Improving

Relay Based Cellular Networks Performance in Highly User Congested and Emergency Situations

Haibo Mei

Submitted for the degree of Doctor of Philosophy

School of Electronic Engineering and Computer Science
Queen Mary, University of London

January 2012

To my loved family, specially my wife

ABSTRACT

Relay based cellular networks (RBCNs) are the technologies that incorporate multi-hop communication into traditional cellular networks. A RBCN can potentially support higher data rates, more stable radio coverage and more dynamic services. In reality, RBCNs still suffer from performance degradation in terms of high user congestion, base station failure and overloading in emergency situations. The focus of this thesis is to explore the potential to improve IEEE802.16j supported RBCN performance in user congestion and emergency situations using adjustments to the RF layer (by antenna adjustments or extensions using multi-hop) and cooperative adjustment algorithms, e.g. based on controlling frequency allocation centrally and using distributed approaches. The first part of this thesis designs and validates network reconfiguration algorithms for RBCN, including a cooperative antenna power control algorithm and a heuristic antenna tilting algorithm. The second part of this thesis investigates centralized and distributed dynamic frequency allocation for higher RBCN frequency efficiency, network resilience, and computation simplicity. It is demonstrated that these benefits mitigate user congestion and base station failure problems significantly. Additionally, interweaving coordinated dynamic frequency allocation and antenna tilting is investigated in order to obtain the benefits of both actions. The third part of this thesis incorporates Delay Tolerate Networking (DTN) technology into RBCN to let users self-organize to connect to functional base station through multi-hops supported by other users. Through the use of DTN, RBCN coverage and performance are improved. This thesis explores the augmentation of DTN routing protocols to let more un-covered users connect to base stations and improve network load balancing.

ACKNOWLEGMENTS

I would like to express my deep and sincere gratitude to my supervisor, Dr. John Bigham for his helpful advice and direction throughout the entire work. His wide knowledge and logical way of thinking have been of great value for me. His understanding, encouraging and personal guidance have provided a good basis for the present thesis.

I would like to thank Prof. Zhiguang Qin, Dr. Eliane Bodanese, Dr. Peng Jiang, Dr. Stefan Poslad and Dr. Athen Ma for their help.

I would also like to thank all my friends at QMUL, with whom I have spent four pleasurable years.

Finally, I would like to dedicate my thesis to my family for their continuous support and love, specially my wife.

CONTENTS

List of Acronyms

AC	Admission Control
ACO	Ant Colony Optimization
ACI	Adjacent Channel Interference
AMC	Adaptive Modulation and Coding
AODV	Ad hoc On-Demand Distance Vector Routing
ARS	Ad hoc Relaying Station
BOA	Bubble Oscillation Algorithm
BS	Base Station
BSW	Binary Spray and Wait
CCI	Co-Channel Interference
C-DFA	Cell-colouring based Distributed Frequency Allocation
CDMA	Code division multiple access
CP	Cyclic Prefix
CS	Channel Sharing
DDFFA	Distributed Dynamic Fractional Frequency Allocation
DFA	Distributed Frequency Allocation
DFFA	Dynamic Fractional Frequency Allocation
Dynamic FFR	Dynamic Fractional Frequency Reuse
DFT	Discrete Fourier Transform
DPGCA	Distributed Planner Graph Colouring Algorithm
DSDV	Dynamic Destination-Sequenced Distance-Vector routing
DSR	Dynamic Source Routing
DTN	Delay Tolerate Network
EDT	Electrical Down-Tilt
EESM	Exponential Effective SINR Mapping
EWMA	Exponentially Weighted Moving Average
FFR	Fractional Frequency Reuse
FFT	Fast Fourier Transform
G-CAPCA	Greedy-Cooperative Antenna Power Control Algorithm
GLB	Geographic Load Balancing
iCAR	integrated Cellular and Ad Hoc Relaying system
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Invert Fast Fourier Transform
ISI	Inter-symbol-interference
LLH	Least Longest Hop
LMP	Least Maximum Path-loss
LOS	Line of sight
LTE	Long Term Evolution
MAC	Media Access Control
MDT	Mechanical down-tilt
MMR	Mobile Multi-hop Relay
MPG	Minimum Performance Guarantee
MRP	Minimum Relaying hop Path-loss
MS	Mobile Station

MTP	Minimum Total Path-loss
NLOS	Non-Line-Of-Sight
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
ONE	Opportunistic Network Environment
ORAA	Orthogonal Resource Allocation Algorithm
PMP	Point-To-Multipoint
PRoPHET	Probabilistic Routing Protocol using History of Encounters and Transitivity
QoS	Quality of Service
RAPID	Resource Allocation Protocol for Intentional DTN routing
RBCN	Relay Based Cellular Network
RF	Radio Frequency
RS	Relay Station
SINR	Signal to Interference and Noise Ratio
SOFDMA	Scalable Orthogonal Frequency Division Multiple Access
SRD	Shortest Relaying hop Distance
STD	Shortest Total Distance
TDD	Time Division Duplex
TTL	Time To Live
UAV	Unmanned Air Vehicle
UC-CAPCA	Utility Comparison based Cooperative Antenna Power Control Algorithm
WCDMA	Wideband code division multiple access
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Access Network

List of Figures

List of Tables

CHAPTER 1 Introduction

Wireless networks have become more and more important to people's social and business life. Cellular networks are the most widely used type of wireless network. They apply powerful facilities to provide seamless radio coverage over large areas and support stable and efficient user communication.

In current research, cellular networks are augmented by the addition of relays to form Relay Based Cellular Networks (RBCNs) [18][23-25]. The RBCNs combine the merits of cellular networks and multi-hop communication for better performance. The RBCNs can also work with wireless technologies like Mobile WiMAX or LTE to support wireless broadband communication. In this thesis, the RBCN working under IEEE 802.16j [1] standard and in MMR (Mobile Multi-hop Relay) mode [2] is assumed. The MMR mode can enhance RBCN performance in three ways: 1) Mobile Station (MS)* to Base Station (BS) connection can either be a direct link or via a multi-hop relay. The multiple connection choices enhance the flexibility and resilience of MS to BS connection (Figure 1.1 (1)). 2) MMR expands BS radio coverage and makes improved non-line-of-sight propagation a capability of RBCN (Figure 1.1 (2)). 3) MMR enhances the RBCN to eliminate interference and realize radio resource efficiency by realizing short distance hops from MS to BS (Figure 1.1 (3)).

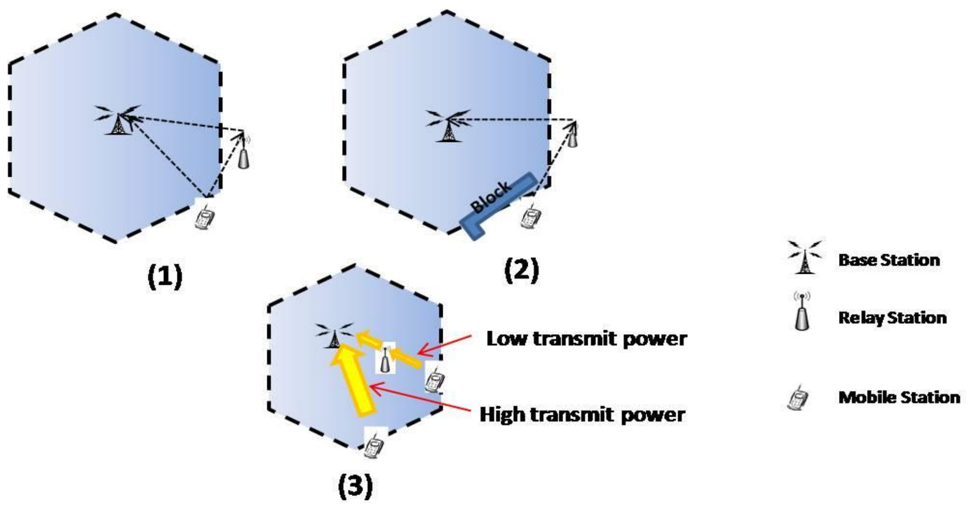


Figure 1.1 Functions of the MMR mode in IEEE 802.16j supported RBCN

* MS represents the user in rest of this thesis.

In RBCN, the relay station (RS) is the device supporting the MMR mode. In this thesis, a RS works as decode-and-forwarding relay and uses either a transparent relay model or non-transparent relay model. In network operation, a RS in transparent relay model simply relays data and control information between MS and BS. In the non-transparent relay model, a RS also has other network enhancing functions, including flexible radio resource assignment, scheduling, bandwidth request and allocation, QoS support and MS handover support.

The ubiquitous deployment of RBCN makes it highly desirable to consider how to manage them in the context of different kinds of emergency and overloading, and to consider enhancing the flexibility not only by simple RF alteration but through co-working with other wireless technology such as extending coverage through interaction with Delay Tolerate Networks (DTN). This thesis investigates solutions to improve the performance of RBCN in high user congestion and emergency situations that will be explained next. High RBCN capacity, throughput and user Quality of Service (QoS) are the solution criteria. In this thesis, the higher the RBCN capacity and throughput, the better the solution is. Because Mobile WiMAX uses channel Signal to Interference and Noise Ratio, Adaptive Modulation and Coding and data rate threshold, user QoS has been guaranteed in RBCN. However, the solutions proposed in this thesis do not deliberately consider improving QoS to a specific user. Instead, satisfying basic data rate is the main goal to a user.

1.1 Improving RBCN performance when there is high user congestion

In RBCN, users are not commonly distributed uniformly over a cell, and individual user may ask for a different type of service, such as a voice call, a stream video or a file download. Thus, demand can be localised and such localised user congestion may bring down RBCN capacity and throughput.

This thesis utilizes antenna reconfiguration and dynamic frequency allocation to BSs and RSs to ameliorate the user congestion problem in RBCN. Antenna reconfiguration can adjust the radio coverage of the BSs and RSs (through antenna power control and antenna tilting) for geographic load balancing. Alternatively, dynamic frequency allocation can increase frequency efficiency and channel condition to serve more congested users. A comparison of the efficiency of each approach is made.

Antenna power control and antenna tilting based antenna reconfiguration are investigated in Chapter 4, where a cooperative antenna power control algorithm and a heuristic antenna tilting algorithm in RBCN are designed and validated. In Chapter 5 and Chapter 6, centralized and distributed dynamic frequency allocations are investigated in RBCN. A Dynamic Fractional Frequency Allocation (DFFA) algorithm is presented and validated in Chapter 5 and a Distributed Dynamic Fractional Frequency Allocation (DDFFA) algorithm in Chapter 6. Chapter 5 also investigates dynamic frequency allocation and antenna tilting combined solutions and compares them. The integrated solutions combine the effects of dynamic frequency allocation and antenna tilting to better relieve user congestion.

1.2 Improving RBCN performance in emergency situation

RBCN BSs are the facilities to provide radio coverage and support seamless radio coverage over a wide area. In reality, BSs may fail or have decreased antenna function if an accident or a storm or a malicious action happens. In such situations, a section of users may not have radio coverage. The failure of one BS will also influence other BSs. This is because BSs nearby may have to take over extra user demand from the perimeter of the coverage of the failed BS. In reality, the BS failure or function decreasing may be caused by different kinds of emergency situations, like catastrophic weather (heavy rain, tornado), earthquake, terrorism attack etc, that physically influence BS function. Therefore, relieving the BS failure problem in such emergency situations is highly important. Practical solution that rebuilds the wireless communication quickly and stably can save people from danger and inconvenience.

Incorporating supplementary facilities like Unmanned Air Vehicles, temporary base stations with e.g. satellite backhaul, or Robots into a radio coverage hole to compensate the BS failure is a feasible choice that has been used in the past[8][44]. However, this method takes time and relies on the ability and distribution of supplementary facilities.

In this thesis, in order to solve the BS failure problem quickly prior to the availability of auxiliary equipment, two approaches are investigated. The first is simple tilting of antennas linked to frequency allocations over the network. Antenna tilting in Chapter 4 and integrated solution in Chapter 5 are such solutions. The second solution is to use DTN in user terminals that can make smart phones communicate with each other through multiple hops. DTN is utilized to let un-covered MSs self-organize to connect to a BS directly or indirectly through multiple hops, without requiring simultaneous end to end connectivity. The DTN solution approach is shown in Figure 1.2. In this figure, BS *A* fails to provide radio coverage causing a radio coverage hole (the yellow area), and MSs in this hole lose connection to BS. The solution is that MSs in the hole self-organize into a DTN to connect to each other or to functional BSs or RSs. For example, delay tolerate connections *a* and *b* are built for a MS connecting to functional BS *B*. Additionally, two MSs can talk to each other through delay tolerate connections without BS help, which is valuable in emergencies for very short range communication. In this solution, DTN routing protocols need to be designed to support BS load balancing (so that congested points of access to the backbone are avoided) and to enhance the probability of DTN communication from the MSs to the BSs. In this thesis, Geographic Routing and Ant Colony Optimization are utilized to augment the existing DTN routing. This work is discussed in Chapter 7.

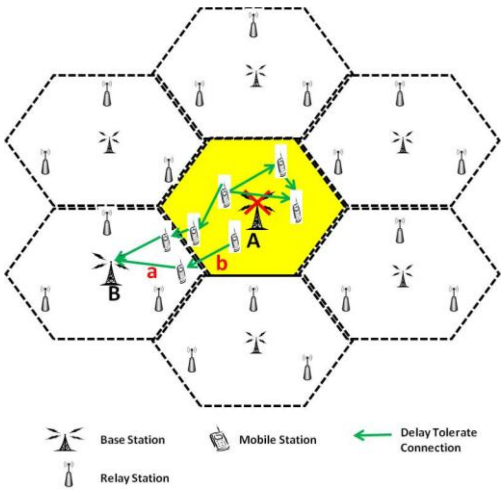


Figure 1.2 Base station failure problem and DTN solution

1.3 Contributions

In summary, the main contribution of this thesis is to relieve user congestion and emergency problems in a RBCN. The proposed solutions are based on RBCN network reconfiguration and dynamic frequency allocation, and RBCN co-working with DTN. Through these solutions, RBCN capacity and throughput could be improved. The contributions are summarised as follows:

- Design cooperative antenna power control and antenna tilting as network reconfiguration solution to user congestion and BS failure problems. Related algorithms are designed and compared to state of art algorithms.

- Centralized and distributed dynamic frequency allocation schemes are designed to improve frequency efficiency. User congestion problem can be greatly relieved by this work. Specific algorithms are designed and validated.

- Investigate dynamic frequency allocation and antenna reconfiguration into integrated solutions. These solutions propose to add the benefits of the two actions to better relieve user congestion and BS failure problems. The working relationship of dynamic frequency allocation and antenna reconfiguration is investigated and compared.

- Use DTN technology to ameliorate BS failure problem in RBCN. Traditional DTN routing algorithms are augmented by Geographic Routing and Ant Colony Optimization to enable un-covered MSs to better connect to functional BSs. Specific augmented DTN routing algorithms are designed and validated.

The author's publications are listed in Appendix C.
This thesis is organized into 7 chapters as listed below.

Chapter 2 Background: The background of this thesis is introduced, including RBCN technology, user congestion and BS failure problems, antenna reconfiguration and frequency allocation, and DTN technology.

Chapter 3 RBCN system model and simulator: This chapter first discusses the system model of RBCN. Most part of the work in this thesis is based on this model. Secondly, the simulation tools used are introduced, including a system level RBCN simulator developed at Queen Mary and the Opportunistic Network Environment (ONE) DTN simulator developed in the Helsinki University of Technology.

Chapter 4 Antenna power control and antenna tilting based network reconfiguration in RBCN: This chapter extends the research on network reconfiguration to increase RBCN performance in user congestion and emergency situations. Cooperative antenna power control and heuristic antenna tilting solutions are designed to reconfigure BS and RS antenna coverage. Related algorithms and their validation in the system-level RBCN simulator are designed.

Chapter 5 Centralized dynamic frequency allocation and integrated solutions in RBCN: This chapter firstly designs a centralized dynamic frequency allocation algorithm for high frequency efficiency in RBCN. Secondly, it applies antenna tilting and dynamic frequency allocation into integrated solutions to better improve RBCN performance. The validation of integrated solutions uses the system-level RBCN simulator.

Chapter 6 Distributed dynamic frequency allocation: To avoid the drawbacks of centralized algorithm, this chapter investigates a cell colouring based distributed dynamic frequency allocation approach. A related Distributed Dynamic Fractional Frequency Allocation algorithm is designed for RBCN. This algorithm is validated in RBCN system level simulator.

Chapter 7 Extending RBCN coverage in emergencies using DTN: This chapter realizes wireless communication in emergency by augmenting RBCN with DTN. This work augments traditional DTN routing protocols to improve MSs to BSs connection and cell load balancing. This work is validated in the ONE simulator.

Chapter 8 Conclusion and Possible Extensions: This chapter gives an indication of how this work could be developed. It proposes: 1) to investigate better centralized and distributed control methods to carry out network reconfiguration and dynamic frequency allocation to further relieve user congestion problem in RBCN. 2) to investigate better integrated solutions to relieve RBCN user congestion and BS failure problems. 3) to design more practical DTN routing to better improve RBCN performance in emergency.

CHAPTER 2 Background

In this section, the IEEE802.16j supported RBCN using multi-hop communication and related implementations are described. Afterwards, frequency allocation, antenna reconfiguration and DTN technology are described in the context of improving performance of RBCN in the presence of user congestion and BS failure problems.

2.1 Multi-hop communication in cellular networks

Cellular networks are the principal networks to provide wireless communication in large area. In cellular networks, BSs are distributed over the network area and each connects to back bone networks through wired lines. Each of these BSs forms an individual cell with coverage determined by the topography, environmental factors such as weather, antenna configuration and antenna power. In a cell, users can only get service from the BS, and the boundary between the cells is determined by antenna power and tilting. All the cells work together seamlessly to cover the whole network without coverage holes and support mobility across cells. A cellular network structure is shown in Figure 2.1(a) where a hexagon represents the coverage of a cell. More details on cellular networks can be found in [3].

Cellular networks are widely used because they support high frequency efficiency and user mobility. To support user mobility, cells essentially cooperate to provide seamless coverage to the whole environment. Thus, a user moving out of a cell can handover to other cell and still receives wireless communication as satisfactorily as static users. To support frequency efficiency, the same frequency band in cellular networks can be reused without causing high co-channel interference (CCI) in the BSs that are far apart from each other. There are a number of frequency reuse schemes [4-5]. One scheme is shown in Figure 2.1(b). In this example, the cellular network employs frequency reuse factor 3 and every 3 cells form a cluster. Therefore, the total frequency band is divided into 3 parts, and each of the 3 cells in a cluster uniquely uses one part of the frequency band. Based on this division, there is no CCI within the member cells in a cluster, and the CCI within the co-channel interfering cells that are not in same cluster is relatively decreased because the cells are far away from each other. However, because a cell can only have 1/3 of the total frequency band in this frequency reuse scheme, this scheme has low frequency efficiency. For example in Figure 2.1(b), in one cluster, the red cell only has 1/3 of the frequency band, so the red cell will have no CCI to the green cells and the blue cell that each also takes 1/3 of the frequency band in the cluster. Thus, the red cell only can use 1/3 of the total frequency band. In practice, there is a trade off on the frequency reuse factor and frequency efficiency. The higher the factor is, the lower CCI will be, but the frequency efficiency will be lower, and vice versa[4]. In Mobile WiMAX used in this thesis, the frequency reuse factor is set to 1(fully reuse) to obtain the highest frequency efficiency. In order to decrease CCI, Fractional Frequency Reuse (FFR) and related augmented scheme are employed. These will be discussed later in this thesis.

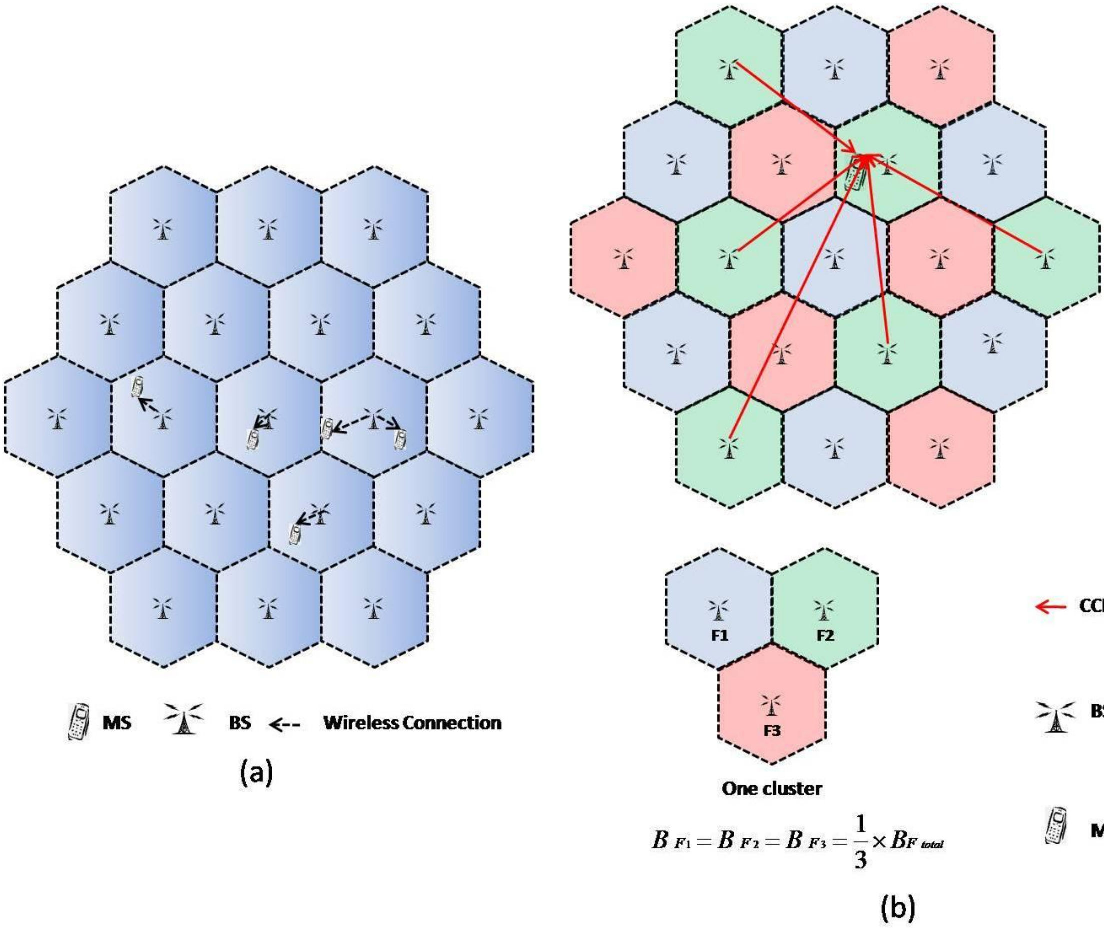


Figure 2.1 Cellular networks structure and frequency reuse with factor 3

Traditional cellular networks cannot achieve the high frequency and power efficiencies required to satisfy the growing user demand, nor provide the QoS for the last-mile wireless broadband communication in a non-line-of-sight [6] environment. One solution to these problems is to bring more BSs into cellular networks. However, this will increase the network investment, which is impossible in the commercial world when companies could be focussing on the deployment of future technologies. Thus, another solution where cellular networks are augmented using multi-hop communication for higher performance is more applicable [7]. The multi-hop is realized through the help of MSs, moveable relay devices, or fixed RSs. This is shown in Figure 2.2. Fundamentally, the main benefits of multi-hop communication in cellular networks are BS coverage extension, network capacity and throughput increase.

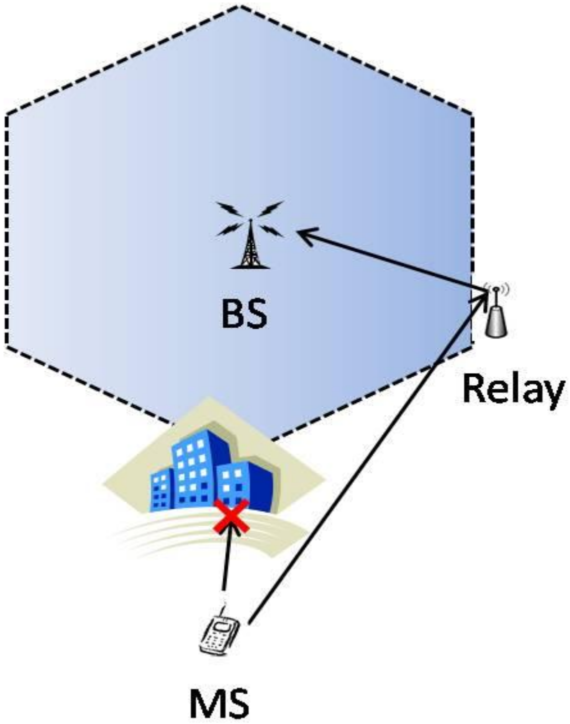


Figure 2.2 Multi-hop Communication in Cellular Networks

There are some augmented cellular networks with multi-hop communication capability in literature. In [8], flexible multi-hop communication in cellular networks is realized by using Unmanned Air Vehicles (UAV). A UAV acts as relay. It can move among users gathering data like a polling system, and then forward data to the BS. This design can theoretically avoid connection failure between users and BSs, thus improve user throughput. The drawbacks of this solution are low stability and low efficiency. This is because UAVs are incorporated into cellular networks in a loose and temporary manner, and UAVs have limited relay ability. In [9] integrated cellular and Ad Hoc Relaying systems (iCAR) is proposed. In iCAR, ad hoc relaying stations (ARS) is used for multi-hop communication. An ARS has limited mobility. It is placed at strategic locations, and relays signal between mobile users and BSs. There are three levels of relaying in iCAR: primary relaying, secondary relaying and cascaded relaying. iCAR is a complicated system. It entails channel switching. This forces user devices having complicated functions, which is arguably not practical.

In this thesis, RBCNs are considered. The RBCN in use augments fixed relay station into cellular networks for multi-hop communication. It works under Mobile WiMAX technology and takes IEEE802.16j as standard. Compared to UAVs based multi-hop communication and iCAR, the RBCN has a more stable and powerful multi-hop communication ability and is easier to implement.

2.2 Mobile WiMAX and OFDMA related to RBCN

WiMAX (Worldwide Interoperability for Microwave Access) [10] technology is based on IEEE802.16 standard [11] that is worked out by IEEE802.16 task group [12]. It makes use of OFDMA (Orthogonal Frequency Division Multiple Access) scheme [13] and is a proposed technology for fixed broadband wireless communication. The name “WiMAX” was created by the WiMAX Forum [14], which was formed in June 2001 to promote conformity and interoperability of the standard.

Compared to WiMAX, Mobile WiMAX[15] is supported by IEEE802.16e standard [16], and implements broadband wireless communication into mobile devices. In order to support movable devices to get voice calls, video streams, file downloads, Mobile WiMAX augments OFDMA into SOFDMA (scalable-OFDMA) and includes related modifications. Mobile WiMAX salient features are High Data Rates, Quality of Service (QoS), Scalability and Mobility. Mobile WiMAX supports variety of transmission modes, from point-to-multipoint (PMP) to mesh mode. Mobile WiMAX cellular networks using the PMP transmission model are the interest of this thesis.

Currently, IEEE 802.16 relay task group [17] is in the process of finishing IEEE 802.16j [1], the multi-hop Relay Specification for 802.16. As discussed before, this amendment will be fully compatible with 802.16e Mobile WiMAX, but a BS specific to 802.16j will be required for RSs to operate. In [18], the work presents an introduction to the upcoming IEEE 802.16j amendment and provides insight about the obstacles that practical system designers face when incorporating relaying into a wireless broadband network.

OFDMA [13] has emerged as one of the most promising modulation and multiple access schemes for future broadband wireless networks in the Media Access Control (MAC) layer. It is frequency division multiple access (FDMA) augmented with time division multiple access (TDMA) as shown in Figure 2.3. In this figure, frequency and time resource are divided into "slots". A slot includes certain amount of sub-carriers (combined as a sub-channel) in frequency domain and symbols in time domain for wireless communication. The slots are the atomic frequency resource to be allocated to users on a per-frame basis. When frequency and time resources are limited, OFDMA can enable more users to obtain communication service with adequate QoS by dynamically allocating slots to users. The frequency band is divided into sub-carriers by OFDM in the physical layer.

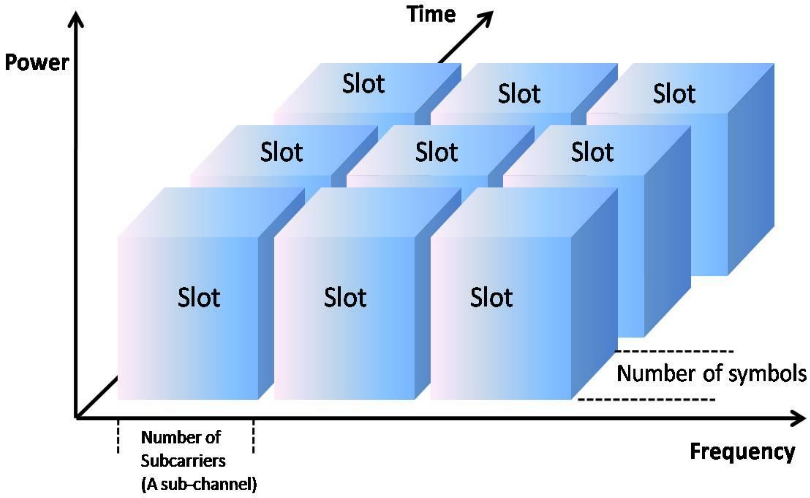


Figure 2.3 Multiple access scheme in OFDMA

OFDM is a multicarrier modulation technique being widely adopted in a widespread variety of high-data-rate communication systems including WiMAX, 3G being developed by 3GPP [19], LTE[20] and 4G cellular systems. OFDM popularity for high-data-rate applications stems primarily from its efficient and flexible elimination of inter-symbol-interference (ISI). The basic solution to eliminate ISI in OFDM is orthogonal frequency band division. OFDM uses an efficient computational technique namely, discrete Fourier transform (DFT), to overcome the daunting requirement for multiple radios in both the transmitter and the receiver to realize frequency band division. DFT lends itself to a highly efficient implementation commonly known as the Fast Fourier Transform (FFT) and its inverse (IFFT). In OFDM, the FFT and IFFT can create a multitude of orthogonal sub-carriers using a single radio. Each sub-carrier takes small part of the total frequency band. OFDM also uses antenna signals, cyclic prefix(CP) and guard band to improve frequency division performance. More about antenna signals， cyclic prefix and guard bands can be found in [21].

In OFDMA, OFDM divides frequency band into sub-carriers, then these sub-carriers are permutated into sub-channels through certain permutation scheme, such as the diversity scheme: Partially Used Sub-Carrier (PUSC). Thus, one OFDMA sub-channel is composed of a prescribed number of sub-carriers according to the system spectrum and OFDMA configuration. This is shown in Figure 2.4. For example, a sub-channel consists 24 data sub-carriers and 4 pilot sub-carriers when Mobile WiMAX works in 5MHz frequency band with 512 FFT size [15].

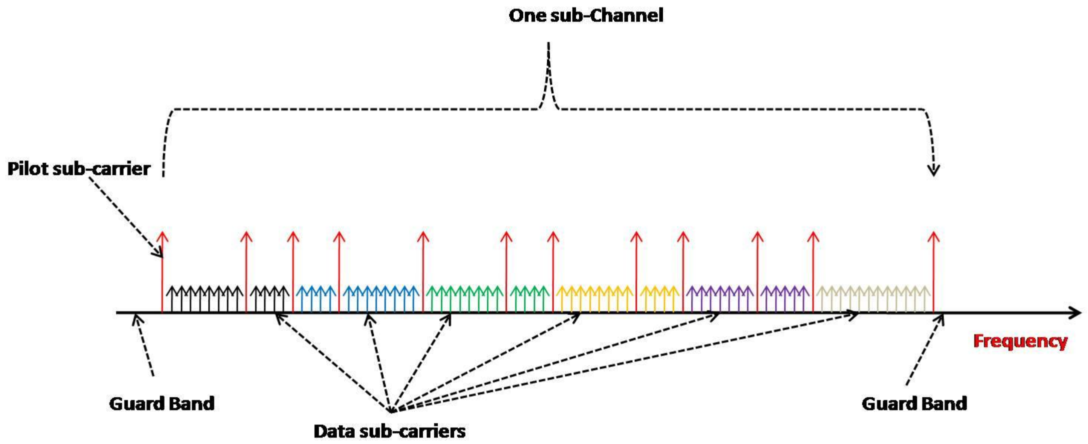


Figure 2.4 Sub-carrier permutation in a OFDMA sub-channel

In Mobile WiMAX, OFDMA is updated into scalable OFDMA (SOFDMA). SOFDMA supports a wide range of bandwidths to flexibly address the need for various spectrum allocation and usage model requirements. The scalability is supported by adjusting the FFT size in OFDM while fixing the sub-carrier frequency spacing at 10.94 kHz. Since the resource unit sub-carrier bandwidth and duration is fixed, the impact to higher layers is minimal when scaling the sub-channel frequency bandwidth. The variable FFT size allows for optimum operation and implementation of the system over a wide range of channel bandwidths and radio conditions, which is suitable for mobile and portable operations. The FFT size can take any of the following values: 128,512, 1024 and 2048. More about SOFDMA can be found in [22]. In this thesis, because Mobile WiMAX only works in 5MHz frequency bandwidth, there is no frequency bandwidth diversity and FFT size is fixed (to be 512). Thus there is no difference between OFDMA and SOFDMA in this thesis.

In this thesis, the RBCN channel model is based on OFDMA. It takes channel (equal to sub-channel in [15]) as the atomic frequency resource. As shown in Figure 2.4, a channel is composed of a certain number of OFDM sub-carriers in frequency domain following Mobile WiMAX configuration. Therefore, in this thesis, it is assumed that there are fixed number of available channels in RBCN. For example, there are 15 channels in total in RBCN when it is working in 5 MHz frequency band and having a 512 FFT size as the Mobile WiMAX configuration. Based on this channel model, the frequency resource allocation in RBCN system level is modelled on a per-user basis. In comparison, a richer model based on the frequency-time resource on a per-frame basis is discussed in [15]. The richer model is for RBCN link level, and is not considered in this thesis.

According to the per-user based frequency resource allocation, each BS in a RBCN, as the resource holder, could have certain amount of channels. The channel amount in each BS is adjusted by frequency allocation algorithms, and decides the capacity and throughput of this BS. In networking operation, a user can get access the BS in the downlink with satisfactory data rate by taking up several channels from the BS. How many channels taken up by a user from the BS is decided by the user service type and the channel data rate that is decided by channel quality and Adaptive Modulation and Coding (AMC). In principle, the higher channel quality is, the less channels are required by the user. Alternatively, the simpler the service a user asking, like voice call, the less channels are required by the user.

The network reconfiguration and frequency allocation that runs periodically in the RF layer are based on the above channel model in this thesis. It will be discussed further in system model in the next chapter.

2.3 IEEE 802.16j supported RBCN

The RBCN used in this thesis is based on IEEE802.16j standard [1], which adds relay capabilities into IEEE802.16e [14] supported Mobile WiMAX cellular networks by using a fixed RS. RBCN works with a MMR model as discussed in Chapter 1. In [18] and [23-25], the benefit of fixed RS working in cellular networks and related research issues are summarized. This thesis strictly works on this Mobile WiMAX based RBCN. All the BSs and RSs follow Mobile WiMAX features in different network layers. Compared to other wireless technology like UMTS[20], Mobile WiMAX supports wireless broadband communication in higher data rate while users are in high mobility.

2.3.1 Relay Station in RBCN

RS is the type of device to realize multi-hop communication in RBCN. The functions of RSs are critical to RBCN performance. In a RBCN, a RS may connect to a BS through wireless connection in line of sight. A RS can be decode-and-forward (digital form) or amplify-and-forward (analog form). In decode-and-forward schemes, where RSs are also referred to as digital repeaters, bridges, or routers, the RSs regenerate the signal by fully decoding and re-encoding the signals prior to retransmission. Decode-and-forwarding is suitable for traffic types that are less sensitive to delay and require large bandwidth to accommodate required high data rates. By contrast, in the simpler and faster amplify-and-forward system, RSs essentially act as analog repeaters at the cost of increasing the transmission noise level. Amplify-and-forward is suitable for the traffic that requires low data rate but is sensitive to delay. [24]

A RS in RBCN can work in transparent or non-transparent relay modes. Transparent relay mode means that RSs do not forward BS frame header information to MSs for interference limitation. Therefore, the MSs helped by transparent RS need to directly receive frame header information from the charging BS. This forces MSs to be close to covering BS. Thus, transparent RSs cannot extend the coverage of a RBCN. Instead, it only increases BS capacity by helping quality MS to BS connection with low power. In practice, transparent relay mode only supports a maximum of two hop multi-communication. Compared to transparent relay model, non-transparent RSs can forward (or forward with modification) BS frame header information to a MS (centralized scheduling) or generate its own frame header information to a MS (distributed scheduling). Thus non-transparent RSs can both extend RBCN coverage and increase BS capacity. However, this brings in higher interference between neighbour RSs. The non-transparent relay mode can support more than 2 hop multi-communication. [23]

This thesis tries to augment cellular networks for large-area broadband communication. Thus RBCN employs decode-and-forward relay, and both transparent and non-transparent relay modes are considered. Multi-hop communication is limited to 2 hops (it will be extended in a later chapter by using DTN). For simplicity, in the experiments, a RS is located at fixed locations near the boundary of its charging BS. The BS-RS connection is assumed to be decided a priori during network planning, so dynamic RS location adjustment [26] is not considered in this thesis. A typical RBCN network distribution used in this thesis is shown in Figure 2.5.

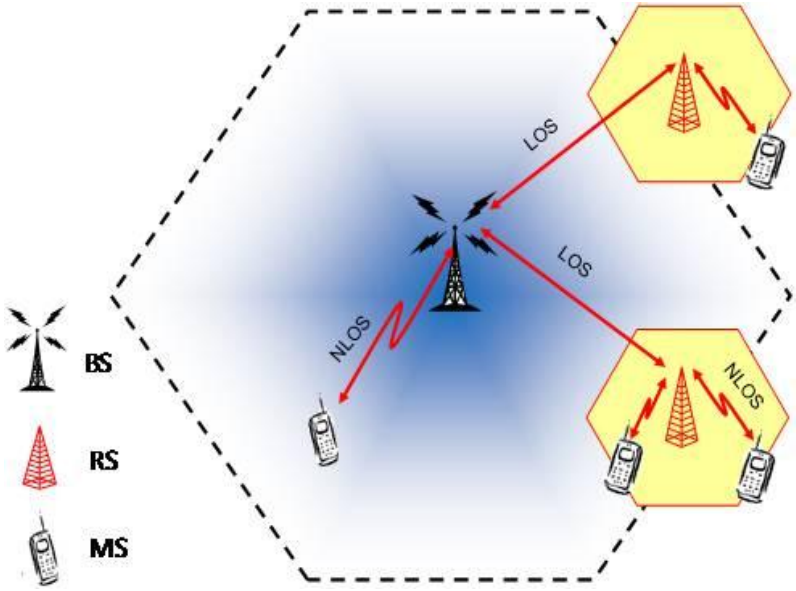


Figure 2.5 A basic structure for a relay based cellular network

Because of the additional RS facilities, RBCN realization is more complicated compared to traditional cellular networks. Since this thesis focuses on system level RBCN performance, it only considers network reconfiguration and frequency allocation in RF layer, and MS Admission Control (AC) and radio resource management in MAC layer. Other aspects in RBCN are not discussed.

2.3.2 Admission control in RBCN

In RBCN, how a MS selects an access station (RS or BS) is important to the network performance. As discussed before, MMR enables a MS to have multiple choices of access facility viz. BS or RS. Thus RBCN needs to have an admission control (AC) scheme to let MS access network and obtain wireless resource for communication in QoS.

In [27] and [28], RS selection of MSs is a simple AC scheme designed to be either geographically or path-loss based. In geographical selection, Shortest Total Distance (STD) Selection, Least Longest Hop (LLH) Selection or Shortest Relaying hop Distance (SRD) Selection are employed. In principle, a MS prefers the RS which is the closest to itself in geographical selection. In path-loss based selection, Minimum Total Path-loss (MTP) Selection, Least Maximum Path-loss (LMP) Selection， and Minimum Relaying Hop Path-loss (MRP) Selection are possibilities. Path-loss based selection follows the same idea as geographical selection that a MS prefers close access station to connect to. However, a MS makes the RS choice based on specific wireless condition, which better reflects the wireless topography. Additionally, in [27] and [28], how a MS can select a RS rather than BS or vice versa is discussed. The method is that a MS prefers a RS rather than a BS if no BS can provide a channel having Signal to Interference and Noise Ratio (SINR) higher than a prescribed threshold, but the RS can. In [29], AC for MS employs another strategy that guarantees scalable QoS provisioning in multiple user demand situations. In that work, a MS accesses the BS or RS that provides the highest data rate based on OFDMA-TDD. If a MS selects a RS, the allocated channels in the 2 hops together should give the highest data rate compared to BS according to the modulation and coding level of the links. Otherwise, the BS is preferred. The drawback of this method is extra message delivery and the delay between MS to BS. This is because each MS needs to send its data rate request and delay sensitivity to nearby BSs. This is more complicated than the methods in [27] and [28] but gives better user QoS and is practical.

In RBCN of this thesis, a MS is covered by an access station (BS or RS) only if this station can provide the MS channel with SINR in the antenna tilting scheme or antenna signal strength in the cooperative antenna power control scheme above a predefined fixed threshold. A MS may be covered by several access stations (BSs or RSs). To guarantee that a MS receives service with required QoS, this thesis considers both the geographical selection (simply employs STD selection) in [27-28] and the data rate-based BS or RS selection scheme adopted in [29] in different applications. In STD, it is assumed that if a MS is close enough to a RS (the geographic distance or path loss below certain threshold), this MS decides to connect to the RS, otherwise it connects to the closest BS. The data rate-based scheme is shown in Figure 2.6. The data rate calculations in one hop and two-hop BS to MS connections are defined in the system model discussed in next chapter. In two-hop connections, the data rate calculation is different between transparent relay model and non-transparent relay model.

Like the work in [27-29], the AC mechanism in this thesis assumes that a RS is an entry entity at the same level as a BS. A MS makes no distinction between a RS or BS as an entry entity. This is a practical and easy to realise approach when the RS to BS connection is fixed and the connection is in satisfactory working state. Another benefit of such a MS AC method is that a MS can easily find an entry entity providing a high quality channel or good coverage.

