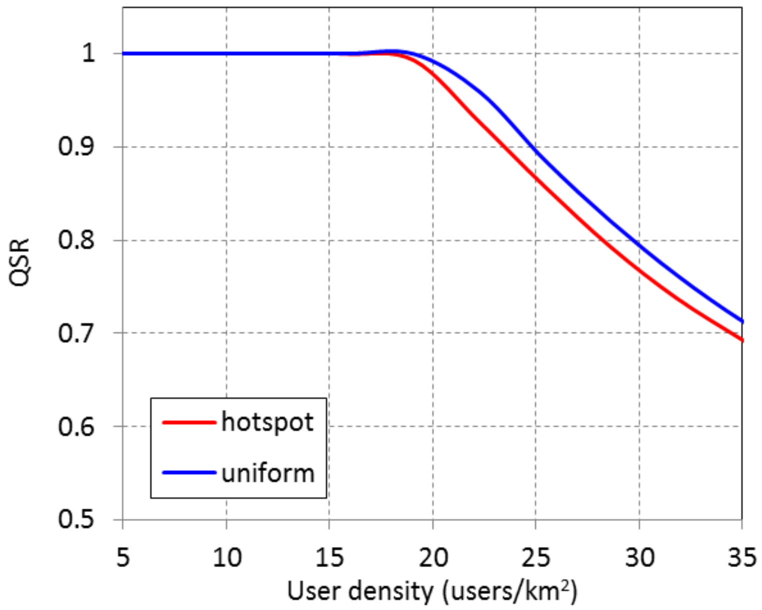

Figure 50 The impact of user distribution on QSR

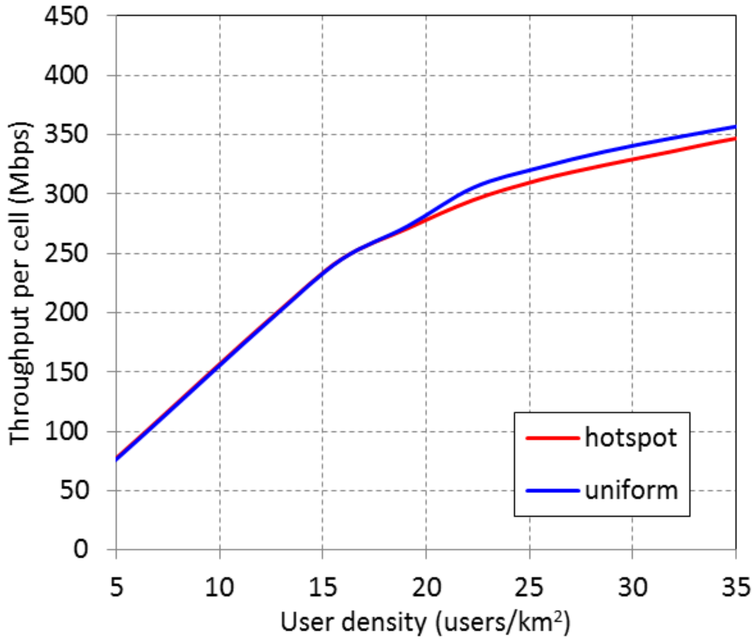

Figure 51 The impact of user distribution on system throughput

4.6 Summary

This chapter introduced the QoS-aware resource allocation algorithm. The current research status on resource allocation in OFDMA network is investigated, showing the importance of

QoS in the resource allocation problem. The approach in this thesis is to maximise the QSR of the system. The problem is formulated as a game with BSs as individual players trying to get as many qualified users as possible. An iterative algorithm allows agreement to be reached when no single player changes their allocation decision. The QoS-aware algorithm is embedded in the local planning layer and is formed by 3 basic parts: prioritised SC allocation, SC release and SC reallocation. The algorithm is validated and tested in different aspects. It shows good performance when compared with three well-known algorithms (IWF, Max C/I and RR).

Chapter 5 Enhanced SC Allocation

5.1 Introduction

Chapter 4 introduced the QoS-aware SC allocation method and compared it with two typical methods: a fair method of allocation (RR) and a method that emphasises throughput (Max C/I). IWF as a typical distributed algorithm used in a game which gives better balance on individual and system performance was also compared with the proposed algorithm. It was mentioned in that chapter that the intention behind this approach was initially to implement the effect of CR, but without the need for sensing or a geo-location database [7]. To differentiate from CR network, Chapter 1 introduced briefly the concept of “SSR”, which is considered in more detail here.

The term “SSR” in this thesis is taken to mean:

- a CR network that aims to always satisfy all the PUs but allowing SUs to make use of the network without having to pay attention to the PUs (i.e. no sensing); or
- a more generalised OFDMA network having users with different serving priorities while allocating spectrum, but still capable, where required, of ensuring that PUs can always achieve their QoS provided there is sufficient resource for all the PUs.

The concept came from CR as an alternative to the normal approach of only allowing SUs to access spectrum if there are no PU noticeable in that spectrum. It achieves the same purpose as CR but by a different approach. It allows PUs and SUs to compete for the spectrum, but subject to the premise that PUs can always achieve their QoS provided there is sufficient resource for all the PUs. Hence this can also be regarded as a CR network that aims to always satisfy PUs, without SUs having to pay attention to the PUs at the expense of sacrificing the transparency of SUs to the PUs.

To make it more generalised, the PU can be regarded as a user with absolute highest priority on the spectrum while the SU has lower priority. So when they compete, the PU can always have the desired spectrum and its QoS can always be achieved. The users can be set with different priorities so that they will have various interactive behaviours when sharing the spectrum. The division between users can be based on the network operators (NOs) to which they belong, or to different priorities between users for the same NO. As NOs are encouraged to share their spectrum to gain spectrum utilization frequency [9], the SSR is also suitable for the scenarios in Figure 52 where operators unite their allocated spectrum [71] and mark their users with priorities on occupying the spectrum.

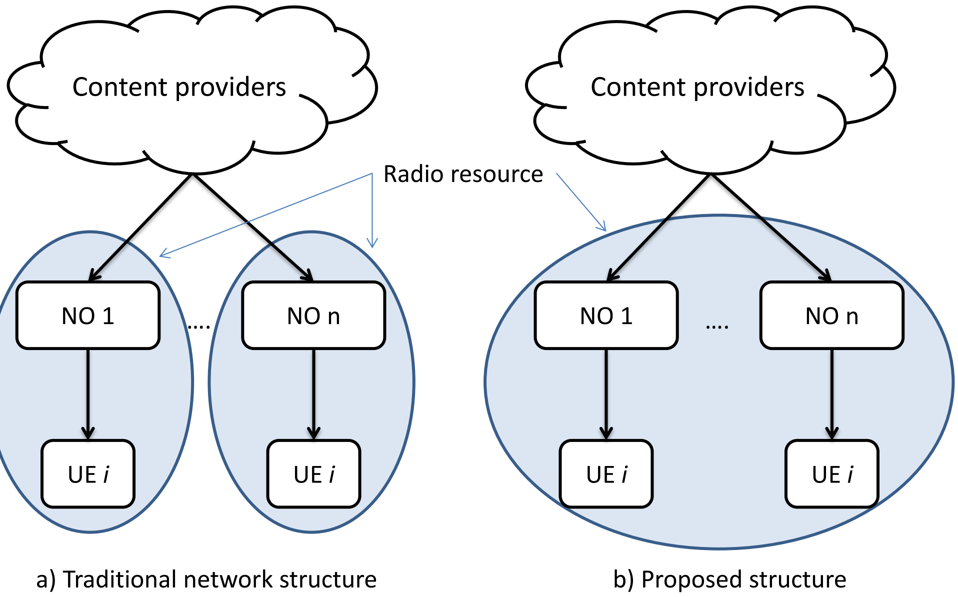

Figure 52 Network structure comparison: traditional and proposed

Because this approach has general applicability, OFDMA is used as the multiple access technique for CR [20]. The problem then becomes one of allocating SCs to ensure that PUs get the resource needed while at the same time trying to serve as many SUs as possible.