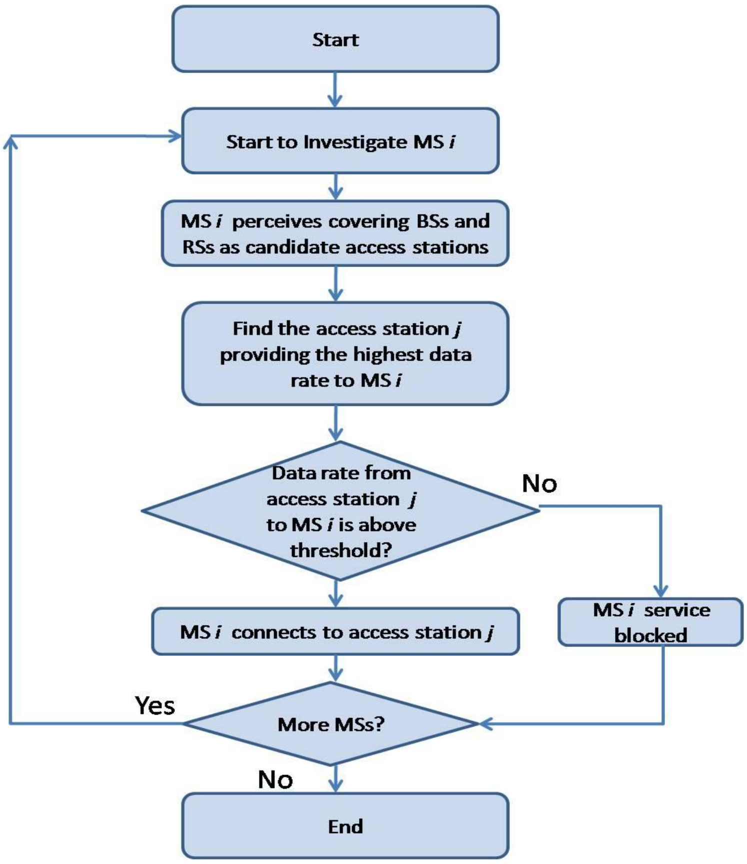


Figure 2.6 MSs admission control in RBCN using a data rate-based selection scheme

2.3.3 Radio resource management in RBCN

In this thesis, downlink frequency allocation is the only consideration in RBCN radio resource management. Power allocation and uplink frequency allocation are not considered in frequency allocation schemes. Based on this assumption, it is assumed that antenna power of each BS or RS is fixed in RBCN when frequency allocation happens (but antenna power can be changed for cell coverage adjustment). Therefore, in MS scheduling, attaching specific channels with fixed power to covering MSs in each cell is the only issue.

In RBCN, frequency allocation in a BS follows the same principle as the works in traditional cellular networks. However, RBCN should consider the extra frequency requirement of RS to MS connections in each cell. Thus traditional frequency allocation needs to be augmented. The solutions to the extra frequency requirement are different between transparent relay mode and non-transparent relay mode in RBCN.

Frequency allocation in transparent relay model

The scheme to handle the extra frequency requirement in the transparent relay model in this thesis is based on a simple but effective frame structure [30] shown in Figure 2.7. The simple frame structure is based on a practical frame structure in [2] for IEEE 802.16j MMR. Compared to the complicated RBCN frame structures in [31], this simpler one ensures that the RS to MS connection shares the BS allocated channels with RS to BS connection in separate time slots both in two-hop downlink and uplink. Thus RS to MS connection in any two-hop does not cause extra frequency requirement. This Channel Sharing (CS) is deliberately designed for the RS transparent relay model. In CS, if a MS is directly linked to a BS, the BS allocated channel and time slot usage are the same as in a normal cellular network. When a MS is indirectly linked to a BS by a RS relay, the time slot of the BS allocated channel is divided into two parts. One part is for when the BS sends the data to the RS, and all RSs with direct connection with a BS receive the same transmission in this part of the time slot. The other part of the time slot is for when a RS relays the data to a MS. The most obvious benefit of CS in RBCN is the simplification of frequency allocation. This is because a transparent RS in a BS can share the channels in that BS without causing extra channel overhead, so a frequency allocation algorithm does not need to consider deliberately allocating channels to a RS. Another benefit of CS is that it is more likely to avoid a RS-MS connection from causing intra-cell and inter-cell interference in the cell that covers the RS.

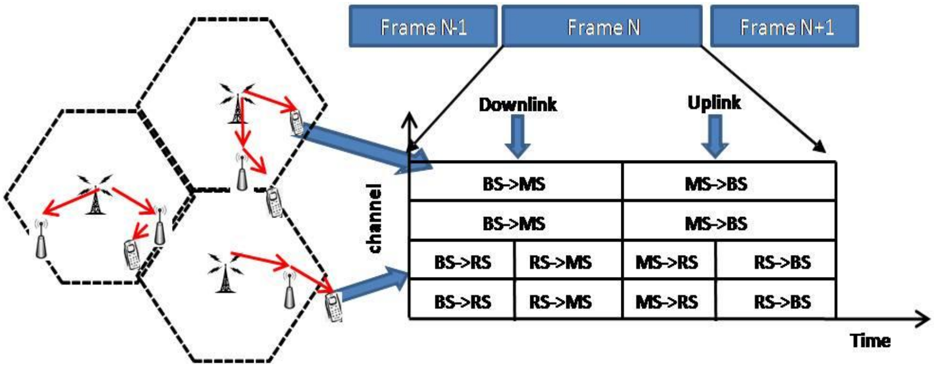


Figure 2.7 Frame structure of RBCN in transparent relay mode[30]

Frequency allocation in the non-transparent relay model

Compared to the transparent relay model, the non-transparent relay model involves more complicated frequency allocation. Any RS-MS connection cannot share the channel used in BS-RS connections unlike the CS scheme. A RS to MS connection in the non-transparent relay model needs extra channels and these extra channels may increase inter-cell and intra-cell interference. This is because non-transparent RS transmits data bursts and control information to the MS at the same time as the BS transmits data bursts and control information to MS or RS in each cell [31]. Figure 2.8 shows the frame structure for the non-transparent relay mode.

In [27-28], Smart Channel Selection and Random Selection are presented as solutions. Smart Channel Selection performs channel reusability checks among all the channels from adjacent cells to select optimal channels for RS to MS connections. This avoids CCI because the reusable channels from adjacent cells are not used currently in the cell that the RS is located in. Specifically, when a RS to MS connection in a cell wants to use channels from other cells, the reused channels from adjacent cells are checked for whether they will cause CCI to the channels used in the RS's cell. If they do, the adjacent channels will not be used by the RS to MS connection. Different from Smart Channel Selection, Semi-Smart Channel Selection and Random Channel Selection do not perform a channel reusability check. Semi-Smart only selects the channels having highest SINR from adjacent cells. Random Channel Selection blindly selects random channel from adjacent cells. Obviously, Smart Channel Selection is the best method. However it involves a high computational cost compared to the Semi-Smart and Random Channel Selection methods.

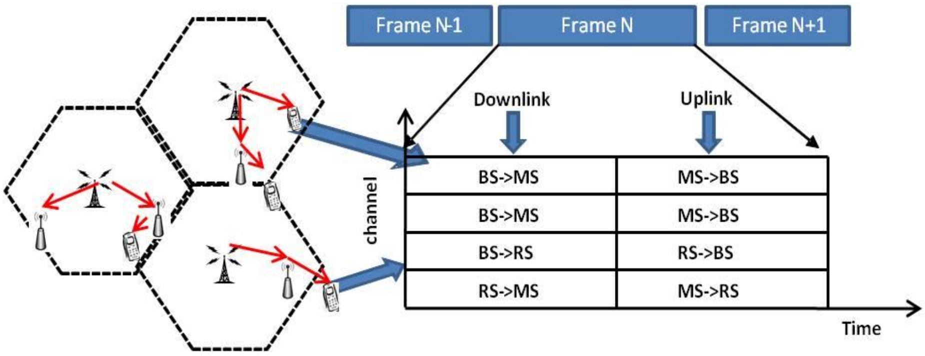


Figure 2.8 Frame structure of RBCN in non-transparent relay mode

MS Scheduling

MS scheduling in a RBCN cell is another important issue on radio resource management. In RBCN, MS scheduling is also different between transparent relay model and non-transparent relay model. If RBCN works in transparent relay model, MS scheduling in RBCN is centralized that only the BS makes scheduling decisions. Centralized scheduling in RBCN is fundamentally the same as for traditional cellular networks. If RBCN works in non-transparent relay model, MS scheduling in RBCN could be performed either in centralized way or distributed way where both BS and RS can make scheduling decisions [23]. A number of scheduling mechanisms previously designed in Mobile WiMAX can be used in RBCN. Because MS scheduling is not the main consideration of this thesis, a simple but well known scheduling scheme is used: minimum performance guarantee (MPG) opportunistic scheduling [32]. This will be explained in the system model in the next chapter. More sophisticated scheduling schemes like proportional fairness can be found in [33].

2.4 Antenna reconfiguration and frequency allocation to improve RBCN performance

As introduced in Chapter 1, antenna reconfiguration and dynamic frequency allocation are intended to improve RBCN performance in congested and emergency situations. Antenna reconfiguration is employed in two ways: antenna power control and antenna tilting. The motivation in this thesis is to keep the modifications to the RF layer simple so that simple antennas can be used. Dynamic frequency allocation can be realized by a number of strategies and these will be explored. Figure 2.9 shows the sequence of antenna reconfiguration and dynamic frequency allocation within RBCN components.

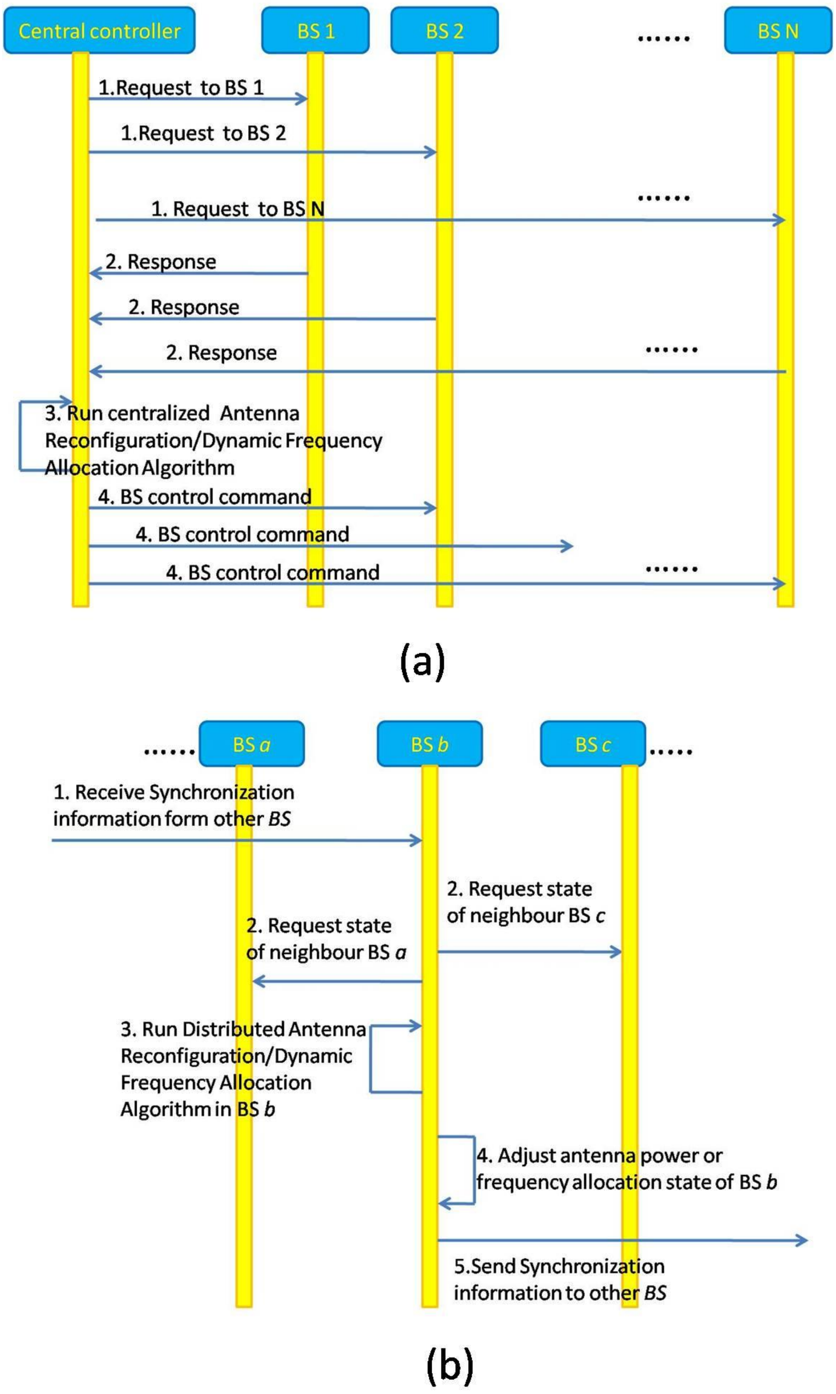


Figure 2.9 Sequence of Centralized and Distributed Antenna Reconfiguration/Dynamic Frequency Allocation in RBCN

Figure 2.9(a) shows the sequence of centralized antenna reconfiguration/dynamic frequency allocation. There is a central controller in RBCN that runs centralized antenna reconfiguration/dynamic frequency allocation algorithms with respect to its gathered load, antenna power and frequency allocation states of all the BSs. After finishing the algorithm, the central controller will send the BS control command to let related BSs (or related RSs) change their antenna power or frequency allocation state. More about centralized solutions will be discussed in Chapter 4 and 5. Figure 2.9(b) shows the sequence of distributed antenna reconfiguration/dynamic frequency allocation. Compared to centralized solution, distributed solution does not need central controller. Each BS works out its antenna power and frequency allocation state according to its gathered neighbour BSs load, antenna power and frequency allocation states. All these distributed BSs in RBCN synchronize to each other to work in sequence or parallel by exchanging information within neighbours. More about distributed solution will be discussed in Chapter 6.

2.4.1 Antenna power control

In Mobile WiMAX, a channel has sub-carriers to send the antenna signal to receivers. The sub-carriers in OFDM are shown in Figure 2.4. In a channel, pilot sub-carriers carry channel quality information (SINR) between BS and MS to let the MS know the radio coverage of the source station (the higher SINR is, the better BS coverage is). In this way, users can use channel SINR to perceive and evaluate antenna radio coverage and decided whether they are covered and could be admitted by the BS. Thus, if antenna power of a BS is changed, the channel SINR and the BS radio coverage changes to MSs. For high network throughput, the antenna power needs to be controlled to eliminate CCI.

In the literature, antenna power control has been researched in different wireless communication technologies. In [34-36], CDMA and WCDMA controls pilot power as one part of the antenna power for BS coverage maintaining and CCI control. In [34], a rule based technique that optimizes pilot power settings of CDMA cellular systems is presented. The rule based technique gives significant improvement in antenna interference reduction with some improvement in coverage and capacity allowing a substantial reduction in deployment efforts spent in optimizing pilot powers. However, antenna power control to relieve user congestion problem is not considered in [34]. In [35], antenna power utilization in WCDMA channel quality estimation, cell selection, and handover are estimated. The paper considers the problem of minimizing the total amount of pilot power subject to a coverage constraint. Antenna power interference elimination is its focus. It does not implement radio coverage adjustment through antenna power control. In addition to [34-35], a common pilot power control for load and coverage balancing in WCDMA is discussed in [36]. The pilot power is controlled with simple heuristic rules. If the load balance or the coverage balance deviates significantly from zero, the pilot power is changed. The load balance has always precedence over the coverage balance. [36] does not adjust antenna power in a cooperative way. In this thesis, the antenna power control concept in [34-36] is used in OFDMA based Mobile WiMAX. Even through an OFDMA channel has pilot sub-carriers, but these pilot sub-carriers cannot independently change their power. Therefore, only antenna power control mechanism can be used for cell coverage adjustment in this thesis.

In this thesis, antenna power control is used to cooperatively change the radio coverage of RBCN BSs and RSs for geographic load balancing. This is called cooperative antenna power control. Geographic load balancing [37] means that when users are not uniformly distributed, wireless network BSs try to adjust the RF physical layer and other layer parameters to serve these users to eliminate service congestion. Under geographic load balancing, wireless networks can have higher capacity, throughput, resource efficiency and user Quality of Service. One example of geographic load balancing is shown in Figure 2.10 and 2.11.

In Figure 2.10, it is assumed that BS *A* is heavily loaded and some of the users cannot get service while BS *B* is lightly loaded. Thus, BS *B* and *A* suffer from low capacity and low user Quality of Service. Geographic load balancing is illustrated for this case in Figure 2.11, where BS *A*, *B* and related BSs use cooperative antenna power control. Specifically, the lightly loaded BS *B* expands its radio coverage and heavy loaded BS *A* shrinks its radio coverage to let some users handover from a heavily loaded BS to a lightly loaded BS. Geographic load balancing results in more users being served in comparison to Figure 2.10.

Some geographic load balancing related algorithms have been discussed in literature. In

[38], agent based cooperative negotiation for geographic load balancing is discussed. In [39], the bubble oscillation algorithm (BOA) is introduced, which gives equivalent performance but less computation. The analogy developed is that cells are bubbles and demand is related to the pressure. The bubbles adjust and oscillate to a cell shape where the load is balanced over the network. In [40], a utility function is introduced for utility-based cooperative control approach. Different antennas are considered including omni-directional, sectored, and semi-smart in [38-40].

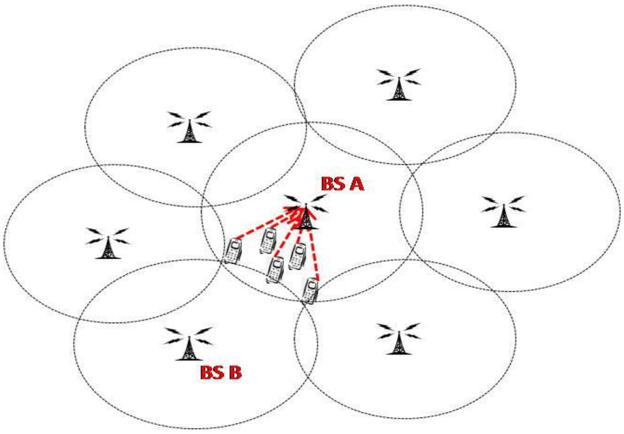


Figure 2.10 Un-balanced user load

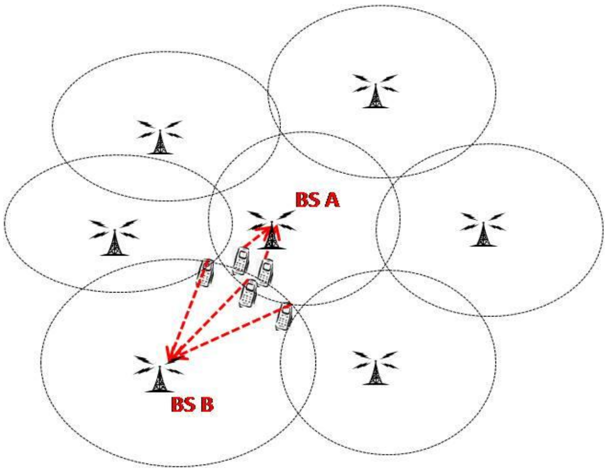


Figure 2.11 Balanced user load

2.4.2 Antenna tilting

BS antenna tilting is a common practice in cellular networks. By changing the outer frontier of a sector through tilting up or down the antenna vertical radiation angle, a network operator has the capability to alter power distribution and cell coverage. This is guided by measurements and network planning, which is an essential support in cellular networks. As shown in Figure 2.12(a), the principal tilting mechanism is to change the ‘look direction’ of the main beam, which is the direction where the antenna directional gain is at its maximum. Antenna tilting can be implemented mechanically—mechanical tilting (MDT) or electrically—electrical tilting (EDT) [41]. Mechanical tilting is usually accomplished by physically tilting the antenna using brackets or shims. When the antenna has tilt, the antenna main lobe is more precisely directed towards the intended area. However, mechanical tilting is exclusively in the main-lobe direction and the antenna radiation pattern is not down tilted at all in the side-lobe direction [42]. The antenna mechanical tilting can only be conducted by on-site visit of engineers. Most commonly BS antenna tilt angles are selected in advance during network planning, and only go through an adjustment process when an antenna is installed. Thus MDT is not applicable to network reconfiguration. Therefore, electrically tilted antennas become an attractive choice for antenna selection. Antenna electrical tilting is carried out by adjusting the relative phases of the antenna elements of an antenna array in such a way that the radiation pattern can be tilted uniformly in all horizontal directions [43]. EDT makes real time antenna reconfiguration practical. This thesis considers EDT in antenna tilting.

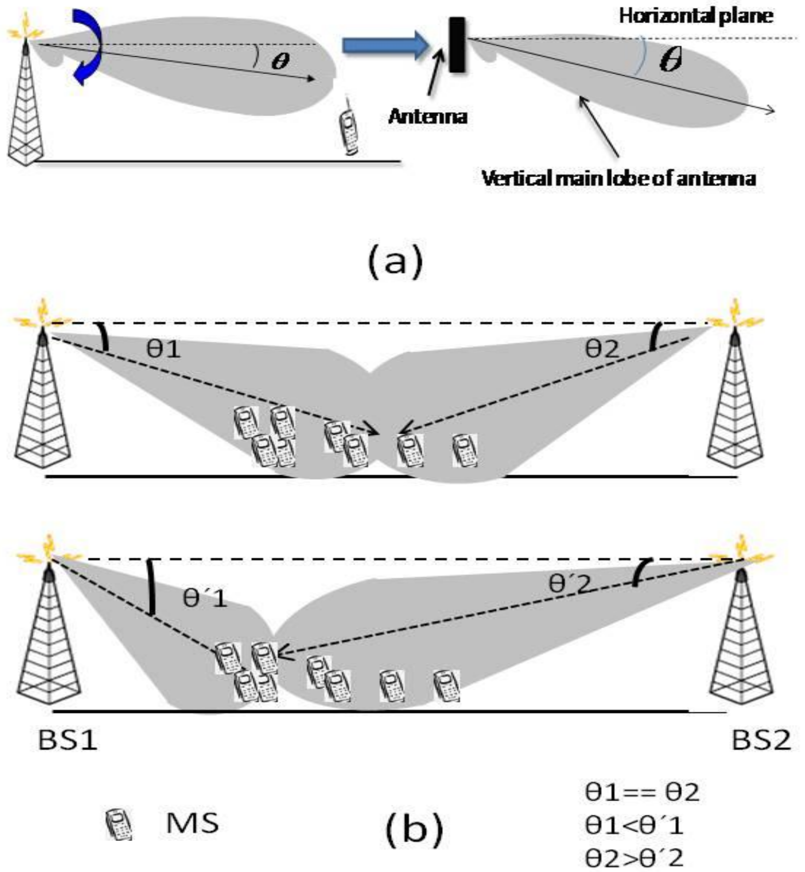


Figure 2.12 Antenna Tilting to relieve user congestion problem

Like cooperative antenna power control, one of the important utilizations of antenna tilting in this thesis is also for geographic load balancing. This is shown in Figure 2.12(b). In that figure, MSs are covered by BSs that can provide good quality channels (SINR above fixed threshold). Thus, if a heavily loaded BS tilts down its antenna to have a lower distribution range, the SINR of its channels will increase at points close to the BS at the cost of un-covering some other MSs farther from the BS. This channel SINR change can therefore result in some MSs of a heavily loaded BS being handed over to other BS. This can be accommodated if the opposing BS is more lightly loaded and the antenna in that BS tilts up. Thus user congestion in heavily loaded BS can be relieved. For example of Figure 2.12(b), the heavily loaded BS_1tilts down its antenna ($\theta_1^{'} > \theta_1$), and the lightly loaded BS_2 tilts up its antenna ($\theta_2^{'} < \theta_2$). In this way, BS_2coverage is expanded, and BS_1 coverage is shrunk. After this, some users in BS_1 will handover to BS_2. Thus, this cooperative tilting between $BS_1$and BS_2 balances the load between these two BSs.

Antenna tilting can also be used to mitigate coverage holes caused by BS failure. In the proposed solution, an antenna can be purposely reconfigured to tilt up towards a coverage hole. Through this way, loss of communication through BS failure can be mitigated. The limitation of this solution is that BSs have limited ability to tilt up their coverage so they cannot solve the BS failure problem on their own. However, the benefits of this solution include: 1) because antenna tilting exists in cellular networks, this solution does not involve additional facilities. 2) this solution can work with other solutions like the one proposed in [44] that uses supplementary facilities to mitigate a coverage hole or with the DTN solution in this thesis. For example, if a BS failure happens, the tilting solution in this thesis can be carried out firstly to limit the BS failure effect before requiring supplementary facilities or users to build up delay tolerant connections. Similarly, antenna power control can also be applied to solve the BS failure problem. However this thesis only considers antenna tilting. In addition, antenna tilting working with frequency allocation in the proposed integrated solutions can further mitigate BS failure problem and this will be discussed in Chapter 5.

Notionally, cooperative antenna power control and antenna tilting can be applied in real time in RBCN, as the algorithms may not have high complexity. However, it is more likely they would be utilized periodically during the day to manage different profiles, essentially providing contextual dynamic updates to the configurations established by the network planning tools. This mitigates the increase in handovers and gives stability to the network coverage. However, the potential for near real time application exists. Cooperative antenna power control and antenna tilting of this thesis are mainly investigated in Chapter 4.

2.4.3 Frequency allocation to improve RBCN performance

In commercial cellular networks, frequency resource shortage is a severe problem hindering high network capacity and throughput. This problem is exacerbated when users require advanced services requiring more frequency bands, such as video-streams, file downloads, or are un-evenly distributed. The user congestion and BS failure problems in RBCN also may aggravate the shortage problem. This frequency resource shortage also exists in RBCNs.

Frequency allocation can increase frequency efficiency, so is a solution employed to mitigate the shortage problem and relieve user congestion and BS failure problems. As discussed before, frequency allocation belongs to radio resource management in cellular networks. If frequency allocation is performed again when MSs distribution changes or network antennas are reconfigured, it will effectively benefit network performance on capacity and throughput. There have been lots of frequency allocation algorithms for cellular networks and a summary can be found in [45-46]. These algorithms can be centralized or distributed and can be constrained to fixed or dynamic allocation, or can constrain the dynamic schemes to be what are called hybrid algorithms. In practice, the distributed and dynamic frequency allocation algorithms are the most suitable ones in current cellular networks. They have attracted lots of research attention.

In [47] and [48] centralized frequency allocation, sub-optimal fixed frequency allocation is carried out for the downlink of two-hop cellular relay networks. In [47], RS-MS connection reuses the adjacent cell frequencies in the pre-configured and fixed (PreF) frequency allocation scheme. In [48], the authors describe and analyze the Orthogonal Resource Allocation Algorithm (ORAA) and a modified one based on static fractional frequency reuse. In [49], fixed fractional frequency reuse in Mobile WiMAX is augmented to be applicable to RBCN. In [50], a solution is proposed to avoid the low frequency efficiency problem of fixed allocation and employ dynamic frequency allocation scheme based on fractional frequency reuse in two hop cellular relaying networks. However the work in [50] only considers dynamic frequency allocation inside a cell and hence cannot relieve user congestion problem very much. The works in [47-50] target the RBCN in non-transparent relay model.

As shown in [48-49], fractional frequency reuse (FFR) is a good choice for frequency allocation in RBCN. Frequency allocations in Mobile WiMAX and IEEE 802.16j supported RBCN are based on FFR. In [51], FFR is summarized and analyzed. FFR is a novel mechanism to increase frequency efficiency, network capacity and throughput. In FFR (normally static FFR), each cell is divided into an inner area and an outer area, and channels in different areas have different frequency reuse factors in a cell. The division of inner area and outer area is based on geographical distance or channel SINR from location to the cell centre. In the inner area, the frequency reuse factor is 1. Even though a low frequency reuse factor might cause high CCI, the inner areas of two adjacent cells are geographically far away, so CCI will be low. On the other hand, the outer areas between two adjacent cells are geographically close with each other, so the frequency reuse factor in the outer area of a cell should be higher to decrease CCI on the cell boundary. FFR is shown in Figure 2.13(a).

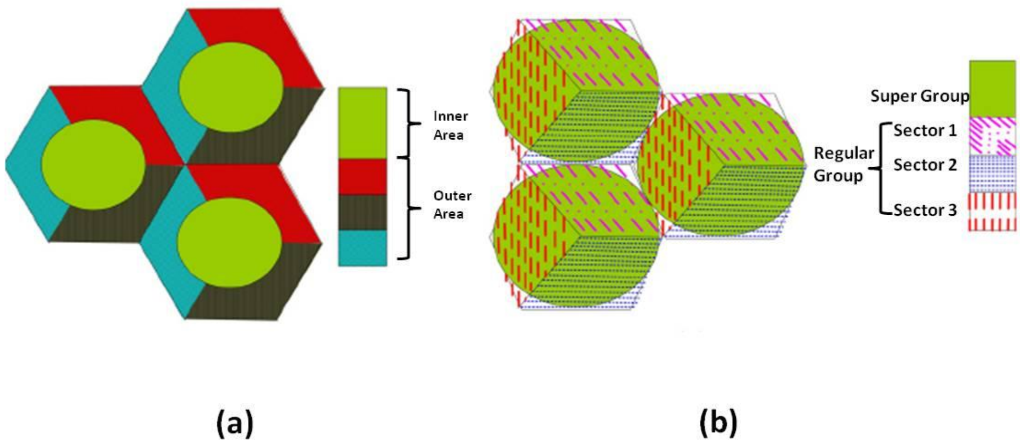


Figure 2.13 Static FFR (a) and Dynamic FFR (b) in cellular networks [52]

The drawback of static FFR is that frequency is not efficiently used. For example, MSs in the outer area cannot use the channels allocated in the inner area even through the inner area has free channels, and vice versa. In [51], the authors proposed that channel allocation in the inner area and the outer area is adjustable according to MSs distribution and QoS. Unfortunately, no detailed solution is provided in [51]. Dynamic FFR as a dynamic frequency allocation algorithm is shown in Figure 2.13(b) and designed in [52] to overcome the low frequency efficiency problem. In Dynamic FFR, there is no boundary between the inner area and the outer area. Instead, channels are dynamically grouped into one super group and 3 regular groups by a centralized RCN DSA algorithm. These 3 regular groups are individually allocated to 3 sectors, and channels in a regular group are only available to the sector that the regular group allocated in. Channels in the super group are available to all the 3 sectors in a cell. Thus, MSs in a sector can either use the channels in their regular group or the channels in the super group. How a MS is allocated a channel is decided by the BS DSA algorithm described in [52]. Through this mechanism, frequency efficiency is improved compared to FFR.

Centralized algorithms as described in [47-52] are limited by the computing ability of the central controller to provide network stability and scalability [45]. In [53-56], distributed frequency allocation (DFA) is investigated in cellular networks. All these works involve BS-BS communication between adjacent cells to make distributed channel allocation decisions with no resource to a central entity. Such method causes more BS signalling and communication delay so has lower efficiency. In [53], DFA algorithms are designed to on a cell by cell basis. The channel allocation decision is carried out in each cell independently. The channel allocation decision in a cell is made after referring to the channel allocation state of neighbour cells. Because each cell needs to decide the allocation of a single channel step by step, the algorithm has low efficiency. In [54], a DFA algorithm called LP-DDCA is designed which considers CCI. A modified LP-DDCA both considering CCI and adjacent channel interference is designed in [55]. In LP-DDCA and modified LP-DDCA, when a cell makes a channel allocation decision, it refers to its Augmented Channel Occupancy table to find a channel that does not cause CCI or adjacent channel interference. The augmented Channel Occupancy table in a cell includes the channel allocation state of neighbouring cells and is updated in real time. Table construction and updating involve a high cell signalling cost. In [56], a more complicated DFA algorithm is designed. This algorithm involves more messaging within cells to decide the channel allocation referring to real time user communication requests and movement. This algorithm in [56] avoids CCI, infinite number of cell messaging, mutual influence and deadlock. Additionally, the principles of DFA are also analyzed in [56]. However, compared to [53-55], the distributed channel allocation in [56] is highly complicated. There seams to be little work on DFA in RBCN.

Chapter 5 and Chapter 6 of this thesis will investigate centralized and distributed dynamic fractional frequency allocation based on Dynamic FFR explained in [52].

2.5 Delay tolerate networking

In this thesis, it is assumed that a cooperative business agreement has been reached to allow the cooperating network technology in RBCN. DTN is the network considered. This thesis discusses improving RBCN performance in the context of disruption and failures through the help of DTN.

2.5.1 Intermittent connection and bundle protocol in DTN

The DTN [57-60] origin was to support interplanetary communication, when communication could only take place when devices are close. DTN is a type of ad-hoc network and realizes user point-to-point intermittent connection through multiple hops. In applications, DTN targets stressed environments where there is only intermittent connection. In stressed environments, network facilities are scarce and sometimes short of energy, so users cannot get stable and real-time wireless communication.

Intermittent connectivity is an unstable wireless connection compared to traditional end-to-end connections, because the connection between two nodes could be easily lost when nodes are in high mobility or low energy supply or highly influenced by the catastrophic environment. DTN carries out communication between users using a store-forward message switching mechanism to overcome the intermittent connectivity drawback, limiting transmission to messaging, images or video clips or walkie talkie. One example of store-forward message switching mechanism is shown in Figure 2.14. In this figure, MS *A* wants to send message to MS *C* via MS *B* at time t_1. However, MS *C* is far away from MS *B*, so current message transmission cannot succeed. In this situation, the message is stored and waits in MS *B*. When MS *C* moves close enough to MS *B* at t_2, MS *B* continually transmits this waiting message to MS *C* if this message time to live has not expired. If the message time to live expires before next forwarding available, the message will be discarded. The exact mechanism depends on the routing protocol. From this example, it can be surmised that MS *A* to MS *C* has long delivery delay.

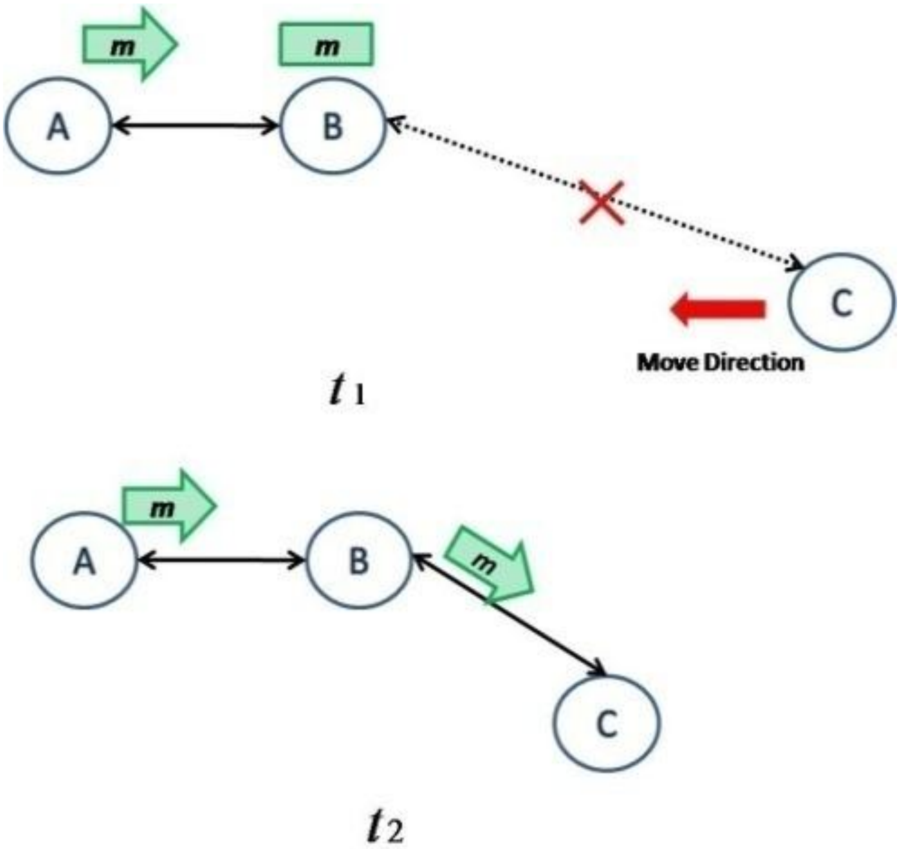


Figure 2.14 Store-forward message transmitting

It is obvious that DTN structure is quite different from traditional internet architecture. DTN makes use of bundle protocol [61-63] to augment the protocol stack of the transmitting or receiving entity to realize intermittent MS communication. The bundle protocol is above transport layer of the network, but conceptually below the application layer. Each DTN entity has a bundle layer implementation in its protocol stack to enable each data transmission. The bundle protocol defines a sequence of contiguous data blocks as a bundle. Each bundle is variable in size and carries application layer data. Thus, in DTN, each MS packs its transmitted data into a bundle and forwards the bundle to its next hop. This bundle will (probably) eventually arrive at the destination MS through the chosen routing protocol. Figure 2.15 shows the DTN bundle module in Android Smart Phone that has DTN applications. In that figure, DTN bundle protocol enables Android smart phones to communicate with each other through Wi-Fi or Bluetooth in DTN way. Bundle protocol realization is not the main consideration of this thesis, but DTN routing using the bundle protocol is.

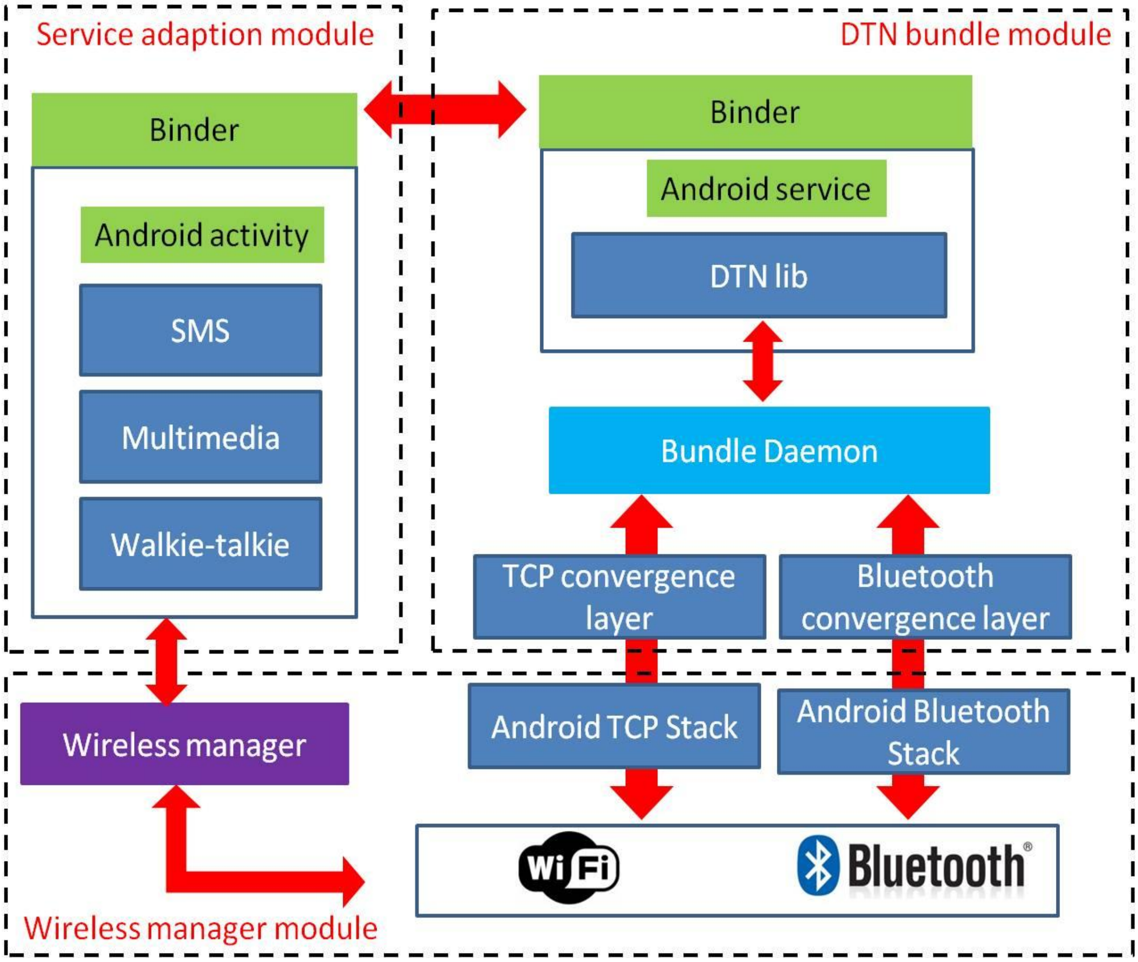


Figure 2.15 Bundle protocol realization in Android smart phones [63]

2.5.2 DTN routing protocols

As shown in Figure 2.14, in DTN, the nodes are in limited energy supply, limited computing power, high mobility and sparse distribution. Thus DTN routing does not provide end-to-end connection throughout message delivering. Therefore, the critical challenge for DTNs is determining routes through the network without ever having synchronous end-to-end connections, or even knowing which "routers" will be connected at any given time. Thus, DTN routing is a new routing model, which consists of a sequence of independent, local forwarding decisions, based on current connectivity information and predictions of future connectivity information. In each node, a forwarding decision should ideally bring the node carrying packet "closer" to the destination. High message delivery rate, low delivery delays, routing efficiency, self-configuration and network scalability are the most important metrics in DTN routing.

Conventional ad-hoc routing protocols would fail in DTN. This is because ad-hoc routings seek synchronous end-to-end route from source to destination (all the connections in an end-to-end route exist at the same time), which is not practical in DTN. Therefore, DSDV[64], DSR[65] and AODV [66] as the representative ad hoc routing protocols all have limited performance with respect to dynamic scalability and a high routing overhead. DTN routing can only be per-contact routing and reactive routing. This is because the topology in DTN may change drastically, the route explored by proactive routing, source routing or per-hop routing might not exist when message forwarding happens in DTN. Depending on the number of copies of a single message that may coexist in the network, DTN routing can define two major categories, namely single-copy routing and multiple-copy routing.

The works in [67-68] analyse single copy and multiple-copy in detail. Single-copy saves routing expense i.e. by using less bandwidth, smaller user buffer size and energy consumption. It saves unnecessary message copies while realizing satisfactory routing efficiency. In [67], the single-copy realisation is based on utility comparisons. The utility is designed according to estimated delay. In [67], a hybrid “Seek and Focus” Algorithm is created as an optimal single-copy algorithm. On the other hand, multiple-copy routings like the Epidemic algorithm in [69] gives high routing effect if network resources are not highly limited. Additionally, it brings no challenge to the user processing ability, as it does not need complicated forward prediction. Multiple-copy also avoids the trivial problems like choosing the right utility threshold or having to choose the number of copies. Practically, multi-copy schemes appear more suitable for DTN routing.

In [70], the Spray and Waiting algorithm is discussed and proposed to be an optimal multi-copy algorithm. This algorithm has good balance on DTN routing effect and efficiency. The Spray and Wait algorithm performance and setting the copy number are also discussed in [70]. Binary Spray and Wait algorithm is validated to be the best multi-copy algorithms currently. In [71], the authors describe the RAPID algorithm. In RAPID, a message is directly forwarded to destination if possible, otherwise its copy will be forwarded to a high utility node. The utility is updated by referring different metrics like minimizing average delay, minimizing missed deadlines, minimizing maximum delay, and with the help of metadata within neighbour nodes. In [72], the authors describe the MaxProp algorithm. MaxProp uses historic user contact information to calculate the cost of the message copy forwarding path. In message copy forwarding, the next hop is the one among the paths giving the smallest cost. MaxProp uses several complementary mechanisms and buffer management to guarantee high routing effect and efficiency. In [73], the authors describe the PRoPHET algorithm: Probabilistic Routing Protocol using History of Encounters and Transitivity. Like MaxProp, PRoPHET makes use of the fact that real users are not likely to move around randomly, but rather move in a reasonably predictable fashion based on repeating behavioural patterns such that if a node has visited a location several times before, it is likely that it will visit that location again. Thus PRoPHET uses historic local user contact information to predict the next hop, which increasese the probability of the message copy sending to destination.

Chapter 7 of this thesis will augment traditional DTN routing protocols including Epidemic, Binary Spray and Wait, and PRoPHET to let DTN help mitigate the RBCN BS failure problem.

2.6 Summary

This chapter provides background for this thesis. Firstly, IEEE802.16j supported RBCN used in this thesis is introduced. Secondly, RBCN user congestion and BS failure problems and their proposed solutions based on network reconfiguration and frequency allocation are discussed. Thirdly, DTN cooperation with RBCN is introduced. DTN is used to extend the coverage of the RBCN.

CHAPTER 3 RBCN system model and simulator

This chapter first discusses the model of RBCN used. The network reconfiguration and frequency allocation solutions of this thesis are mainly validated on this model. Afterwards, the simulation tools in use are introduced, including a system level RBCN simulator developed at Queen Mary and an open source simulator called Opportunistic Network Environment (ONE). The DTN simulator was developed in the Helsinki University of Technology.

3.1 Model of RBCN structure, antenna power control and antenna tilting

The RBCN structure model used in this thesis is shown in Figure 3.1 and 3.2 and is based on the work in [31] and [74].There are 19 BSs in Figure 3.1. Each BS has 3 120°sector antennas or 6 60°sector antennas to provide its radio coverage. Alternatively, the RBCN structure with 61 BSs is shown in Figure 3.2 where each cell has 3 120° sector antennas. Figure 3.3 shows the Signal to Interference and Noise Ratio (SINR) of all the locations in RBCN with different frequency reuse factor. This figure clearly shows the coverage of sector antennas. In Figure 3.3, a BS employs 3 120°sector antennas, and a RS works in transparent relay model. The antenna gain of 60°sector antenna and 120° sector offered to users in different direction is shown in Figure 3.4.

In a cell, there are fixed 3 RSs, each placed in the location 2/3 radius away from BS centre. This RS distribution improves BS coverage and capacity satisfactorily while neither requiring too many RS facilities nor creating high interference from RSs to adjacent cells. A RS antenna is omni-directional. RSs work in decode-and-forward model and either transparent relay or non-transparent relay model.

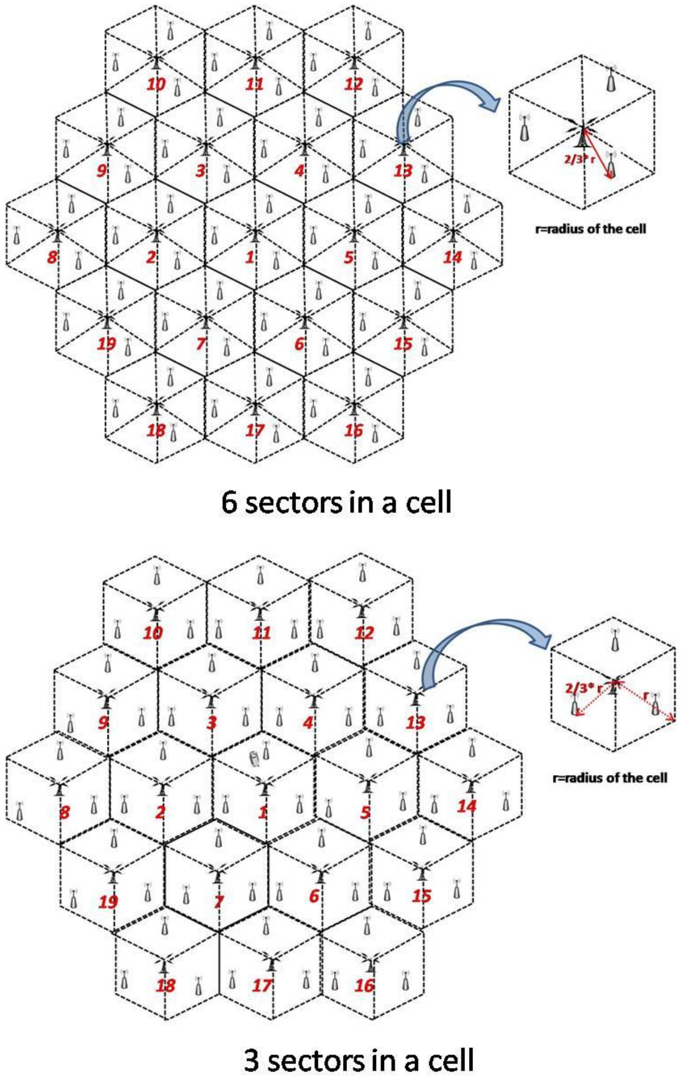


Figure 3.1 RBCN with 19 cells

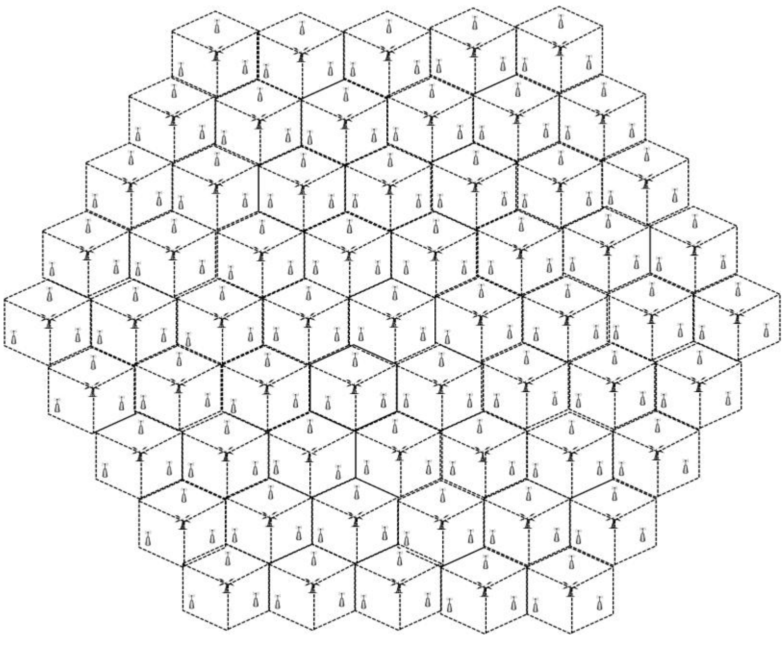
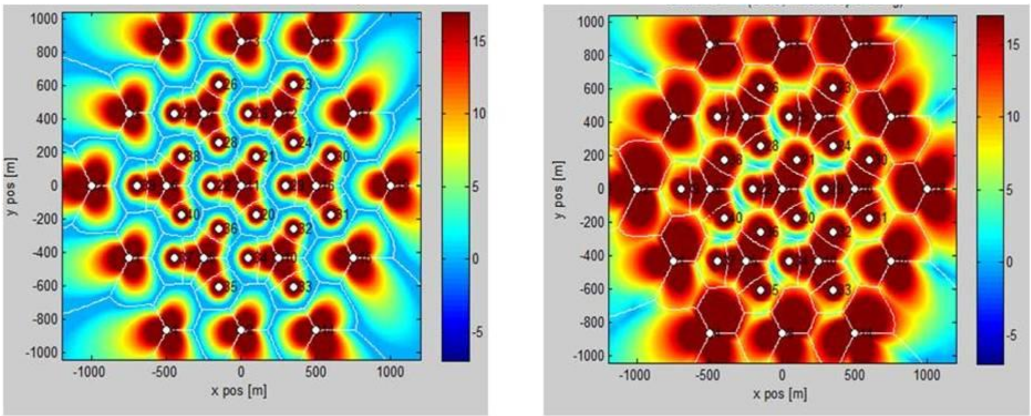


Figure 3.2 RBCN with 61 cells each having 3 sectors



Frequency Reuse Factor 1 **Frequency Reuse Factor 3**

Figure 3.3 SINR in frequency reused RBCN where sector antenna is 120° and RS works in transparent relay model

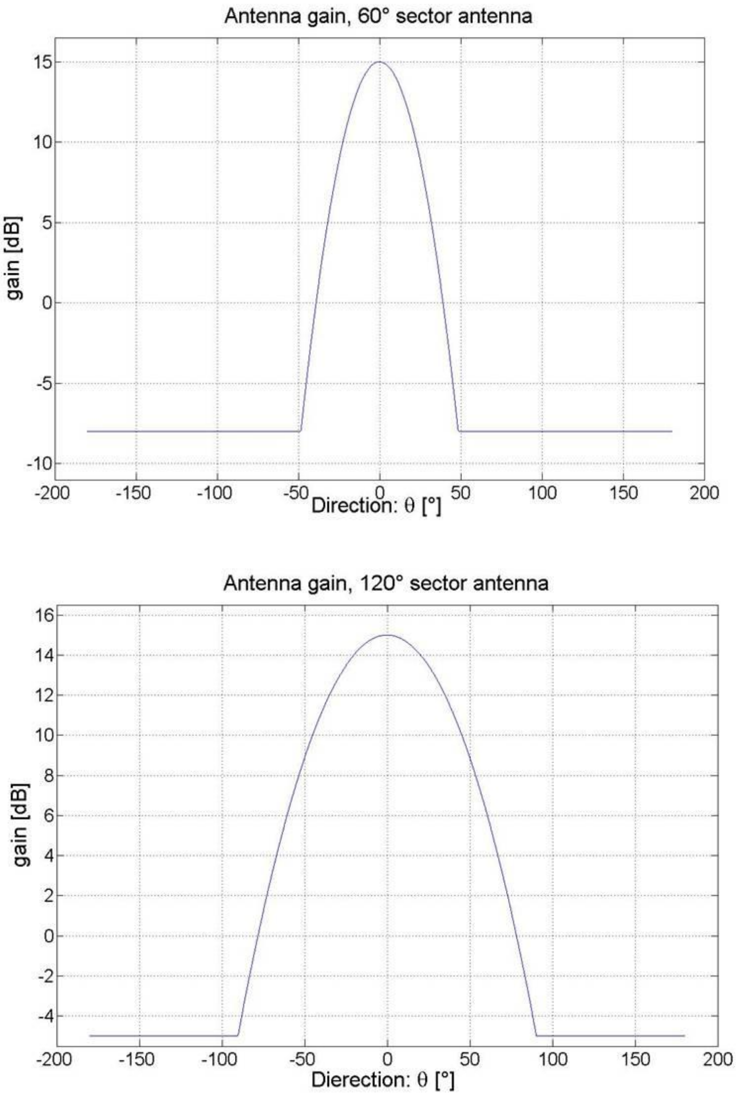


Figure 3.4 Antenna gain of sector antenna

In the tilting scheme of this thesis, it is assumed that BS antenna power of sectors is fixed but their tilt state is adjustable, and RSs antenna cannot tilt but their antenna power can be changed. Specifically, each sector antenna can tilt within 3 tilting states: *Up*, *Normal* and *Down*. If a sector antenna tilts up, its coverage expands. If a sector antenna tilts down, its coverage shrinks. If sector antenna titling is *Normal*, the sector antenna is in its default state. Figure 3.5 shows the antenna gain of a 60° sector in *Up*, *Normal* and *Down* states. On the other hand, a RS antenna cannot tilt, but can increase or decrease its antenna power to have 3 coverage states: *Expanded*, *Normal*, and *Shrunk*. *Normal* is the default state of an RS antenna.

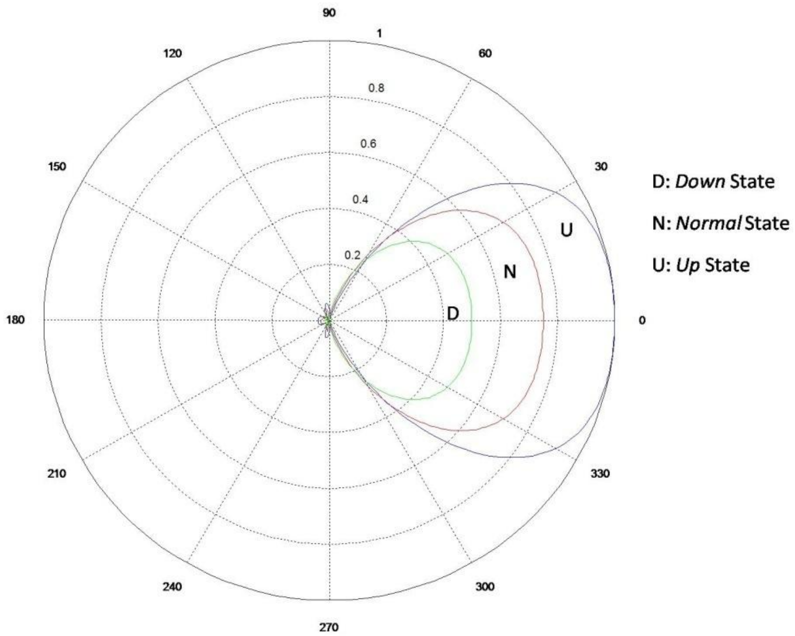


Figure 3.5 Three tilting states of 60° sector antenna

However, in the more constrained cooperative antenna power control scheme, sector antenna and RS antennas cannot tilt but their antenna power can be changed. In this mechanism, antenna power changes are allocated to be more precise in their cell coverage adjustment compared to the antenna tilting mechanism. The model of the coverage adjustment caused by antenna power changing will be further discussed in Chapter 4.

3.2 Radio propagation model

The radio propagation model in this thesis employs two modes. A more realistic one considers path loss in flat terrain with light tree densities and shadowing, and a simpler one only considers path loss in open space environment.

3.2.1 The propagation model

$$P_{i,j,b} = G_{i,j,b} \times P_b \quad (3.1)$$

$$G_{i,j,b} = 10^{-\frac{L_{i,b}+S_{i,b}-G_{i,b}}{10}} \quad (3.2)$$

In (3.1), $P_{i,j,b}$ represents antenna power received by MS i from BS or RS b through channel j. P_b is the power of BS or RS b. If the station is a BS, P_b is fixed at P_1. If the station is RS, P_b is defined to be: P_2 (P_2<P_1). $G_{i,j,b}$ is the channel gain of channel j received by MS i in the coverage of BS or RS b. $G_{i,j,b}$ is formulated in (3.2). In (3.2), channel gain $G_{i,j,b}$ is decided by antenna gain $G_{i,b}$, path loss $L_{i,b}$ and shadowing $S_{i,b}$ referring MS i in BS or RS b. Path loss $L_{i,b}$ is formulated in (3.3). This path loss model is discussed in [75]. Shadowing model is discussed [76] that incorporate log-normal distribution and spatial correction into path loss to model signal fading caused by blocks e.g. buildings, trees. Because shadowing model scheme is not the main concern of this thesis, shadowing model detail is not presented here. More can be found in [76]. Fast fading is not considered in this work. $G_{i,b}$ is formulated in (3.4).

$$L_{i,b} = A + 10 \times \gamma \times log_{10}\left(\frac{d}{d_0}\right) + \Delta PL_f + \Delta PL_h \quad (3.3)$$

In (3.3), $L_{i,b}$ is the antenna power received by MS i from BS or RS b. The distance between MS i and BS or RS b is d. $d_0 = 100$m and $d > d_0$. A=$20 \times log_{10}\left(\frac{4\pi d_0}{\omega}\right)$ and $\gamma = (3.6 - 0.005h_b + \frac{20}{h_b})$. ω is the wave length in meter and h_b is the antenna height of BS or RS, which is between 10m and 80m. $\Delta PL_f = 6 \times log_{10}\left(\frac{f}{2000}\right)$ dB. f is the channel frequency in MHz. $\Delta PL_h = -20 \times log_{10}\left(\frac{h}{2}\right)$ dB. h is the receiving MS/RS antenna height between 2m and 10m.

$$G_{i,b} = \begin{cases} G_M - min\left(12\left(\frac{\theta}{70}\right)^2, 20\right) \ (for\ 120^{\circ}\ sector\ antenna) \\ G_M - min\left(12\left(\frac{\theta}{35}\right)^2, 23\right) \ (for\ 60^{\circ}\ sector\ antenna) \\ G_{RS} \qquad (for\ RS\ omnidirectional\ antenna) \end{cases} \quad (3.4)$$

In (3.4), antenna gain formulation is different between BS and RS. BS antenna is sector antenna, while RS antenna is omni-directional antenna. Considering the sector antenna, G_M is the sector antenna gain, which is a fixed value. θ $(-180^{\circ} < \theta < 180^{\circ})$ is the angle between the direction from MS i to BS and the direction of BS sector antenna. Obviously, the antenna gain of MS i is decided by BS sector antenna pattern and the location of MS i. This antenna gain definition is discussed in [75], and shown in Figure 3.4. Considering RS, the channel gain received by MS i from the RS is constant and denoted by G_{RS}.

3.2.2 A simple model

The simple model is formulated in (3.5). It is based on path loss in open space environment. The path loss model is discussed in [77].

$$P_{i,j,b} = Pattern_{\theta} \times \frac{P_b}{\tau \times (d_{i,b})^{\varphi}} \quad (3.5)$$

In (3.5), $P_{i,j,b}$ represents antenna power received by MS i from BS or RS b through channel j. P_b is the power of BS or RS b. If the station is a BS, P_b is fixed at P_1. If the station is RS, P_b is defined to be P_2 ($P_2 < P_1$). τ is power fade factor and φ is path loss factor (2 in an vacuum) that are defined in [77]. $d_{i,b}$ is the distance between MS i and BS or RS b. $Pattern_{\theta}$ is the pre-defined antenna pattern parameter specified by $\theta(-180^{\circ} < \theta < 180^{\circ})$. $Pattern_{\theta}$ defines antenna pattern of sector antenna or omni-directional antenna. For example, if antenna is omni-directional, $Pattern_{\theta} = 1$ ($\forall\theta \in \{-180^{\circ}, 180^{\circ}\}$). θ is the angle between the direction from MS i to source antenna b and the direction of source antenna b.

The two propagation models are based on an ideal model of the environment. In [77], the authors discuss more radio propagation models. Additionally, in principle, the modelling can be based on the models of environment generated by Kejiong Li in [78]. Modelling realistic environments and predicting coverage models is the focus of her work and the work could readily be used to make this work applicable to realistic environments.

3.3 Channel and data rate model

As discussed in Chapter 2, RBCN is assumed to have fixed number of channels in total based on the Mobile WiMAX configuration and each channel has a prescribed number of OFDM sub-carriers. Following this channel model, the frequency allocation in RBCN system level is on a per-user basis.

The SINR of a channel indicates the channel quality. In a cell, the SINR of all the allocated channels is sent to a BS or control centre instantly to allow scheduling and frequency resource management decisions. In OFDM, channel SINR is sent to BS through antenna sub-carriers. SINR in a channel is decided by transmission power and antenna gain of source station, signal propagation, noise, and intra and inter cell interference. Because the OFDM based channel model avoids adjacent channel interference (ACI) [45], so there is no intra-cell interference if the allocated channel is used uniquely to MS in a cell. However, inter-cell interference caused by frequency reuse (co-channel interference) and noise are unavoidable. (3.6) formulates the SINR of channel *j* with respect to MS *i* in BS or RS *b*. This thesis employs average SINR to simplify the formulation of channel SINR. The richer OFDMA channel quality model: Exponential Effective SINR Mapping (EESM) is discussed in [31].

$$SINR_{i,j,b} = 10 \times log_{10}\left(\frac{P_{i,j,b}}{N+\sum_{k=1}^{|Q|} P_{i,j,Q_k}}\right) \quad (3.6)$$

In (3.6), $SINR_{i,j,b}$ is SINR of channel *j* offered to MS *i* in the coverage of BS or RS *b*. The definition and formulation of $P_{i,j,b}$ are discussed in (3.1) or (3.5) depending on the adopted radio propagation model. P_{i,j,Q_k} is the interfering power of channel *j* received by MS *i* from interfering BS:Q_k. Q is the set of all the interfering BSs to MS *i*, and Q_k denotes one interfering BS in Q. Q is based on the allocation of channel *j* after frequency allocation. N is the noise, which is constant in this thesis.

Based on the SINR formulation in (3.6), the channel quality of each MS to BS or RS link can be evaluated. Afterwards, IEEE8002.16j RBCN employs Adaptive modulation and Coding (AMC) [15] to decide the data rate of each channel. In AMC, different modulation and coding schemes could enable a channel to have different data rates. The modulation and coding scheme employed in a channel is decided by the channel SINR. If a channel has a higher SINR, this channel employs modulation and coding scheme that leads to higher channel data rate and vice versa. The relationship between channel quality and channel data rate in AMC is shown in table 3.1. This thesis only considers downlink at 5MHz. If a MS directly connects to a BS, the data rate received by this MS can be easily calculated. For example, $R_{i,j,b}$ is the date rate of channel *j* that is allocated to MS *i* by BS *b*. $R_{i,j,b}$ is decided by$SINR_{i,j,b}$. If $(11.2 > SINR_{i,j,b} > 9.4)$, QPSK1/2 is the scheme employed in channel *j*, so $R_{i,j,b} = \frac{3.17}{|C|}$mbps, where *C* is the set including all the channels. However, if a MS connects to a RS for two-hop communication, the channel data rate calculation is more complicated. Depending on different RBCN relay models, data rate calculations in two-hop communication are different.

Table3.1 Modulation and Coding referring SINRs in AMC

Modulation	Code Rate	5MHz Downlink	
		Data Rate (mbps)	SINR(dB)
QPSK	1/2	3.17	9.4
	3/4	4.75	11.2
16 QAM	1/2	6.34	16.4
	3/4	9.50	18.2
64 QAM	1/2	9.50	22.7
	3/4	14.26	24.4

If RBCN works in transparent relay model, (3.7) is used to calculate the data rate received by MS *i* in a two-hop connection. In (3.7), MS *i* connects to BS *b* through RS *r* using channel *j*. $R_{i,j,r}$ is the data rate of channel *j* that is allocated to MS *i* .

$$min\left(SINR_{i,j,b\rightarrow r}, SINR_{i,j,r\rightarrow i}\right) \xrightarrow{AMC} R_{i,j,r} \tag{3.7}$$

In (3.7), $SINR_{i,j,b\rightarrow r}$ is the SINR of channel *j* in BS *b* to RS *r* hop. $SINR_{i,j,r\rightarrow i}$ is the

SINR of channel j in RS r to MS i hop. Both $SINR_{i,j,b\rightarrow r}$ and $SINR_{i,j,r\rightarrow i}$ can be calculated through formulation (3.6). The modulation and coding employed in channel j is decided by the lower SINR: $min(SINR_{i,j,b\rightarrow r}, SINR_{i,j,r\rightarrow i})$. This is because the RSs work using the transparent relay model, so modulation and coding scheme of the allocated channel in each hop is the same and decided by the BS. Thus the BS should choose the lower SINR to make sure the adopted modulation and coding is applicable in both hops. After modulation and coding scheme being decided, $R_{i,j,r}$ can be calculated like the way that used in MS directly connecting to BS case.

If RBCN works in non-transparent relay model, (3.8) is used to calculate the data rate received by MS i in a two-hop connection. (3.8)augments the two-hop channel data rate calculation in [29]. In (3.8), MS i connects to BS b through RS r using channel j. $R_{i,j,r}$ is the data rate of channel j that is allocated to MS i .

$$R_{i,j,r} = \frac{1}{\frac{1}{R_{i,j,b\rightarrow r}}+\frac{1}{R_{i,k,r\rightarrow i}}} = \frac{R_{i,j,b\rightarrow r}\times R_{i,k,r\rightarrow i}}{R_{i,j,b\rightarrow r}+R_{i,k,r\rightarrow i}} \quad (3.8)$$

In (3.8), $R_{i,j,b\rightarrow r}$ is the data rate of channel j in BS b to RS r hop. $R_{i,k,r\rightarrow i}$ is the data rate of RS r to MS i hop using channel k other than channel j. Because non-transparent model does not allow two hops to use the same channel, channel j cannot be used in RS r to MS i hop. Channel k is decided by Smart Channel Selection scheme that is explained before in this thesis. $R_{i,j,b\rightarrow r}$ and $R_{i,k,r\rightarrow i}$ can be calculated like the case that MS directly connecting to BS.

3.4 System level RBCN simulator

This thesis validates RBCN network reconfiguration and dynamic frequency allocation based solutions using a system level RBCN simulator that was developed by QMUL. The simulation parameters are list in table 3.2.

3.4.1 System level RBCN simulator working procedure

Table 3.2 System RBCN Simulator Parameters

Frequency Bandwidth FFT size	2.3 GHz 5MHz 512
Number of channels	15
Cells layout	3 or 6-sectored hexagonal 19 cells and 61 cells
RS model	transparent or non-transparent relay model
Inter BS distance	500m
Distance between BS and charging RS	333m
BS height	32m
RS height	10m
MS terminal height	2m
Sector Antenna pattern and Azimuth	$G_M - min\left(12\left(\frac{\theta}{70}\right)^2, 20\right)$; 120°
	or $G_M - min\left(12\left(\frac{\theta}{35}\right)^2, 23\right)$; 60°[75]
RS Antenna Pattern	Omni-directional
BS and RS antenna gain	16 DBi 10 DBi
BS and RS Transmission power	43 dBm 37 dBm
Thermal noise density	-174dBm/Hz
MS noise figure	7 dB
Antenna Power	30 dBm
Antenna Power threshold	-80 dBm
Antenna Power handover threshold	-74 dBm
Macroscopic path-loss	$L_{i,b} = A + 10 \times \gamma \times log_{10}\left(\frac{d}{d_0}\right) + \Delta PL_f + \Delta PL_h dB$[75]
	or $P_r = Pattern_\theta \times \frac{P_t}{\tau \times (d)^\varphi}$ [77]
Shadow fading	lognormal, space-correlated [76], μ = 0; σ = 10 (dB)
Shadow fading correlation	Inter-site: 0.5, Intra-site: 1 [76]
UE speed and data rate threshold	5 KM/h; 432.8 kbps
Scheduler	MPG opportunistic scheduling

The system level RBCN simulator follows the RBCN model discussed before, and mainly simulates network reconfiguration, frequency allocation, user to BS and RS admission control and radio resource allocation when users are unevenly distributed over the cells. It is a hybrid discrete event and time step simulator. This simulator uses time step simulation to move from one MSs demand snapshot (represent as MSs distribution scenario) to another snapshot to simulate RBCN performance in different user demand. The work procedure of the simulator is shown in Figure 3.6 and each step is explained below.

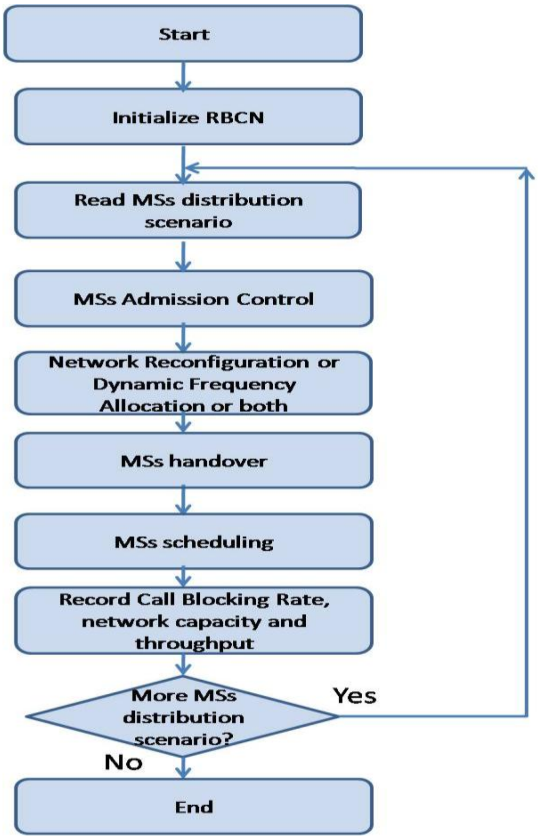


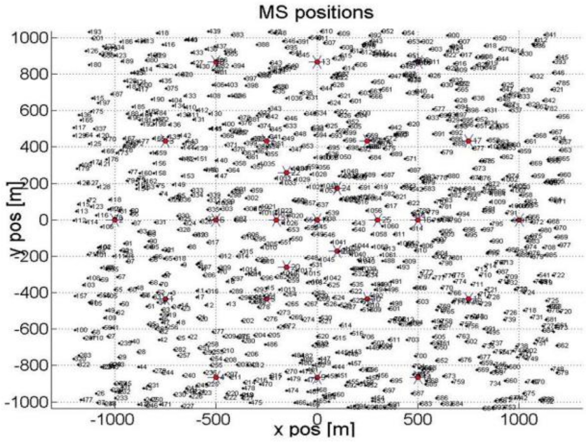
Figure 3.6 Working procedure of System Level RBCN simulator

Initialize RBCN

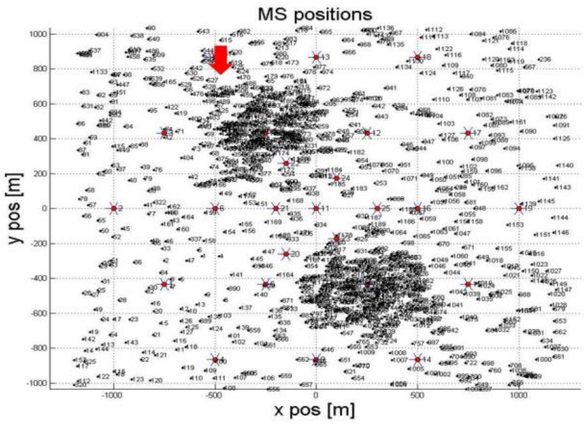
In the beginning, BS antennas and RS antennas are set to have the default coverage i.e. default antenna power or antenna tilting. Frequency allocation is also in default allocation depends on the scheme RBCN employs.

Read MSs distribution scenario

MSs demand at a specific time is modelled by a MSs distribution scenario that simulates MSs geographical distribution at that time. Once the simulator reads in one MSs distribution scenario, the simulator successfully models MSs demand in RBCN.



MS distribution scenario 1: user uniform distribution



MS distribution scenario 30: the highest user congestion

Figure 3.7 MSs distribution scenarios taken at different time

A MSs distribution scenario can be a snapshot of real or generated MSs distribution for the RBCN. Thus, if MSs are moving (depends on different movement modes), a series of different MSs distribution scenarios can be obtained by taking snapshots at appropriate times. For example, a series of MSs distribution scenarios are shown in Figure3.7. In this figure, MSs distribution scenario (1) is taken when users are distributed uniformly, while MSs distribution scenario (30) is taken when many users have converged into 2 dense hot spots. Obviously, if the system level RBCN simulator reads the series of MSs distribution scenarios and performs the simulation accordingly, the RBCN performance referring different user distributing situations can be evaluated. MSs distribution settings used in the simulations of this thesis are attached in Appendix A. Because the MSs distribution settings are provided and RBCN system level simulation parameters are listed in Table 3.2, all the simulations in this thesis can be regenerated.

MSs admission control

In this step, all the MSs try to connect to the appropriate BS or RS through application of the Admission Control policy discussed before. If there is user congestion，some users may successfully connect to BS or RS but some may not.

Network reconfiguration or dynamic frequency allocation

In order to let more users obtain service form a BS or RS in user congestion situation or BS failure situations. The solutions based on RBCN network reconfiguration (cooperative antenna power control or antenna tilting) or dynamic frequency allocation or future integrated solutions are carried out in this step. Low call block rate and high network throughput are the purpose of such solutions

MSs handover

Because BSs and RSs radio coverage or condition and allocation of channels are changed by last step, part of MSs could handover from one BS or RS to other one. Ideally, through RBCN network reconfiguration, MSs in heavy loaded BS can handover to light loaded BS. Thus geographic load balancing can be realized. Alternatively, through dynamic frequency allocation, heavy loaded BS can get more channels in good quality to relieve its user congestion and BS failure problems.

MSs scheduling

In this step, a BS or RS (if distributed scheduling) schedules its covered MSs to allocate radio resource to each MS. This thesis employs minimum performance guarantee (MPG) opportunistic scheduling [32][52].

Record call blocking rate and network throughput

When MSs scheduling finishes, network capacity, network throughput and call blocking rate are recorded. The records indicate the effect of network reconfiguration and dynamic frequency allocation solutions. According to the employed AC scheme, (3.10) and (3.11) formulates that the solutions should maximize RBCN capacity and throughput. (3.12) formulates the solutions should minimize RBCN call blocking rate (*CB*).

$$if\ \left(max_{b\in W_i}(R_{i,b}) \geq D\right)\{S(i) = 1\};\ else\ \{S(i) = 0\} \quad (\forall i \in M) \tag{3.9}$$

$$Max \sum_{i\in M}(S(i)) \tag{3.10}$$

$$Max\ \sum_{i\in M}(S(i) \times max_{b\in W_i}\left(R_{i,b}\right)) \tag{3.11}$$

$$Min(CB\ = \frac{|M| - \sum_{i\in M}(S(i))}{|M|}) \tag{3.12}$$

In (3.9), D is the data rate threshold leading to satisfactory MS service. In this work, it is assumed that all MSs require the same type of wireless service, so D is fixed and the same within all MSs. M includes all the MSs in the network. These MSs are assumed non-uniformly distributed in the network. W_i is the set of cells that cover MS i. W_i is controlled by network reconfiguration. $R_{i,b}$ is the data rate offered to MS *i* by cell *b*, that is decided by the quality of allocated channel decided by MS scheduling. $R_{i,b}$ can be adjusted by network reconfiguration and dynamic frequency allocation.

After finishes the steps, system level RBCN simulator can terminate or read in other MSs distribution scenario (if existed) to simulate RBCN performance referring different MS distributions.

3.4.2 System level RBCN simulator validation

Simulator validation is to verify that a simulator provides rational results and reveals realistic performance of the simulated object. The validation can be based on the comparison between simulation results and the theoretical results, and also can be carried out by comparing the results of target simulator to the results of existing simulator that acts as benchmark. The results comparison between two simulators should use the same parameter setting and MSs distributions.

In this thesis, the comparison between two simulators is complicated and there is no available simulator deliberately simulating RBCN system level performance that can be used as benchmark (only few numbers of simulators working on WiMAX simulation using NS-2 [79] and other simulation tools mentioned in [74]). Thus, the system level RBCN simulator validation here compares the simulation results to the theoretical results of Mobile WiMAX cellular network. As discussed before, the system level RBCN simulator takes the network throughput as the result to indicate RBCN performance. Therefore, the validation is to compare the simulated RBCN throughput to the theoretical throughput of Mobile WiMAX cellular network whose configuration parameters are shown in table 3.3.

In this validation, the RBCN employs the same Mobile WiMAX configuration parameters in table 3.3 and works in transparent relay model. It is assumed that the frequency reuse factor is 1 and there is no FFR, thus each sector in a cell has all the available 15 channels offered to MSs. Therefore, the maximal number of users that could be served in RBCN is $6 \times 15 \times 19 = 1710$. The mutual interference of sectors in a cell is ignored. The radio propagation model used in the simulation is formulated in (3.1). To make the validation be more straightforward, it is assumed that the MSs distribution is uniform over the network and each MS asks for the same type of service, and the antenna power and tilting state of BSs and RSs are fixed. The comparisons between simulated throughput of RBCN and Mobile WiMAX cellular network and theoretical throughput of Mobile WiMAX cellular network are shown in Figure 3.8 and 3.9. The system level RBCN simulator simulates Mobile WiMAX cellular network when it has no RSs.

Table 3.3 Mobile WiMAX Parameters used in validation

Frequency Bandwidth FFT size	2.3 GHz 5MHz 512
Number of channels	15
DL PUSC:	
Null Sub-carriers	92
Antenna Sub-carriers	60
Data Sub-carriers	360
Cells layout	6-sectored hexagonal 19 cells
Inter BS distance	500m
BS and MS height	32m 2m
BS antenna gain	16 DBi
BS Transmission power	43 dBm
Thermal noise density	-174 dBm/Hz
MS noise figure	7 dB

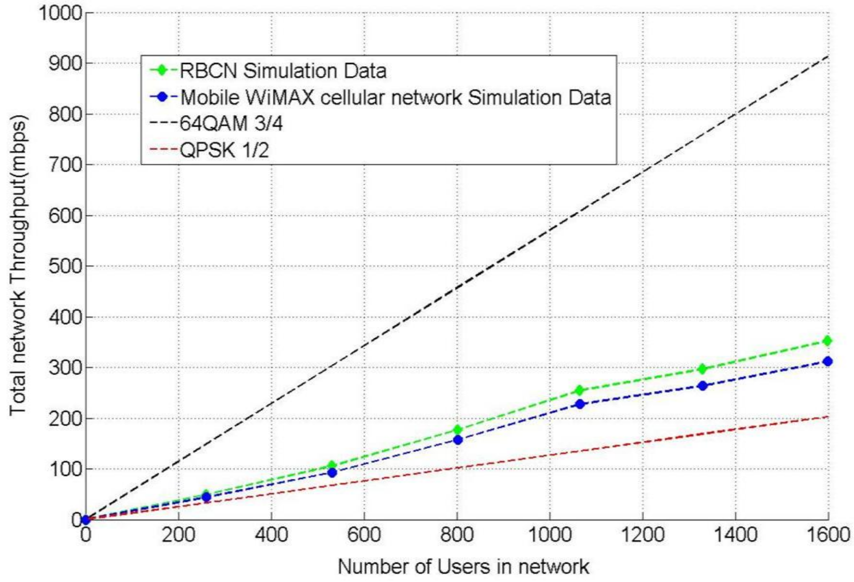


Figure 3.8 Simulated and theoretical network throughput considering different MSs distributions

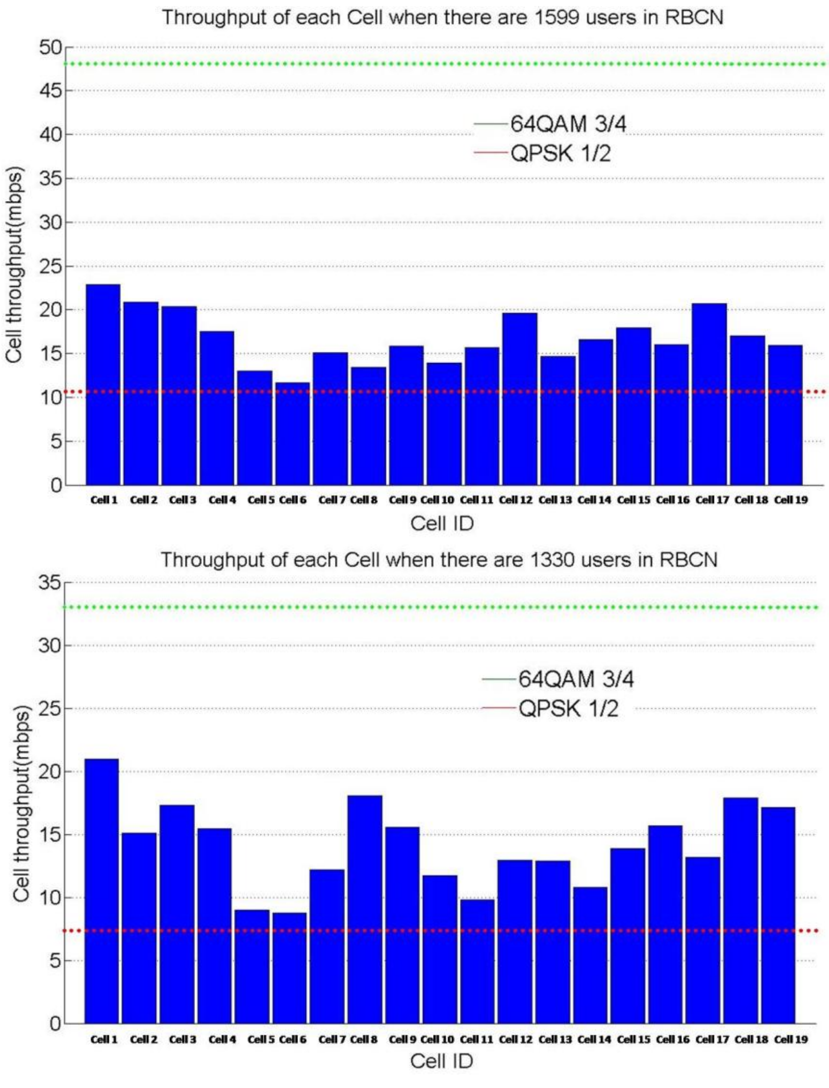


Figure 3.9 Throughput of each cell for two different MSs distribution scenarios

As shown in Figure 3.8, when there is more and more MSs, throughput of Mobile WiMAX cellular network and RBCN both increase. The simulated network throughput of RBCN and Mobile WiMAX cellular network are always between the theoretical maximal throughput (when every OFDMA channel offered to MSs able to use 64QAM 3/4 modulation and coding scheme) and the theoretical minimal throughput (when every OFDMA channel offered to MSs only able to use QPSK 1/2 modulation and coding scheme) of Mobile WiMAX cellular network. This indicates that the simulated network throughput of RBCN and Mobile WiMAX cellular network is in rational range, thus the simulator does reveal realistic performance of RBCN and Mobile WiMAX cellular network on network throughput. In addition, the RBCN simulated throughput is higher than Mobile WiMAX cellular network simulated throughput. This reveals the fact that RBCN augments traditional cellular network to have higher capacity and throughput. The throughput increasing of RBCN over cellular network is highly related MSs distribution and RS implementation and distribution in RBCN.

In Figure 3.9, the throughput of each cell in RBCN is shown considering two different MSs distribution scenarios. As shown in this figure, the throughput of each cell is always between the theoretical maximum and minimum cell throughput according to Mobile WiMAX configuration. Therefore, together, the validation shown in Figure 3.8 and 3.9 proof system level RBCN simulator is a rational simulator.

3.5 Opportunistic Network Environment (ONE) simulator

The ONE simulator [80-82] was developed by Helsinki University of Technology and is mainly designed to simulate DTN routing protocols. The DTN routing effect and efficiency in RBCN will be evaluated using ONE. Because the ONE simulator is a well known open source simulator, the validation of the simulator itself has not been undertaken in this thesis.

The ONE simulator allows users to create scenarios based upon different synthetic movement models [83] and real-world traces and offers a framework for implementing routing and application protocols for DTN networks. It already includes six well-known DTN routing protocols. Interactive visualization and post-processing tools support evaluating experiments and an emulation mode allows the ONE simulator to become part of a real-world DTN test-bed.

This thesis incorporates RBCN into ONE simulator. To deliberately evaluate the effect and efficiency of user to BS or user to user DTN connecting, ONE simulator ignores the RBCN actions that are simulated in the system level RBCN simulator, including admission control, radio resource management, dynamic frequency allocation and network reconfiguration. Instead, ONE simulator only considers BSs coverage and the routing performance of user to BS connection or user to user connection. In practice, BSs with fixed location, broad and fixed coverage, high transmission data rate, and large buffer size are added to original ONE simulator. For example, one scenario in use is shown in Figure 3.10. In that figure, the big green circles represent BS coverage, and the small green circles represent MS coverage. Three BSs covering Queen Mary University of London (QMUL), and 100 MSs with DTN application in QMUL try to connect to BSs through DTN connections. Because the three BSs cannot, in this simulation, cover QMUL fully (as shown in Figure 3.10, there is coverage gap), some MSs should connect to BS through multiple hops. This scenario will provide the test bed for augmented DTN routings of this thesis. This scenario will be discussed in Chapter 7 and its configuration file is attached as Appendix B.