The overall spectrum sharing problem in CR can be classified into two basic approaches: *overlay spectrum sharing* and *underlay spectrum sharing* as described in §2.2.3. Strictly speaking in traditional CR networks, whichever spectrum sharing technique is used, PUs have the absolute highest priority and will not make any changes to their resource allocation, while SUs need to always ensure that their transmissions will not affect the PUs' transmissions.

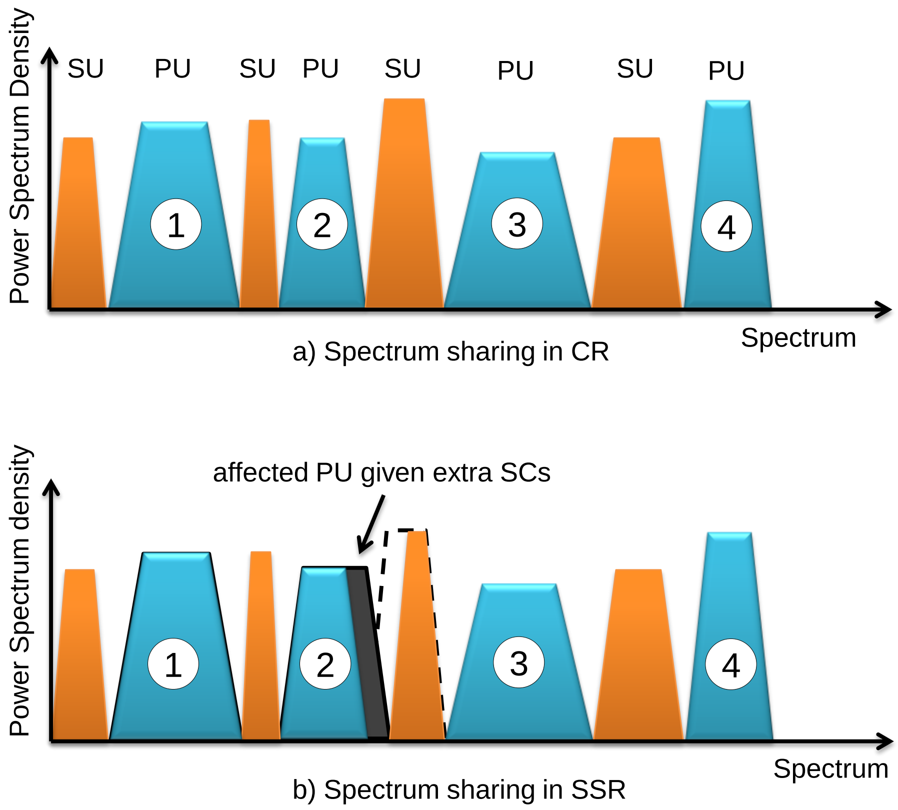

Figure 53 Spectrum sharing in CR and SSR

CR depends on sensing to avoid the interference from SUs to PUs, but in SSR, instead of avoiding conflicts, it permits the existence of interference but compensate PUs with more spectrum to maintain their transmission quality. So the premise is different: for SSR, as long as the PU gets its required resource it does not matter whether it has to change its SC allocation to accommodate SUs – this is illustrated in Figure 53(b) where the addition of SUs to the mix of users has meant that PU2 has to be given extra SCs to allow it to achieve its required resource despite the extra interference introduced by the SUs. However, it may mean that a smaller amount of spectrum is available for SUs and this represents a small reduction in capacity that is a price to pay for the benefit of this approach. In such a way, no sensing hardware and geo-location information are required in SSR; this means the concept can easily be applied to different types of existing network.

The resource allocation approach in a SSR network is a novel topic to consider. As the sensing difficulties have delayed the development of CR [7], this approach can provide an alternative to dealing with PU and SU sharing authorised spectrum. It is a combination of resource allocation in OFDMA and spectrum sharing in CR: it should consider individual QoS requirements as well as user priority. It not only needs to efficiently allocate SCs among users but also needs to guarantee that PUs are all qualified if there are having enough resources.

For a multi-cell SSR network, overlay spectrum sharing is employed in one cell. As OFDMA is adopted within every cell, SUs will not cause any interference to the PUs in the same cell but ICI from surrounding cells (from both PUs and SUs) may impact PUs. There is neither a centralised unit to manage the overall system, nor spectrum sensing to ensure that the PUs are not affected by the co-SC users, so another mechanism has to be provided to allow the PUs to achieve their required QoS. Instead of preventing SUs getting service, a compensation mechanism is designed for the PUs to adjust their SC allocation scheme and occupy extra SCs to ensure that their transmission quality is maintained, despite interference from adjacent cells. Accordingly, all users in the system interact with each other's adjustments.

The aim of the resource allocation in an SSR network is to maximise the system capacity in terms of QSR as well as considering the user priority. It not only needs to efficiently allocate SCs among users but also needs to guarantee, where possible, that PUs are all qualified.

In the SSR network, the goals of the radio resource allocation are:

- to mitigate the ICI caused by radio frequency(RF) bandwidth reuse;
- to increase the system capacity in terms of QSR and

- to provide and maintain individual QoS requirement for all the PUs and as many of the SUs as possible.

5.2 QoS and Priority-aware SC allocation algorithm (QP algorithm)

The proposed algorithm described in Chapter 4 showed how SCs are allocated to satisfy the required QoS of users, but it did not address the priorities. This aspect is considered here with three example cases:

Case 0: two groups of users (G_1 and G_2) exist with equal priority.

Case 1: a group of users G_1 has higher priority than the other users in G_2 to demonstrate that G_1 will have a higher QSR than G_2. It represents the scenarios where different types of users of an operator or two operators share spectrum. Nowadays, operators sharing spectrum is encouraged [9].

Case 2: a group of users G_1 has the absolute highest priority over all other users so that those in G_1 will always achieve their required QoS provided that there are sufficient resources. This case can be regarded as a generalised CR scenario with G_1 representing PUs. The intention is to have the same overall effect as in traditional CR, guaranteeing transmission by PUs, but without the need for sensing.

The enhancement to the algorithm includes: (i) *priority compensation* and (ii) *enhanced SC reallocation*.

5.2.1 *Priority compensation*

This module, particularly necessary for Case 2, is to compensate the unqualified G_1 (PUs) to ensure they get guaranteed QoS, even with the extra interference generated by serving SUs. This is a form of strict priority allocation.

For every sector, the pool of unqualified PUs and the pool of vacant SCs are constructed. For every unqualified PU, the vacant SCs of that sector are ranked in order of SINR. The algorithm allocates extra SCs until the bitrate reaches its requirement. If no vacant SC from its sector is available, it starts borrowing vacant SCs from the other two sectors in the same cell using the same ranking and choice procedure. The SC allocation information is updated after each PU reaches its bitrate.