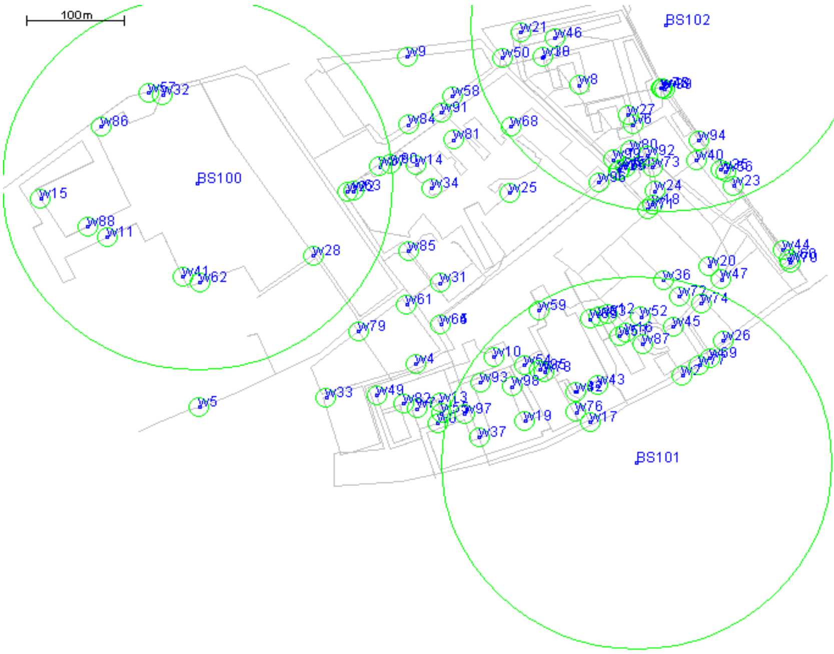


Figure3.10 Scenario of base stations covering QMUL in ONE simulator

The simulation parameters related to QMUL scenario is list in table 3.4 below. User in this scenario employs the shortest path map based movement model. In this model, a user randomly picks up a position in the map as next location, then follows the shortest path to that position. This is a simple model. More realistic movement model in ONE can be found in [83].

Table 3.4 ONE parameters in QMUL scenario

Network update interval:	0.1 second
Simulation time：	6 hours
MS wireless interface:	Bluetooth
MS transmit speed:	250 kBps
MS transmit range:	10 m
MS buffer size:	10 M
BS wireless interface:	Cellular network
BS transmit speed:	10 mBps
BS transmit range:	150 m
BS buffer size:	200 M
Number of MSs:	100
Number of BSs:	3
MS movement model:	Shortest path map based movement
MS moving speed:	10~50 km/hour
MS wait time:	0~2 minutes
Message time to live (TTL):	5 minutes
Message generating interval:	30~60 seconds
Message size:	500kB~1MB
DTN routing employed:	Epidemic, Binary spray and wait, PRoPHET

The whole procedure of the ONE simulation is shown in Figure 3.11.ONE simulates DTN routing periodically. It updates network state in each update interval. In one update, ONE updates location of MSs and processes messages generation and propagation in the whole network. In message propagation, ONE discards messages that are out of TTL and routes living messages form source to destination following the adopted DTN routing protocol. When an update finishes, the DTN routing log is updated, including the number of generated and discarded messages, number of message deliveries, number of messages reaching the destination, and number of hops. When the ONE simulation finishes, message delivery probability, message response probability, buffer size overhead ratio, message average latency and average number of hops can be calculated out presented as outputs. The results can then indicate the performance of the DTN routing protocol under test.

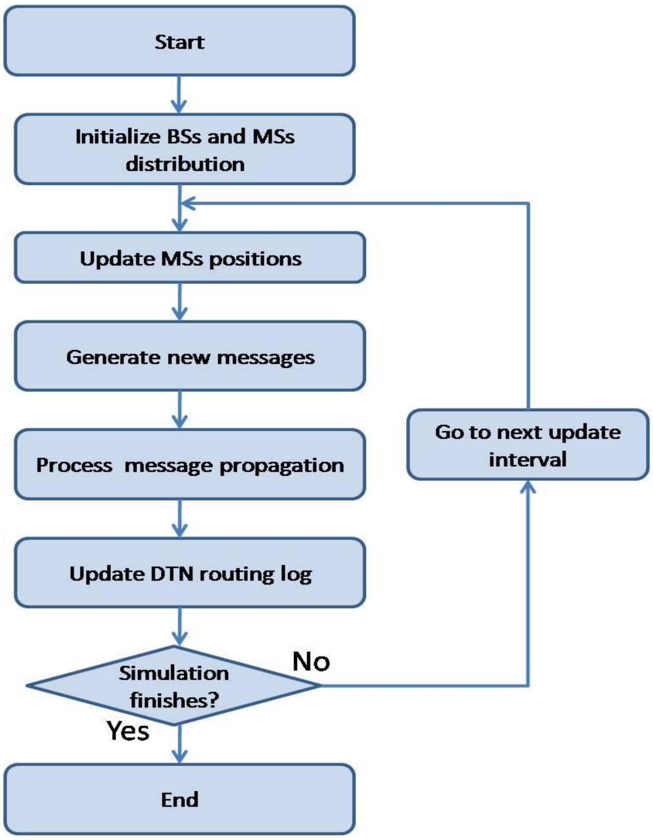


Figure 3.11 Simulation procedure of ONE simulator

Simulation based on ONE simulator will be discussed in Chapter 7.

3.6 Summary

This chapter models RBCN at the system level using a simulator developed in Queen Mary. This simulator takes network call blocking rate, capacity and throughput as criteria to evaluate network reconfiguration and dynamic frequency allocation solutions. Additionally, to assess benefits in using DTN for coverage extension in BS failure situations, the ONE simulator is introduced.

CHAPTER 4 Antenna power control and antenna tilting based network reconfiguration in RBCN

This chapter investigates system level network reconfiguration to relieve user congestion and BS failure problems in RBCN. Firstly, a new cooperative antenna power control algorithm named Utility Comparison based Cooperative Antenna Power Control Algorithm (UC-CAPCA) is designed to relieve user congestion. Through simulation using the system level RBCN simulator, UC-CAPCA is seen to have great performance improvement compared with a greedy cooperative antenna power control algorithm in literature. Secondly, a heuristic antenna tilting algorithm is designed to relieve RBCN user congestion problem and extend radio coverage in an emergency. The validation of this antenna tilting algorithm also uses the system level RBCN simulator.

4.1 Cooperative antenna power control

UC-CAPCA is a centralized algorithm and would be installed in central controller of RBCN. The computation of UC-CAPCA is based on the model of the propagation environment at each antenna power in RBCN. The actual BSs and RSs coverage is only performed after the algorithm had been completed. Thus, referring to a specific MSs distribution, UC-CAPCA firstly calculates the optimal coverage of the BSs and RSs, then the BSs and RSs are actually reconfigured to realize the computed coverage for geographic load balancing. The role of UC-CAPCA in RBNCs is shown in Figure 4.1. How often UC-CAPCA could be triggered by the central controller is a network system setting problem. In practical, UC-CAPCA running interval should neither too short nor too long. In the simulation of this thesis, UC-CAPCA running interval is set to 5ms which is the same as the frame duration in Mobile WiMAX. The further antenna tilting algorithm and all frequency allocation algorithms of this thesis also follow the same periodically running frequency in RBCN simulation.

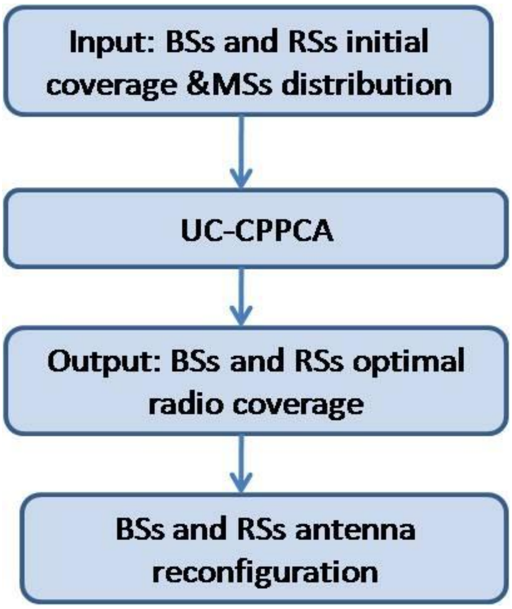


Figure 4.1 Role of UC-CAPCA in RBCN reconfiguration

4.1.1 Antenna coverage adjusting by antenna power control

$$P_b = k \times P_1 \qquad (b \text{ is BS}) \tag{4.1}$$

$$P_b = k \times P_2 \qquad (b \text{ is RS}) \tag{4.2}$$

Sectors and RS are the two types of network entity in UC-CAPCA. In UC-CAPCA, it is assumed that antenna power following a 60° sector and omni-directional RS can be controlled to change. This is formulated in (4.1) and (4.2), which are augmented from (3.1) of Chapter 3. k is the antenna power control parameter that can control a sector or RS to have 10 different antenna power levels leading to 10 different coverage ranges. These 10 coverage ranges are modelled as 10 coverage band. RBCN uses non-transparent RS. Thus an omni-directional RS antenna can carry out radio coverage expansion and shrinking through omni-antenna power adjustment on its own.

Based on (4.1) and (4.2), the radio adjustable coverage of each entity (sector or RS) is modelled in the following manner: 1). part of radio coverage range of each entity is equally divided into 10 coverage bands ranging from -5 to 5. 2). the default radio coverage of an entity is the 0 coverage band. If an entity is at its minimal coverage, its coverage band is -5. Minimal coverage of a BS or RS is the coverage state when BS or RS has the lowest antenna power. If an entity is at its maximal coverage, its coverage band is 5. Maximal coverage of a BS or RS is the coverage state when BS or RS has the highest antenna power. Such model is shown in Figure 4.2 and 4.3. Through this model, the algorithm can measure entity radio coverage adjustment with respect to the coverage band. For example in Figure 4.3, sector *2* of BS *1* has expanded its coverage to band 3. Another example is that sector *5* of BS *2* has shrunk its coverage to band -3.

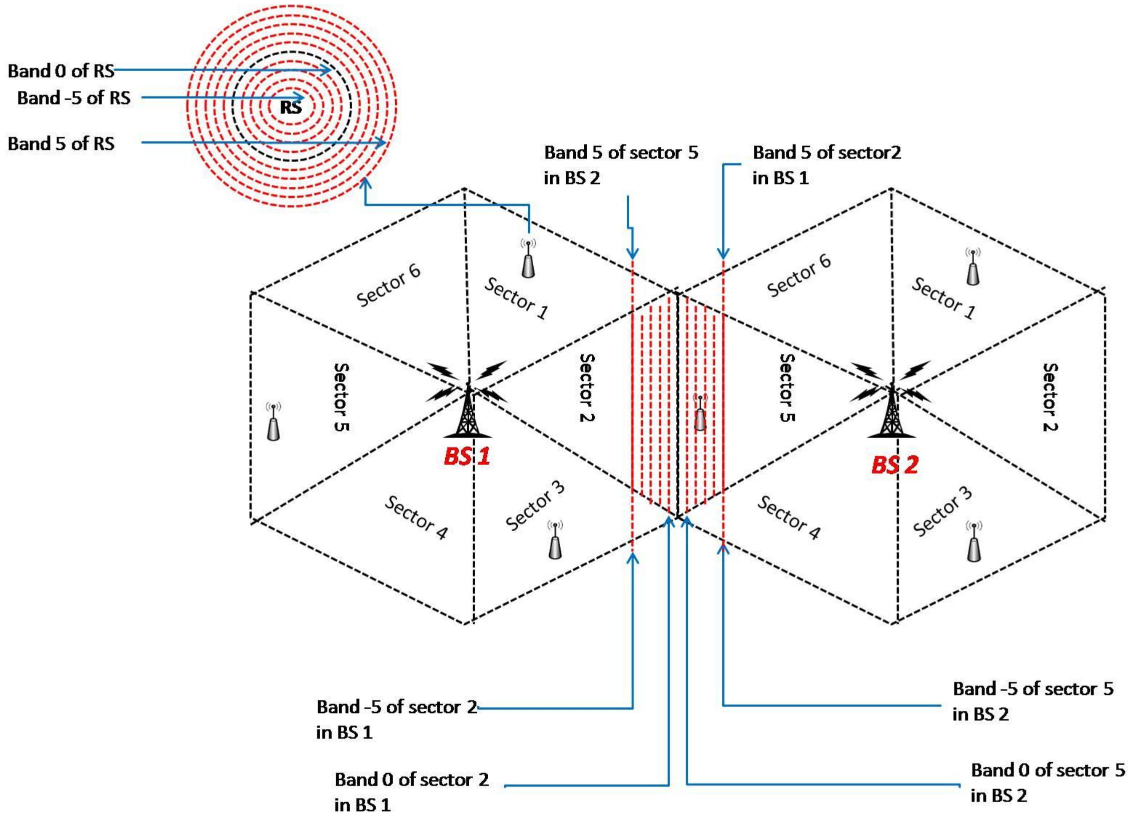


Figure 4.2 Sector and RS as RBCN entity

Figure 4.3 illustrates the radio coverage overlap limitation mechanism in UC-CAPCA. In Chapter 2, the issue of radio coverage overlap within neighbour cells is described. Some overlap is necessary because cellular networks suffer from radio coverage holes if there is no radio coverage overlap within neighbour cells. On the other hand, radio coverage overlap should be limited as radio resource inefficiency and high interference may happen. Thus, a radio coverage overlap limitation scheme is required by UC-CAPCA (also in antenna tilting scheme later). When UC-CAPCA controls entities to change their radio coverage, the algorithm needs to consider the coverage overlap limitation scheme to obtain acceptable networks radio coverage. For example in Figure 4.3, if sector 2 of BS 1 expands its radio coverage to band 3, sector 5 of BS 2 has to shrink coverage to band -3. The role of radio coverage overlap limitation in UC-CAPCA is discussed later.

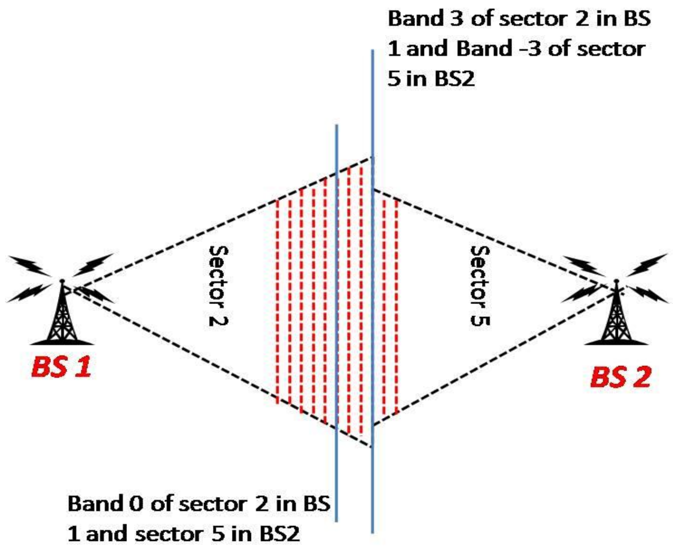


Figure 4.3 Radio Coverage Overlap Limitation

UC-CAPCA models RBCN radio propagation using open space path loss model defined in (3.5) of Chapter 3. The admission control scheme in RBCN here employs STD scheme as discussed in Chapter 2.

4.1.2 UC-CAPCA algorithm

UC-CAPCA mainly consists R iterations (R is a pre-defined constant). In an iteration, UC-CAPCA chooses the most suitable sector or RS (so called Best Entity) to change their radio coverage through antenna power control. The obtained network coverage in an iteration is the start state of next iteration. UC-CAPCA finishes when it reaches the number of allowed iterations or user congestion does not exist anymore in the RBCN (UC-CAPCA converges). In this way, gradually UC-CAPCA obtains a near optimal BSs and RSs radio coverage after a numbers of iterations. There are 3 actions in an iteration as shown below.

1. Find the best entity (labelled as m) to expand its coverage by one band. The best entity is the RBCN entity having the highest utility.

2. Apply the radio coverage overlap limitation scheme. Specifically, the opposing entity of entity m shrinks radio coverage if its overlap area with entity m passes a certain threshold. Opposing entity of entity m means the entity that has radio propagation

direction directly pointing to entity m.

3. Update MSs connections to BSs or RSs through handover under the newly changed radio coverage.

The whole procedure of UC-CAPCA is shown in table 4.1. In table 4.1, T is the number of entities. R is the number of allowed iterations. U_i is the utility of expanding coverage in entity i.

Table 4.1 Utility based Cooperative Antenna Power Control Algorithm

Initialize BSs and RSs (entities) to their default coverage;

REPEAT: Iteration index: $n=1$;

REPEAT: Entity index: $i=1$;

Compute utility U_i of entity i;

$i \leftarrow i + 1$

UNTIL $i > T$;

$m = \arg_{\mathrm{i}}(\max U_i)$;

IF (radio coverage of entity m currently includes band j)

Expand radio coverage of entity m to include band $(j + 1)$;

ENDIF

Perform radio coverage overlap limitation scheme;

Update MSs connections through handover;

$n \leftarrow n + 1$

UNTIL $(n > R)$ or No user congestion existed

4.1.3 Best Entity in UC-CAPCA

As discussed, finding the best entity in an iteration is critical. The candidate entity needs to satisfy three criteria to become the best entity:

1. The candidate entity can cover as many un-served MSs as possible if expanding its current coverage by one band.

2. These MSs newly covered by the candidate entity can get service in acceptable quality. The method to measure and compare the quality is explained in (4.3), (4.4) and Figure 4.4.

3. The candidate entity coverage expansion can cause an opposing entity to discard more MS connections. The opposing entity discards MS connection because the opposing entity has to shrink its radio coverage for radio coverage overlap limitation. Afterwards, those discarded MS connections can re-connect to the candidate entity. This criterion used follows the rule that if a candidate entity coverage expansion causes its opposing entity to lose more MS connection, MSs re-connections can happen more frequently and make RBCN more close to geographic load balancing.

These three criteria are incorporated in the definition of utility formulated in (4.3). The best entity in an iteration is the candidate entity having the highest utility.

$$U_i = \left(\frac{C_{free}}{C_{total}}\right)^{\gamma} \times \left(\sum_{j \in G_{per}^{i}} D_j + \alpha \sum_{j \in G_{opt}^{i}} (k_j \times D_j) + \beta \sum_{j \in G_{discard}^{i}} D_j\right) \tag{4.3}$$

U_i is the utility of expanding coverage in entity i. α, β and γ are weights deciding how different factors influence U_i. D_j is the demand of MS j (fixed and equal among all the MSs in this thesis). G_{per}^{i} is the group of MSs covered by entity i in its next coverage band. $G_{discard}^{i}$ is the group of MSs whose connections are discarded by the opposing entity of entity i if shrink. G_{opt}^{i} is the group of MSs which can get the best service from entity i in its next coverage band. In order to get G_{opt}^{i}, the algorithm evaluates each of the MSs that are covered by entity i in its next coverage band ($\forall i \in G_{per}^{i}$). Take MS q ($q \in G_{per}^{i}$) as an example. In Figure 4.4, suppose MS q can be covered by different candidate entities in their next band including entity i (one sector of BS *A*), entity k (one sector of BS *B*), and entity j (one RS of BS *C*). The algorithm computes the hypothetical antenna power offered to MS q by these candidate entities. The hypothetical antenna power is calculated according to formulation (4.4). (4.4) follows the simple open space path loss radio propagation mode discussed in (3.5). If the highest hypothetical antenna power received by MS q is from entity i, then entity i supposes to provide MS q the best service, then k_i is set to 1. Otherwise k_i is set to 0 in (4.3).

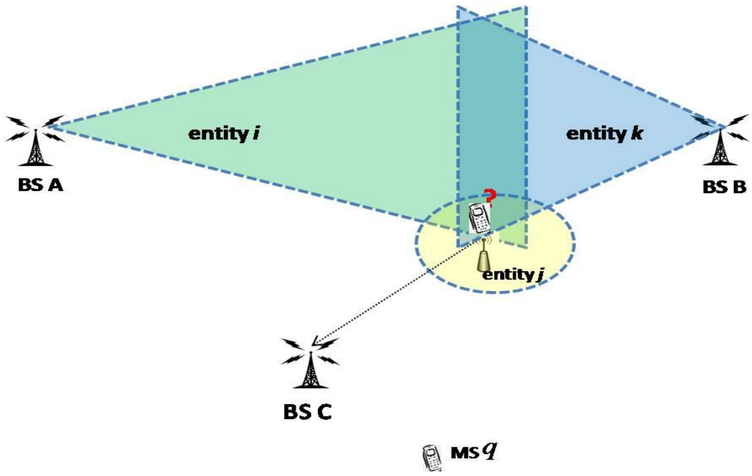


Figure 4.4 MS finding the best entity

$$\begin{cases} P_{rec} = Pattern_{\theta} \frac{p_{tal}^{j+1}}{\tau \times (d_{actual})^{\varphi}} \\ p_{tal}^{j+1} = \frac{P_{tres\,hold} \times \tau \times (d_{j+1})^{\varphi}}{Pattern_{\theta}} \end{cases} \rightarrow P_{rec} = P_{tres\,hold} \times (\frac{d_{j+1}}{d_{actual}})^{\varphi} \quad (4.4)$$

In (4.4), $P_{tres\,hold}$ is fixed and represents the antenna power threshold guaranteeing that radio coverage of entity i can be detected by MS. Entity i now has coverage band j. P_{tal}^{j+1} is the antenna power of entity i guaranteeing radio coverage of entity i can extend to coverage band $j+1$. d_{j+1} is the distance from entity i to the border of coverage band $j+1$. P_{rec} is the antenna power received by MS q which is d_{actual} away from entity i . τ is power fade factor and φ is the path loss factor.

$\frac{C_{free}}{C_{total}}$ in (4.3) is the ratio of free capacity C_{free} to total capacity C_{total} of entity i. $\frac{C_{free}}{C_{total}}$ represents capacity state of entity i . If entity $\frac{C_{free}}{C_{total}}$ is low, it means entity i is heavily loaded so is less likely to offer high utility to the MS. γ is the parameter coordinating $\frac{C_{free}}{C_{total}}$ effect on utility. The coordinating effect of γ is shown in Figure 4.5. The optimal γ has the effect that if $\frac{C_{free}}{C_{total}}$ of entity i is higher than certain effectiveness threshold, further $\frac{C_{free}}{C_{total}}$ changing will have no effect on utility. The closer γ becomes optimal, the better coordinating effect γ will have. Figure 4.5 just briefly show the existence of optimal γ, so there is no specific value on shown on y-axis in Figure 4.5.

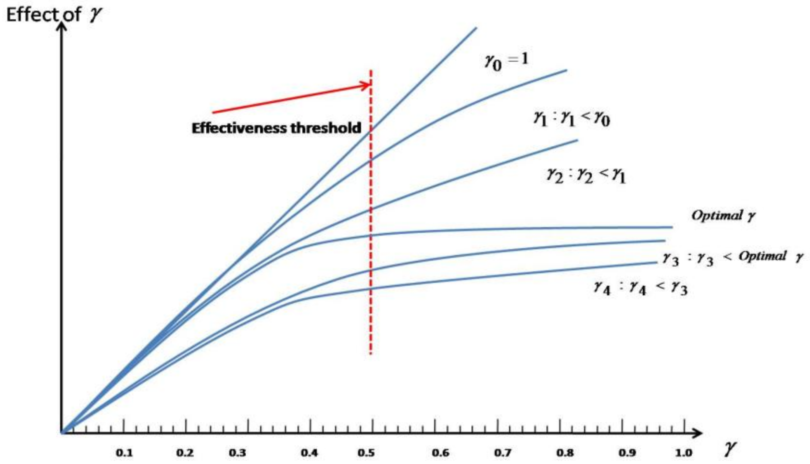


Figure 4.5 γ coordinating effect on $\frac{C_{free}}{C_{total}}$ in utility definiation

4.1.4 Greedy cooperative antenna power control algorithm

This section introduced a greedy based cooperative antenna power control algorithm (G-CAPCA) in literature [84]. This algorithm works under the same premises as the UC-CAPCA except that both BS and RS use omni-directional antenna. In G-CAPCA, BS always has priority of expanding radio coverage over RS.

Like UC-CAPCA, G-CAPCA goes through *R* iterations. In an iteration, the algorithm decides which BSs and RSs expand their radio coverage by one coverage band and which BSs and RSs shrink radio coverage accordingly. In the end, BSs and RSs radio coverage newly acquired in this iteration is the initial coverage of next iteration. Thus after *R* iterations, the whole network radio coverage obtained through G-CAPCA should be (near) optimal for balanced geography load.

The procedure in an iteration of G-CAPCA is listed below, and the whole procedure of G-CAPCA is shown in table 4.2.

1). Each BSs and RSs utility of expanding coverage is calculated. Then the total utility of every cell is acquired by adding all the utilities of its attributed BS and RSs. The utility calculation formation is defined in (4.5) (step 3 of table 4.2).

2). Cell coverage expansion is carried out for all RBCNs cells. Basically, in a cell, the BS expands its coverage by one coverage band if it has not reached its maximum capacity(the number of MSs the BS can serve) and maximum coverage. Otherwise, if the BS has reached its maximum coverage band but not its maximum capacity, one of the RSs of the cell will be chosen to increase its coverage by one coverage band instead. The chosen RS is the one that has the highest utility out of all the RSs in this cell and has not reached its maximum coverage band and maximum capacity. The maximum capacity means how many MSs a BS or RS can serve (steps 7 and 8 of table 4.2).

3). Cells adjust their radio coverage cooperatively to limit radio coverage overlap. Specifically, if two cells have their overlap area above certain threshold, one of the cell having lower utility must shrink its RS coverage or BS coverage for the sake of radio coverage overlap limitation (step 10 of table 4.2).

4). MSs update their connections to BS or RS under this newly changed radio coverage (step 10 of table 4.2).

5). The newly obtained BSs and RSs radio coverage is stored and passed to next iteration to be the initial entities radio coverage.

Utility of cell i is defined in (3.6):

$$\begin{cases} U_i^{total} = U_{BS}^l + U_{RS1}^m + U_{RS2}^n + U_{RS3}^t \\ U_j^k = d_k + \omega \times d_k^f \end{cases} \quad (4.5)$$

In (4.5), U_i^{total} is cell i utility. It composes of BS and RSs utility: U_{BS}^l, U_{RS1}^m, $U_{RS2}^n$and U_{RS3}^t. These BS and RSs belong to cell i. $U_{BS}^l$is the utility of BS, which is in its coverage band l. $U_{RS1}^m$is utility of $RS1$, which is in its coverage band m . U_{RS2}^n is utility of $RS2$, which is in its coverage band n, U_{RS3}^t is utility of $RS3$, which is in its coverage band t. U_{BS}^l, U_{RS1}^m, $U_{RS2}^n$and$U_{RS3}^t$are defined by U_j^k. In U_j^k, j represents

BS or RS. k represents its current coverage band. d_k means the demand of MSs inside current coverage band k of j. d_k^f means the demand of all MSs outside band k of j and up to the maximum coverage of j. Each unit of demand outside band k of j is given greater weight ω. This represents that greater potential MS a BS going to serve, the higher utility the BS or RS can have. According to such utility definition, it can be told that this algorithm is greedy.

Table 4.2. Greedy based Cooperative Antenna Power Control Algorithm

1: Initialize BSs and RSs for coverage without black hole;
Initialize times of iterations over all cells to R; T =total number of cells;
2: REPEAT: iteration index: n=1; {
3: REPEAT: cell index $i=1$; { Compute utility of cell i ; $i \leftarrow i+1$ }UNTIL $i>T$
4: Sort cells in descended order stored in list L by Utilities;
5: REPEAT: {
6: Get first cell from L and label it e ;
7: Suppose cell e currently covers band j ;
IF (cell e not at its maximum capacity & not at its maximum coverage){
Expand cell e to cover band $j+1$;}
8: ELSE IF (cell e not at its maximum capacity){
Find the RS: R_k having the highest utility in cell e and not
being at its maximum capacity and coverage;
suppose R_k currently includes band l;
Expand R_k to cover band $l+1$;}
9: Erase cell e from L; } UNTIL there is no cell in L;
10: Cooperative cell coverage adjustment for all cells, and MSs handover; $n \leftarrow n+1$;
} UNTIL $n>R$ or there is no un-served MSs;
11: END

4.1.5 Simulation

UC-CAPCA simulation in system level RBCN simulator here employs 60° sector antenna and RSs work in non-transparent relay mode. It is assumed there are 19 BSs in network whose layout is the same as Figure 3.1 of Chapter 3. The radio propagation mode is the simple open space path loss model introduced in (3.5) of Chapter 3. Because there is no frequency allocation in consideration, it is assumed each cell has all the available channels. Admission control scheme in RBCN here employs STD scheme.

The simulation intends to validate that UC-CAPCA better relieves user congestion problem. UC-CAPCA is compared to G-CAPCA and conventional RBCN. Conventional RBCN means there is no cooperative control mechanism in RBCN. The merits and drawbacks of UC-CAPCA are evaluated through these comparisons. Because there is no deterministic MS distribution in RBCN and each MS moves randomly, it is hard to find the optimal network reconfiguration solution leading to the best geographic load balancing. Thus, UC-CAPCA can only be compared to other existed solutions as benchmarks and proved to be closer to optimal solution than those benchmark solutions.

There are three repetitions of an individual simulation and the results are shown by Figure 4.6. Each simulation refers to a different hotspot configuration. Hotspots are in the locations where MSs gather. Hotspot configuration is part of the MSs distribution setting. Specifically, different hotspot configurations have different number, position and size of hotspots, and each hot spot is set to have a different number of MSs. Generally speaking, if a hotspot configuration has a greater number of hotspots and more MSs in each hotspot, MSs in this configuration are more prone to congest. In a hotspot configuration, there are 100 MSs distribution scenarios obtained by periodically taking a MSs distribution snapshot. Because MSs gradually gather into a hotspot, the MSs distribution becomes more and more congested from MSs distribution scenario 1 to MSs distribution scenario 100. It is assumed that each MS in a particular scenario is randomly active with certain waiting time.

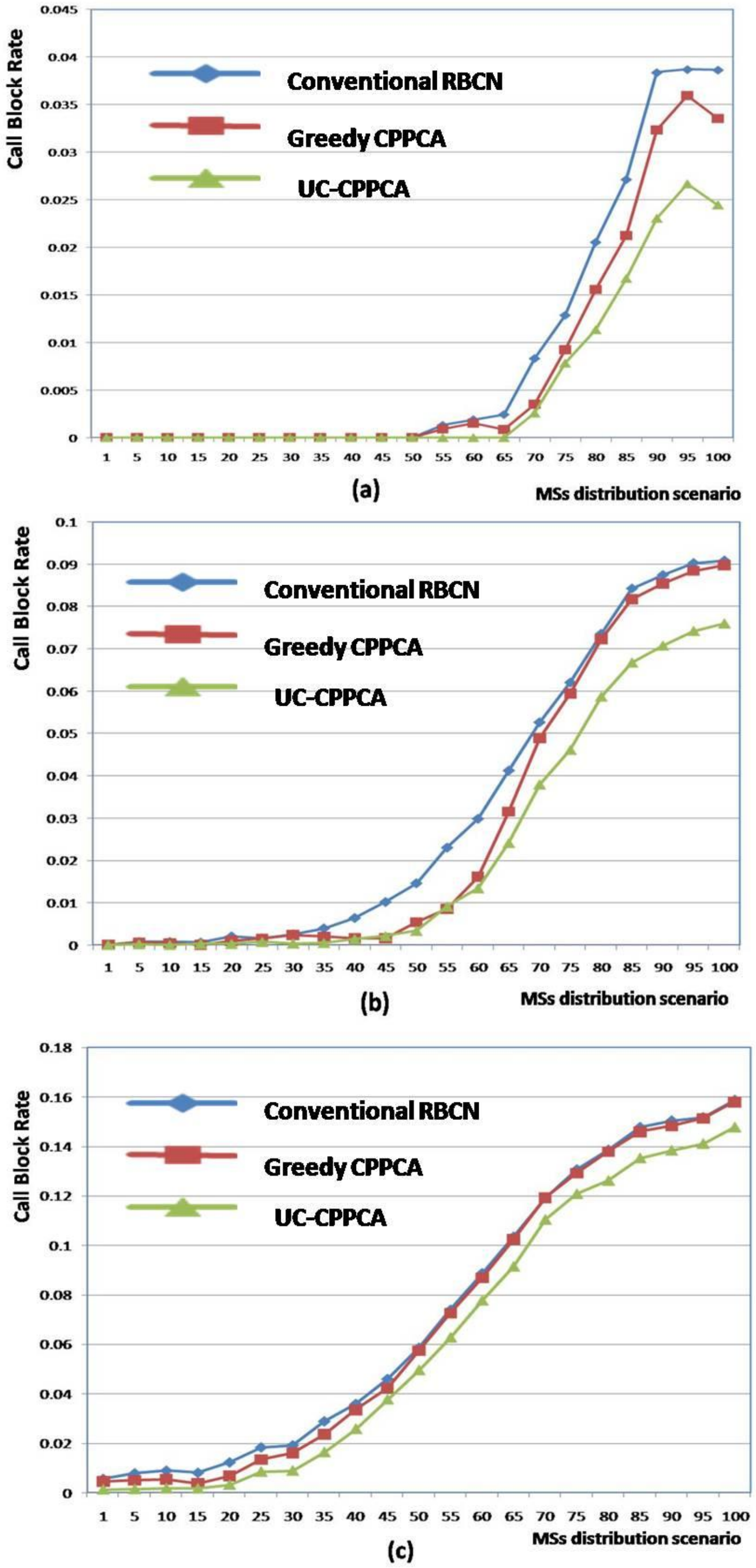


Figure 4.6 UC-CAPCA compared to G-CAPCA and conventional RBCN

In Figure 4.6, the performance of the cooperative antenna power control algorithms is compared to other solutions in three different hotspot configurations. In detail, Figure 4.6(a) shows the outcome of simulator running with 4 hotspots, and 500 MSs in each hotspot. Figure 4.6 (b) shows the outcome of the simulator running with 4 hotspots, and 750 MSs in each hotspot. Figure 4.6 (c) shows the outcome of the simulator running with 4 hotspots, and 1000 MSs in each hotspot. Obviously, from Figure 4.6 (a) to Figure 4.6 (c), more and more MSs are more prone to gather to higher congestion. In practice, cooperative antenna control will take longer time to converge when MS distribution is in higher congestion. This is because cooperative antenna control algorithms will run more calculations to find a reasonable network configuration leading to geographic load balancing. Therefore, the simulation time related to Figure 4.6(c) is the highest, and Figure 4.6(a) related simulation time is the lowest.

There are two considerations to compare the performances of different algorithms.

1). Different algorithms give different call blocking rates in each scenario simulation. This can reveal which algorithm can realize better geographic load balancing for RBCN. Call blocking rate as formulated in (3.12) of Chapter 3 is a criterion that indicates network capacity. It is the ratio of served users to the total number of users. The lower call blocking rate is, the higher RBCN capacity is.

2). Different algorithms give different increasing rates of call blocking rate corresponding to MSs becoming more and more congested. This increasing level of call blocking rate reveals which algorithm enables RBCN to be more resilient to user congestion.

In (a), (b) and (c) of Figure 4.6, UC-CAPCA always gives the lowest call blocking rate, while G-CAPCA gives lower call blocking rate compared to the conventional RBCN. Alternatively, when MSs distribution coalesces from MSs distribution scenario 1 to 100, call blocking rates keep on increasing. When MSs distribution becomes highly coalesced, geographic load balancing becomes difficult to realize. In this case, it can be found that call blocking rates of G-CAPCA and conventional RBCN increase at a faster speed. On the other hand, UC-CAPCA call blocking rates increases almost at a static speed. For example in (b) of Figure 4.6, the call blocking rates of G-CAPCA suddenly increase when simulation goes from MSs distribution scenario 60 to 70. Under the same situation, UC-CAPCA always keeps call blocking rates increasing in a stable rate. As a result, it can be concluded that UC-CAPCA enables RBCN more resilient to high user congestion.

In summary, UC-CAPCA does give the best performance on releasing user congestion problem compared to G-CAPCA and conventional RBCN.

4.2 Heuristic antenna tilting

The antenna tilting algorithm in this thesis employs a greedy heuristic search with no look ahead. Like cooperative antenna power control algorithm, the computation of the algorithm is based on a model of the propagation environment at each tilt angle and antenna power. The actual tilting is only performed after the search had been completed. This antenna tilting algorithm intends to both relieve user congestion and BS failure problems.

4.2.1 Antenna tilting to change coverage

Antenna tilting here is a centralized algorithm and RSs in RBCN work in transparent relay mode. 60° sector antenna is considered here. The admission control scheme in RBCN employs the data based AC scheme. As discussed in RBCN model in Chapter 3, antenna power of each sector antenna in a cell is fixed. However, a sector antenna can tilt within 3 tilting states: *Up*, *Normal* and *Down* in antenna tilting schemes. *Normal* is the default state of a sector antenna. An RS antenna cannot tilt, but can increase or decrease its transmission power to have 3 coverage states: *Expanded*, *Normal*, and *Shrunk*. *Normal* is the default state of an RS antenna. In order to model such antenna tilting abilities, MS received sector antenna gain defined in (3.4) and RS antenna power defined in (3.1) are augmented to be (4.6) and (4.7).

$$G_{i,b} = \alpha\left(G_M - min\left(12\left(\frac{\theta}{35}\right)^2, 23\right)\right) \ (b \text{ is } 60^{\circ} \ sector\ antenna) \tag{4.6}$$

In (4.6), α is the antenna tilt parameter that has 3 values: 1, 0.75, and 1.25 representing *Normal*, *Down* and *Up* tilting states of a sector antenna respectively. Other parameters are the same as the ones in (3.4).

$$P_b = \beta \times P_2 \qquad (b \text{ is RS}) \tag{4.7}$$

In (4.7), β has three values: 1, 0.75, and 1.25 corresponding to *Normal*, *Shrunk*, and *Expanded* coverage states of a RS. P_2 is the fixed antenna power of RSs as defined in (3.1).

4.2.2 Antenna tilting algorithm

The procedure of antenna tilting algorithm is shown in table 4.3 below.

In table 4.3, $S_{s,b}$ represents sector s of BS b. $LD_{s,b}$ represents the load difference within S_{ij} and its opposing sector S_{s,b_opp}, so $LD_{s,b}$=$L_{s,b}$- L_{s,b_opp}. $LD_{t\hbar re}$ is the load difference threshold, which indicates whether a sector is heavily loaded ($LD_{ij} > LD_{t\hbar re}$) and so tilt down or not ($LD_{ij} > LD_{t\hbar re}$). L_{ij} and L_{s,b_opp} represent the load of S_{ij} and S_{s,b_opp}. L_{ij} $(\forall b \in B, \forall s \leq S)$ is decided by L_{ij} and the user distribution: $M_{s,b}$. $M_{s,b}$ is all the MSs connecting to sector s of BS b or to the RS located in sector s of BS b. U indicates whether there is user congestion or not. B is the set including all the BSs in RBCN and S is the number of sectors in a cell. R is the set including all the RSs in RBCN.

In the beginning, each sector or RS and related MS connections are set to the default tilting state: $\{\alpha_{s,b} = 1, \beta_r = 1, M_{s,b}\}$ $(\forall b \in B, \forall s \leq S, \forall r \in R)$. When running, in each search loop (steps 2 to 17), the algorithm finds the sector: $S_{(s,b)_{sele}}$ that has the highest load difference from their opposing sector ($max_{b\in B,s\leq S}(LD_{s,b})$) (step 13) to tilt down (step 14, $\alpha_{(s,b)_{sele}}$ set to 0.75). If there is a RS (say RS r) in the coverage of $S_{(s,b)_{sele}}$ the RS will decrease its antenna power to the shrunk state (step 14, β_r set to 0.75). Afterwards, the opposing sector $S_{(s,b)_{sele\_opp}}$ is tilted up (step 14, $\alpha_{(s,b)_{sele\_opp}}$ set to 1.25). If there is a RS (say r_{opp}) in the coverage of $S_{(s,b)_{sele\_opp}}$, the RS will increase its transmission power to *Expanded* state (step 14, $\beta_{r_{opp}}$ set to 1.25). After the two sectors and related RS change their tilting and antenna power respectively, users influenced by the antenna reconfiguration will handover from the heavy loaded cell to light loaded cell to realize load balancing (step 15). Therefore, after a number of MS handovers caused by antenna tilting, $M_{s,b}$ is changed to $M_{s,b}^{conf}$ $(b \in B, s \leq S)$ that users are more evenly loaded. In the next loop, the tilted antennas will not tilt any more (step 7). Antenna tilting finishes when there is no further opportunity for antenna tilting, and$\{\alpha_{s,b}, \beta_r, M_{s,b}^{conf}\}$ $(\forall b \in B, \forall s \leq S, \forall r \in R)$ is the output.

Table 4.3 Heuristic Antenna Tilting

Input: $\alpha_{s,b} = 1$ $(\forall b \in B, \forall s \leq S)$, $\beta_r = 1$ $(\forall r \in R)$; *U=true;* $M_{s,b}$ $(b \in B, s \leq S)$

Output: $\{\forall \alpha_{s,b}$ $(b \in B, s \leq S)$, $\forall \beta_r$ $(r \in R)\}$; $M_{s,b}^{conf}$ $(b \in B, s \leq S)$

Initialization: $L_{s,b}$ $(\forall b \in B, \forall s \leq S)$

WHILE (U){

    U=false;

    FOR *b=1:*$|B|$

        FOR *s=1:S*

        IF ($S_{s,b\_op} == NULL$)&&($L_{s,b} < 0$) {$\alpha_{s,b}$= *1.25;*$\beta_r = 1.25$; $LD_{s,b}$*=0;*}; END IF

        IF ($S_{s,b\_opp} \neq NULL$)&& ($\alpha_{s,b}$ *≠1*) {$LD_{s,b}$*=0*}; END IF

        IF ($S_{s,b\_opp} \neq NULL$)&& ($\alpha_{s,b}$*==1*) {$LD_{s,b}$=$L_{s,b}$- L_{s,b_opp} }*;* END IF

        IF ($LD_{s,b} > LD_{thre}$) {U= *true*}*;* END IF

        END FOR

    END FOR

    IF (U){

        Make sector choice: $S_{(s,b)_{sele}}$ *=arg* $(max_{b \in B, s \leq S}(LD_{s,b}))$*;*

        $\alpha_{(s,b)_{sele}}$ *= 0.75,* $\alpha_{(s,b)_{sele\_opp}} = 1.25$; $\beta_r = 0.75$; β_{r_opp} *=1.25*

        Users handover;}

    END IF

}END WHILE

Additionally, to relieve the BS failure problem, antenna tilting purposely expands cell coverage towards the coverage hole. If there is coverage hole in front of $S_{s,b}$, $S_{s,b}$ will not be able to perceive any opposing sector ($S_{s,b\_opp} == NULL$). Thus if $S_{s,b}$

has free channels ($L_{s,b} < 0$), $S_{s,b}$ will tilt up its antenna towards the coverage hole to decrease the hole. If $S_{s,b}$ has a RS (say r) in coverage, RS r also will set its transmission power to *Expanded* state towards the coverage hole (step 6).

This antenna tilting algorithm is simplified. The antenna tilting effect is limited by channel allocation. If a sector has only a few channels, antenna tilting cannot solve the user congestion problem greatly. Further channels would need to be allocated. The second reason is that this simple algorithm cannot guarantee finding an optimal antenna tilting solution. This could be improved by incorporating a look ahead policy into the search algorithm, but that is not explored directly here. The third reason is antenna tilting in the algorithm only has three tilting states: $\{\alpha_{s,b} \in \{0.75,1,1.25\}, \quad \beta_r \in \{0.75,1,1.25\}\}$ $(\forall b \in B, \forall s \leq S, \forall r \in R)$. Thus the tilting cannot change antenna power distribution to a high precision. To reduce the limitations of the simple antenna tilting, one approach is to combine antenna tilting with frequency allocation into an interwoven solution and this is described in Chapter 5. Of course, the benefits of tilting are very dependent on the service. For this reason, two different demand scenarios are considered in the simulations, one where tilting is expected to have a better effect, and one where there should be a marginal effect.

4.2.3 Simulation

As discussed before, antenna tilting simulation in system level RBCN simulator employs 60° sector antenna and RSs work in transparent relay mode. It is assumed there are 19 BSs in network whose layout is the same as Figure 3.1 of Chapter 3. The radio propagation mode is the one discussed in (3.1) of Chapter 3. The simulation here validates antenna tilting effect on both user congestion and BS failure situations. It is assumed that each sector has all the available channels (so no frequency allocation scheme, normally FFR, in use). Admission control scheme in RBCN here employs the data based AC scheme.

Antenna tilting effect is highly related to user scenarios. To validate antenna tilting effect, simulation first uses 10 lightly congested MSs distribution scenarios and not considers BS failure. In each of these 10 user distribution scenarios, there is only one fixed hotspot on the border of two cells and no user outside the hotspot.   From scenario 1 to scenario 10, more and more users are in the hotspot. It is assumed that all the users in distribution scenarios are active during the whole simulation time. Because there are only two cells in the whole network, the network throughput is low (less than 1.4 mbps). In comparison, Figure 4.8 and Figure 4.9 show the 19 cells RBCN has much higher throughput than the two cells case in Figure 4.7. This shows that RBCN network throughput is closely related to number of BSs and user demand in the network.

The network throughput formulated in (3.11) of Chapter 3 is compared between antenna tilting algorithm and conventional RBCN case in Figure 4.7. Network throughput is the total data rate of all the served users. The higher the throughput is, the better the algorithm. In Figure 4.7, antenna tilting much improves network throughput compared to conventional RBCN case. However, when the hotspot becomes too hot in scenarios: 5,6,7,8,9 and 10, the antenna tilting algorithm cannot more improve network throughput. According to these results, antenna tilting does relieve user congestion problem.

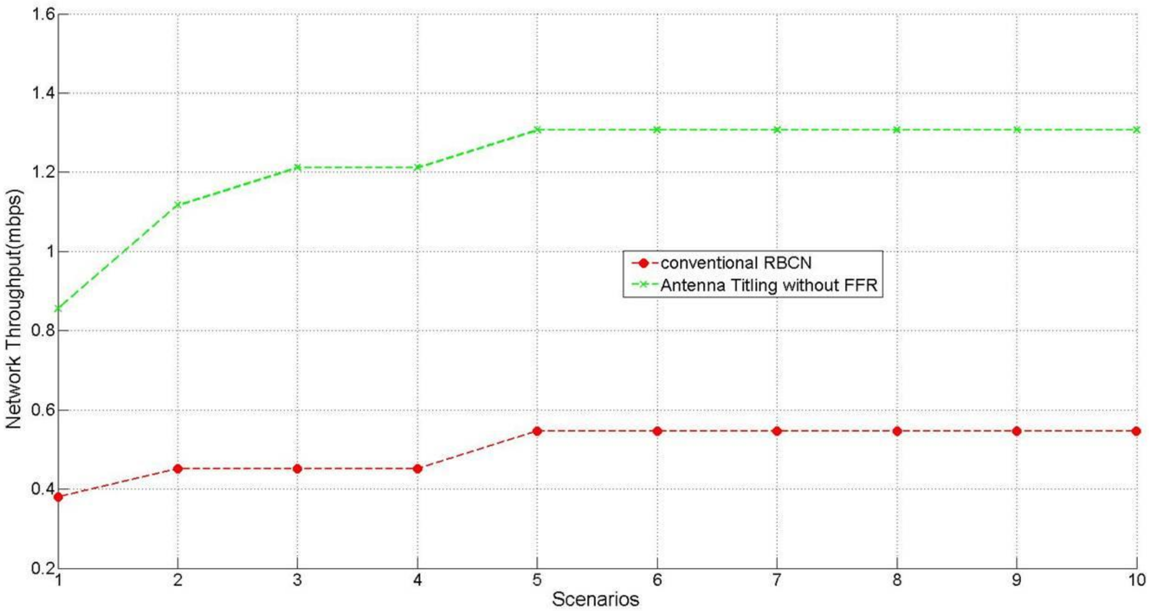


Figure 4.7 Network throughput comparison to proof antenna tilting effect

Alternatively, to explore the limitation of antenna tilting, 30 high user congestion scenarios are considered in Figure 4.8 and 4.9. In Figure 4.9, BS failure is also investigated. It is assumed that two BSs fail to provide radio coverage. BS 3 and 6 and their RSs in Figure 3.1 of Chapter 3 are assumed to fail to simulate BS failure.   Users are highly congested in two hotspots in scenario 1 and gradually disperse till scenario 30 because of Straight Walking moment with speed: 5 KM/h. Straight Walking Model means user randomly select a direction to move in each movement. Like before, it is also assumed that all the users in distribution scenarios are active during the whole simulation time.

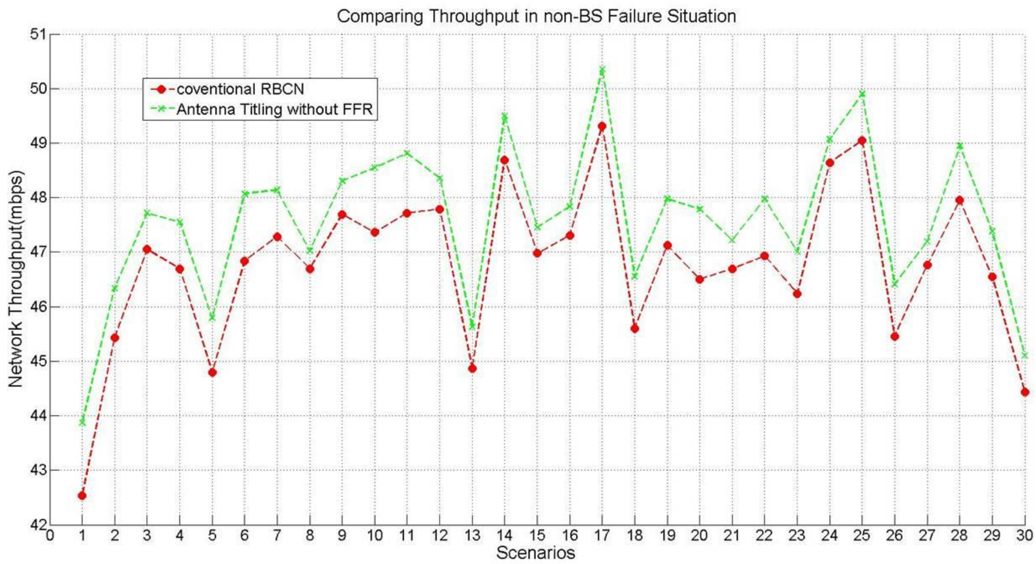


Figure 4.8 Antenna tilting effect in high user congestion situation

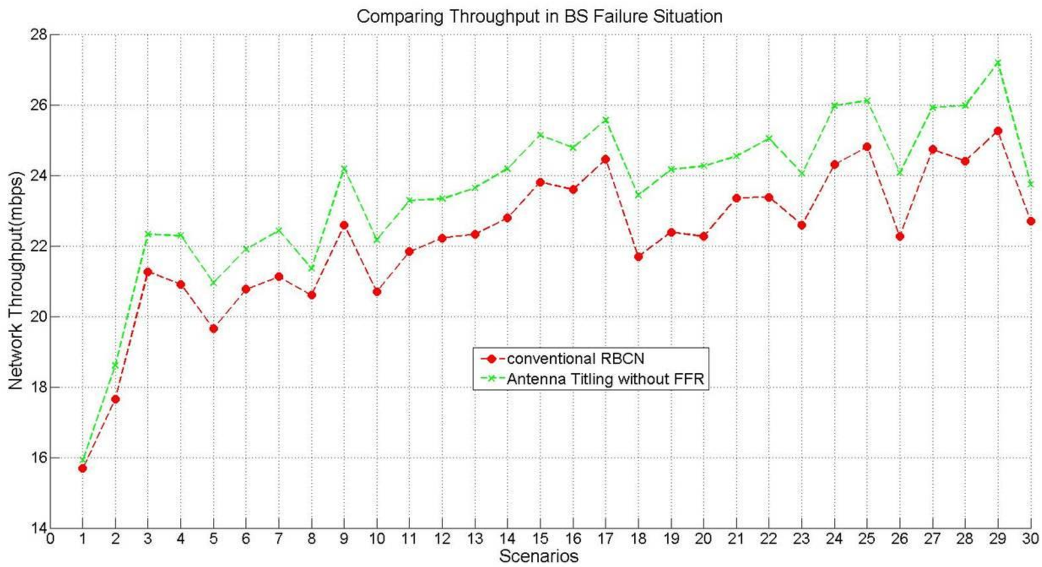


Figure 4.9 Antenna tilting effect in high user congestion and BS failure situations

As shown in Figure 4.8 and 4.9, antenna tilting algorithm in high user congestion case can marginally increase network throughput both in BS failure and non-BS failure situations compared to non algorithm case. However, antenna tilting can give better throughput improvement in BS failure situation. This is shown in Figure 4.10.

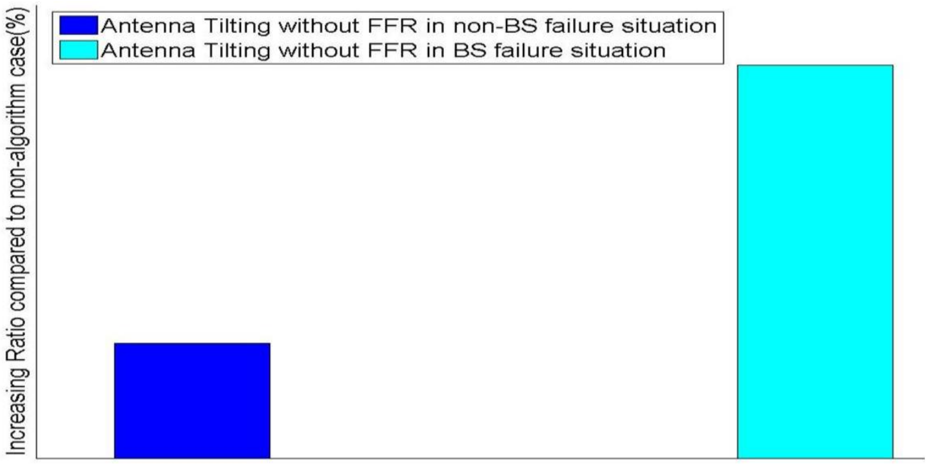


Figure 4.10 The throughput increasing ratio compared to conventional RBCN case led by antenna tilting both in non-BS failure and BS failure situations

In Figure 4.10, the throughput increasing ratio compared to conventional RBCN case led by antenna tilting in BS failure and non-BS failure situations is shown. Obviously, antenna tilting in BS failure situation improves network throughput in much higher ratio than in non-BS failure situation. Thus antenna tilting does have effect on releasing BS failure problem.

In summary, antenna tilting algorithm can relieve user congestion and BS failure problems.

4.3 Summary

This chapter investigates the effects of cooperative antenna power control and antenna tiling to relieve user congestion and BS failure problems of RBCN. The core activity of the two solutions is a simple heuristic searching for a good antenna configuration. In application, the cooperative antenna power control algorithm: UC-CAPCA deliberatively works to solve the user congestion problem. The antenna tilting algorithm works to both solve user congestion and BS failure problems. These two algorithms are both validated in the system level RBCN simulator. However, cooperative antenna power control and antenna tilting here employ simple heuristic search to find proper antenna to be configured, and there is no look ahead scheme that could lead to better antenna coverage adjustment. The next chapter looks at avoiding these drawbacks.

Chapter 5 Centralized Dynamic frequency allocation and integrated solutions in RBCN

This chapter firstly designs centralized dynamic frequency allocation algorithms for high frequency efficiency in RBCN. Mobile WiMAX and IEEE802.16j supported RBCN normally employ Fractional Frequency Reuse (FFR) as a frequency allocation solution. However, FFR is not a flexible solution [51]. For example, MSs in the outer area of a cell cannot use the channels allocated in the inner area even through the inner area has free channels, and vice versa. Dynamic Fractional Frequency Reuse (Dynamic FFR)[52] is proposed to be a better frequency allocation solution compared to FFR. Based on Dynamic FFR, this chapter first designs a centralized Dynamic Fractional Frequency Allocation (DFFA) algorithm. The differences between DFFA and Dynamic FFR is that DFFA is designed deliberately for RBCN and uses channel borrowing for higher degree of frequency allocation.

Secondly, this chapter applies the antenna tilting algorithm discussed in Chapter 4 and DFFA into an integrated solution to better improve RBCN performance. These integrated solutions suppose to mitigate the low effect of antenna titling by addressing the frequency allocation problem that limits the benefits. The working relationship of these two actions is mainly investigated.

The validations of DFFA and the integrated solutions use the system-level RBCN simulator and consider BS failure and user congestion problems.

5.1 Centralized dynamic frequency allocation

In this thesis, a so called Dynamic Fractional Frequency Allocation (DFFA) algorithm is designed to be a centralized algorithm. DFFA augments the Dynamic FFR algorithm in by using channel borrowing [45].

5.1.1 RBCN channels in DFFA

In DFFA, it is assumed that antenna power or tilting in RBCN is fixed (tilting is flexible in integrated solution later). This is to avoid the high complexity and cost problem of radio resource allocation that is investigated in [85-86]. In [85-86], they work on simultaneous antenna power and frequency allocation in BS, which are highly complicated. In DFFA, the RBCN works in RS transparent relay mode. Thus DFFA does not need to deliberately consider RSs. The RBCN employs 60° sector antenna. The radio propagation mode in use is based on the model in (3.1) of Chapter 3. The admission control scheme in RBCN employs data rate based AC scheme as discussed in Chapter 2.

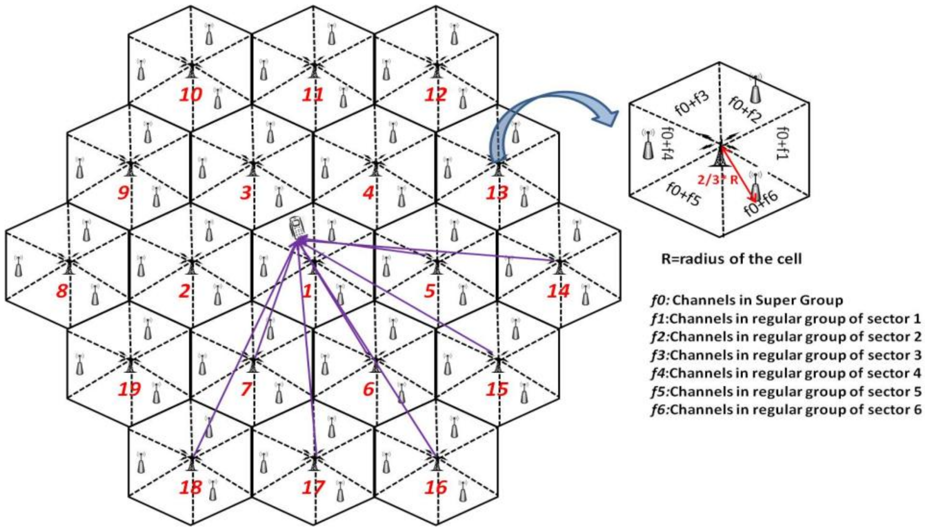


Figure 5.1 RBCN structure based on Dynamic FFR

Employing the same idea of Dynamic FFR, DFFA uniformly groups channels into one super group and 6 regular groups through channel grouping. In a cell, the 6 regular channel groups are allocated to 6 sectors to decrease CCI at the cell boundary. The channel grouping result is the same within all the cells in RBCN and shown in Figure 5.1.

When grouping a channel, the channel can only be uniquely attached into one group i.e. either super group or one of the 6 regular groups. The super group and 6 regular groups are different sets having different channels (*f0~f6* are different). The channels in super group can be used by the MSs in all the 6 sectors. Channels in a regular group can only be used by the MSs in the sector that the regular group allocated in. Thus, MSs in a sector can use the channels either from the super group or related regular group according to scheduling. For example of Figure 5.1, in sector *i*, a MS has the possibility to be allocated the channels in *fi* from the regular group or *f0* from the super group (*f0*+*fi*).

The DFFA channel grouping is formulated in (5.1) and (5.2). In (5.1) and (5.2), C is all the channels. S is the total number of sectors in a cell (S =6). $x_j^{s,reg}$ ($s \leq S$) is Boolean and represents whether channel *j* belongs to regular group of sector *s* ($x_j^{s,reg} = 1$) or not ($x_j^{s,reg} = 0$). x_j^{super} represents whether channel *j* belongs to super group of the BS ($x_j^{super} = 1$) or not ($x_j^{super} = 0$). (5.1) and (5.2) show that in DFFA channel grouping, each channel can only be grouped in the super group or one of the 6 regular groups. When finishing channel grouping, $\{x_j^{s,reg}, x_j^{super}\}(\forall s \leq S, \forall j \in C)$ are the output and the grouping is the same in each cell.

$$x_j^{super} + \sum_{s=1}^{S} x_j^{s,reg} = 1, \qquad (\overline{x_j^{super}}) = \sum_{s=1}^{S} x_j^{s,reg} \tag{5.1}$$

$$\sum_{j \in C}(x_j^{super} + \sum_{s=1}^{S} x_j^{s,reg}) = |C| \tag{5.2}$$

After channel grouping, $x_j^{s,reg}$ $(\forall s \leq S, \forall j \in C)$ is further adjusted to be $x_{j,b}^{s,reg}$ $(\forall b \in B, \forall s \leq S, \forall j \in C)$by channel borrowing in DFFA. *B* is all the BSs in the network. $x_{j,b}^{s,reg}$ represents whether channel *j* in regular group of sector *s* of cell *b* or not. $x_{j,b}^{s,reg}$ $(\forall b \in B, \forall s \leq S, \forall j \in C)$ could be different in each cell so these cases are more suitable to relieve user congestion. Because super grouped channels in a cell have already been available to all sectors, there is no channel borrowing for super grouped channels. Thus, $\{x_j^{super}, x_{j,b}^{s,reg}\}$ $(\forall b \in B, \forall s \leq S, \forall j \in C)$ is the final output of DFFA. Therefore, after channel borrowing, the channel allocation will be different from the case in Figure 5.1.

A MS in a cell receives CCI from its interfering cells. Depending on the allocated channel in the MS, the interfering cells are different. In a cell, if a MS is allocated a channel from the super group, the interfering cells are all the other cells in the network. For example, if a MS in cell *1* is allocated a channel from super group, this MS receives interference from the cells: *2-19*. Alternatively, if a MS is allocated a channel from regular group of the sector it locates in, the interfering sectors are the ones that are allocated in the same regular group and direct to the MS. For example, a MS in cell *1* allocated a channel from regular group of sector *3* only receives interference from cell: *5,6,7,14,15,16,17* and*18*. Additionally, in DFFA, RS is assumed to be transparent, so only BS in a cell can cause CCI to other cells while all RS will not cause CCI.

Based on such channel grouping, (5.3) calculates the received data rate of a user in a cell. Date rate of each user can be used to evaluate the capacity and throughput of RBCN as formulation in (3.10)~(3.11) of Chapter 3. In (5.3), $R_{i,b}$ is the data rate received by MS *i* from cell *b*. $x_{i,j,b}^{super}$ represents whether MS *i* is allocated channel *j* from super group of cell *b* or not. $x_{i,j,b}^{s,reg}$ represents whether MS *i* is allocated channel *j* from regular group of sector *s* in cell *b* or not. $x_{i,j,b}^{super}$ and $x_{i,j,b}^{s,reg}$ are decided by $\{x_j^{super}, x_{j,b}^{s,reg}\}$and BS scheduling. $R_{i,j,b}^{super}$ and $R_{i,j,b}^{reg}$ are the data rate of channel *j* when it is allocated to super group and regular group in cell *b*. $R_{i,j,b}^{super}$ and $R_{i,j,b}^{reg}$ can be calculated according to channel data rate model discussed in Chapter 3.

$$R_{i,b} = \sum_{j\in C}(x_{i,j,b}^{super} R_{i,j.,b}^{super} + \sum_{s=1}^{S}(x_{i,j,b}^{s,reg} R_{i,j,b}^{reg})) \quad (5.3)$$

5.1.2 Dynamic fractional frequency allocation algorithm

DFFA comprises two parts. The first part is Channel Grouping (CG). The second part is cooperative channel borrowing (CCB). CG realizes channel grouping in a centralized manner resulting in each cell having the same super channel group and regular channel group: $\{x_j^{s,reg}, x_j^{super}\}(\forall s \le S, \forall j \in C)$. After CG, CCB is carried out to adjust $x_j^{s,reg}$ to be $x_{j,b}^{s,reg}(\forall b \in B, \forall s \le S, \forall j \in C)$. CCB makes use of simple channel borrowing to let a heavily loaded sector have more channels. In theory, the final frequency allocation: $\{x_j^{super}, x_{j,b}^{s,reg}\}(\forall b \in B, \forall s \le S, \forall j \in C)$ obtained by CG and CCB can lead to higher RBCN capacity and throughput. Because of RS transparent relay mode, DFFA does not need to consider RSs, but the data rate calculation follows (3.7) of Chapter 3 if MS to BS connection is two-hop. After DFFA, each BS uses minimum performance guarantee (MPG) opportunistic scheduling [32] to schedule and allocate channels to MSs in each cell. The computation of DFFA algorithm is based on a model of the environment and the propagation environment at antenna. The actual frequency allocation is only performed after the DFFA algorithm had been completed.

Channel grouping

Table 5.1 Channel Groupig in Dynamic Fractional Frequency Allocation

Inputs: $R_{i,j,b}^{super}$, $R_{i,j,b}^{reg}$ ($\forall i \in M, \forall j \in C, \forall b \in B$); $M_{s,b}$ ($b \in B, s \leq S$);
Outputs: updated $x_j^{s,reg}$, x_j^{super} ($\forall$ j $\in$ C, $\forall$ s $\leq$ S) ;
Initialization: ($\forall$ j $\in$ C, $\forall$ s $\leq$ S) : $x_j^{s,reg} = 0$, g^S=0; $C^s = \sum_{b\in B} \sum_{i=1}^{\|M_{s,b}\|} D$;
$W_j^{s,reg} = \sum_{b\in B} \frac{\sum_{i\in M_{s,b}} R_{i,j,b}^{reg}}{\|M_{s,b}\|}$; $W_j^{super} = \sum_{b\in B} \frac{\sum_{i\in(\cup_{s\leq S} M_{s,b})} R_{i,j,b}^{super}}{\| \cup_{s\leq S} M_{s,b}\|}$; $U_j^{s,reg} = \frac{W_j^{s,reg} - W_j^{Super}}{\max_s (W_j^{s,reg})}$;
FOR *j*=1: |C| do: //channel grouping starts
1. FOR s=1:S do: IF (C^s> g^s) {put s in to S' };END IF End FOR;
2. IF ($S' == \{\}$){ $S' = S$;} END IF
3. Find sector channel pair (s^*, j^*) that satisfies $j^* = max_{(s',j')}(U_{j'}^{s',reg})$ ($s' \in S' \in C$);
4. IF ($U_{j^*}^{s^*,reg} < 0$) {$g^s = g^s + W_{j^*}^{Super} \frac{\sum_{b\in B} \|M_{s,b}\|}{\sum_{b\in B} \| \cup_{s\leq S} M_{s,b}\|}$, ($\forall s \leq S$)};
5. ELSE {$x_{j^*}^{s^*,reg} = 1$; $g^{s^*} = g^{s^*} + W_{j^*}^{s^*,reg}$; };
6. END IF
7. Remove j^* from C;
8. END FOR
9. $x_j^{super} = \overline{\sum_{s=1}^{S} x_j^{s,reg}}$ ($\forall$ j $\leq$ C, $\forall$ s $\leq$ S) ;

Channel Grouping is shown in table 5.1 below. CG in this thesis augments the RNC DSA algorithm in [52]. CG here works in RBCN and there are 6 regular groups allocated to 6 sectors. At the beginning of CG, channels are all grouped in the super group ($x_j^{s,reg} = 0, (\forall j \in C, \forall s \leq S)$). When running, CG evaluates each channel to decide whether to allocate this channel to a regular group of a sector or not (steps 1 to 9). For example for channel *j*, if the utility of grouping channel *j* to regular group of sector s ($U_j^{s,reg}$) is currently positive and maximal compared to grouping channel *j* to regular group of other sectors, channel *j* will be grouped to the regular group of sector s (step 5). However, if none of the channel grouping utilities is positive ($U_j^{s,reg} \leq 0, \forall\, s \leq S$), channel *j* will be remained in super group (step 4). This utility based channel grouping guarantees allocating channels to the most suitable group, thus improves RBCN capacity and throughput.

The utility calculations are hypothetical with sense that no physical allocation is done. For example of $U_j^{s,reg}$, $U_j^{s,reg}$ relates to W_j^{super} and $W_j^{s,reg}$. W_j^{super} is the sum of channel *j* proposed average data rate to all cells if channel *j* is hypothetically grouped to super group. $W_j^{s,reg}$ is the sum of channel *j* proposed average data rate to all cells if channel *j* is hypothetically grouped to regular group of the sector s. The methods depend on the model of the world. The hypothetical data rate calculation relates to antenna configure and user distribution: $M_{s,b}$ $(b \in B, s \leq S)$ according to the model in Chapter 3. $M_{s,b}$ is all the MSs connecting to sector s of BS *b* or to the RS located in sector s of BS *b*.

Additionally, in a sector, CG uses the comparison between user data rate requirement (say C^s of sector s, D is the data rate requirement of a user) and actual user data rate (g^s) of the sector to improve sector channel grouping fairness. Specifically, if sector s cannot satisfy data rate requirement ($C^s > g^s$), sector s will be put into S' (step 3). Further, if a channel is decided to be allocated to regular group, the channel is more prone to be allocated to the regular group of the sectors in S'. CG finishes when all the channels being evaluated.

Cooperative channel borrowing

After CG, each cell in RBCN has the same channel grouping: $\{x_j^{s,reg},\ x_j^{super}\}(\forall s \leq S, \forall j \in C)$. This is not applicable to user congestion situations and may lead to low RBCN throughput and capacity. In principle, channels should be allocated flexibly within sectors that need to support different user load. Thus, CCB is designed in this work to adjust channels in regular group from default state: $\{x_{j,b}^{s,reg} = x_j^{s,reg} (\forall b \in B, \forall s \leq S, \forall j \in C)\}$ to adjusted state: $\{x_{j,b}^{s,reg} (\forall b \in B, \forall s \leq S, \forall j \in C)\}$ where $x_{j,b_1}^{s,reg} \neq x_{j,b_2}^{s,reg}$ if user distributions in cell b_1 and cell b_2 are different.

CCB is a centralized channel borrowing algorithm [45]. Through channel borrowing, the heavily loaded sectors can borrow channels form light loaded sectors. Heavily loaded sector (say sector k of cell e) means this sector has larger number of users: $|M_{k,e}|$than the number of available channels: $\sum_{j\epsilon C}(x_j^{super} + x_{j,e}^{k,reg})$. When running, CCB gives the most heavily loaded sector (say sector k of cell e:$S_{k,e}$) of the network the highest priority to borrow channels. $S_{k,e}$ firstly borrows the channels that are not locked to itself. Channel locking means that a channel cannot be used nor lent to other sectors by the sector that the channel is locked in. A channel is locked in $S_{k,e}$ only if this channel has been already allocated in one of the interfering sectors of $S_{k,e}$. Interfering sectors of $S_{k,e}$ include the adjacent sectors of $S_{k,e}$ in cell e and the opposing sector of $S_{k,e}$ in the neighbour cell of cell e. Afterwards, if necessary, $S_{k,e}$secondly borrows the locked channels from lending sector and makes them un-locked in itself. The lending sector is the interfering sector of $S_{k,e}$that has free channel to lend to $S_{k,e}$. If $S_{k,e}$borrows any channel in those two steps, the borrowed channel is locked right away in interfering sectors of $S_{k,e}$to eliminate CCI. CCB finishes when all the heavily loaded sectors of the network have been sequentially considered.

5.1.3 Simulation

The DFFA simulation experiments are carried out in system level RBCN simulator. The simulation employs 60° sector antenna and RSs work in transparent relay mode. It is assumed there are 19 BSs in network whose layout is the same as Figure 3.1 of Chapter 3. The radio propagation mode is the mode discussed in (3.1) of Chapter 3. Admission control scheme in RBCN here employs data based AC scheme.

To evaluate DFFA, the RBCN system level simulator runs DFFA, Dynamic FFR and conventional RBCN case in a series of high congested user scenarios both in BS failure and non-BS failure situations. Users are highly congested in two hotspots in scenario 1 and gradually disperse till scenario 30 as a consequence of the Straight Walking movement. It is assumed that all the users in distribution are active during the whole simulation time. BS 3 and 6 and their RSs are assumed to fail to simulate BS failure. Figure.5.2 shows the performance of each solution on network throughput in non-BS failure situation. Figure 5.3 shows the solutions in BS failure situation.

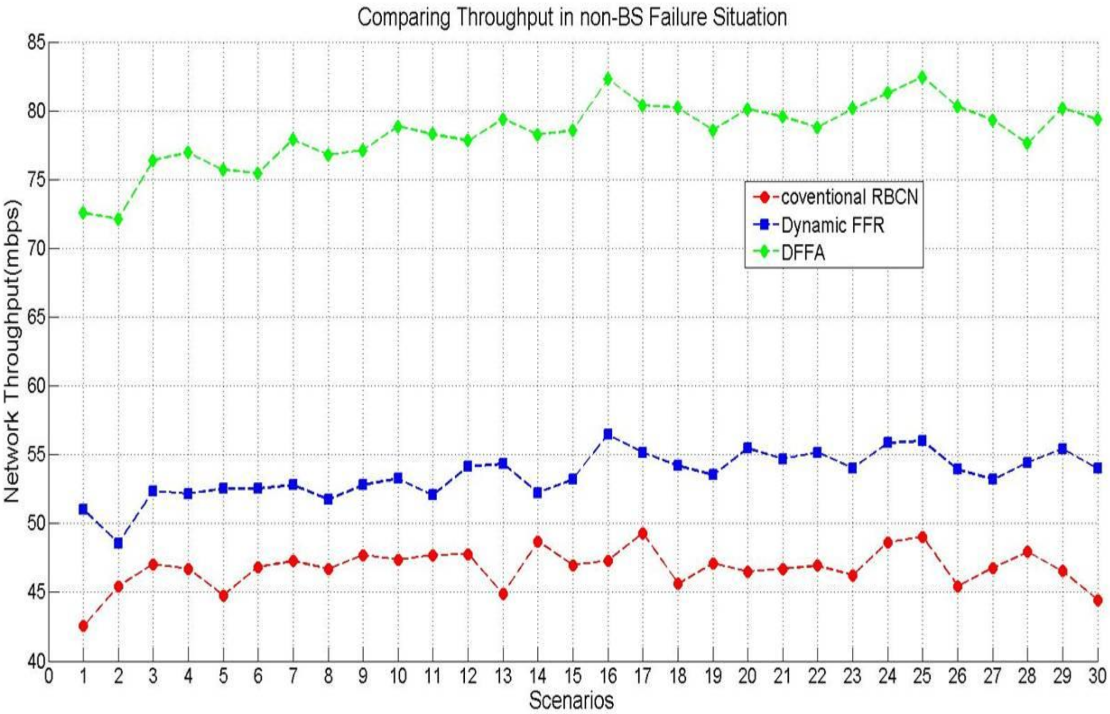


Figure.5.2 Comparison of DFFA in non-BS failure situation for the two large hotspot sequence of scenarios

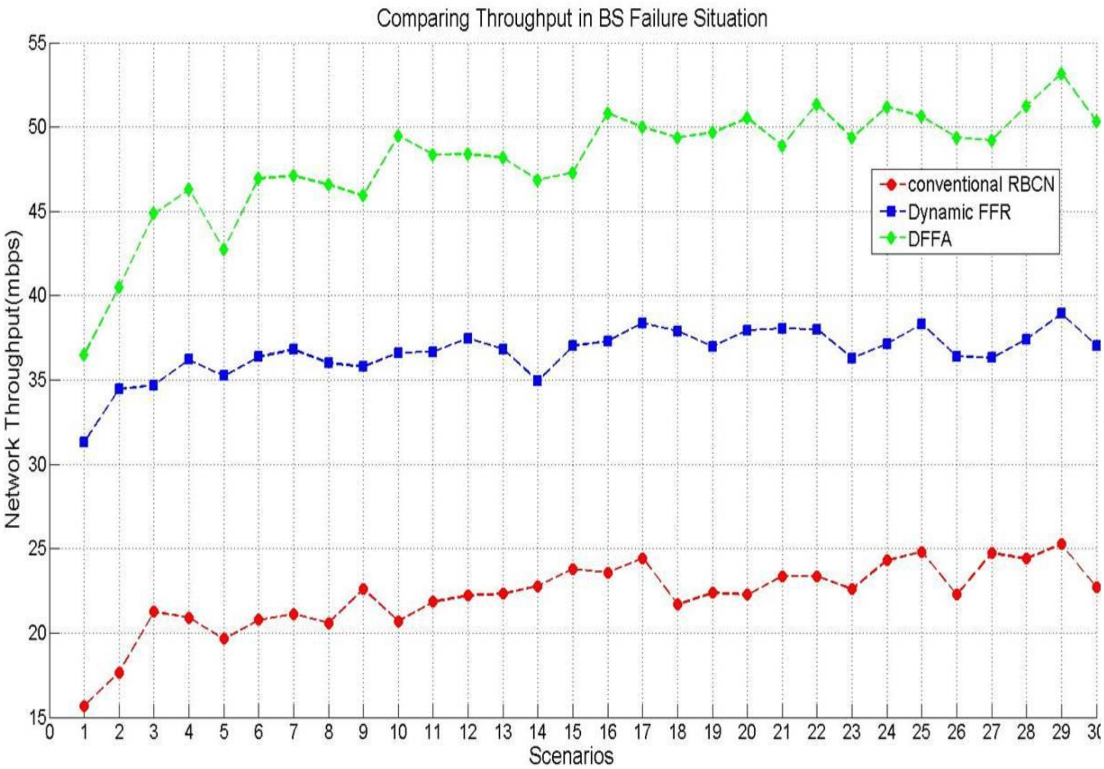


Figure. 5.3 Comparison of DFFA in BS failure situation for the two large hotspot sequence of scenarios

In Figure.5.2 and 5.3, as users becomes less congested from scenario 1 to scenario 30, network throughput increases. Compared to Dynamic FFR, and the baseline conventional RBCN case, DFFA greatly increases network throughput (defined by (3.11) in Chapter 3) both in BS failure and non-BS failure situations. As discussed in Chapter 4, RBCN throughput is highly related to BSs number and user demand. Because RBCN simulated in Figure 5.2 and 5.3 has 19 cells and high user demand, the RBCN throughput is high (maximally 82 mbps). However, because of BS failures, Figure 5.3 shows lower RBCN throughput than Figure 5.2. It is obvious that Dynamic FFR improves network performance better in the BS failure situation than in non-BS failure situation. If users are highly congested in functional BSs, Dynamic FFR increases network throughput less. Therefore, DFFA is a better frequency allocation algorithm than Dynamic FFR.

5.2 Dynamic frequency allocation and antenna tilting composed integrated solution

To our knowledge, only a few works discuss co-working between frequency allocation and antenna reconfiguration. In [87], the authors combines antenna power reconfiguration with dynamic frequency allocation in OFDMA cellular networks. The antenna power reconfiguration was carried out after a partitioning-based dynamic frequency allocation algorithm to let users be served and have good quality channels. This is similar to the work of this thesis. However, the partitioning-based dynamic frequency allocation algorithm and antenna power reconfiguration did not consider user congestion and BS failure problems. To the same issue, in [85-86], the authors investigate channel and power allocation in individual BS after network planning or reconfiguration. Each BS allocates a fixed number of channels and limits its power to its covered MS. Such channel and power allocation in a BS is to keep high BS throughput and MS fairness. The optimal solution is a simultaneous channel and power allocation. The optimization is a mixed binary integer programming problem with nonlinear constraints, which increases the computational difficulty. To avoid these drawbacks, sub-optimal solutions are employed in [85-86]. For example, similar to the sequential solution in this thesis, [86] carried out channel allocation and power allocation in small steps.

This section explores the working relationship of antenna reconfiguration and frequency allocation and designs specific DFFA and antenna tilting algorithms to be applied sequentially or interwoven (integrated solution) in user congestion and BS failure situations. These solutions avoid antenna reconfiguration and frequency allocation running in parallel like the work in [85-86]. In practice, it is hoped that the sequential solution brings in adding effect of the two actions on improving RBCN throughput and capacity, and the integrated solution is better than sequential solution. Specifically, there are three questions addressed: 1). is there any additional benefit from applying the other control action when the first has been applied in sequential application? 2). is one ordering of sequential application better than another? 3). is there any significant benefit if antenna tilting and DFFA work in integrated solution?

5.2.1 Working relationship of antenna tilting and dynamic frequency allocation

In practice, if the frequency allocation and antenna titling run in parallel, network reconfiguration will be computationally complex. For example, in DFFA algorithm, the channel grouping is based on utility calculation, which relates to $R_{i,j,b}^{super}$ and $R_{i,j,b}^{reg}$ $(\forall\, i \in M, \forall\, j \in C, \forall b \in B)$. Because $R_{i,j,b}^{super}$ and $R_{i,j,b}^{reg}$ are controlled by antenna tilting states: $\{\alpha_{s,b}, \beta_r\}(\forall b \in B, \forall s \leq S, \forall r \in R)$ defined in (4.6) and (4.7) of Chapter 4, if antenna tilting runs simultaneously with DFFA, an interaction occurs. Another example is in antenna tilting algorithm, the degree of overload (say $L_{s,b}$) in a sector is decided by channel allocation: $\{x_j^{super}, x_{j,b}^{s,reg}\}(\forall b \in B, \forall s \leq S, \forall j \in C)$ obtained by DFFA. Thus, interaction also occurs in antenna tilting if there is simultaneous DFFA running.

To sidestep the complexities of simultaneous running, antenna tilting and DFFA are made work sequentially or iteratively (integrated solution) here and then compared. In the sequential solution, DFFA and antenna tilting works in order: first run DFFA, then tilting or the other way around. In the integrated solution, there is no ordering, but DFFA and tilting are interweaving in smaller steps. Sequential solutions and the integrated solution are shown in Figure 5.4 and 5.5, and they are applied in BS failure and non-BS failure situations in RBCN.

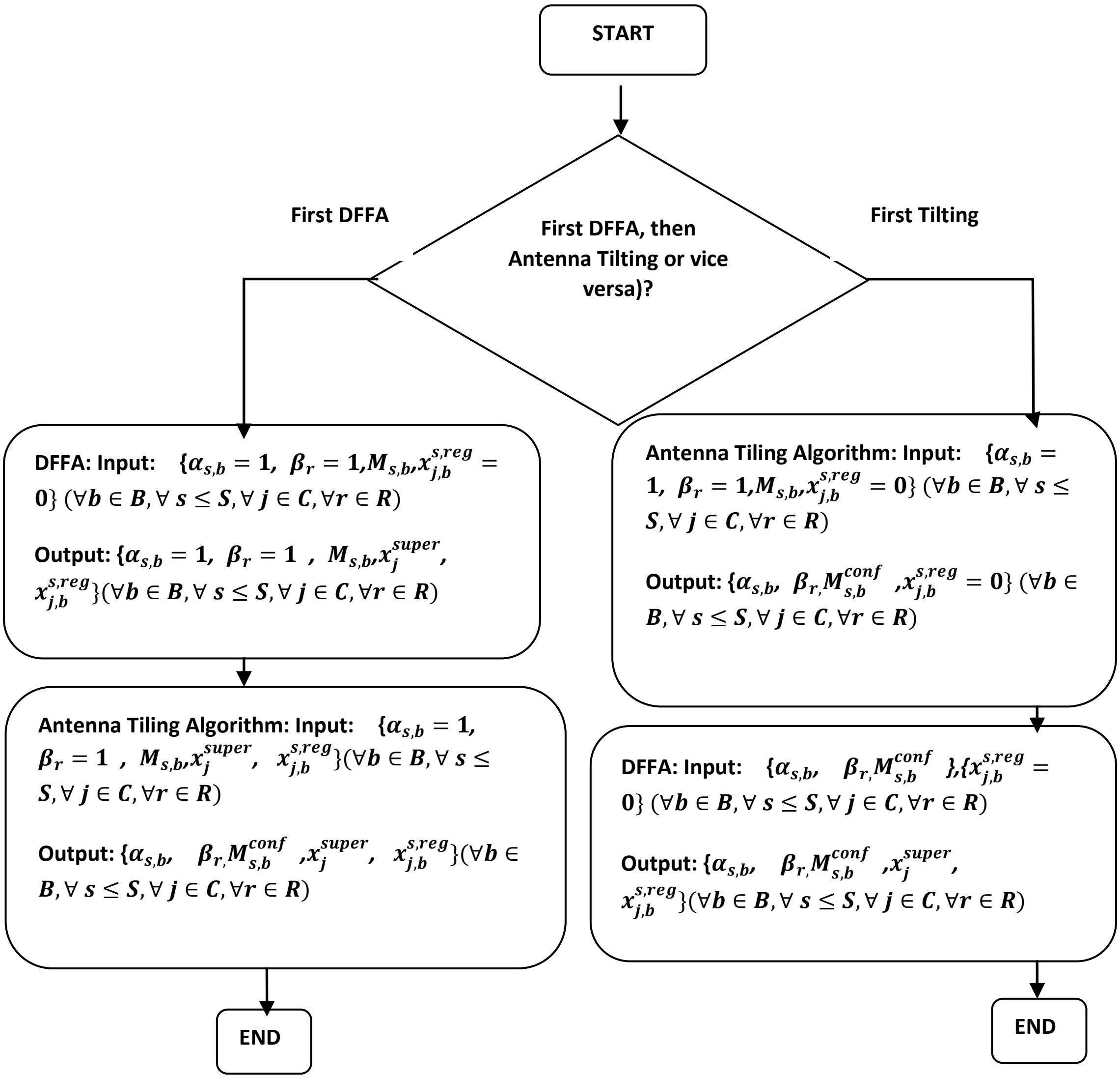


Figure.5.4 Sequential Solution

In the sequential approach, the order could affect the result. First DFFA then antenna tilting could be a better sequential solution. This is because heuristic antenna tilting in this thesis is highly sensitive to frequency allocation, thus carrying antenna tilting based on frequency allocation that is later changed, tilting could negate the benefits. Thus intuitively carrying out DFFA before tilting is a better option in the sequential solutions. This will be validated in simulation next.