If the cell runs out of vacant SCs before all unqualified PUs are compensated, a procedure of forcing qualified SUs to give up their SCs is triggered. Qualified SUs have to give up their SCs one by one and put them back in the vacant SC pool for the unqualified PUs to choose. This is done in decreasing order of the amount of SCs occupied by SUs. After one SU has released its SCs, the ranking of vacant SCs is recalculated and the unqualified PU will recheck whether it can reach the required bitrate. The compensation for that PU will only stop when the required bitrate is achieved. The process will continue until all the unqualified PUs in the system are compensated or the cell containing the unqualified PU does not have any qualified SUs. This compensation protects PUs' transmissions. The pseudo-code is shown as below:

Pseudo-code 4 Priority compensation

```
FOR cell n ∈ N
    WHILE I_n^{unQ} ∩ G_1 ≠ ∅  %unqualified PU
        User i* = arg min_{i∈I_n^{unQ}∩G_1} (d_{ni}^n);
        Calculate r_{ni*};
        Obtain M_{ns}^{unQ} for i*;
        WHILE r_{ni*} < r_{ni*}^{req}
            IF M_{ns}^{unQ} ≠ ∅  %SC allocating
                m* = arg max_{m∈M_{ns}^{unQ}} (SINR_{ni*}^m);
                Allocate SC m* to user i* and Calculate r_{ni*};
                Update a_{ni*}^m and M_{ns}^{unQ};
            ELSE
                IF M_{ns'}^{unQ} ≠ ∅  %SC borrowing
                    m* = arg max_{m∈M_{ns'}^{unQ}} (SINR_{ni*}^m);
                    Allocate m* to i* and Calculate r_{ni*};
                    Update a_{ni*}^m, M_{ns'}^{unQ};
                ELSE
                    IF I_n^Q ∩ G_2 ≠ ∅   % SU giving up
                        User j* = arg max_{j∈I_n^Q∩G_2} (A_{nj});
                        m* = arg max_{m∈M_{nj*}} (SINR_{ni*}^m);
                        Allocate SC m* to user i* and Calculate r_{ni*};
                        Update a_{ni*}^m, a_{nj*}^m and I_n^{unQ};
                    END
                END
            END
        END
    END
END
```

5.2.2 *Enhanced SC reallocation*

The SC reallocation is the process where the priority level is assigned to G_1 and G_2 using the difference in serving order as a mechanism.

All unqualified users (G_1 for PUs and G_2 for SUs) are considered in this stage, but PUs still have a strict priority in choosing SCs over SUs for a Case 2 scenario.

The enhanced SC allocation is different from the original SC reallocation module in §4.3.3 in the serving order. Here, the serving order is formed by combining two queues in a way reflecting their priority. In every cell, the unqualified G_1 and G_2 users are ordered *within their group* according to the distance from the BS, but the serving order between groups reflects the overall priority between groups.

- For Case 0, the serving order is $\{G_1, G_2, G_2, G_1, G_1, G_2, G_2, G_1 \ldots\}$ as G_1 and G_2 have equal rights on occupying SCs.
- For Case 1, the serving order can be weighted to put more G_1 users towards the top of the order so they get allocated SCs first. For example the order $\{G_1, G_1, G_2, G_1, G_1, G_2, \ldots\}$ would help G_1 get better SCs with less ICI. It could be thought that this distribution would qualify roughly twice as many G_1 – although this is complicated by other factors as shown in the results. It should be noted that when all the G_1 users have been put in the queue, all the remaining users will be G_2.
- For Case 2, the serving order puts all G_1 users in front of G_2.

The algorithm is as follows and the overall flow chart is shown in Figure 54:

i) **Initialise prioritised SC allocation** and initialise the correction factor $CF_{n,i}$ of every user to be 0.

ii) SC release and then increase θ_{ni} for unqualified users by 1.

iii) **Priority compensation**: determine the unqualified PUs in the system and those PUs are compensated to achieve their required bitrate. If insufficient vacant SCs are available, SUs have to release their SCs in decreasing order of the number of SCs they had previously obtained.

iv) **SC reallocation** for those users still unqualified

v) SC release

vi) Priority compensation

vii) Go back to step (iv) and continue the process until the SC allocation result converges or the maximum iteration value is reached.

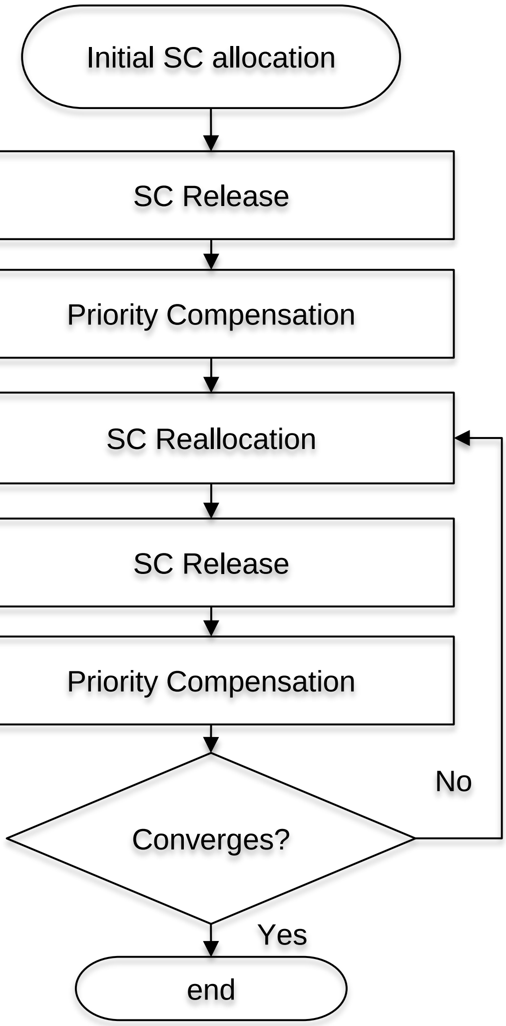

Figure 54 The flow chart of the proposed algorithm

In this algorithm, not all users keep changing their SC allocation scheme during iterations. There are only two situations that one user needs to change its allocation scheme:

i) A user becomes unqualified: the user will release all the SCs it has taken. An unqualified PU has a second chance to get SCs via the priority compensation module in this iteration, but if it still cannot be satisfied, it needs to go through the SC reallocation in the next iteration. An unqualified SU will need to wait for the reallocation in the next iteration after releasing all its SCs.

ii) If, during the priority compensation process, a PU needs extra SCs an SU will have to release its SCs to provide them.

So actually if a user can always reach its required bitrate during the whole process, it will never change its allocation strategy. Only those users falling into the two situations described above will need to change their SC allocation scheme. That ensures that SCs are only reallocated when necessary, which also keeps the convergence speed fast by providing as much certainty as possible.

Taking the required bitrate threshold as the criterion of whether a user enters the SC reallocation or priority compensation modules, the number of qualified users is always increasing from iteration to iteration. Also by checking whether every user's bitrate threshold is met after every iteration of resource allocation, as few users as possible are involved in the reallocation process - and those that are involved do so for as few times as possible.

The key protection for the PUs is realised through two features:

i) PUs have highest priority in choosing SCs during SC reallocation module. Since user-level priority takes precedence over distance-priority, no matter where the PUs are located (in the centre or at the edge of the cell) they will always have the first choice of resources.

ii) The priority compensation mechanism is specially designed to protect PUs by changing them from unqualified to qualified in that iteration, even with the risk of decreasing the system capacity.

However, in the simulation it became apparent that enhancing the SC reallocation, by giving high priority to PUs in choosing SCs, increased the number of qualified PUs sharply so that only a small number of PUs remained unqualified. Priority compensation, therefore, only had to deal with a small amount of unqualified PUs. For this reason it has a fast processing speed and only decreases the system capacity a small amount compared with the system without PU protection.

5.2.3 *Simulation results*

5.2.3.1 *Case investigation*

Experiments to investigate the behaviour of the three example cases is shown here. The conditions of the experiments are: (i) parameter Set 2 is used; (ii) the numbers of users in G_1 and G_2 in all three cases are equal; (iii) all users require 1Mbps.

Figure 55 shows the Combined QSR (CQSR) in the three cases as the total number of user increases. CQSR is defined here as the ratio of the individual QSRs of G_1 and G_2: CQSR=QSR_1/QSR_2.

For Case 0, CQSR is maintained at 1, which shows that each type has equal priority on the resource and the algorithm is implementing that priority.