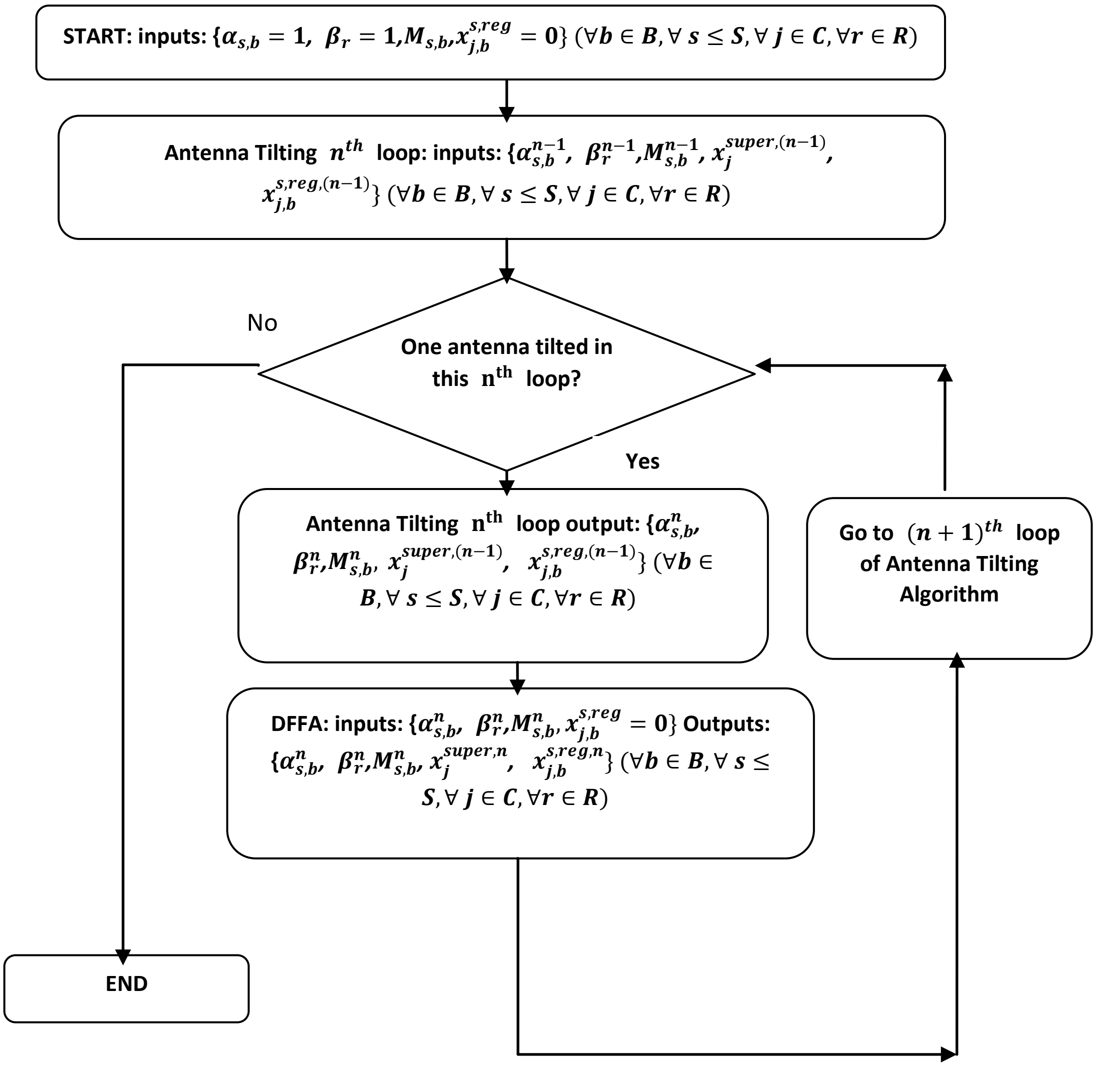


Figure.5.5 Integrated Solution

In order to avoid the possibly negative interactions in sequential solutions, integrated solution is now described. In integrated solution, iterative interweaving of smaller steps of DFFA and antenna tilting algorithm is realized. In Figure.5.5, DFFA is embedded into the previous antenna tilting algorithm. Specifically, if there is a period of antenna tilting, DFFA will be carried out right away before going into the next tilting loop. Take the n^{th} loop as an example. The n^{th} loop of the antenna tilting algorithm takes the output of $(n-1)^{th}$ loop: $\{\alpha_{s,b}^{n-1},\ \beta_r^{n-1}, M_{s,b}^{n-1}, x_j^{super\ ,(n-1)},\ \ x_{j\ ,b}^{s,reg\ ,(n-1)}\}$ $(\forall b \in B, \forall\ s \leq S, \forall\ j \in C, \forall r \in R)$ as input. $\{\alpha_{s,b}^{n-1},\ \beta_r^{n-1}, M_{s,b}^{n-1}\}$ $(\forall b \in B, \forall\ s \leq S, \forall r \in R)$ is the antenna tilting state obtained by the antenna tilting algorithm running in the $(n-1)^{th}$ loop. $\{\ x_j^{super\ ,(n-1)},\ \ x_{j\ ,b}^{s,reg\ ,(n-1)}\}$ $(\forall b \in B, \forall\ s \leq S)$is the frequency allocation obtained by DFFA running in the $(n-1)^{th}$ loop. In the n^{th} loop, if there is one antenna tilted,

$\{\alpha_{s,b}^{n-1},\ \beta_r^{n-1}, M_{s,b}^{n-1}\}$ $(\forall b \in B, \forall\, s \leq S, \forall r \in R)$is changed into $\{\alpha_{s,b}^{n},\ \beta_r^{n}, M_{s,b}^{n}\}(\forall b \in B, \forall\, s \leq S, \forall r \in R)$. Afterwards, DFFA is carried out taking$\{\alpha_{s,b}^{n}, \beta_r^{n}, M_{s,b}^{n}, x_{j,b}^{s,reg} = 0\}$ $(\forall b \in B, \forall\, s \leq S, \forall\, j \in C, \forall r \in R)$ as input to get $\{x_j^{super,n},\ \ x_{j,b}^{s,reg,n}\}$ $(\forall b \in B, \forall\, s \leq S, \forall\, j \in C, \forall r \in R)$. DFFA ignores the frequency allocation$\{x_j^{super,(n-1)}, x_{j,b}^{s,reg,(n-1)}\}$ $(\forall b \in B, \forall\, s \leq S)$ obtained in last loop, and starts from the default frequency allocation state$\{x_{j,b}^{s,reg} = 0\}$ $(\forall b \in B, \forall\, s \leq S)$. When DFFA finishes, $\{\alpha_{s,b}^{n}, \beta_r^{n}, M_{s,b}^{n}, x_j^{super,n},\ \ x_{j,b}^{s,reg,n}\}$ $(\forall b \in B, \forall\, s \leq S, \forall\, j \in C, \forall r \in R)$ is the final output of n^{th}loop, and the antenna tilting algorithm goes in to the next loop. The integrated solution finishes when there is no antenna tilting processed in the search loop

As shown in Figure 5.5, DFFA runs multiple times, and each DFFA running starts from the initial state without inheriting the output of last time of DFFA running. Thus, a drawback to the integrated solution is the relatively higher computing complexity. This will be investigated in simulation next.

5.2.2 Simulation

The simulation setting for integrated solutions is the same as DFFA simulation. The cases in evaluation are listed below. DFFA+Tilting and Tilting+DFFA belong to sequential solution.

- *DFFA+Tilting:* First perform DFFA, then antenna tilting
- *Tilting+DFFA:* First perfom antenna tilting, then DFFA
- *Integrated Solution*: DFFA and antenna titling performed iteratively

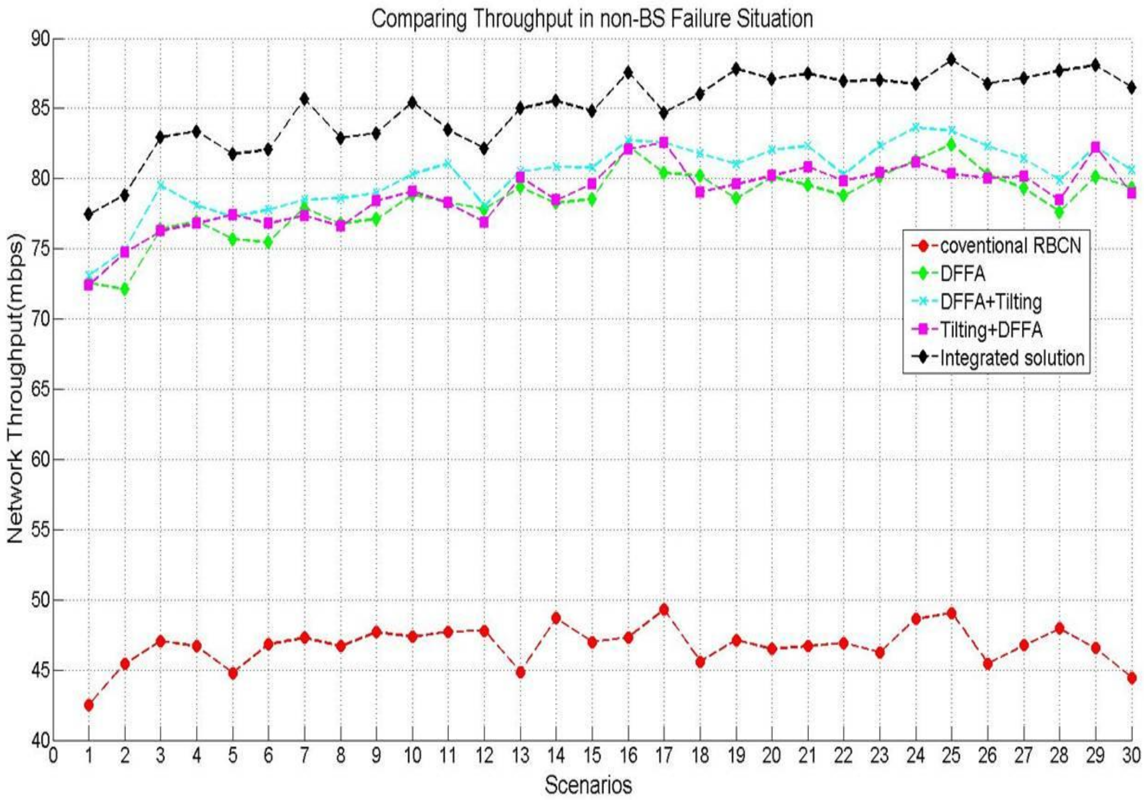


Figure 5.6 Comparison of algorithms in non-BS failure situation for the two large hotspot sequence of scenarios

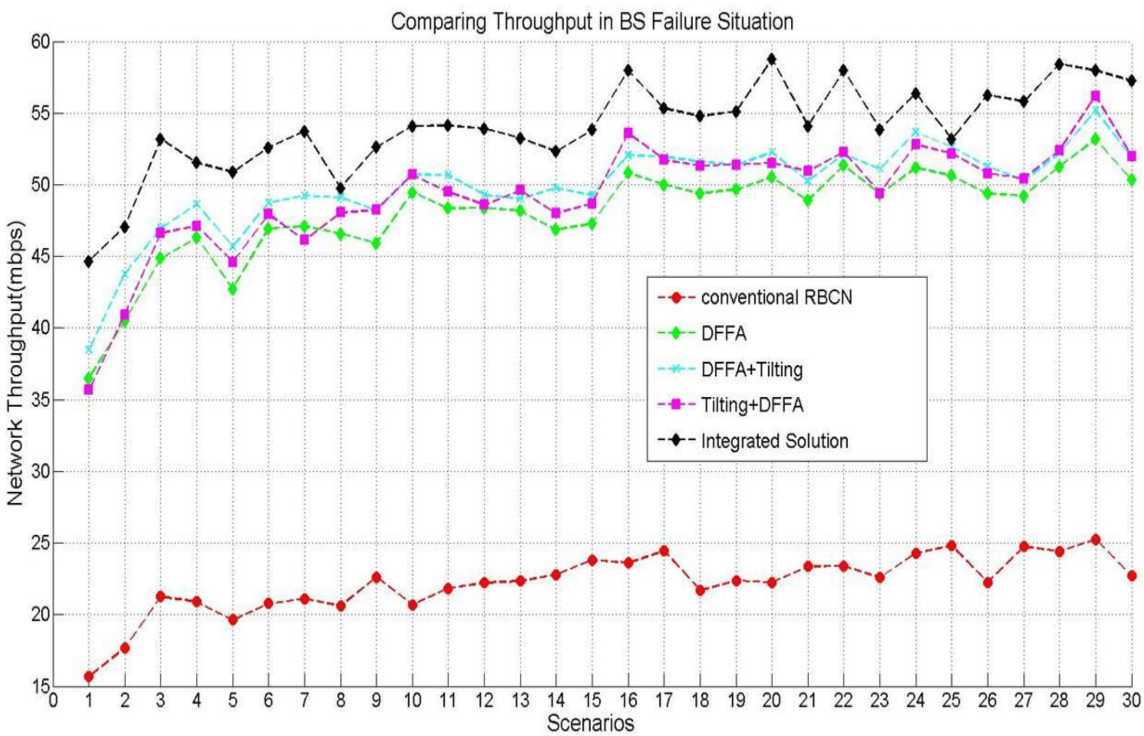


Figure 5.7 Comparison of algorithms in BS failure situation for the two large hotspot sequence of scenarios

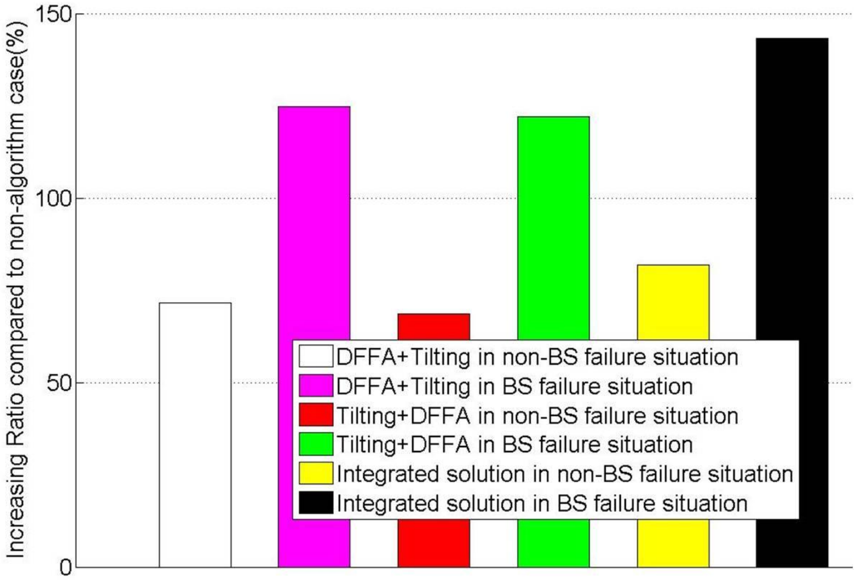


Figure 5.8 Throughput increasing effect of different solutions compared to conventional RBCN case in BS failure and non-BS failure situations

Figure 5.6, 5.7 and 5.8 show the effect of DFFA+Tilting, Tilting+DFFA and Integrated Solution compared to DFFA and conventional RBCN cases in the BS failure and non-BS failure situations. Figure 5.6 and 5.7 compare the network throughput led by different solutions in BS failure and non-BS failure situations. Figure 5.8 compares the throughput increasing effect of different solutions compared to non algorithm case. According to Figure 5.6 and 5.7, the sequential solutions only have a limited benefit when combined. DFFA+Tilting marginally increases network throughput compared to DFFA both in BS failure and non-BS failure situations. Obviously shown in Figure 5.8, Tilting+DFFA gives slightly lower network throughput increasing effect than DFFA+Tilting, both in the BS failure and non-BS failure situations. Thus DFFA+Tilting is a better sequential solution than Tilting+DFFA for this kind of scenario as would be expected. Compared to the sequential solutions, the Integrated Solution has better performance. The Integrated Solution always better improve RBCN throughput than DFFA+Tilting and Tilting+DFFA.

As discussed in before, a drawback of Integrated Solution is the high computing complexity. Figure.5.9 shows the running time comparison of different solutions. Obviously, Integrated Solution does cost much running time than sequential solutions. The Integrated Solution working in non-BS failure situation costs even higher time than working in BS failure situation. This is because when all BSs are functional in non-BS failure situation, the Integrated Solution has to spend more computation to consider antenna configuration and frequency allocation of every BS. In practice, the running time can be reduced considerably by fast local computations. Future work of this thesis will investigate better integrated Solution and distributed approach to decrease the complexity.

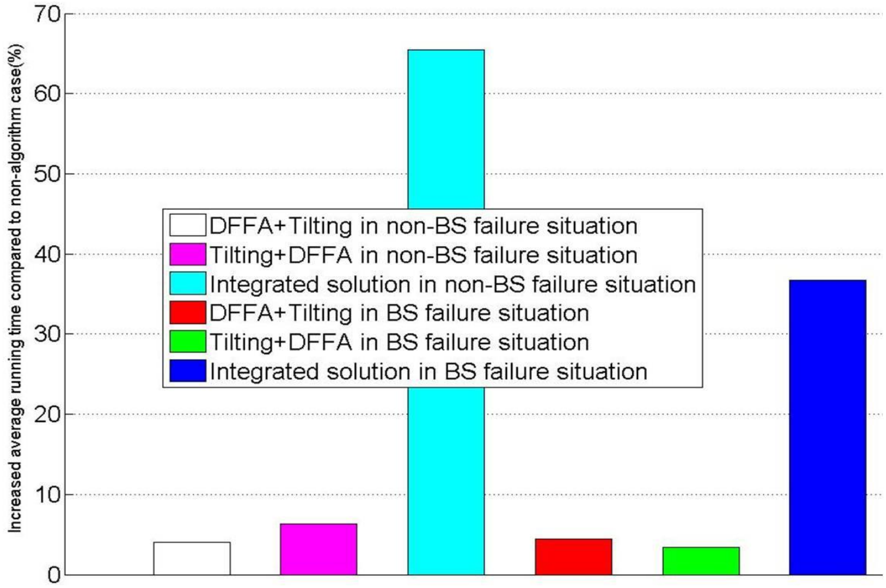


Figure.5.9 Increased average running time of different solutions compared to conventional RBCN case in BS failure and non-BS failure situations

5.3 Summary

This chapter designs a novel dynamic frequency allocation algorithm: Dynamic Fractional Frequency Allocation (DFFA) in RBCN. DFFA is based on Dynamic FFR and works in centralized way. Through simulation, it is shown that DFFA improves RBCN throughput better than Dynamic FFR. Afterwards, the co-working between DFFA and antenna tilting is investigated, in order to better reconfigure RBCN for higher throughput. The relationship between the two actions in the co-working is investigated. Through validation, it is proved that integrated solution where DFFA and antenna tilting working iteratively is better than simple sequential solution. However, the integrated solution causes a high computational complicity and is simple. Future work could investigate advanced integrated solutions that required low complexity and which give improved benefits.

Chapter 6 Distributed dynamic frequency allocation

To better design distributed and dynamic frequency allocation algorithms for high RBCN capacity and throughput, this chapter firstly designs a cell colouring based distributed frequency allocation (C-DFA) approach for cellular networks. C-DFA is applicable in all types of cellular networks. It leads to higher computational efficiency, and is simpler to realize compared to the traditional DFA algorithms in [53-56]. C-DFA utilizes a distributed planar graph colouring algorithm (DPGCA) [88] to colour cells. A key assumption made in this chapter is that the graph, where the BSs in the cells are the nodes and the adjacency of cells is represented by lines between nodes, is planar. The cell labelling can be done prior to the frequency allocation. Cells with the same colour can allocate frequencies simultaneously without causing influencing each other. The algorithm cycles around the colours. This simultaneous processing can improve DFA efficiency while not sacrificing DFA effectiveness.

Obviously, the innovation of this work is that C-DFA makes traditional DFA, which works in sequential cell processing, into a parallel cell processing that greatly improves the DFA efficiency. However, C-DFA still follows the traditional DFA methodology as the works in [53-56].This thesis has investigated the difference between distribution and parallelism. It is not a simple issue. This thesis keeps the use of the word distribution to refer to the autonomous processes working across the wireless networks, but it uses the word parallel to refer to fact that some are working concurrently, and this is synchronized by message between the BS (or the computational entity) in the cells.

Following C-DFA, DDFFA is deliberately designed for fractional frequency reuse RBCN. DDFFA turns Dynamic FFR into a distributed version. Compared to Dynamic FFR, DDFFA in RBCN not only adds the merits of a distributed approach, but also guarantees that different cells have different channel allocations, so leading to finer frequency allocations.

6.1 Cell colouring based DFA

Traditional DFA in [53-56] lets a single cell carry out frequency allocation alone while keeping frequency allocation of other cells state static. C-DFA in this thesis employs the same idea. However, because DFA carries out the frequency allocation one cell after another, it has low efficiency. C-DFA improves DFA efficiency by using cell colouring.

As discussed in [4-5], if two cells are out of interference distance of each other, frequency allocation in these two cells will have no mutual influence. Thus if non-influencing cells carry out frequency allocation simultaneously, DFA efficiency will be increased while not sacrificing DFA effectiveness. For example in Figure 6.1, cell *4,9,14,17* and *19* that are not in interference distance of each other can simultaneously run frequency allocation.

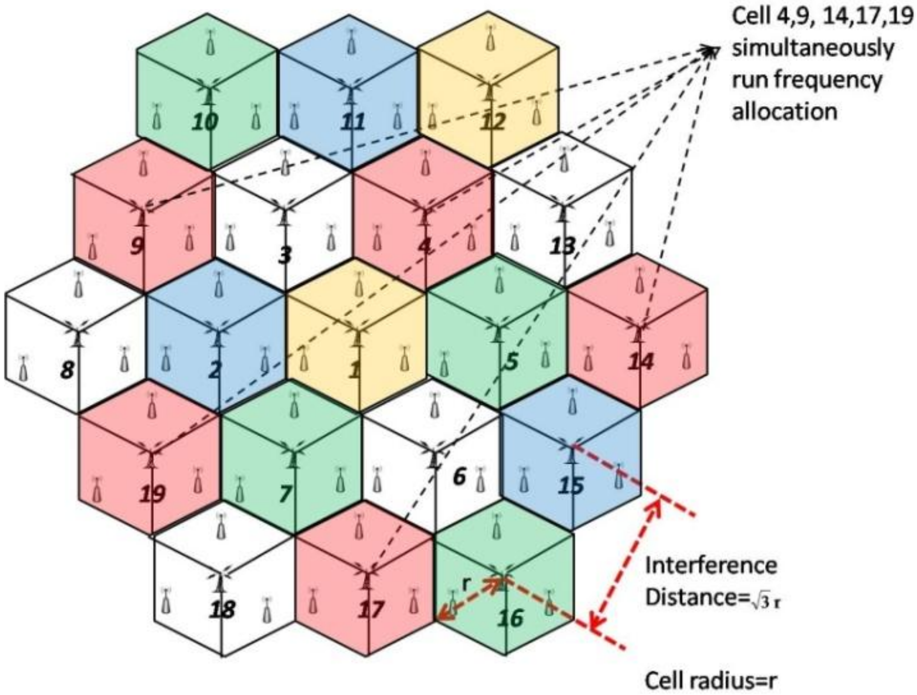


Figure.6.1 Simultaneous Frequency Allocation in C-DFA

Based on this phenomenon, C-DFA employs DPGCA to colour non-influenced cells into same colour. Afterwards, C-DFA lets cells of the same colour simultaneously carry out frequency allocation, and does not allow different coloured cells to run at the same time. For example in Figure 6.1, cell *4,9,14,17* and *19* in red can run frequency allocation simultaneously. At the same moment, cell *13* is in white and in the interference distance of cell *4* and *14*, so it cannot run frequency allocation. C-DFA works on one colour after another colour until frequency allocation becoming optimal (C-DFA converge) or C-DFA running out of allowed steps. Through this way, efficient DFA is realized by C-DFA.

This cell colouring based distributed approach was utilized previously in [89] but not for frequency allocation. In [89], distributed cooperative control for cellular networks to geographic load balancing was realized through the help of DPGCA in the context of semi-smart antennas.

Distributed planner graph colouring algorithm

C-DFA employs DPGCA. DPGCA is discussed in [88]. It colours node to let adjacent nodes not have same colour as shown in Figure 6.1. The procedure of DPGCA is shown in table 6.1. DPGCA turns a planer graph into directed acyclic graph (DAG) through a distributed DAG-generation algorithm and assigns colours to the DAG nodes. These two actions are run in parallel. One example of DAG is shown in Figure 6.2.

Table 6.1 Distributed Plannar Graph Colouring Algorithm

Input: $x[i] = \text{Integer}(\text{Random}(1,10))(\forall \text{i} \in \text{G})$; K; $OG_{max} = |K| - 1$;

Output: C[i] ; $(\forall i \in G)$

1. WHILE (*guard*[*i*]==*false*; (∃i ∈ G))
2.   WHILE (*guard*[*i*]==*false*)
3.   *guard[i]=true*;
4.   FOR *j*=1:length(*succ*[*i*])
5.   IF ($out[i] <= OG_{max}$)&&($C[i]==C[j]$)&& ($b \in (K - succolor[i])$)
                    {$C[i]=b$; *guard*[*i*]=*false;*}
6.   ELSE IF ($out[i] > OG_{max}$) {$x[i]$ =(*max setofx*[*i*])+1; *guard*[*i*]=*false;*}
7.   ENDIF
8.   END FOR
9.   END WHILE
10. END WHILE

The DAG can only have the number outgoing edges on a node and this is no more than a prescribed limit:OG_{max}. OG_{max} is set to be |*K*|-*1* in DPGCA, where K is all the number of colours chosen. In DAG, a node i has outgoing edge to *j* only if the condition:

$(x[i] < x[j])||((x[i]==x[j])\&\&(i<j))$ is satisfied. $x[i]$ is the reference value of node i that is integer values and assigned randomly between *1* to *10* in the beginning of DPGCA. During the running of DPGCA, each node is set to have a proper reference value. Thus the considered planer graph can be turned into a DAG. Because each node maximally has (|*K*|-*1*) outgoing edges, |*K*| colours are enough to colour cells without causing adjacent nodes having same colour in DPGCA. Therefore, if DAG of a planer graph is obtained, DPGCA will surely converge and get the wanted colouring: $C[i]$ ($\forall i \in G$, G is the set of all the nodes).

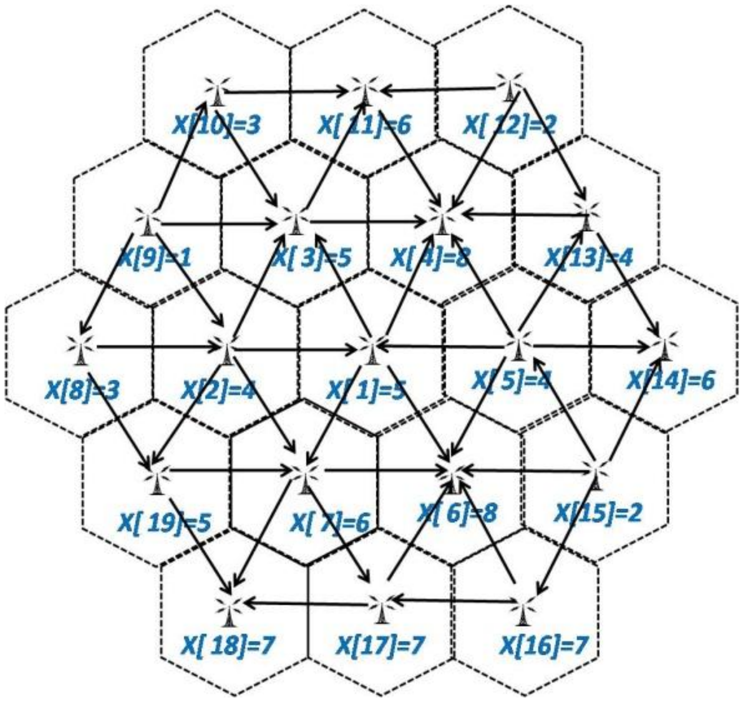


Figure 6.2 Cell nodes set to Directed Acyclic Graph with $OG_{max} = 5$

DPGCA will converge only if condition: (*guard*[i]==*true* ($\forall i \in G$)) is satisfied. *guard*[i] is Boolean and denotes whether node i satisfies the colouring requirements (*guard*[i]==*true*) or not (*guard*[i]==*false*). The requirements are: { $(out[i] <= OG_{max})\&\&(\sim\exists j \in succ[i] \rightarrow C[i] == C[j])$}. $out[i]$ is the number of outgoing edges of node *i*. $C[i]$ denotes the colour of a node *i*. $succ[i]$ denotes the set of nodes each of which is connected with an outgoing edge from node *i*. { $(out[i] <= OG_{max})\&\&(\sim\exists j \in succ[i] \rightarrow C[i] == C[j])$ } means node i should satisfy DAG condition, and no node in $succ[i]$ having the same colour as node *i*.

In order to satisfy (*guard*[i]==*true* ($\forall i \in G$)), DPGCA will run until convergence (step 1 to 10 of table 6.1). When running, DPGCA will check every node to test whether this node satisfies $\{ (out[i] <= OG_{max})\&\&(\sim\exists j \in succ[i] \rightarrow C[i] == C[j])\}$ or not. For example, for node i, if $(out[i] > OG_{max})$, that means node i does not satisfy DAG condition. $x[i]$ will be set to be ((*max setofx*$[i]$)+*1*) (step 6 of table 6.1). (*max setofx*$[i]$) denotes the maximal reference value within nodes in $succ[i]$. Through this setting, node i could have $(out[i] < OG_{max})$ so satisfy DAG condition. On the other hand, if $((out[i] <= OG_{max})\&\& (\exists j \in succ[i] \rightarrow C[i] == C[j]))$, node i will choose another colour b in $(K - succolor[i])$(step 5). $succolor[i]$ represents the set of colours of all the nodes in $succ[i]$. Because $|succolor[i]| < (|K| - 1)$, $(K - succolor[i])$ will never be empty. Thus node i will surely find a non-conflicting colour to the nodes in $succ[i]$. After processing each node in finite times, DPGCA will converge and obtain the wanted colouring.

In practice, the number of colours used in DPGCA: $|K|$ is adjustable. In [88], the authors proved that DPGCA will surely converge and get the wanted colouring if 6 or more than 6 colours are used, but DPGCA cannot guarantee converging when the colours are less than 6. If cellular network layout is simple, DPGCA will converge even if used colour is less than 6. However, the number of colours used in DPGCA cannot be less than 4 according to Four Colour Theorem.

Cell colouring based DFA approach

The procedure of C-DFA is shown table 6.2. After cell colouring by DPGCA, the frequency allocation algorithm is carried out iteratively. In one step, only one colour is considered and frequency allocation algorithm is simultaneously run to the cells in that colour. In next step, the frequency allocation algorithm moves to another colour in the set (cycling when at end) and works on the cells of that colour simultaneously. The frequency allocation algorithm moves from one colour to another colour step by step until no frequency allocation leads to network throughput increase any more (C-DFA converges) or C-DFA runs out of allowed iteration steps (T_{steps}). As discussed before, cells can independently make decisions in one session of frequency allocation in C-DFA. Thus DFA is increased in efficiency.

Table 6.2 The procedure of C-DFA

1.	Colour cells through DPGCA ;
2.	*Step*=0; *i*=1; //*i* is the colour index in *K*
3.	DO{
4.	Simultaneously Run frequency allocation (e.g. Channel Grouping or Channel Borrowing of DDFFA) for cells in colour *K* [*i*] ;
5.	*i=(i+1)%* $\lvert K \rvert$;
6.	$Step$= $Step$ +*1*;
7.	} WHILE (Network throughput increases)&&($Step$ <T_{steps})
8.	END

The number of colours in use affects C-DFA performance. Suppose there are $|K|(|K| \geq 4)$ colours in use and $|B|$ cells in networks, the number of cell running in parallel is $\frac{|B|}{|K|}$. The worse situation is that C-DFA cannot converge until C-DFA runs out of iteration steps (T_{steps}). There is a trade off between the number of colours and C-DFA iterations. Less colours in use leads to more cells running in parallel, so C-DFA running takes less time and saves BS-BS communication. On the other hand, more colours in use lead to cells in same colour being far away from each other, so there will be less mutual influence between the same coloured cells. Thus C-DFA could converge more readily. Additionally, more colours can make DPGCA converge more quickly to get a wanted cell colouring. In [89], this issue is analyzed. Simulation later will illustrate this point.

Like the works in [53-56], one limitation of C-DFA is BS-BS communication overhead. However, the BS-BS communication in C-DFA will not be more than traditional DFA and not hinder C-DFA application. If there are $|B|$ cells in cellular network, in one time of frequency allocation considering all the BSs once, there are only $|\mathrm{B}| \times 6$ times of BS-BS communications because each cell only considers its 6 neighbour cells. Another limitation of C-DFA is that its application is limited by interference distance. Because DPGCA can only guarantee adjacent cell having different colours, C-DFA is based on the assumption that the interference distance of two cells is $\sqrt{3}\mathrm{r}$ as shown in Figure. 6.1. Otherwise, two non-adjacent cells that have the same colour will have mutual influence to each other so C-DFA will not be applicable. For example in Figure.6.1, if the interference distance is $2\sqrt{3}\mathrm{r}$, part of the cells in red are in the interference distance of each other. Thus red cells cannot run frequency allocation simultaneously because of mutual influence. Future work needs to add more criteria on the selection of simultaneously running cells not only based on colours to relieve the interference distance limitation, but on geographic distance.

6.2 Distributed dynamic fractional frequency allocation

Based on C-DFA, DDFFA is deliberately designed to be a novel DFA algorithm in RBCN. Like DFFA discussed before, DDFFA is based on Dynamic FFR.

6.2.1 RBCN channels in DDFFA

In DDFFA, it is assumed that antenna power or tilting in RBCN is fixed in default value. RBCN works in RS non-transparent relay mode. RBCN employs 120° sector antenna. The radio propagation model in use is based on the model in (3.1) of Chapter 3. Because it is difficult to utilize the data rate based AC scheme in non-transparent relay RBCN, admission control scheme in RBCN employs STD scheme as discussed in Chapter 2.

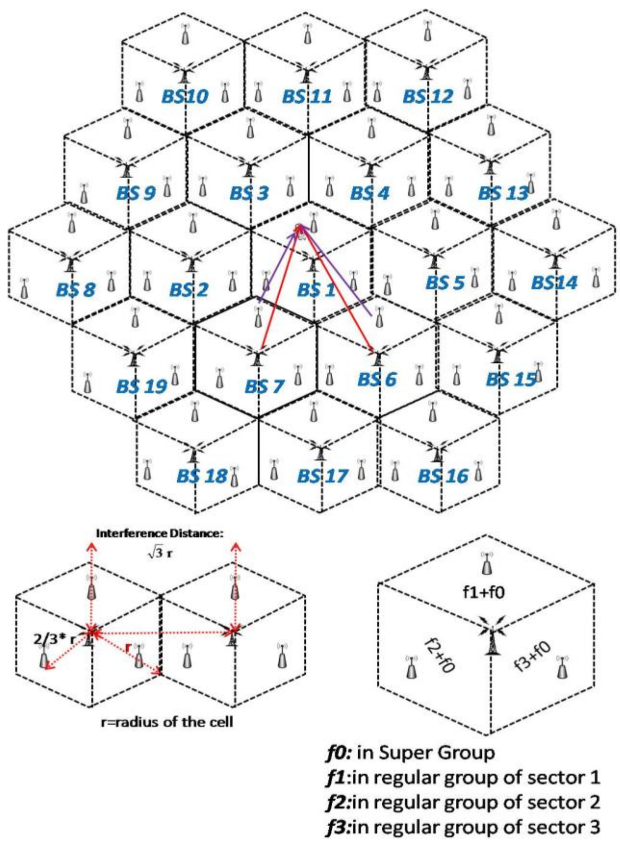


Figure 6.3 Dynamic Fractional Frequency Reused RBCN structure

RBCN channels considered in DDFFA are shown in Figure.6.3. In this figure, each cell in RBCN divides all the network available channels into a super group (*f0*) and 3 regular groups (*f1~f3*), and the 3 regular groups are allocated to 3 sectors to decrease CCI at the cell boundary. In a cell, a channel can only be uniquely attached into one group i.e. either super group or one of the 3 regular groups. The super group and 3 regular groups in a cell are different sets having different channels (*f0~f3* are different). The channels in the super group of a cell can be used by the MSs in all the 3 sectors. Channels in a regular group of a cell can only be used by the MSs in the sector that the regular group it is allocated in. Thus in each cell, MSs in a sector (say sector *i*) can use the channels either from the super group or the regular group of the sector *i* (*f0+fi*) according to scheduling.

Obviously, the channel grouping is identical to the model in the DFFA case. However, in DDFFA different from DFFA, the grouping of super group and regular groups in a cell is made independently by each cell. Thus each cell has different super grouped and regular grouped channels compared to others. This heterogeneous and distributed channel division leads to finer frequency allocation. In addition, this channel grouping will be further altered by distributed channel borrowing to be more suitable to non-uniform demand. This is explained later.

A MSs in a cell receives interference from its interfering cells *Q*. As discussed before, in order to support C-DFA, the cell interference distance is $\sqrt{3}r$ in this model, where r is the cell radius. Hence cells, whose BSs are more than $\sqrt{3}r$ distance away from the BS of considered cell, are assumed not to cause CCI to the MSs in the cell. For example in Figure.6.3, cell *8~19* will not cause CCI to the MSs in cell *1* because cell *8~19* have their BSs more than $\sqrt{3}r$ distance away from the BS of cell *1*. Depending on the allocated channel of a MS, the interfering cells to a MS are different. If a MS is allocated a channel from the super group of its cell, the interfering cells are all the cells within the interference distance. For example, a MS in cell *1* allocated a super group channel receives interference from BS cells: *2~7*. If a MS is allocated a channel from a regular group of one sector, the interfering sectors are only the ones among interfering cells that have the same regular group and direct adjacent to the covering cell of the MS. For example, MS in cell *1* having regular group channel of sector *1* only receives interference from BS cell *6* and *7*. In an interfering cell, both co-channel BS and RS will cause interference.

Like (5.1) and (5.2), channel grouping of DDFFA is formulated in (6.1) and (6.2). $x_{j,b}^{s,reg}$ is Boolean and represents whether channel j belongs to regular group of sector $s(x_{j,b}^{s,reg} = 1)$ or not $(x_{j,b}^{s,reg} = 0)$ in cell b. $x_{j,b}^{super}$ is Boolean and represents whether channel j is grouped to super group $(x_{j,b}^{super} = 1)$ or not $(x_{j,b}^{super} = 0)$ in cell b. C is all the channels. S is the total number of sectors in a cell (S =3 in this work). B is the set of all the cells. (6.1) and (6.2) show that in a cell of RBCN, one channel can only be grouped in the super group or only one regular group.

$$x_{j,b}^{super} + \sum_{s=1}^{S} x_{j,b}^{s,reg} = 1,\ (x_{j,b}^{super}) = \overline{\sum_{s=1}^{S} x_{j,b}^{s,reg}} (\forall\, b \in B, \forall\, j \in C) \tag{6.1}$$

$$\sum_{j \in C}(x_{j,b}^{super} + \sum_{s=1}^{S} x_{j,b}^{s,reg}) = C \quad (\forall\, b \in B) \tag{6.2}$$

DDFFA will carry out distributed channel borrowing after the channel grouping. Thus the channel grouping relationship shown in (6.1) and (6.2) will not be hold after distributed channel borrowing. Thus, $\{x_{j,b}^{s,reg}, x_{j,b}^{super}\}\ (\forall\, b \in B, \forall\, j \in C)$ is the input of distributed channel borrowing. This will be explained later.

Based on such channel grouping, in (6.3), it calculates the received data rate of MS i ($R_{i,j,b}$) provided by channel j in cell b when MS i directly connects to BS. In (6.3), $x_{i,j,b}^{super}$ represents whether MS i is allocated channel j from super group of cell b or not. $x_{i,j,b}^{s,reg}$ represents whether MS i is allocated channel j from regular group of sector s in cell b or not. $x_{i,j,b}^{super}$ and $x_{i,j,b}^{s,reg}$ are decided by the channel allocation led by DDFFA and cell scheduling. $R_{i,j,b}^{super}$ and $R_{i,j,b}^{reg}$ are the data rate of channel j offered to MS i when channel j is allocated to super group and regular group in cell b. $R_{i,j,b}^{super}$ and $R_{i,j,b}^{reg}$ are calculated through the data rate model discussed Chapter 3. (6.4) formulates the data rate obtained by MS i from channel j when MS i connects BS through two hops and is relayed by RS r in cell b. This data rate calculation follows formulation (3.8) in Chapter 3 that defines the data rate calculation in non-transparent relay model. In (6.4), $R_{r,j,b}$ represents data rate of BS-RS connection offered by channel j. In $R_{r,j,b}$ calculation, cell b takes RS r as a user, and the calculation follows (6.3). $R_{i,r}$ is the data rate of RS-MS connection which is decided by the condition of the reused channel selected by Smart Channel Selection scheme from adjacent cells. The calculation of $R_{i,r}$ also follows (6.3).

$$R_{i,j,b} = x_{i,j,b}^{super} R_{i,j,b}^{super} + \sum_{s=1}^{S}(x_{i,j,b}^{s,reg} R_{i,j,b}^{reg}) \tag{6.3}$$

$$\begin{cases} R_{i,j,b} = \frac{1}{\frac{1}{R_{r,j,b}}+\frac{1}{R_{i,r}}} = \frac{R_{r,j,b} \times R_{i,r}}{R_{r,j,b}+R_{i,r}} \\ R_{r,j,b} = x_{r,j,b}^{super} R_{r,j,b}^{super} + \sum_{s=1}^{S}(x_{r,j,b}^{s,reg} R_{r,j,b}^{reg}) \end{cases} \tag{6.4}$$

6.2.2 Distributed dynamic fractional frequency allocation algorithm

DDFFA follows C-DFA and augments Dynamic FFR to create a better distributed frequency allocation algorithm in RBCN. DDFFA includes two parts: Distributed Channel Grouping (DCG) and Distributed Channel Borrowing (DCB). DCG and DCB employ the distributed approach in C-DFA. The computation of the DDFFA algorithm is based on a model of the environment and the propagation environment created by the antenna. The actual frequency allocation is only performed after the DDFFA algorithm has been completed.

DDFFA first carries out DCG to group channels into either a super group or a regular group in each cell, then using DCB to adjust the channel grouping for finer frequency allocation grade and to handle extra channel requirements of non-transparent RS using Smart Channel Selection for RS-MS connection. Because DCB works out Smart Channel Selection for RS-MS connection later, DCG simply assumes that all the MSs directly connect to BSs in its computation, so the data rate calculation follows the one-hop case. Such an assumption simplifies DCG and will be seen not to negate the effect of DDFFA.

Distributed Channel Grouping

As discussed in previously, in C-DFA if every cell carries out DCG in step 4 of C-DFA, then distributed channel grouping is realized. DCG finishes when C-DFA finishes or network throughput cannot be improved further. Compared to Dynamic FFR, DCG lets different cell have different channel grouping. This is more applicable in practice than

Dynamic FFR when the user distribution in the network is non-uniform. The procedure of DCG in a cell (say b) is shown in table 6.3.

Table 6.3 Distributed Channel Grouping in a cell

Inputs: target cell b; $R_{i,j,b}^{super}$, $R_{i,j,b}^{reg}$ $(\forall\, i \in M_b, \forall\, j \in C)$; $\{x_{j,b}^{s,reg}, x_{j,b}^{super}\}(\forall\, j \in C, \forall\, s \leq S)$;

Outputs: Adjusted $\{x_{j,b}^{s,reg}, x_{j,b}^{super}\}(\forall\, j \in C, \forall\, s \leq S)$;

Initialization:$(\forall\, j \in C, \forall\, s \leq S)$, $W_j^{super} = \frac{\sum_{i\in M_b} R_{i,j,b}^{super}}{|M_b|}$; $W_j^{s,reg} = \frac{\sum_{i\in M_{s,b}} R_{i,j,b}^{reg}}{|M_{s,b}|}$; $C^s = \sum_{i=1}^{|M_{s,b}|} D$; g_b^s=0 ; $S' = \{\}$;

FOR j=1: C do:

IF $(x_{j,b}^{super} == 1)$ $(\forall\, s \leq S)$, $U_j^{s,reg} = W_j^{s,reg} - W_j^{super}$; END IF

IF $(\exists s^{\wedge} \leq S \rightarrow x_{j,b}^{s^{\wedge},reg} == 1)$, $U_j^{super} = W_j^{super} - W_j^{s^{\wedge},reg}$; END IF END FOR

FOR j=1: C DO:

1. FOR s=*1:S* do: IF ($C^s > g^s$) {put s in to S' };END IF END FOR;
2. IF ($S' == \{\}$){ $S' = S$;} END IF
3. IF $(x_{j,b}^{super} == 1)$
4. Find sector s^*, that satisfies $max_{(s',j)}(U_j^{s',reg})$ $(s' \in S')$;
5. IF $(U_j^{s^*,reg} > 0)$ $\{x_{j,b}^{s^*,reg} = 1;\ x_{j,b}^{super} = 0;\ g^{s^*} = g^{s^*} + W_j^{s^*,reg};\ \}$;
6. ELSE { $g^s = g^s + W_j^{super} \frac{|M_{s,b}|}{|M_b|}$; $(\forall\, s \leq S)$};
7. END IF
8. ELSE IF $(\exists s^{\wedge} \leq S \rightarrow x_{j,b}^{s^{\wedge},reg} == 1)$
9. IF ($U_j^{super} > 0$) $\{x_{j,b}^{s^{\wedge},reg} = 0;\ x_{j,b}^{super} = 1;\ g^s = g^s + W_j^{super} \frac{|M_{s,b}|}{|M_b|}; (\forall\, s \leq S)\}$
10. ELSE $\{g^{s^{\wedge}} = g^{s^{\wedge}} + W_j^{s^{\wedge},reg}\}$
11. END IF
12. END IF
13. Remove j from C;
14. END FOR

In table 6.3, when starting channel grouping in cell b, algorithm takes current channel allocation state of cell b as input:$\{x_{j,b}^{s,reg}, x_{j,b}^{super}\}(\forall\, j \in C, \forall\, s \leq S)$. Such channel allocation state is obtained from last time of DCG running in cell b. In the beginning, the group changing utility in each channel is calculated in cell b. For example of channel j, if channel j is in super group $(x_{j,b}^{super} == 1)$, $U_j^{s,reg}$ $(\forall\, s \leq S)$ is calculated. $U_j^{s,reg}$ is the utility of grouping(adding) channel j into the regular group of sector s. The utility calculation is based on a form of hypothetical reasoning. Specifically, considering all the users (M_b) and each set of users in different sector $M_{s,b}$ $(\forall\, s \leq S)$ in cell b ($M_b = \cup \sum_{s\leq S} M_{s,b}$, $M_{s,b}$ is all the MSs connecting to sector s of BS b or to the RS located in sector s of BS b), if channel j is changed from super group to regular group, the utility of changing group of channel *j* is defined to be the difference between the potential average data rate if channel *j* is allocated to regular group of sector s ($W_j^{s,reg}$) and the average data rate if channel *j* stays in super group (W_j^{super}). Similarly, if channel *j* is in regular group of sector $s^{\wedge}$ $(\text{i.e.} \exists s^{\wedge} \leq S \rightarrow x_{j,b}^{s^{\wedge},reg} == 1)$, then U_j^{super} is calculated. U_j^{super} is the utility of grouping channel *j* from regular group to super group.

Afterwards, based on group changing utility of each sector, the algorithm evaluates each channel to decide whether to change its group or not (step 1-14). Specifically for channel *j*, if ($x_{j,b}^{super}$ $== 1$) and the utility of grouping channel *j* to regular group of sector $s^*$is positive and maximal compared to other sectors ($U_j^{s^*,reg} = max_{(s',j)} \left(U_j^{s',reg} \right) (s' \leq S')$), channel *j* will be grouped into the regular group of sector s^*(step 5). Otherwise, channel *j* will remain in the super group (step 6). Alternatively, if ($\exists s^{\wedge} \leq S \rightarrow x_{j,b}^{s^{\wedge},reg} == 1$) and the utility of grouping channel *j* to super group (U_j^{super}) is positive, channel *j* will be grouped into super group (step 9). Otherwise, channel *j* will remain in regular group of sector $s^{\wedge}$(step 10). Channel grouping of cell *b* finishes when all the channels have been evaluated, and the adjusted $\{x_{j,b}^{s,reg}, x_{j,b}^{super}\}(\forall\, j \in C, \forall\, s \leq S)$ is the output.

Additionally, channel grouping considers sector fairness. If it is decided to allocate a channel from the super group into a regular group in cell *b*, the regular group of a sector whose available average data rate (g^s) is smaller than its data rate requirement: C^s is more likely. These sectors are put into S' to have priority (as step 4: the algorithm only considers the candidate sectors in S'). However, if there is no such sector, S' is set to be *S* so no sector is given priority. C^s of each sector is fixed if users always require same type of service and user distribution is fixed. g^s is updated each time of channel regrouping (say channel *j*) by W_j^{super} and $W_j^{s,reg}$.

Distributed Channel Borrowing

After DCG,$\{x_{j,b}^{s,reg}, x_{j,b}^{super}\}(\forall\, j \in C, \forall\, s \leq S, \forall\, b \in B)$ is the channel grouping state of all the cells in the network. Because DCG considering average data rate but does not consider the number of users in the utility based channel grouping,$\{x_{j,b}^{s,reg}, x_{j,b}^{super}\}(\forall\, j \in$

$C, \forall\, s \leq S, \forall\, b \in B$) is not applicable to the user congestion problem. This may lead to low RBCN throughput and capacity. In principle, channels should be allocated flexibly within sectors considering different user load. Thus, DCB is designed as the second part of DDFFA to further adjust $x_{j,b}^{s,reg}$ $(\forall\, j \in C, \forall\, s \leq S, \forall\, b \in B)$ in the context of different user loads. Because $x_{j,b}^{super}$ $(\forall\, j \in C, \forall\, b \in B)$ denotes the channels in the super group that have frequency reuse factor 1, $x_{j,b}^{super}$ $(\forall\, j \in C, \forall\, b \in B)$ is hard to adjust. Thus $x_{j,b}^{super}$ $(\forall\, j \in C, \forall\, b \in B)$ is not considered in DCB.

Additionally, because DCB considers extra channel requirement of non-transparent RS, which is not considered in DCG, $x_{j,r} (\forall\, r \in R, \forall\, j \in C)$ will be obtained by DCB as the channel allocation in each RS. $x_{j,r}$ is Boolean and denotes whether channel *j* is allocated to RS *r* or not. R is the set of all RSs. In summary, after DCB, the final $\{x_{j,b}^{s,reg}, x_{j,b}^{super}\}$ $(\forall\, j \in C, \forall\, s \leq S, \forall\, b \in B)$ and $x_{j,r} (\forall\, r \in R, \forall\, j \in C)$ are the output of DDFFA.

Like DCG, DCB distributes the channel borrowing algorithm in [45] into by employing C-DFA. Every cell carries out DCB in step 4 of C-DFA. The whole DCB procedure finishes when network throughput cannot be improved any more or DCB runs out of allowed C-DFA steps.

When performing channel borrowing in a cell, say cell *b*, a heavily loaded sector can borrow channels to satisfy its user requirement. A heavily loaded sector (say sector *k* of cell *b*: $S_{k,b}$) means this sector has more users: $|M_{k,b}|$ than the number of available channels: $\sum_{j \in C}(x_{j,b}^{super} + x_{j,b}^{k,reg})$. A heavily loaded $S_{k,b}$ firstly borrows the channels that are not locked in itself. Channel locking means that a channel can neither be used nor lent to other sectors by the sector that the channel is locked in. A channel is locked in $S_{k,b}$ only if this channel has been already allocated in one of the interfering sectors of $S_{k,b}$. Interfering sectors of $S_{k,b}$ include the adjacent sectors of sector *k* in cell *b* and the opposing sector of sector *k* in the neighbouring cell of cell *b*. Afterwards, $S_{k,b}$ borrows the locked channels from lending sector. The lending sector is the interfering sector of $S_{k,b}$ that has free channel to lend to sector *k*. If $S_{k,b}$ borrows any channel in those two steps, the borrowed channel is locked right away in interfering sectors of $S_{k,b}$ to eliminate CCI.

After finishing evaluating all the heavily loaded sectors in cell b, DCB considers RS in cell b (say RS r if existed). Based on Smart Channel Selection, RS r evaluates all the channels in C to selected satisfied channels. For example, RS r selects channel j if condition: $\left(\exists j \in C \rightarrow \left(SINR_{r,j} = max_{j \in C}(SINR_{r,j})\right)\right) \& (SINR_{r,j} > SINR_{threshod}))$ is satisfied. RS r finishes Smart Channel Selection when it finds enough channels for its users or all the available channels have been evaluated.

6.3 Simulation

The simulations consider two RBCN cases: 19 cells and 61 cells as shown in Figure 3.1 and 3.2 in Chapter 3. It employs 120° sector antenna and RSs work in non-transparent relay mode. The radio propagation mode is the mode discussed in (3.1) of Chapter 3. Admission control scheme in RBCN here employs STD scheme. In 19 cells case, it is assumed that users are highly congested. Alternatively, in the 61 cells case, users are lightly congested and there are less users in the network. There are 30 and 10 user distribution scenarios each in the two cases respectively. It is assumed that all the users are active during the whole simulation time and each user employs the Straight Walking Model with speed 10 km/h.

The simulations in this thesis consider 6,7,8 and 9 as the number of colours in DDFFA. These numbers of colours enable DPGCA to converge easily.

Evaluate DDFFA in 19 cells when users are highly congested

Figure 6.4 compares DDFFA to centralized Dynamic FFR in [52], DCG and conventional RBCN case. RBCN running in DCG means that there is no DCB in DDFFA. It is used to validate that channel borrowing does indeed augment channel grouping for finer frequency allocation. In addition, DDFFA running with cell colouring is also compared to DDFFA running without cell colouring. In the latter case this means there are no cells running in parallel.

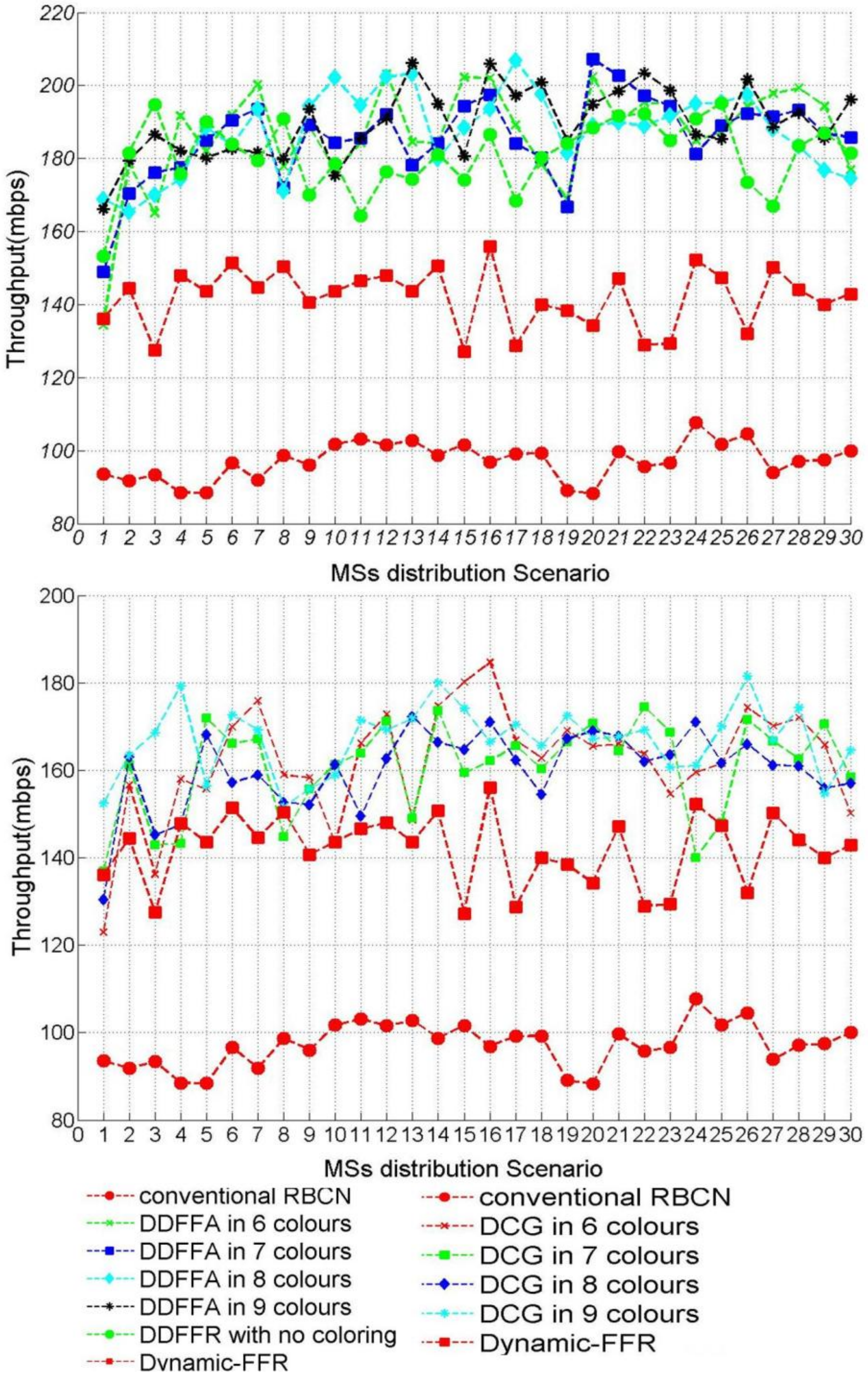


Figure 6.4 DDFFA compared to Centralized Dynamic FFR, DCG and conventional RBCN case in highly congested RBCN with 19 cells

As shown in Figure 6.4, DDFFA significantly improves the effect of frequency allocation compared to centralized Dynamic FFR, DCG and conventional RBCN case when using 6,7,8 and 9 colours. When DDFFA uses a different numbers of colours it has almost the same frequency allocation effect. Therefore, DDFFA is shown to be a better frequency allocation algorithm, and channel borrowing does indeed augment channel grouping to provide finer frequency allocation in DDFFA. In addition, DCG is obviously better than centralized Dynamic FFR in Figure 6.4. Thus DCG as a distributed channel grouping method that groups channels heterogeneously is seen to have better effect than Dynamic FFR, which uniformly groups channels.

In Figure 6.4, DDFFA with cell colouring has the same frequency allocation effect as DDFFA without cell colouring. This demonstrates that C-DFA approach does not decrease the effectiveness of DFA but has the benefit of letting the cells run frequency allocation in parallel.

In Figure.6.5, the DDFFA average running time using 6,7,8 and 9 colours are compared with respect to the 30 MSs distribution scenarios. The average running time of DDFFA with cell colouring is also compared to the average running time of DDFFA without cell colouring. According to the results, DDFFA using 6,7,8 and 9 colours significantly reduces running time compared to DDFFA without cell colouring. This shows that C-DFA approach does improve DFA efficiency.

As discussed before, the less colours used in DDFFA, the more cells can run frequency allocation in parallel and more save DDFFA running time. Thus as number of colours increases, DDFFA could cost more running time. This is indicates in Figure 6.5 where DDFFA with 6 colours (leading to at least $\left\lfloor \frac{|B|=19}{|K|=6} \right\rfloor = 3$ cells running in parallel) having the shortest running time, and DDFFA with 9 colours (leading to $\left\lfloor \frac{|B|=19}{|K|=9} \right\rfloor = 2$ cells running in parallel) having the longest time. However, there is a trade-off related to C-DFA iterations and number of colours as discussed before. In Figure 6.5, this trade-off is indicated by the result that DDFFA with 8 colours takes less time than 7 colour case. Because cells running in parallel are further away in the 8 colour case than in the 7 colour case, DDFFA with 8 colours is easier to converge and has less iterations. Therefore, DDFFA with 8 colours takes less running time than 7 colour case even through the latter case has more cells running in parallel.

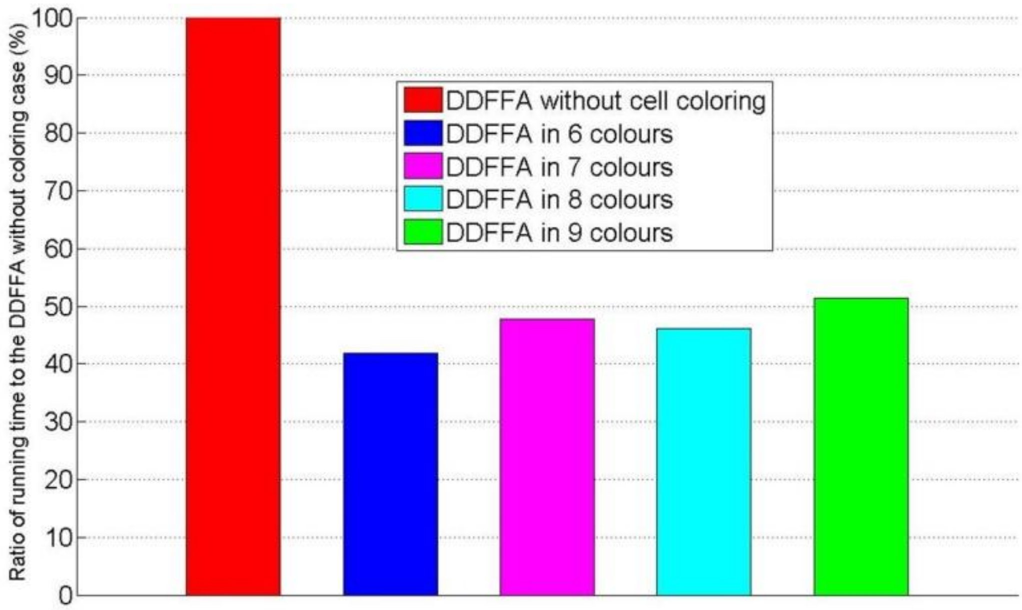


Figure.6.5 Ratio of average DDFFA running time using different number of colours to the DDFFA without cell colouring case in a highly congested RBCN with 19 cells

Evaluate DDFFA in 61 cells when users are less congested

Like the 19 cells case, Figure 6.6 compares DDFFA to centralized Dynamic FFR, DCG and conventional RBCN case in less congested RBCN and now with 61 cells. The effects of DDFFA with different number of colours and DDFFA without cell colouring are also compared.

Figure 6.6 shows the same results as in Figure 6.4. Thus, taken together, the scenarios demonstrates that DDFFA and C-DFA approach are better frequency allocation solutions both in local and large scale RBCNs when users can be highly or lightly congested. In Figure 6.6, the centralized Dynamic FFR has no effect for MSs distribution scenarios 3~9. This illustrates clearly the benefit of DDFFA and DCG over Dynamic FFR.

Like Figure 6.5, in Figure 6.7, the DDFFA average running time using 6,7,8 and 9 colours are compared for 10 MSs distribution scenarios in 61 cells RBCN. The average running time of DDFFA with cell colouring is also compared to the DDFFA without cell colouring case. Obviously, like the results in Figure 6.5, DDFFA with cell colouring significantly decreases running time compared to DDFFA without cell colouring in Figure 6.7. In addition, DDFFA using 7 colours has the shortest running time other than

6 colour case in Figure 6.7. This again illustrates the trade-off related to C-DFA iteration and number of colours.

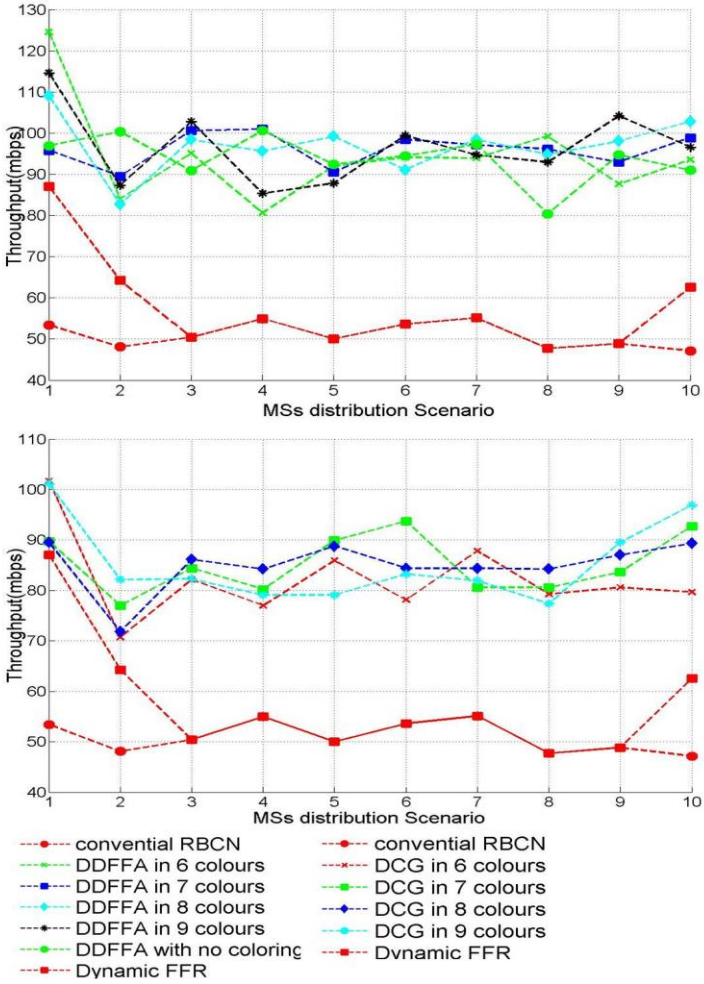


Figure 6.6 DDFFA compared to Centralized Dynamic FFR, DCG and conventional RBCN case in less congested RBCN with 61 cells

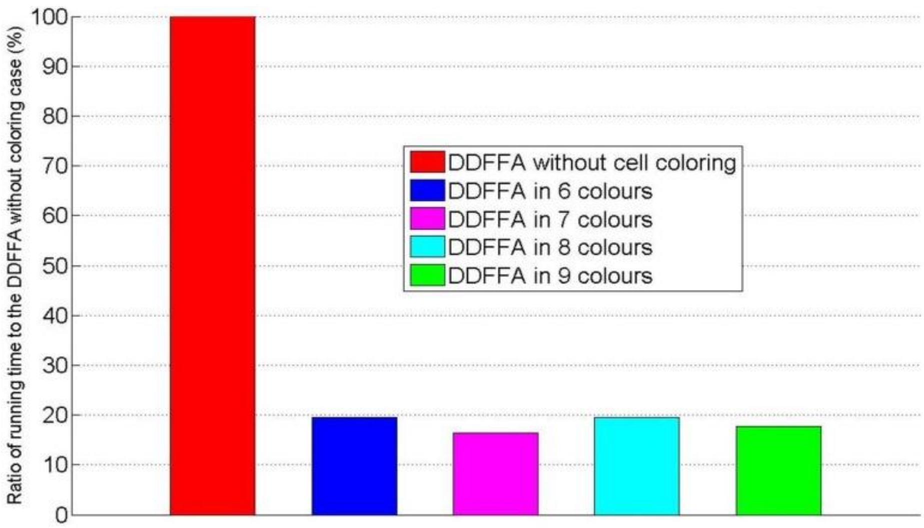


Figure 6.7 Ratio of average DDFFA running time using different number of colours to the DDFFA without cell colouring case in less congested RBCN with 61 cells

In summary, the simulations in this section indicates the potential of C-DFA and related DDFFA algorithms, showing that they have better frequency allocation effect and efficiency compared to Dynamic FFR in RBCN.

6.4 Summary

This chapter investigates Distributed Frequency Allocation solution that guarantees efficiency in cellular networks. The cell colouring based DFA (C-DFA) is designed as a novel solution. Based on C-DFA, a so called Distributed Dynamic Fractional Frequency Allocation (DDFFA) algorithm is designed specifically for RBCN. The simulation validates the effect and efficiency of DDFFA. However, C-DFA is limited by the cell interference distance premise. Future work will add more limitations on the selection of simultaneously running cells in C-DFA not only based on colours to relieve the interference distance limitation.

Chapter 7 Extending RBCN coverage in emergencies using DTN

This chapter considers a technique to support wireless communication in emergencies, when BS may fail or be saturated, by extending RBCN coverage through DTN. As discussed before, using DTN in RBCN can extend RBCN coverage into areas where antenna tilting (Chapter 4) or the integrated solution (Chapter 5) cannot reach. However, a DTN solution in RBCN depends on the distribution and capability of the MSs to transport using the DTN protocol and so it must be regards as limited solution. The DTN solution can work together with antenna tilting and integrated solutions in RBCN to mitigate the emergency problem.

This chapter is intended to develop the techniques for network reconfiguration into more extreme emergency situations than those considered in previous chapters. Here a BS or multiple BSs can fail. Whereas tilting and frequency allocation have been shown to perform very well, it is no longer adequate. Now methods other than discussed in Chapter 4-6 are necessary for filling the uncovered areas. Mobile devices that communicate using DTN concepts are used in this chapter to mitigate RBCN emergency problems. To guarantee DTN works with RBCN seamlessly, more technical issues are involved [63]. Additionally, how a DTN solution in emergency problem work with RBCN antenna reconfiguration and frequency allocation needs to be considered. However, this thesis only discusses augmenting DTN routing to improve a DTN solution on RBCN emergency problem.

This chapter augments DTN routing using geographic routing(as a bench mark) and Ant Colony Optimization (ACO) to improve MS to BS connection and load balancing. Three DTN routing protocols Epidemic, Binary Spray and Wait, and PRoPHET are augmented. Compared to the geographic method described, the ACO does not require MSs and BSs to provide their geographic location, which is more appropriate to the context. This work is validated in the Opportunistic Network Environment (ONE) simulator.

7.1 RBCN BS Failure Problem and DTN solution

As discussed before, in RBCN, an accident or a storm or a malicious action may cause a BS to fail, to tilt and so be unable to provide radio coverage. At the same time, RS radio coverage would fail if its uplink BS fails. The mitigation is to allow MSs in the hole in the coverage to self-organize to connect to each other or to functional BSs or RSs using delay tolerate connections. A simple example is displayed in Figure 7.1 where failure in BS *A* causes a radio coverage hole (the yellow area) and MSs in this hole lose connection to the BS. In this example, delay tolerate connections *a* and *b* are built for a MS connecting to functional BS *B*. In addition, two MSs can also talk to each other through delay tolerate connections without BS help.

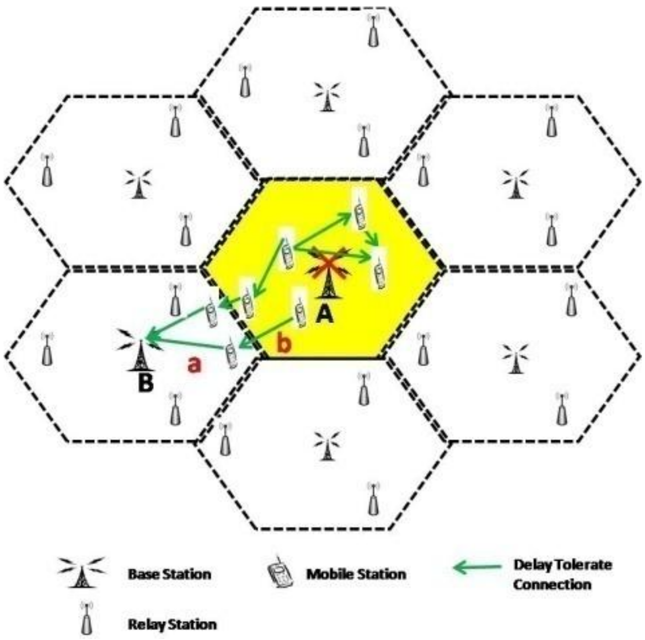


Figure 7.1 BS failure problem and DTN solution

As discussed in Chapter 2, DTN is a type of ad-hoc network designed to work in environments where connections may be intermittent and no end to end connection for any moment of time is needed. In any RBCN BS failure situation in this thesis, un-covered MSs in coverage hole may be moving, short of power supply and even sparsely distribute. Therefore, DTN as a pragmatic solution is suitable to support MS to BS communication in such RBCN BS failure situation. In practice, the DTN solution can only use a limited form of communication, like "walkie talkie", and store and forward message switching mechanism.

This thesis investigates a DTN solution based on the assumption that the RBCN BSs can communicate to DTN augmented MSs. The bundle protocol discussed in Chapter 2 supports such applications that cross two network technologies. This thesis focuses on augmenting DTN routing to better extend RBCN coverage, the bundle issue is not considered. More on bundle issue can be found in [61-63].

7.2 DTN Routing

As discussed in Chapter 2, DTN routing imposes a new routing model, which consists a sequence of independent, local forwarding decisions, based on current connectivity information and predictions of future connectivity information. In each node, a forwarding decision should ideally bring the node carrying packet "closer" to the destination. High message delivery rate, routing efficiency, self-configuration and low delivery delays are the most important routing metrics. Routing efficiency criteria include energy-efficiency and fewer transmissions. The work of this chapter augments three representative DTN routing protocols: Epidemic, Binary Spray and Wait, and Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) discussed below.

Epidemic

Epidemic scheme is: The source node, which has *N* neighbour nodes, sends *N* copies of a message, one to each of its *N* neighbour nodes. Afterwards, each neighbour node checks (by comparing a hash) whether the received message copy has been received previously. If it has, the neighbour node discards the message copy, otherwise the neighbour node will keep this message copy and send the same copy to all its neighbour nodes just as the source node did.

Binary Spray and Wait (BSW)

In BSW [70], there are two phases:

a. Binary Spray phase: The source node of a message initially starts with *L* copies of this message. Any node *A* that has $n > 1$n > 1 n > 1message copies (source or relayed) , when it encounters another node *B* with no copies, it hands over to *B* $\lfloor n/2 \rfloor$ ⌊n/2⌋n > 1n > 1n > 1copies and keeps $\lceil n/2 \rceil$⌈n/2⌉ copies for itself; when *A* is left with only one copy, it switches to direct transmission, i.e. a node carrying one message copy will forward this message copy to another MS it encounters only if this MS is the message's destination.

b. Wait phase: Each of the nodes carrying one message copy performs direct transmission. There will be *L* nodes each carrying one message, because the Binary Spray phase runs time until there is no node holding more than 1 message copy. The *L* message copies sprays to *L* nodes.

PRoPHET

PRoPHET [73] determines the delivery predictabilities in each node. The node *M* stores delivery predictabilities $P(M, D)$ for each known destination *D*. If the node has not stored a predictability value for a destination, $P(M, D)$ is assumed to be zero. The delivery predictabilities used by each node are recalculated at each opportunistic encounter according to three rules:

1) When the node *M* encounters another node *E*, the predictability for *E* is increased: $P(M, E)_{new} = P(M, E)_{old} + (1 - P(M, E)_{old}) \times L_{encounter}$,where $L_{encounter}$ is an initialized constant.

2) The predictabilities for all destinations *D* other than *E* are 'aged': $P(M, D)_{new} = P(M, D)_{old} \times r^k$, where *r* is the aging constant and *k* is the number of time units that has elapsed since the last aging.

3) Predictabilities are exchanged between *M* and *E* and the 'transitive' property of predictability is used to update the predictability of destinations *D* for which *E* has a value on the assumption that *M* is likely to meet *E* again: $P(M, D)_{new} = P(M, D)_{old} + (1 - P(D, M)_{old}) \times P(M, E) \times P(E, D) \times \beta$
, where β is a scaling constant.

Epidemic floods message copies to every neighbour host to maximally increase message delivery rate. However, Epidemic wastes a lot of energy and suffers from severe contention, and hence has quite a low routing efficiency. If network traffic is high, Epidemic routing may have a high delivery delay. Binary Spray and Wait (BSW) augments Epidemic to efficiently forward message copies to neighbour nodes. BSW acquires a good balance on high message delivery rate and routing efficiency, and supports lower delivery delay. Different from Epidemic and BSW, PRoPHET predicts delivery probability using historical node connection information, and makes forwarding decisions accordingly. PRoPHET should have quite high routing efficiency, but it supports lower message delivery rate than Epidemic and BSW because it predicts connection stability roughly.

7.3 Augmenting DTN Routing Protocols using Geographic Routing Methods

In RBCN BS failure situation, if a BS fails, affected MSs would quickly connect to functional BSs to communicate with the outside world. However, traditional DTN routing protocols normally make local forward decisions either randomly or based on delivery probability prediction, and so cannot guarantee routing MSs to BSs quickly and efficiently. Additionally, traditional DTN routing does not consider load balancing, so MSs cannot be purposely routed to lighter loaded BSs. Geographic DTN routing is ostensibly better suited these problems and hence improve RBCN to DTN cooperation. As will be shown, geographic routing can realize load balancing, higher MS to BS message delivery rate, and higher routing efficiency compared to traditional DTN routing.

Specifically, geographic DTN routing is based on MS to BS cooperation. BSs, which know their location, broadcast information like location and capacity to MSs using one of the above mentioned routing protocols. The information issued by BSs is tiny and so has a small effect on DTN routing efficiency. MSs utilize this information to find the optimal BS, which may be the closest one, or the lightest loaded one. This depends on the selection criteria employed. Three criteria are used. Afterwards, based on the optimal BS, MS selects preferred connections through (7.1). These preferred connections are then used in message forwarding. For example, in the geographic Epidemic routing protocol and geographic BSW, after connection selection, MSs only floods message copies through the preferred connections. In geographic PRoPHET, the MS only predicts delivery probability within the preferred connections. In geographic routing the locations of the MSs is assumed known. While this is arguably unrealistic, it provides a benchmark by which the other techniques described can be gauged.

$$\begin{cases} t_{op} = tan^{-1}\frac{(S.y-p_{op}.y)}{(S.x-p_{op}.x)} \\ t_{to} = tan^{-1}\frac{(S.y-T.y)}{(S.x-T.x)} \\ C = \begin{cases} 1 \ (abs(t_{op}-t_{to}) \leq \theta) \\ 0 \ (abs(t_{op}-t_{to}) > \theta) \end{cases} \end{cases} \tag{7.1}$$

In (7.1), t_{op} is the direction from BS_{op} , with coordinate p_{op}, to MS S. t_{to} is the direction of connection $S \rightarrow T$. θ is the range threshold which is chosen as 60^0 . If t_{op} and t_{to} surely are in range, so connection $S \rightarrow T$ is selected ($C = 1$), verse visa.

There are three BS selection criteria in geographic DTN routing. These are MS density, hop count and BS capacity. Employing MS density and hop count, geographic DTN routing can mainly increase MS to BS message delivery rate. Employing BS capacity, routing mainly improves BS load balancing. In this work, firstly, utility based on MS density and hop count are used to select a BS. This should increase MS to BS message delivery rate, and improve routing efficiency. Secondly, utility function based on a wider range of factors is used to select BS. The utility is based on BS capacity, MS density and hop count. This utility approach should simultaneously support high MS to BS message delivery rate, high load balancing, and high routing efficiency.

Utility Based on MS Density and Hop count

In DTN, connections are more likely if MS density is high and the MSs are mobile. Thus if the geographic DTN routing protocol routes a MS close to a BS through a high MS density route, more MSs could connect to BS. Meanwhile, routing efficiency could be improved because a message or its copy is only forwarded along selected routes rather than broadcast.

Specifically, suppose information regarding BS k is represented as $\{p_k, d_k, h_k, t_k\}$ and is received by a MS. p_k is the coordinates of BS k and d_k is the MS density of the route, through which $\{p_k, d_k, h_k, t_k\}$ has traversed from BS k to a MS. h_k is the number of hops $\{p_k, d_k, h_k, t_k\}$ has taken from BS k to the receiving MS and is initially 0. t_k is the BS message generation time. Each MS may receive such BS messages multiple times and from multiple BSs. Afterwards, a MS chooses the BS offering the largest utility U defined in (7.2), as optimal BSBS_{op}.

$$\begin{cases} h_{min} = 1 \\ t_{latest} = max(t_k) \\ d_{max} = max(d_k) \\ U_k = \left(\alpha \times \frac{h_{min}}{h_k} + \beta \times \frac{d_k}{d_{max}}\right) \times (\frac{t_k}{t_{latest}})^{\gamma} \\ BS_{op} = arg_k(maxU_k) \end{cases} \tag{7.2}$$

In (7.2), t_{latest} is the time the MS received the newest BS information. d_{max} is the maximum MS density. α is the weight of MS density. β the weight of hop count, and γ is the weight of recency in utility U_k.

To calculate d_k, there are two ways: maxi-min and maximum average. In the maxi-min way, d_k should be updated in each hop of $\{p_k, d_k, h_k, t_k\}$ forwarding. Specifically, in one hop, MS density d^j of hop j is calculated through (7.3). Then if d_k is bigger than d^j , d_k is updated to be d^j . d_k updating carries on until $\{p_k, d_k, h_k, t_k\}$ arrives at the MS in question, thus MS can know the MS density of the coming route is d_k. In maximum average method, the difference is that MS density like d^j of hop j is recorded in each hop, when $\{p_k, d_k, h_k, t_k\}$ arrives MS, the average of the recorded MS densities is taken as d_k .

$$
\begin{cases}
d^j = \sum_{T=T_1}^{T_n} C_{S\to T} \\
C_{S\to T} = \begin{cases} 1 \ \left(abs\left(t_{op} - t_{to}\right) \le \theta\right) \\ 0 \left(abs\left(t_{op} - t_{to}\right) > \theta\right) \end{cases} \\
t_{to} = tan^{-1} \frac{(S.y - T.y)}{(Sx - T.x)} \\
t_{op} = tan^{-1} \frac{(S.y - D.y)}{(Sx - D.x)}
\end{cases} \quad (7.3)
$$

In (7.3), S is the source node of hop j. D is the end node of hop j. Thus hop j of this BS information forwarding is through connection $S \to D$. T is the node which is close to D and connects to S. Thus if T is in the same direction of connection $S \to D$, T increase density of hop j. T is one of the nodes $\{T_1 \dots T_n\}$which have connections to S. To judge whether T is in direction of connection $S \to D$ or not, t_{op} is direction of connection $S \to D$. t_{to} is the direction of connection $S \to T$. θ is the range threshold which is 60^0. If t_{op} and t_{to} are in range, so T is in the same direction of connection $S \to D$ and increases MS density of hop j, and vice versa. After judging all the nodes in $\{T_1 \dots T_n\}$, the density of hop j is calculated.

Utility Based on BS Load, MS Density and Hop count

BS selection can be based on a different utility functions that include more factors, such as density, BS load, hop count of BS information forwarding message and recency of BS information, to simultaneously support high MS to BS message delivery rate and high load balancing

The k information provided by BS is represented as $\{p_k, d_k, h_k, l_k, t_k\}$. Definitions of p_k, h_k, $d_k$and $t_k$are the same as before. l_k is the load situation(number of loaded users) of the source BS. A MS calculates the utility for choosing from each detected BS based on (7.4).

$$
\begin{cases}
l_{max} = max(l_k) \\
h_{min} = 1 \\
t_{latest} = max(t_k) \\
d_{max} = max(d_k) \\
U_k = \left(\alpha \times \frac{l_k}{l_{max}} + \beta \times \frac{h_{min}}{h_k} + \gamma \times \frac{d_k}{d_{max}}\right) \times \left(\frac{t_k}{t_{latest}}\right)^{\delta} \\
BS_{op} = arg_k(maxU_k)
\end{cases} \quad (7.4)
$$

7.4 Augmenting DTN routing using Ant Colony Optimization

ACO imitates ant behaviours in a colony to solve engineering problems like networking or city traffic management. In an ant colony, ants can communicate indirectly with each other by leaving and smelling pheromones. The communication can let each ant know where the food source is and which is the shortest and un-crowed way leading to there. Thus, even through a single ant has a low intelligence, a large number of ants together can behave efficiently and intelligently. An example is shown in Figure 7.2,

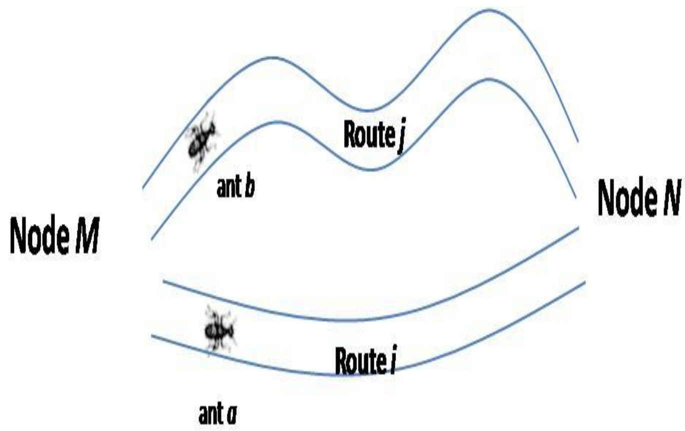


Figure 7.2 Example of ant communication

In Figure 7.2, assuming ant *a* and ant *b* each goes through route *i* and *j* from node *M* to food source node *N*. Route *i* is shorter than route *j*, thus ant *a* first arrive at node *N*. When return, ant *a* knows route *i* is shorter so choose route *i* to go back, because ant *b* has not arrived, so there is no pheromone on route *j* and route *i* has the pheromone lift by ant *a* before. When return, ant *a* enforce pheromone of route *i* again. After ant *b* arrive at node *N*, ant *b* will also choose route *i* to return, because route *i* has double pheromone than route *j*. As a result, route *i* will always has strong pheromone than route *j*, so ants always choose route *i* to node *N* other than route *j*. More about ACO can be found in [90].

ACO can be utilized in DTN routing. One simple way is to treat the messages like ants. The messages update the Enforcement Value (EV) of its passed node in the forwarding process. The updating is time based. EV is used to guide messages back to the destinations. To solve the BS failure problem through ACO, a BS imitates as an ant nest which always has the strongest EV (cf pheromones). The BS information messages are like an ant. A BS having high capacity (cf a prosperous ant nest) has information (cf strong ant) that can leave higher EV to the nodes on the route it travels. Information from different BSs only changes the EV for its source BS. When a MS tries to connect to a BS, DTN routing chooses the connection of a MS that has the highest EV. In this way DTN routing can route MS to light loaded BSs through the routes which can guarantee high message delivery rate.

In order to let the EV guide DTN routing in the BS failure case, pheromone evaporation, aging, limiting and smoothing are used. These methods are used to prevent some routes dominating and suppressing other routes. This is called pheromone control.

- Evaporation

Evaporation means the EV will decrease according to time elapsed. This guarantees recency to EVs. At a node, at the each time of each node update, the EV of BS i: E_i will decrease to $E_i \times (\frac{t_{current}}{t_{last-enforce}})^{\gamma}$ if there is no information from BS *i* to reinforce it.

- Aging

Aging means the BS information increases EV of a more recently encountered node more than a later encountered node. Thus, the node far away from the BS has lower possibility to help routing a MS to this BS.

- Limiting and smoothing

Limiting means the EV of a node cannot increase without limit even through a lot of BS information comes to it. This efficiently avoids node domination. Another technique to avoid node domination is smoothing. Specifically, if an EV of a node is close to its limit, the new BS information can only increase it by a smaller degree compared with what it would do if the node had a low EV. In a node receiving BS information from BS i, E_i is enforced to $E_i^{'}$ according to $E_i^{'} \leftarrow E_i + \propto \times (E_{max} - E_i)$, where $\propto$ is the enforcement coordinator.