In Case 1, there are three phases and Figure 56 (a) illustrates the influence of the service order on the CQSR:

Phase 1: When there are enough SCs to serve all the users, the CQSR is 1 because all users from both types are served with their required bitrates.

Phase 2: As the number of users increases, there are insufficient SCs to qualify all users so that more G_1 users become served at the expense of G_2. As the resources become scarcer, the CQSR becomes higher.

Phase 3: It might be thought that under high load, the 2:1 service pattern would give CQSR = 2 as illustrated in Figure 56 (a). However, the number of SCs required by each user is different. Figure 56 (b) gives an example. The number on each symbol gives the required SCs. When there are only 3 SCs left, the 4th user of G_1 cannot be qualified but the 2nd user of G_2 can be: this simple illustration, therefore, gives a CQSR of 1.5.

For Case 2, on overload the qualified G_2 users are sacrificed so the CQSR increases rapidly to infinity as the denominator of CQSR (QSR_2) drops rapidly to zero.

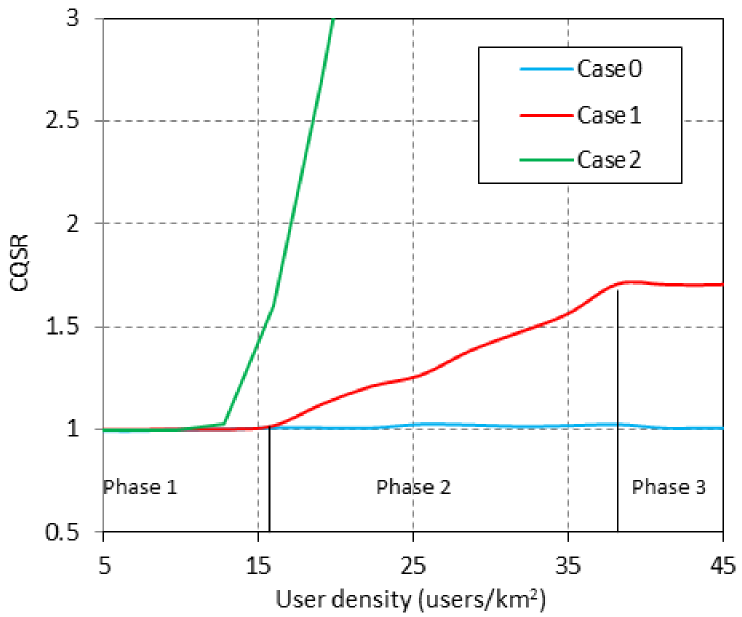

Figure 55 CQSR for each case vs. user density

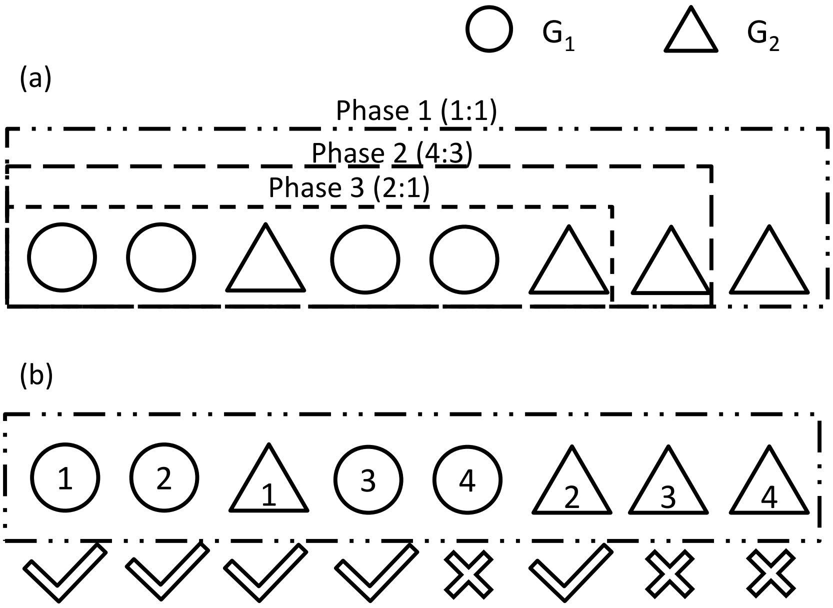

Figure 56 Illustration of queue service behaviour in Case 1

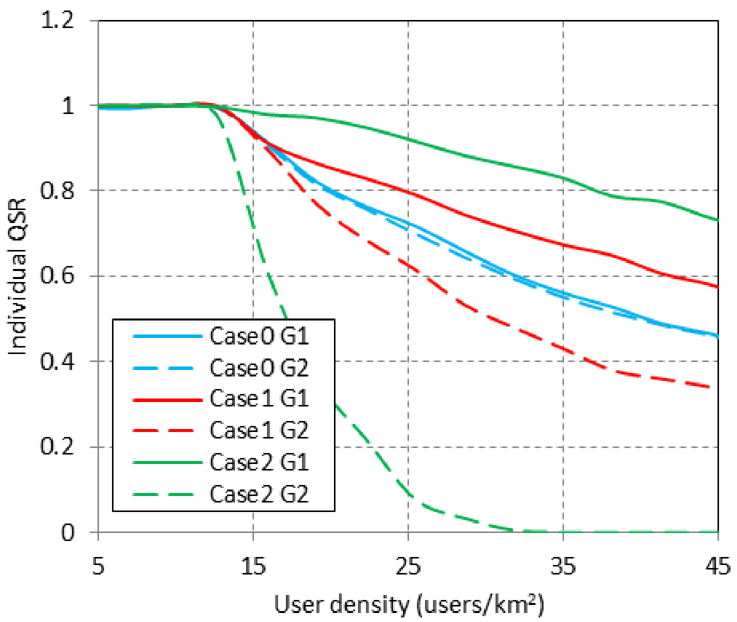

Figure 57 Individual QSR vs. user density

Figure 57 shows the individual QSR of each group in the three cases as the total number of user increases. Individual QSR is the ratio of the number of qualified users to the total number of the users of that group.

Case 0: it is equal for the two groups, as expected, but the individual QSR drops with load since more users from both types become unqualified.

Case 1: The service order should give qualified status to twice as many G_1 users as G_2 users. As explained earlier, it does give priority to G_1 users but doesn't reach CQSR=2.

Case 2: G_1 with highest priority means that on overload the number of users of G_2 drops away rapidly since SCs for all G_2 users may be sacrificed to serve G_1. As explained earlier, in the early stages of overload there might be some G_2 still qualified as there may not be enough SCs to serve the G_1 with the worst channel conditions. As Case 2 realizes CR by priority compensation, it is studied in details in the following tests.

5.2.3.2 Convergence

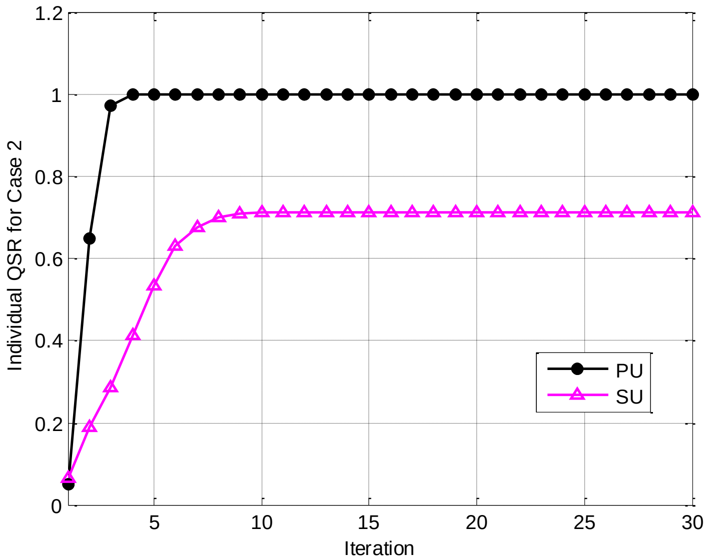

Figure 58 Individual QSR vs. iteration for Case 2

The convergence (thus the NE) for the QP algorithm can always be achieved for all cases. Figure 58 shows the convergence of QP algorithm for Case 2. System parameter Set 1 is in use. This shows one run with 700 users (user density=32 users/km^2) in the system including 40 PUs randomly distributed within the coverage area. All users require 384kbps. Even with the priority compensation module, the algorithm can achieve convergence within a few iterations, the quick convergence being necessary for a changing radio environment.

By compensating PUs, it ensures that all PUs are served at least with their required bitrates, but at the expense of a slightly lower proportion of SUs getting theirs, as would be expected.

5.2.3.3 Changing load

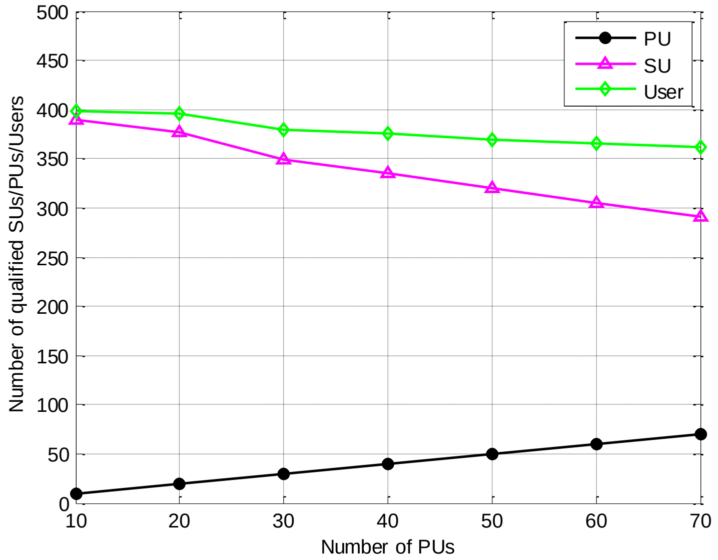

Figure 59 Number of qualified users vs. number of PUs

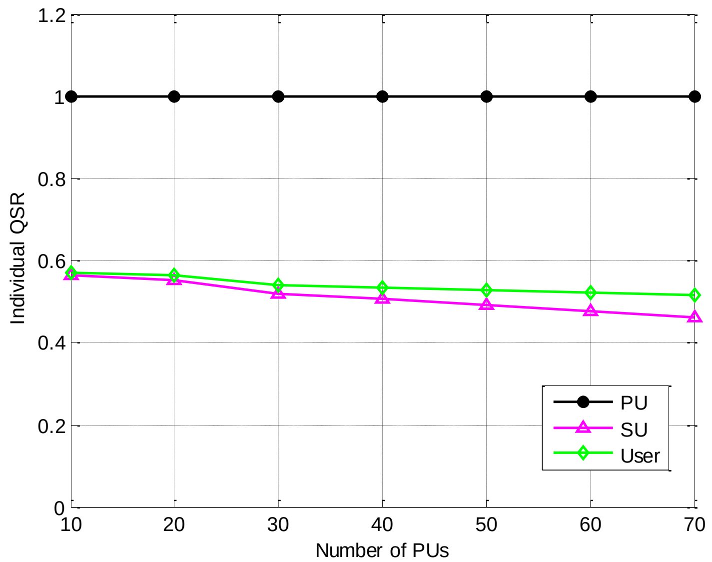

Figure 60 Individual QSR vs. number of PUs

Although Figure 58 shows that all the PUs achieve qualified status in that example, it is useful to consider how the system performs with changing load. This is shown in Figure 59 and Figure 60 where there is a constant total of 700 users but the numbers of PUs in the mix varies. All users have the same capacity requirement of 384kbps.

The results show that all the PUs are served irrespective of the mix of PUs and SUs, but, as would be expected in a priority system this is at the expense of the number of SUs. However, what is also noteworthy is that as the number of PUs increases, the *total* number of users decreases. This is because having two priorities means that users are no longer served in order of their channel conditions, but all PUs have to be served, even before SUs with better channel conditions. Hence the total reduces.

5.2.3.4 Fall-back QoS for SUs

One advantage of the qualified user approach is that each user can have a different QoS requirement and SUs can have their QoS degraded to allow more SUs to be served when there is a large number of PUs. Trade-off between number of users served and the QoS given to each would be a matter for the service providers, but the proposed algorithm does provide the necessary tool to implement a non-homogenous set of requirements.

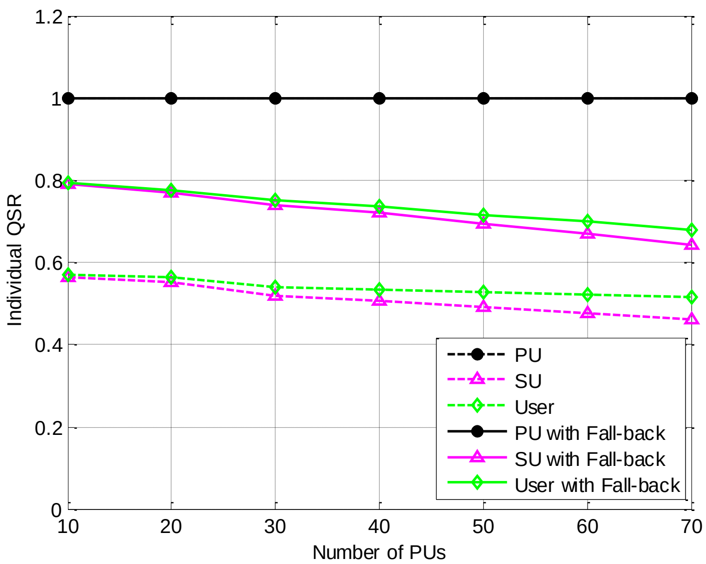

Figure 61 Individual QSR vs. number of PUs with fall-back

Figure 61 gives an example showing the same scenario as Figure 60 except that half the SUs are allowed a capacity of only 128kbps: it is clear that a higher proportion, as expected, of SUs can be served and the proposed algorithm has been able to implement that increase in capacity. The results from Figure 60 are shown as dotted lines for comparison.

5.3 QP algorithm with reactive behaviours

In order to make the QP algorithm to be more applicable when dealing with complicated scenarios and user behaviours, a reactive layer is constructed as mentioned in §3.4 to have a better control of the system performance according to the characteristics of the transmission environment. In the reactive layer, two situations are considered: (i) heavy system load (ii) mobile users during a short period. Different actions are taken in the two situations.

5.3.1 Dealing with heavy load

When the network is heavily loaded, the QSR is low even if the system throughput is still slowly increasing as shown in Figure 33 and some users with poor channel conditions will not be served. The danger to the service provider is that user satisfaction is severely damaged and in a competitive environment those SUs may go elsewhere – all service providers seek to minimise churn.

To deal with this situation the algorithm not only assumes different serving priorities but also that users may have a secondary "fall-back" requirement on bitrate – i.e. if the SCs are insufficient for a user's *required* bitrate it could be more acceptable for the user to be allocated a lower *acceptable* bitrate, rather than not being served at all. Whether a fall-back is acceptable can be set by user or by group.

Here the term "compromised user" is used for a user downgraded to the lower fall-back allocation. This downgrading is done with the permission of the user so the compromised user still counts as a qualified user.

When there are not enough SCs to allocate to every user to achieve their QoS requirement the algorithm will consider whether to downgrade some users from their desired bitrate to the acceptable level. The definition of the acceptable level is that user will still receive a tolerable QoS.

Here it is assumed that all users will accept a downgraded bitrate except G_1 in Case 2, since the calculation always gives PUs hard priority. However, this could be generalised by creating more categories of user, some of which would accept downgrade and others not.

The parameter r_{ni}^{cmp} defines the acceptable compromised bitrate and r_{ni}^{req} the desired bitrate as before for user i in cell n.

The SCs released in the process of downgrading can be reused by other users so that the QSR is increased. However, as will be demonstrated later, this is at the expense of system throughput since more users with worse channel conditions are served so leading to more interference in the system.

The compromise will only happen when it is necessary so that users will, when possible, get their required QoS; it will be triggered only when the QSR drops below a predefined threshold R_{th1} that is set according to the network operator's requirement. For example, if the operator sets R_{th1} to be higher, more users are served, but with more compromised users and lower system throughput than if there was no compromise. Operators can set several criteria to be the trigger points of the compromise. A simple and fast user compromise mechanism which fulfils that task is shown in Figure 62.

Figure 62 shows how the mechanism works. After one run, all served users are allocated their required bitrate r_{ni}^{req}; the unqualified users are allocated nothing. The QSR is measured and compared with the threshold R_{th1}: if the QSR is below the threshold and the compromised user ratio is not 100%, the number of compromised users is increased by a small percentage and the algorithm reruns. A big value accelerates the process but will cause unnecessary compromise while a small value has the opposite effect. It should be a trade-off value. After testing with different simulation runs, 5% is chosen. The process is carried out iteratively until the qualified user ratio reaches the threshold or there are no more users that can be compromised.

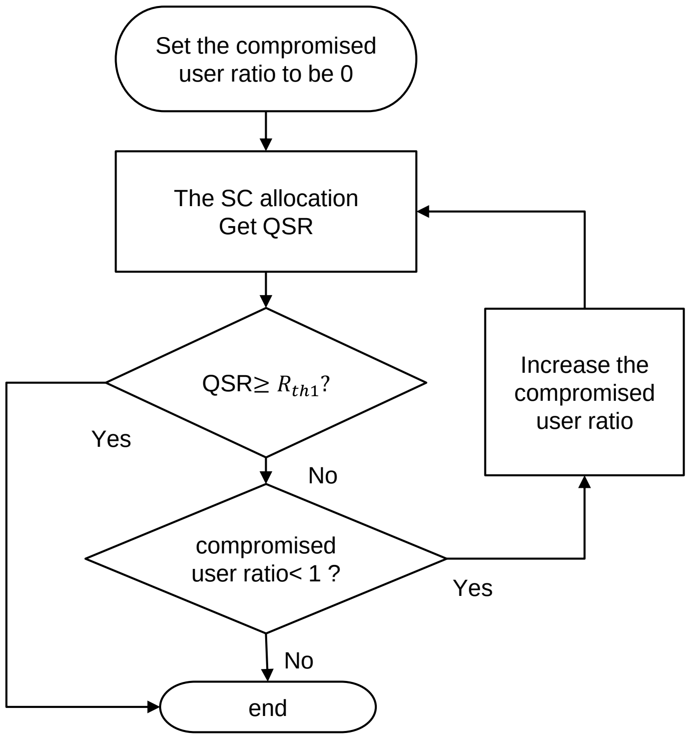

Figure 62 The flow chart of user compromise mechanism

5.3.2 *Dealing with mobile users*

The QP allocation algorithm is designed to allocate SCs in a snapshot. So the locations of users and channel environment are assumed to be unchanged until the SC allocation is finished, hence the need for a fast algorithm. However, in practice, mobile users and static users coexist in the system and it is desirable for all the users to still receive their QoS allocation, even when some are moving. So the SC allocation algorithm needs to be able to deal with the time domain and with various changes of channel conditions. The simplest solution would be to re-run the algorithm periodically, but the channel condition varies unpredictably in the mobile network. If the frequency of re-runs is too low to keep up with the change, the QoS can no longer be guaranteed in real time; conversely, if the frequency is set too high, the system wastes energy and time. Here a self-adaptive re-run mechanism to automatically trigger the re-run process in order to ensure a certain level of performance is achieved. The trigger conditions can be determined by the operators; here they are chosen to be:

i) for all cases, the overall QSR decreases to R_{th2} percent of the previous QSR from the last run of algorithm;

ii) the time since QP algorithm was last run exceeds a maximum value ; or

iii) for Case 2, one user in G_1 becomes unqualified.

Figure 63 shows how it works. At time t=0, the algorithm is run to determine the initial conditions, get the QSR$(t = 0)$ and set a variable τ=0; τ denotes the time since the algorithm was last run. A sample time T_s is defined, not to rerun the algorithm but to evaluate QSR.

At t= T_s, the algorithm evaluates QSR$(t = T_s)$ and the number of unqualified G_1 users (for Case 2) using the previous SC allocation results (i.e. in this case those at t=0) with the new channel information. The shadow fading loss for mobile users is calculated by using the correlated shadow fading model mentioned in §3.6.2.2 between those two time points. If the performance is still above the trigger conditions, the system will continue using the same SC allocation results for the next sample time and τ will be incremented to τ+ T_s. If the trigger conditions are met, the algorithm will re-run, τ will be reset to 0 and new SC allocation results will be obtained and used the next sample time.

If there is no recalculation the network continues to use the SC allocation from the last recalculation until τ reaches a value τ_{max}, at which point a recalculation is forced.

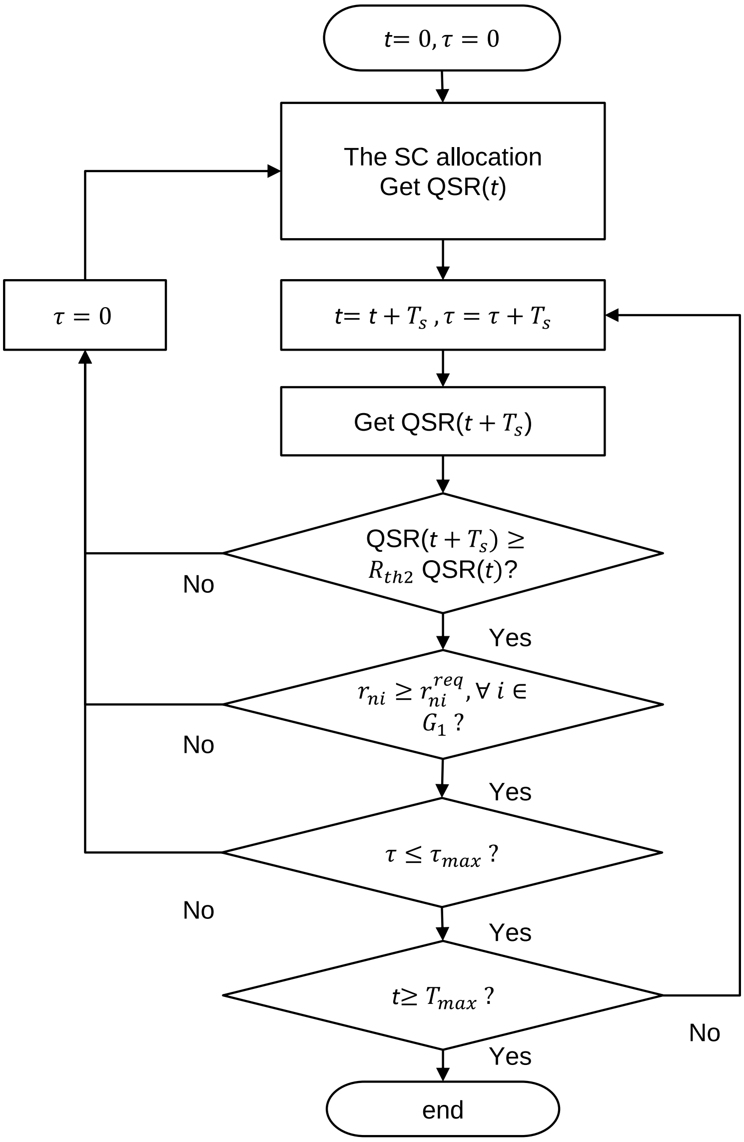

Figure 63 The flow chart of adaptive re-run mechanism

5.3.3 *Simulation results*

The system parameter Set 2 is in use. PUs requires 1Mbps while 50% of the SUs require 1Mbps and the others 500kbps.

5.3.3.1 Dealing with heavy load

Figure 64, Figure 65 and Figure 66 show the total number of qualified users, system throughput and the compromised user ratio as the total number of users in the system increases. Only the 1Mbps SUs can be potential compromised users. The QP algorithm without user compromise (denoted by QP-NC) and with user compromise (denoted by QP-C) is tested. 80% and 95% are used in the user compromise mechanism as the thresholds of QSR and the range of total number of users in the system is 70-1050 (user density range is 3.18-47.7 users/km^2). A wide selection of user numbers shows the overall features of the algorithm when dealing with different network loads.

For QP-NC, there are two obvious phases: when the system is not heavy loaded, all the users can get their required QoS and become qualified (the slope is 1). When there are no longer sufficient resources to satisfy all the users (starting at point A), the ones with worse channel conditions will be dropped first. The system will serve all the users with better channel conditions to maximise the number of qualified users. The slight increase after A is because as more users appear, some of the extra load will be near the centre of the cell: those users with worse channel conditions (e.g. edge users) will then be dropped and their SCs reallocated to SUs with better channel conditions. The system throughput follows the same trend for the similar reason.

For QP-C, the QSR is regarded as the criterion to trigger the user compromise mechanism. By setting the threshold higher, the user compromise will be triggered earlier as the total number of users increases and the users that can compromise will be used up earlier. For the 80% case, C is the trigger point and D is the point where the compromised SU ratio reaches 1. For the 95% case, A is the trigger point and B is the point where the SUs are fully compromised.

The number of qualified users goes up immediately after the compromise is triggered. However, serving more users with worse channel conditions will bring in more ICI, the SC utilization efficiency will be lower and the system throughput will suffer after the trigger.

Also with a higher threshold, the overall system throughput is reduced more with few users (between the points A-D) since more users are compromised earlier, although conversely more users are qualified. Once all the users are compromised (D for the 80% case, and B for the 95% case), the number of qualified user and system throughput follow the same trends as QP-NC. However, as the total number of users served is greater the system throughput is lower because of the larger number with poor channel conditions that are served. There is a slight increase in the number of qualified users as the overall number of users goes up – again because some of the extra ones will have better channel conditions.

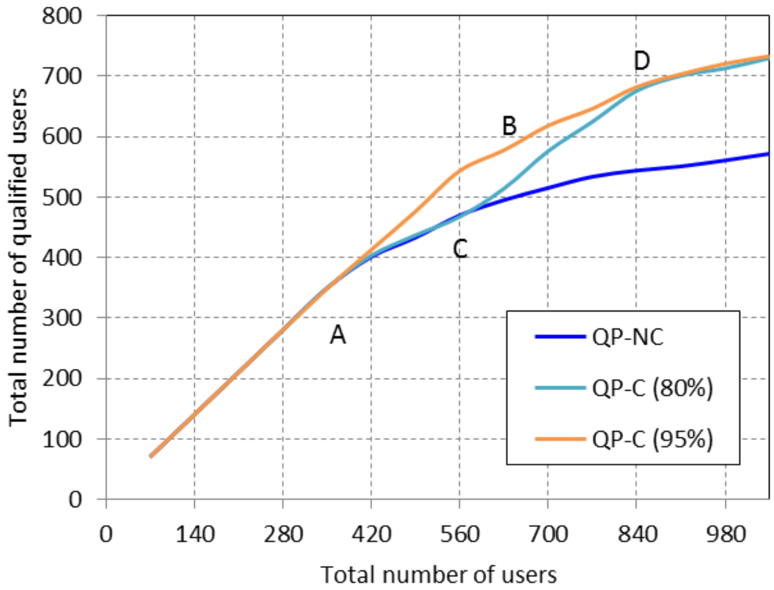

Figure 64 Number of qualified users vs. total number of users

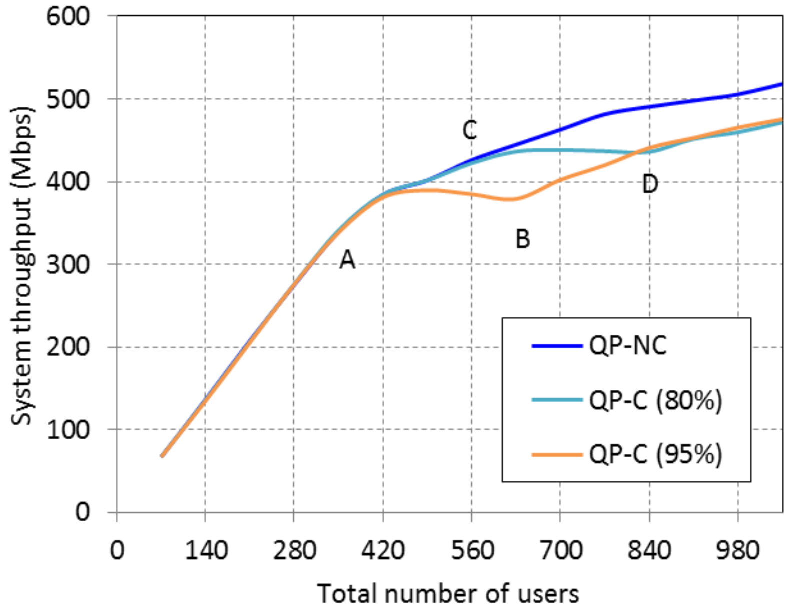

Figure 65 System throughput vs. total number of users

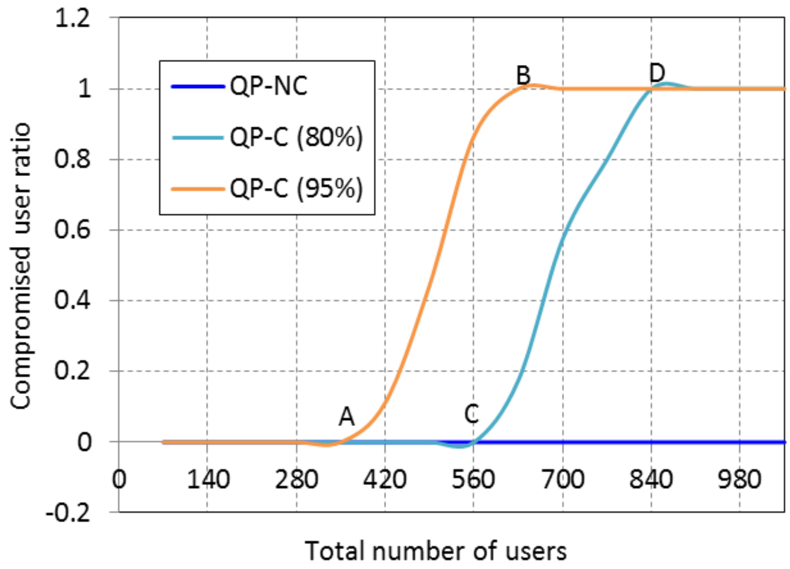

Figure 66 Compromised user ratio vs. total number of users

5.3.3.2 Mobility check

Case 2 is applied in this experiment. It is assumed that 10% of users move in a straight line but at a random direction with vehicle speed v of 120km/hour and the sample time T_s is 50ms (corresponding to 1.6m movement). Slower speeds would be easier to handle and require less frequent changes.

The total number of users is 700 and there are 30 G_1 users and 670 G_2 users. The trigger criterion is either (i) the number of qualified G_1 users dropping by 1 or (ii) the overall QSR dropping by 0.5% (R_{th2}= 99.5%). Setting a relatively high R_{th2} triggers the re-run with higher frequencies. T_{max} is 1s. Figure 67 and Figure 68 show the results for moving users in one run for 1s - the figure will differ from run to run so averaging multiple runs is not realistic but all runs have a similar situation.

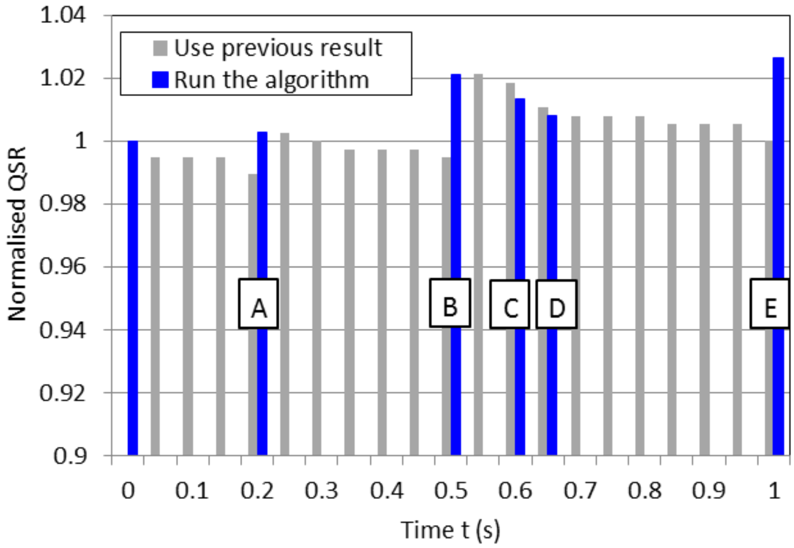

Figure 67 Normalised QSR vs. sample time

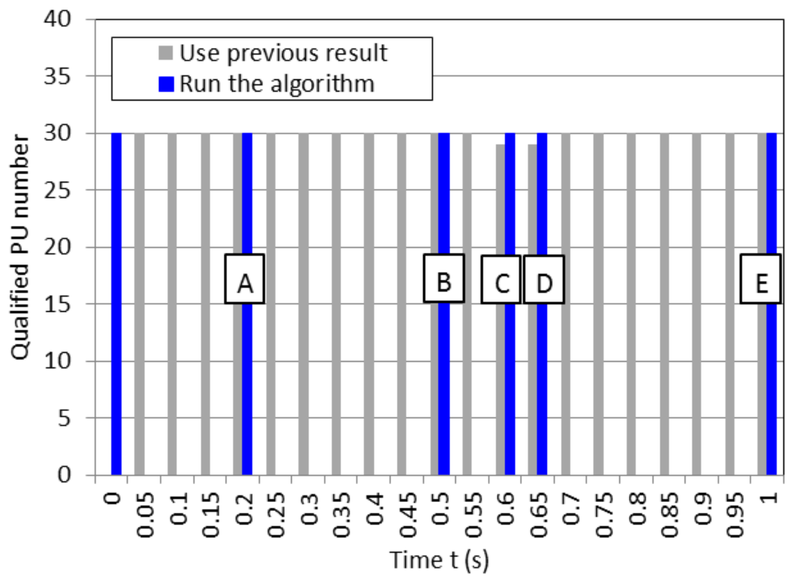

Figure 68 Qualified PU number vs. sample time

In Figure 67, for simplicity of presentation, the results are normalised so that the QSR at t=0 is 1. The SC allocation result of the basic algorithm from the last run is used for every 50ms until at least one of the criteria cannot be met. The results here illustrate changes corresponding to both trigger conditions:

i) At points A, B and E:

Here the qualified user ratio drops by more than 0.5%. After the re-run, the qualified user ratio goes up and actually is higher than the previous performance. This shows that the algorithm can always converge to the best SC allocation map to satisfy the maximum users based on the actual user distribution and channel conditions.

ii) At points C and D:

These two points show when the third trigger condition is met. From Figure 68 it can be seen that the trigger here is because the number of qualified PUs has dropped by 1. The re-run of the algorithm has the major criterion to keep all PUs qualified (even if they have bad channel conditions) and it does that, but at the expense of the SUs. So the re-run shows that the number of qualified PUs has gone back to 30, but the overall QSR is lower than the value without re-running the algorithm. This situation only happens when the dropped PU has really bad channel conditions and hence is vulnerable to changes of ICI. However, this result demonstrates that this algorithm can guarantee the PUs' service even under bad channel conditions.

5.4 **Summary**

This chapter introduced a new concept in networks: SSR network to achieve PU protection via resource compensation mechanism. It is an alternative to protect PU without sensing. The concept is more generalized so that it also fits OFDMA networks with different type of users.

The algorithm proposed in the previous chapter is enhanced in this chapter in three capabilities:

i) dealing with users with different priorities to fit the goal of CR network. Based the previous algorithm, the QP algorithm has one new module called priority compensation and one updated SC reallocation module.

ii) dealing with heavy load. A SU compromise mechanism is triggered to downgrade the QoS of some SUs when system performance is low and PU is unqualified.

iii) dealing with mobile users during a period of time.

i) is embedded in resource allocation in local planning layer while both ii) and iii) are embedded in reactive layer. The reactive layer is in charge of monitoring and measuring the system performance and adjusting the system settings to maintain and improve the system performance when there is a change in transmission environment. The simulation results show good performance and match the expectation very well.

Chapter 6 Conclusion and Future Work

6.1 Specific conclusions

In the thesis, the static spectrum allocation problem in a cellular OFDMA networks is first investigated. Unlike previous literature where emphasis was on throughput-maximisation or power minimisation, this work fully considers individual QoS. The SC allocation is formulated as a non-cooperative game with each BS as an individual player trying to maximise its QSR. A distributed and iterative QoS-aware SC allocation algorithm is applied to achieve the NE of the game. The simulation results show the proposed algorithm can achieve stable and good performance in terms of QSR, system throughput and user fairness with fast convergence. The factors influencing the performance of the algorithm are also investigated.

Furthermore, the proposed algorithm is enhanced by adding user priority awareness (QP algorithm). Enhanced SC allocation and priority compensation modules differentiate users and protect the transmission quality of certain type of users if necessary. Such an approach achieves spectrum sharing between PUs and SUs in a CR network without needing a sensing technique. It is a novel alternative to solve the transmission conflicts between PUs and SUs and it can be easily adopted to spectrum sharing between operators.

In order to make the static QP algorithm more applicable when dealing with heavy system load and with mobile users, reactive behaviours (SU compromise and rerun mechanism) are added. The three-layer architecture divides the overall responsibilities in terms of action timescales into management layer, local planning layer and reactive layer. With those enhancements, the goal of having a spectrum sharing network that can be applied realistically to a CR network is attained.

6.2 Future work

As this piece of work is a novel approach to combining the overall system goal with user priority requirements, there are still several potential improvements that can be considered in the future work.

- Optimal parameter selection

Currently, several constant parameters are set to apply to all users in all cells, for example C_1 and β. A mechanism to adjust those parameters on a scenario basis or on user QoS requirement basis can be proposed; or the general parameters can be more precisely selected as the result of an investigation.

- More QoS indicators

Currently, the QoS indicator is user bitrate because the bitrate is the most important QoS requirement in video streaming transmission. However, other indicators can also be involved, for example, bit error rate.

- Power allocation

This work uses fixed power allocation. However, after subcarrier allocation, the power allocation could be considered to enhance the performance of the system.

- Variable antenna patterns.

Currently, the scenario employs the same antenna for every BS with the same pattern and gain. However, employing semi-smart antennas can offer improved performance by changing antenna patterns to mitigate interference as has been proposed for 3G [73].

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