7.5 Simulation

The work is validated through simulations using the Opportunistic Networks Evaluation

(ONE) simulator. As introduced in Chapter 2, ONE simulator is an open source simulator developed in the department of communications and networking of Helsinki University of Technology.

The scenario in use simulates accident happening in campus of Queen Mary University of London (QMUL). This is shown in Figure 7.3. The simulation parameters are listed in table 3.3 of Chapter3. Specifically, influenced by the accident, each working BS is antenna function limited, thus only has 150m radio coverage and 10mBps transmit speed. The buffer size of a BS is 200M. There are 3 working BSs in the area of QMUL, and suppose 1 BS fails. The BS distribution is shown in Figure 7.4. The green circle in Figure 7.4 is the coverage of functional BSs. The BS with red crosses is the failed one.

Figure 7.3 Map of Queen Mary University of London

Figure 7.4 Scenario showing paths traversed in the campus and the BS failure location

In the simulation, there are 100 MSs. Each MS employs a shortest path map based movement model. In this movement model, MSs choose a random point on the map and then follow the shortest route to that point from their current location. A MS speed ranges from 10~50 KM/hour, and the specific speed of each MS is randomly sampled. A MS waits 0~120 seconds between two times of movement. The specific waiting time is randomly decided. Regarding communication activity, a MS attempts to communicate to a BS every 30 to 60 seconds. The MS for communication is randomly chosen. Each MS has 10m radio coverage and 250kBps transmission speed. The simulation employs a large MS radio coverage, because this can make intermittent connection happen frequently and comparisons are available more quickly. The buffer size of a MS is 10M. All MSs are initially randomly distributed in the whole area of QMUL. DTN messages have 500Kb~1Mb size and 300 second life time. Network running time is simulated to be 6 hours.

MS to BS message delivery rate (MDR), cell load balancing, routing overhead ratio (ROR) and message delivery delay (MDD) are four criteria used to evaluate augmented DTN routing protocols. To evaluate cell load balancing, average BS load difference (ALD) is used. BS load difference means the difference between the load for a particular BS to the average load of the 3 working BSs. Thus, the lower ALD is, the better cell load balancing is. In order to compare augmented DTN protocols comprehensively, a performance function P is defined in (7.5). In (7.5), MS to BS message delivery rate has higher weight to the total performance than load balancing, routing overhead ratio and message delivery rate. The simulation results for the augmented Epidemic, Binary Spray and Wait and PRoPHET DTN routing protocols are show below.

$$\begin{cases} P_i = 0.4 \times \left(\frac{MDR_i}{MDR_{max}}\right) + 0.3 \times \left(1 - \frac{ALD_i}{ALD_{max}}\right) \\ +0.2 \times \left(1 - \frac{ROR_i}{ROR_{max}}\right) + 0.1 \times \left(1 - \frac{MDD_i}{MDD_{max}}\right) \\ ROR_{max} = max(ROR_i) \\ MDR_{max} = max(MDR_i) \\ ALD_{max} = max(ALD_i) \\ MDD_{max} = max(MDD_i) \end{cases} \tag{7.5}$$

In this simulation, utility is defined using the limited definition in (7.2). MS density calculation employs the max-min method. The weights of MS density, hop count and recency are 0.5, 0.5 and 1 in (7.2). Figure 7.5 shows the performance of traditional and augmented Epidemic, BSW and PRoPHET protocols. From Figure 7.5, it can be seen that MS to BS message delivery rate (MDR), routing overhead ratio (ROR) i.e. routing efficiency are improved. However, load balancing (ALD) is worse in augmented PRoPHET compared to traditional PRoPHET. This is because load balancing is not a consider in this geographic DTN routing realization. Meanwhile message delivery delay (MDD) is worse in augmented Epidemic and augmented PRoPHET compared to traditional Epidemic and PRoPHET protocols. This is because all MSs choose the route that has high MS density, and make this route congested, thus message delivery is delayed. With respect to the total performance, compared to traditional protocols, augmented Epidemic and BSW do have improved performance. However, augmented PRoPHET has decreased performance.

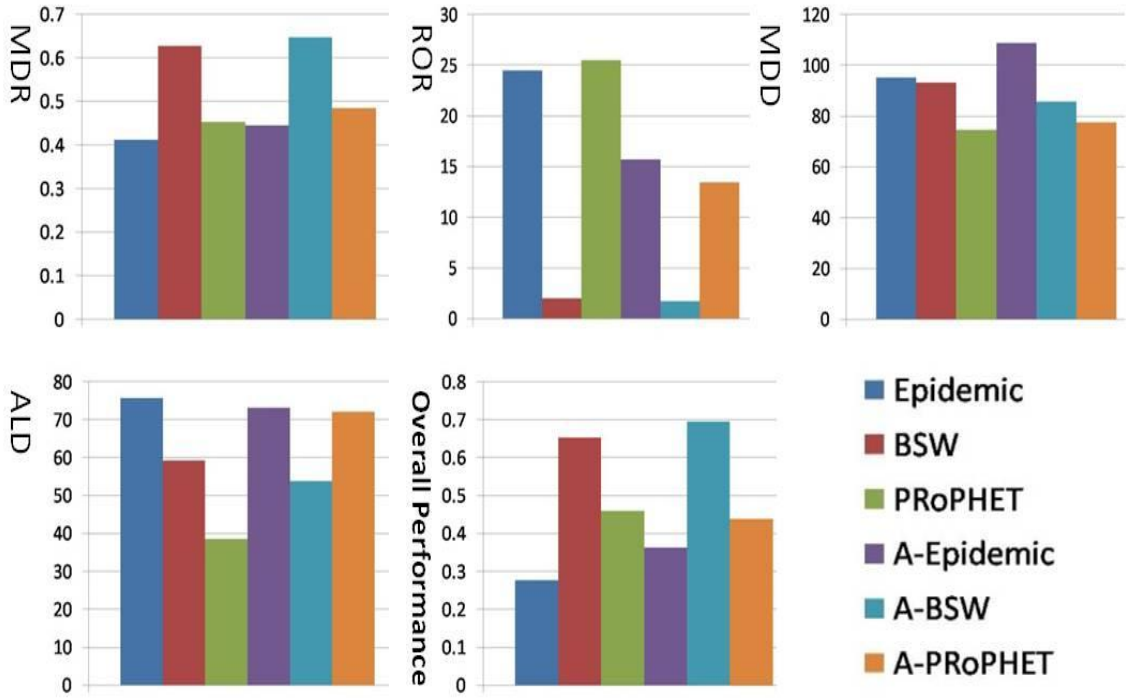


Figure 7.5 The performance of geographic DTN routing with limited utility definition

In this simulation, the utility is defined using (7.4), which is a broader definition. The weights to MS density, BS load, and hop count are 0.25, 0.5 and 0.25 in (7.4). Recency always has weight 1. The performance of traditional and augmented Epidemic, BSW and PRoPHET are shown in Figure 7.6. As shown in this figure, every criterion evaluated does improve as well as the total performance, except for load balancing in augmented PRoPHET. Augmented PRoPHET results in poorer load balancing than traditional PRoPHET. This is because, in PRoPHET, message deliver probability prediction is based on encountered connections. The more connection, the higher the message deliver probability is. Thus if a BS has more connections than other BS, messages are more likely to be delivered to that BS, and so not select the optimal BS found in (7.4). Meanwhile, the utility also makes MSs prefer high MS density route. Thus, MSs could congest along certain route and reduce the achieved load balancing, similarly to the previous simulation.

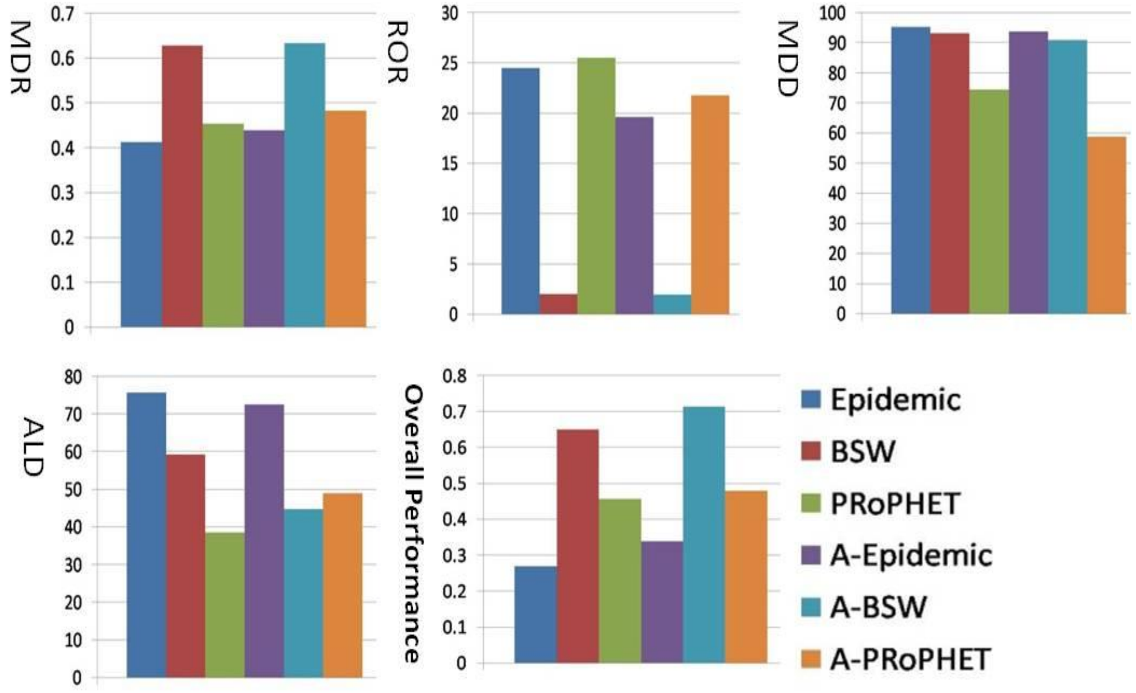


Figure 7.6 The performance of geographic DTN routing with broad utility definition

ACO augmented DTN routing

Figure 7.7 shows the performance of traditional and ACO augmented Epidemic, BSW and PRoPHET. ACO improves DTN routing performance greatly on every criterion and in total performance, except the message deliver delay of PRoPHET. MDD in ACO augmented PRoPHET is worse than traditional PRoPHET. This is because the node selected by ACO, which having the highest EV, is not surly the one having the highest message deliver probability, which is the preferred node in traditional PRoPHET. Thus, augmented PRoPHET needs more time to find the node which has both the strongest value of the two criteria to deliver message.

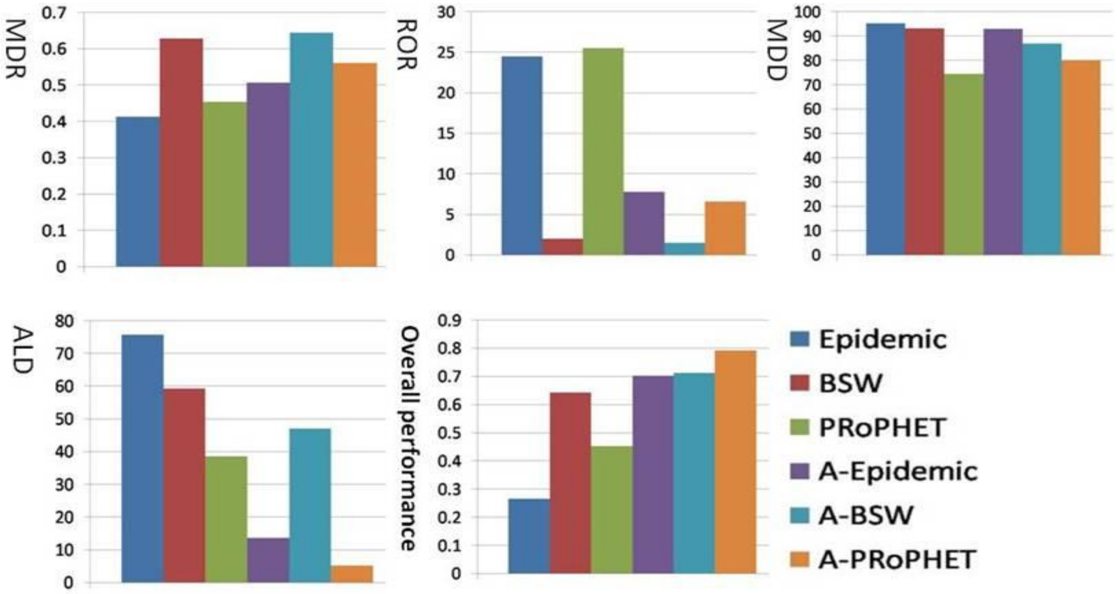


Figure.7.7 ACO augmented DTN routing performance

Finally, the three augmented methods are compared in Figure 7.8. This Figure shows how the augmenting methods improve traditional DTN routing performance (in percentage terms). According to Figure 7.8, in the scenario used, ACO appears to be the best way to improve DTN routing on routing effect and efficiency, and load balancing. As might be expected, geographic DTN routing with the broad utility definition is better than the geographic DTN routing only having the limited utility definition.

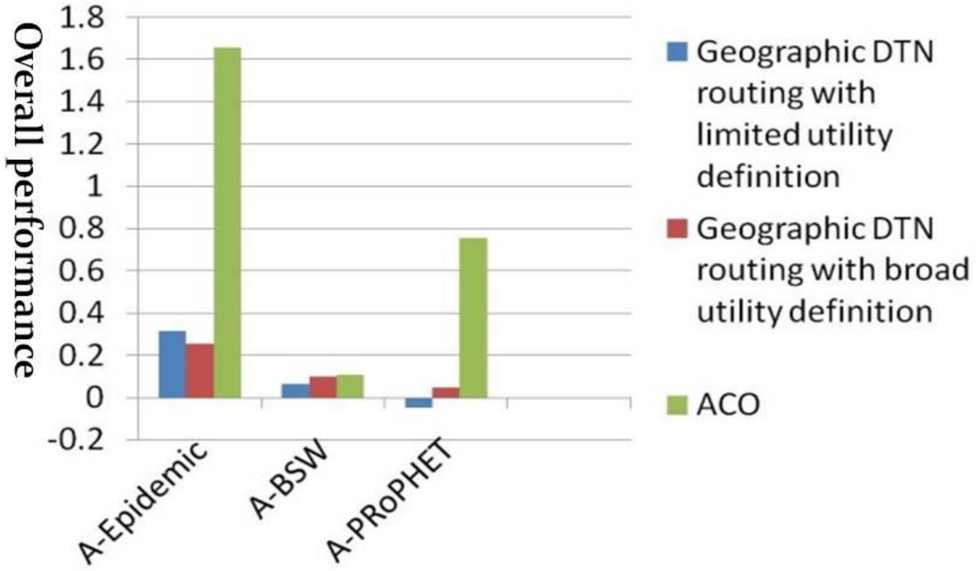


Figure.7.8 Performance comparison within geographic DTN routing and ACO augmented DTN routing

7.6 Summary

Considering BS failure problem in RBCN, this work augments traditional DTN routing protocols using geographic routing method and ACO. Both of the two methods can support high MS to BS message delivery rate, cell load balancing and routing efficiency for the BS failure problem in the scenarios used. Thus it can be concluded this work can extend RBCN coverage in emergency. Comparing the two main approaches, geographic based routing method is un-practical, complicated and does not appear to solve BS failure problem better than ACO. ACO augmented DTN routing does not need to know the MS locations through GPS devices. Future work will create more scenarios linked to more realistic failures and population densities and more ACO technology will be applied to augment DTN routing.

Chapter 8 Conclusion and Possible Extensions

8.1 Conclusion

This thesis investigates the solutions on user congestion and BS failure problems in RBCN. The solutions have three parts: network reconfiguration, dynamic frequency allocation and DTN. The RBCN in consideration makes use of fixed RS for multi-hop communication and is supported by IEEE802.16j standard. In RBCN, the multi-hop is limited to two hops. RSs in RBCN work in decode and forwarding scheme and in transparent or non-transparent relay model.

In network reconfiguration, this thesis designs cooperative antenna power control and antenna tilting to configure BSs and RSs antennas to relieve user congestion problem in RBCN. Specific algorithms: UC-CAPCA and heuristic antenna tilting are designed and verified in RBCN system level simulator. In addition, antenna tilting algorithm is also designed to mitigate BS failure problem and co-work with dynamic frequency allocation (DFFA algorithm). The co-working between antenna tilting and dynamic frequency allocation can be either sequentially or iteratively and have adding effect to better relieve user congestion and BS failure problems in RBCN.

In dynamic frequency allocation, this thesis augments Dynamic FFR into RBCN in a centralized way and then in a distributed way to better improve frequency efficiency and hence relieves user congestion and mitigate BS failure problems. In the centralized approach, a so called Dynamic Fractional Frequency Allocation (DFFA) algorithm is designed. DFFA augments Dynamic FFR into RBCN using channel borrowing. As introduced before, DFFA co-working with antenna tilting is also investigated. In the distributed approach, a cell-colouring based Distributed Frequency Allocation (C-DFA) approach is designed for all cellular networks. Based on C-DFA, a so called Distributed Dynamic Fractional Frequency Allocation algorithm (DDFFA) is designed for RBCN. C-DFA and related DDFFA realize high effect of distributed frequency allocation and efficiency. DFFA and its co-working with antenna tilting and DDFFA all are validated in RBCN system level simulator.

Finally DTN is used to extend RBCN coverage in BS failure situations. Using DTN, un-covered MSs can self-organize to connect to BSs or each other through multiple hops. DTN is suitable for catastrophic environment like the coverage hole caused by BS failure in RBCN. DTN employs technologies including intermittent connection, store and forward message propagation, DTN routing and bundle protocol to realize wireless communication in disaster fields. This thesis focus on augmenting DTN routing protocols to let un-covered MSs better connect to functional BS in BS failed RBCN. Geographic routing and ACO are used to realize the augmentation. Well know DTN routing protocols including Epidemic, Binary Spray and Wait and PRoPHET are augmented. Through simulation in ONE simulator, this augmenting works do improve MSs to BSs connection. Thus RBCN coverage is well extended.

In conclusion, the works of this thesis provides numbers of ways to relieve user congestion and BS failure problems in RBCN. These works enable cellular networking technology to be more widely used and applicable to users in different environments.

8.2 Possible Extensions and limitations

To further relieve user congestion and BS failure problems in RBCN, future work of this thesis could include: 1) investigate better centralized and distributed control methods to carry out network reconfiguration and dynamic frequency allocation. 2) investigate better integrated solutions. 3) design more practical augmented DTN routings to better extend RBCN coverage in an emergency. 4) design RBCN cooperation with WLAN networks to realize heterogeneous networks. The specific works are list below:

Design more intelligent cooperative control solutions in cooperative antenna power control and antenna tilting. The solutions should have a look ahead ability to improve the search and hence to configure antennas more reasonably and in finer grade.

Investigate better co-working between network reconfiguration and frequency allocation. It is proposed that both cooperative antenna power control and antenna tilting can co-work with dynamic frequency allocation. The co-working should not be simply in sequential or iterative. Instead, it should have higher reasoning and better scheme like

Confirm and Cancel. For example in Confirm and Cancel scheme, if a previous configuration of a antenna is proven to be unacceptable when later co-working with dynamic frequency allocation, the antenna configuration can be rolled back and cancelled. This should result in a better solution.

Design cooperative antenna power control, antenna tilting and their integrated solution with dynamic frequency allocation in distributed way. As discussed in this thesis, centralized solutions are unstable and highly dependent on the ability of a central controller. Thus, like the C-DFA approach, the cooperative antenna power control, antenna tilting and the integrated solution are planned to be turned into distributed.

Augment C-DFA in the distributed dynamic frequency allocation solution to be more applicable to cellular networks. As discussed before, C-DFA is highly limited by the interference distance of the cells, and this limitation hinders wide C-DFA application. Future work could add more limitations on the selection of simultaneously running cells not only based on colours in C-DFA to relieve the interference distance problem.

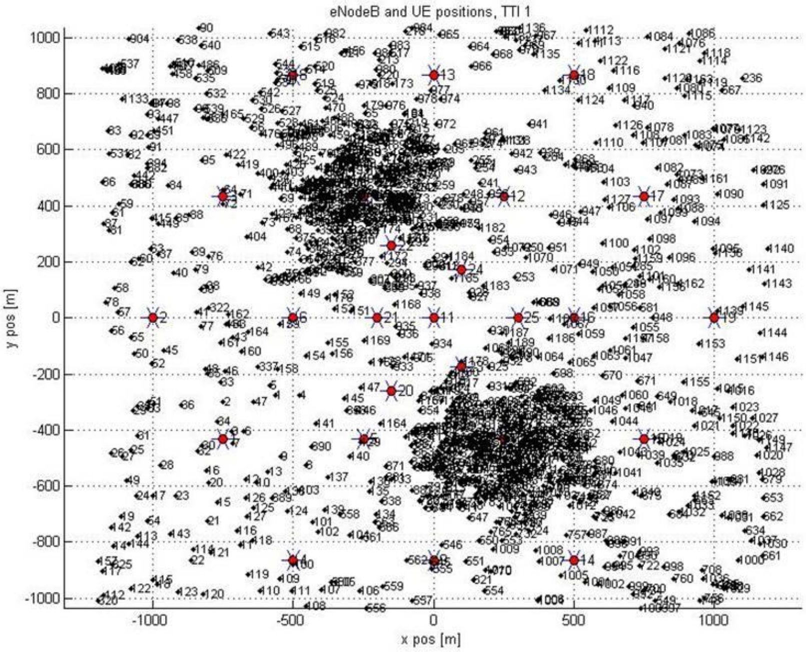
Design more sophisticated methods to augment DTN routing using Pheromone-Heuristic Control and Privileged Pheromone Laying in ACO. Pheromone-Heuristic Control lets ant make route selection decisions not only based on pheromone. Privileged Pheromone Laying mitigates route stagnation by permitting a selected subset of ants to have the privilege to deposit extra or more pheromone. These augmented DTN routing could guide MSs better connect to BSs in coverage hole.

Use MS to BS DTN connection prediction to help augmenting DTN routing in RBCN BS failure problem. In practice, using history connection information can predict future MS to BS DTN connecting. This can avoid the negative effect of user moving on DTN routing. Specifically, MS to BS history connection information like hop count, user density can be used in Exponentially Weighted Moving Average (EWMA) [91] to predict future hop count and user density of the route from this BS to MS.

Investigate RBCN co-working with WLAN to form heterogeneous networks [92]. In reality, cellular networks always co-exist with WLAN such as Wi-Fi networks. Thus RBCN and WLAN co-working is an interesting issue. The future work employs game theory, like the work in [93], on MSs to make them intelligently select either connecting to RBCN or WLAN. Based on this, to relieve the user congestion or BS failure problem in the RBCN situated in a heterogeneous network, it could be proposed to deliberatively change RBCN network configuration to cooperatively co-work with WLAN to enhance the load balance of the whole heterogeneous networks. This work is proposed in [94].

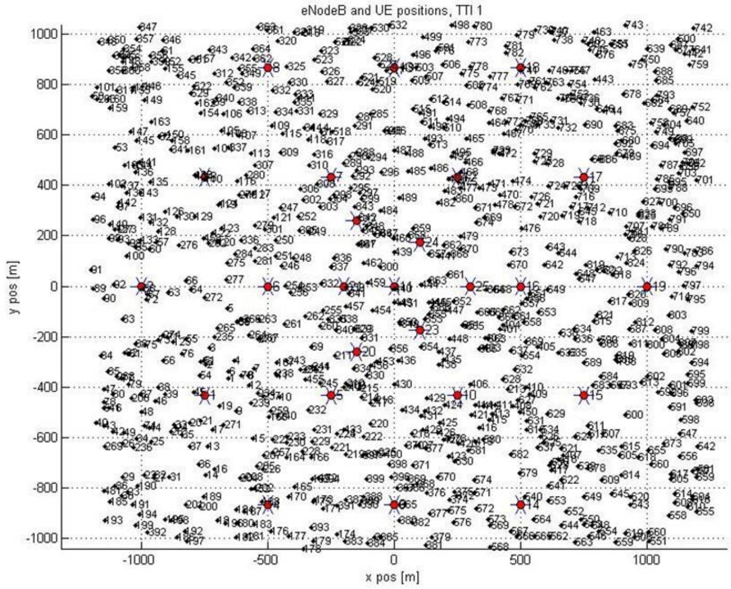
Appendix A-MSs distribution setting in system level RBCN simulation

1. 19 cells, two hotspots MSs distribution: cell 7 and cell 10 are two hotspots centre. Each hot sector(6 sectors in a cell) has averagely 30 users allocated. Each non-hot sector has averagely 2 users allocated.




```
users_sector = 2*ones(19,6);
users_sector (7,1)= users_sector (7,1)*15;
users_sector (7,2)= users_sector (7,2)*15;
users_sector (7,3)= users_sector (7,3)*15;
users_sector (7,4)= users_sector (7,4)*15;
users_sector (7,5)= users_sector (7,5)*15;
users_sector (7,6)= users_sector (7,6)*15;
users_sector (10,1)= users_sector (10,1)*15;
users_sector (10,2)= users_sector (10,2)*15;
users_sector (10,3)= users_sector (10,3)*15;
users_sector (10,4)= users_sector (10,4)*15;
users_sector (10,5)= users_sector (10,5)*15;
users_sector (10,6)= users_sector (10,6)*15;
```

2. 19 cells, uniform MSs distribution: each sector (6 sectors in a cell) has averagely 5 users allocated.




```
users_sector = 5*ones(19,6);
```

3. 61 cells, two hotspot MSs distribution: cell 25 and cell 32 are two hotspots centre. Each hot sector(3 sectors in a cell) has averagely 25 users allocated. Each non-hot sector has averagely 1 users allocated.

```
users_sector = ones(61,3);

users_sector (25,1)= users_sector (25,1)*25;
users_sector (25,2)= users_sector (25,2)*25;
users_sector (25,3)= users_sector (25,3)*25;

users_sector (32,1)= users_sector (32,1)*25;
users_sector (32,2)= users_sector (32,2)*25;
users_sector (32,3)= users_sector (32,3)*25;
```

Appendix B-Setting file of QMUL BS failure scenario in ONE simulator

```
# QMUL settings for the simulation
## Scenario settings
Scenario.name = QMUL_scenario
Scenario.simulateConnections = true
Scenario.updateInterval = 0.003333
# 720s == 6h
Scenario.endTime =720

# "Bluetooth" interface for all nodes
btInterface.type = SimpleBroadcastInterface
# Transmit speed of 2 Mbps = 250kBps
btInterface.transmitSpeed = 250k
btInterface.transmitRange = 30

# High speed, long range, interface for group 4
highspeedInterface.type = SimpleBroadcastInterface
highspeedInterface.transmitSpeed = 10M
highspeedInterface.transmitRange = 200

# Define 6 different node groups
Scenario.nrofHostGroups = 6

# Common settings for all groups
Group.movementModel = ShortestPathMapBasedMovement
#Group.router = SprayAndWaitRouter
#Group.router = EpidemicRouter
Group.router = ProphetRouter
Group.bufferSize = 10M
Group.waitTime = 0, 4
# All nodes have the bluetooth interface
Group.nrofInterfaces = 1
Group.interface1 = btInterface
# Walking speeds
Group.speed = 3, 9
# Message TTL of 300 minutes (5 hours)
Group.msgTtl = 10

Group.nrofHosts = 20

# group1 (pedestrians) specific settings
Group1.groupID = w
Group2.groupID = w
Group3.groupID = w
Group4.groupID = w
Group5.groupID = w

# The BS groups
Group6.groupID = BS
Group6.bufferSize0 = 200M
Group6.bufferSize1 = 200M
Group6.bufferSize2 = 200M
Group6.bufferSize3 = 200M
```

```
Group6.interface1=highspeedInterface
Group6.speed = 0,0
Group6.nrofHosts = 3
Group6.ini_location_0=200,200
Group6.ini_location_1=650,500
Group6.ini_location_2=680,30

## Message creation parameters
# How many event generators
Events.nrof = 1
# Class of the first event generator
Events1.class = MessageEventGenerator
# (following settings are specific for the MessageEventGenerator class)
# Creation interval in seconds (one new message every 25 to 35 seconds)
Events1.interval = 1,2
# Message sizes (500kB - 1MB)
Events1.size = 500k,1M
# range of message source/destination addresses
Events1.hosts = 0,99
Events1.tohosts = 100,102
# Message ID prefix
Events1.prefix = M


## Movement model settings
# seed for movement models' pseudo random number generator (default = 0)
MovementModel.rngSeed = 1
# World's size for Movement Models without implicit size (width, height; meters)
MovementModel.worldSize = 1500, 1000
# How long time to move hosts in the world before real simulation
MovementModel.warmup = 33.33

## Map based movement -movement model specific settings
MapBasedMovement.nrofMapFiles = 1
MapBasedMovement.mapFile1 = data/QMUL.wkt


## Reports - all report names have to be valid report classes
# how many reports to load
Report.nrofReports = 1
# length of the warm up period (simulated seconds)
Report.warmup = 0
# default directory of reports (can be overridden per Report with output setting)
Report.reportDir = reports/
# Report classes to load
Report.report1 = MessageStatsReport

## Default settings for some routers settings
ProphetRouter.secondsInTimeUnit = 30
SprayAndWaitRouter.nrofCopies = 3
SprayAndWaitRouter.binaryMode = true

## Optimization settings -- these affect the speed of the simulation
## see World class for details.
Optimization.cellSizeMult = 5
Optimization.randomizeUpdateOrder = true
```

Appendix C-Author’s publications

1. Conference Papers:

1. Haibo Mei, Bigham J, Peng J, “Cooperative Pilot Power Control in Hybrid Cellula-r Network”, ICIME 2010, April 2010, Chengdu, China.

2. Haris Pervaiz, Haibo Mei, Enhance Cooperation in Heterogeneous Wireless Networks using Coverage Adjustment, The 6th International Wireless Communications& Mobile Computing Conference-(IWCMC 2010), Caen, France.

3. Haibo Mei, Bigham J, Peng J, “Augment Coverage in a Cellular Network with DTN Routing”, WCNC 2011， Cancun， Mexico.

4. Haibo Mei, Peng Jiang, John Bigham, “Augment Delay Tolerant Networking Routing to Extend Wireless Network Coverage”, 2011 International Conference on Wireless Communications and Signal Processing (WCSP), Nanjing, China.

5. Haibo Mei, Peng Jiang, John Bigham, “Dynamic Frequency Allocation and Network Reconfiguration on Relay Based Cellular Network”, WCNC 2012 accepted, Paris, France.

2. Journal Papers under review

4. Haibo Mei, Bigham J,Peng J, “Dynamic Frequency Allocation and Network Recon-figuration on Relay Based Cellular Networks”, IEEE Transaction on Wireless Communication, In processing.

5. Haibo Mei, Bigham J,Peng J, “Distributed Dynamic Frequency Allocation in Fractional Frequency Reused Relay Based Cellular Networks”, IEEE Transaction on Communication, In processing.

REFERENCES

[1] IEEE Draft Standard P802.16j/D5, "Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems— Multihop Relay Specification," May 2008.

[2] Zhifeng Tao, Anifei Li, Koon Hoo Teo, Jinyun Zhang, "Frame Structure Design for IEEE 802.16j Mobile Multihop Relay (MMR) Networks", Copyright Mitsubishi Electric Research Laboratories, Inc., 2008.

[3] Ajay R. Mishra, "Fundamentals of Cellular Network Planning and Optimisation: 2G/2.5G/3G…Evolution to 4G", John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England Copyright © 2004.

[4] Young-June Choi, Cheol Seung Kim, "Flexible Design of Frequency Reuse Factor in OFDMA Cellular Networks", IEEE ICC 2006.

[5] Vincentzio L. Roman "Frequency Reuse and System Deployment in local Multipoint Distribution Service", IEEE Pcrsonal Communications December 1999.

[6] Wylie, M.P., Holtzman, J, "The non-line of sight problem in mobile location estimation", the 5th IEEE International Conference on Universal Personal Communications, 1996.

[7] Ananthapadmanabha R., B. S. Manoj, "Multi-hop Cellular Networks: The Architecture and Routing Protocols", the 12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2001.

[8] Walid Saad, Zhu Han , A Selfish Approach to Coalition Formation among Unimanned Air Vehicles in Wireless Networks, IEEE international Conference On Game Theory for Networks, Istanbul: Turkey (2009).

[9] Hongyi Wu, Chunming Qiao, Integrated Cellular and Ad Hoc Relyaing Systems: iCAR, IEEE journal on selected areas in communications, VOL 19,NO.10, October 2001.

[10] Jeffrey G. Andrews, Fundamentals of WiMAX understanding Broadband Wireless Networking, copy right 2007 Pearson Education, Inc.

[11] IEEE 802.16-2004, "Local and Metropolitan Area Networks, Part 16: Air Interface for Fixed Broadband Wireless Access Systems," Oct. 2004.

[12] IEEE 802.16 Task Group 1: http://www.ieee802.org/16/tg1/.

[13] K. Fazel, S. Kaiser, "Multi-Carrier and Spread Spectrum Systems From OFDM and MC-CDMA to LTE and WiMAX", copy right John Wiley & Sons, Ltd.

[14] WiMAX Forum: http://www.wimaxforum.org/.

[15] Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation, WiMAX

Forum, 2006.

[16] IEEE, “IEEE Std 802.16e-2005 Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands.”, IEEE 802.16e, 2006

[17] IEEE. "IEEE 802.16's Relay Task Group": http://www.ieee802.org/16/relay/.

[18] Steven W. Peters and Robert W. et al, “The Future of WiMAX: Multihop Relaying with IEEE 802.16j”, IEEE Communications Magazine • January 2009.

[19] 3GPP: http://www.3gpp.org/.

[20] Stefania Sesia, Issam Toufik, Matthew Baker, LTE – The UMTS Long Term Evolution, published 2009© 2009 John Wiley & Sons Ltd.

[21] Charan Langton, Orthogonal Frequency Division Multiplex(OFDM) Tutorial, Copyright 2004, www.complextoreal.com.

[22] Vladimir Bykovnikov, “The Advantages of SOFDMA for WiMAX”, Copyright © 2005 Intel Corporation. All rights reserved.

[23] Vasken Genc, Sean Murphy, Yang Yu, and John Murphy, “IEEE 802.16j Relay-Based Wireless Access Networks: An Overview”, IEEE Wireless Communications, Oct 2008.

[24] Ralf Pabst et al, “Relay-Based Deployment Concepts for Wireless and Mobile Broadband Radio”, IEEE Communications Magazine • September 2004.

[25] Peng Jiang, John Bigham, JiayiWu, “Self-organizing relay stations in relay based cellular networks”, Computer Communications 31 (2008) 2937-2945.

[26] Bin Lin, Pin-Han Ho, “Optimal Relay Station Placement in IEEE 802.16j Networks”, IWCMC’07, August 12–16, 2007, Honolulu, Hawaii, USA.

[27] V. Sreng, H. Yanikomeroglu, and D. D. Falconer, “Relay Selection Strategies in Cellular Networks with Peer-to-Peer Relaying”, Vehicular Technology Conference, 2003. VTC 2003-Fall.

[28] V. Sreng, H. Yanikomeroglu, D. Falconer, “Coverage enhancement through two-hop relaying in cellular radio systems,” IEEE Wireless Commun. and Networking Conf. (WCNC’02), March 2002, Orlando, USA.

[29] Peng Jiang, John Bigham, Jiayi Wu, “Scalable QoS Provisioning and Service Node Selection in Relay Based Cellular Networks”, Wireless Communications, Networking and Mobile Computing, 2008. WiCOM '08. 4th International Conference .

[30] Peng Jiang, “Cooperative Control of Relay Based Cellular Networks”, Queen Mary University of London, 2008.

[31] Hui Zeng, Chenxi Zhu, “System-Level Modeling and Performance Evaluation of Multi-hop 802.16j Systems”, International Wireless Communications and Mobile Computing Conference, 2008. IWCMC '08.

[32] Xin Liu, Edwin K. P. Chong, Transmission Scheduling for Efficient Wireless Resource Utilization with Minimum-Performance Guarantees, Vehicular Technology Conference,

2001. VTC 2001 Fall. IEEE VTS 54th, 2011.

[33] Ozgur Oyman, “Opportunistic Scheduling and Spectrum Reuse in Relay-based Cellular OFDMA Networks”, IEEE GLOBECOM 2007.

[34] Robert T.Love, Khaled A. Beshir, Dennis Schaeffer, Robert S.Nikides, “A Antenna Optimization Technique for CDMA Cellular Systems”, IEEE, 1999.

[35] Iana Siomina, Di Yuan, “Antenna Power Management in WCDMA Networks Coverage Control With Respect to Traffic Distribution”, Copyright 2004 ACM 1-58113-953-5/04/0010.

[36] Kimmo Valkealahtl, Albert Hoglund, Jyrki Parkkinen, Ari Hamalainen, “WCDMA common antenna power control for load and coverage balance”, 0-7803-7589-0/02, IEEE, 2002.

[37] L. Du, J. Bigham, “Intelligent Geographic Load Balancing for Mobile Cellular Networks” , Jul. 2004.

[38] John Bigham, Lin Du, “Cooperative Negotiation in a Multi-Agent System for Real-Time Load Balancing of a Mobile Cellular Network”, International Conference on Autonomous Agents, Melbourne Australia, 2003.

[39] L. Du, J. Bigham, and L. Cuthbert, “A Bubble Oscillation Algorithm for Distributed Geographic Load Balancing in Mobile Networks,” The Twenty-third Annual Joint Conference of the IEEE Computer and Communications Societies, IEEE INFOCOM'2004, Hong Kong, March 2004.

[40] Du.L, Bigham J, Cuthbert L.G, “Utility-based distributed geographic load balancing in mobile cellular networks”, IEEE International conference on 3G mobile communication technologies, London, Royaume-UNI, June 2003.

[41] L. Zordan, N. Rutazihana, and N. Engelhart, “Capacity enhancement of cellular mobile network using a dynamic electrical down-tilting antenna system,” in Proc. IEEE VTS 50th Vehicular Technology Conference (VTC ’99), vol. 3, pp. 1915– 1918, Amsterdam, The Netherlands, September 1999.

[42] D. J. Y. Lee and C. Xu, “Mechanical antenna downtilt and its impact on system design,” in Proc. IEEE 47th Vehicular Technology Conference (VTC ’97), vol. 2, pp. 447–451, Phoenix, Ariz, USA, May 1997.

[43] G. Wilson, “Electrical downtilt through beam-steering versus mechanical downtilt [base station antennas],” in Proc. IEEE 42nd Vehicular Technology Conference (VTC ’92), vol. 1, pp. 1–4, Denver, Colo, USA, May 1992.

[44] Stelios Timotheou, Georgios Loukas, “Automomous Networked Robots for the Establishment of Wireless Communication in Uncertain Emergency Response Scenarios”, SAC’09 March 8-12,2009, Honolulu,Hawaii, U.S.A.

[45] Katzela and M.Naghshineh, Channel Assignment Schemes for Cellular Mobile Telecommunication Systems: A Comprehensive Survey, IEEE Personal Communications,

June 1996.

[46] Ming Zhang, Tak-Shing Yum, Comparisons of Channel-Assignment Strategies in Cellular Mobile Telephone Systems, IEEE Transactions on Vehicular Technology. Vol.38. No. 4. November 1989.

[47] H. Hu, H. Yanikomeroglu, D. D. Falconer, et al, "Range Extension without Capacity penalty in Cellular Networks with Digital Fixed Relays", IEEE Globecom'04, 29 November - 3 December 2004, pp. 3053-3057.

[48] Min Liang, Ya Feng Wang, Fan Huang and Da Cheng Yang, An Improved Frequency Reuse Algorithm for Fixed Two-hop OFDMA Cellular Relay Networks, IWCMC’09, June 21–24, 2009, Leipzig, Germany. Copyright © 2009 ACM.

[49] IEEE 802.16 Multi-hop Relay Project, Fractional Frequency Reuse for IEEE802.16j Relaying Mode, IEEE C80216j-06_223.

[50] Tao Liu, Mengtian Rong, Ping Li, Radio Resource Allocation in Two-hop Cellular Relay Network, IEEE, 2006.

[51] Haipeng Lei, Lei Zhang, A novel multi-cell OFDMA System Structure using Fractional Frequency Reuse, The 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'07).

[52] Syed Hussain Ali, Dynamic Frequency Allocation in Fractional Frequency Reused OFDMA Networks, IEEE Transaction on Wireless Communications, Vol. 8, No. 8, August 2009.

[53] L.J.Cimini, Jr. G.J.Foschini, “Distributed Algorithms for Dynamic Channel Allocation in Microcellular Systems”, Vehicular Technology Conference, 1992, IEEE 42nd.

[54] C-LI and P-H Chao, “Local Packing- Distributed Dynamic Channel Allocation at Cellular Base Station,” IEEE GLOBECOM’93.

[55] Chih-Lin I, “Distributed Dynamic Channel Allocation Algorithms With Adjacent Channel Constraints”, PIMRC ’94.

[56] Ravi Prakash, Niranjan G.Shivaratri, “Distributed Dynamic Channel Allocation for Mobile Computing”, PODC '95: the fourteenth annual ACM symposium on Principles of distributed computing.

[57] Forrest Warthman Warthman Associates, Delay-Tolerant Networks(DTNs)-A Tutorial, Version 1.1, March 2003.

[58] Md. Tarikul Islam, DT-Talkie: Interactive Voice Messaging for Heterogeneous Groups in Delay-Tolerant Networks, Consumer Communications and Networking Conference, 2009. CCNC 2009. 6th IEEE.

[59] Kevin Fall, “A Delay-Tolerant Network Architecture for Challenged Internets”, SIGCOMM '03: the 2003 conference on Applications, technologies, architectures, and protocols for computer communications.

[60] Michael Demmer, Eric Brewer, “Implementing Delay Tolerant Networking”, 2003

[61] K. Scott, S. Burleigh, “Bundle Protocol Specification”, November 2007.

[62] Wood, L.; Eddy, W.M, et al, “A bundle of problems”, Aerospace conference, 2009 IEEE

[63] P Jiang, John B, Eliane Bodanese, “Adaptive Service Provisioning for Emergency Communications with DTN”, WCNC’2011.

[64] Charles E. Perkins, Pravin Bhagwat, “Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers”, SIGCOMM 94 -8/94.

[65] David B. Johnson David A. Maltz, “DSR: The Dynamic Source Routing Protocol for Multi-Hop Wireless Ad Hoc Networks”, Ad hoc networking, 2001.

[66] Charles E. Perkins, Elizabeth M, “Ad-Hoc On-Demand Distance Vector(AODV) Routing”, IEEE WMCSA’ 99, New Orleans, LA, February 1999.

[67] Thrasyvoulos Spyropoulos, Konstantinos Psounis, “Single-Copy Routing in Intermittently Connected Mobile Networks”, 2004 First Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, 2004.

[68] Thrasyvoulos Spyropoulos, Konstantinos Psounis, “Efficient Routing in Intermittently Connected Mobile Networks: The Multiple-Copy Case”, IEEE/ACM Transactions on Networking, Vol. 16, NO. 1, Feb 2008.

[69] Ram Ramanathan, Richard Hansenm, “Prioritized Epidemic Routing for Opportunistic Networks”, MobiOpp’07, June 11, 2007, San Juan, Puerto Rico, USA.

[70] Thrasyvoulos Spyropoulos, Konstantinos Psounis, Cauligi. Raghavendra, “Spary and Wati: An Efficient Routing Scheme for Intermittently Connected Mobile Networks”, SIGCOMM’05 Workshops, August 22-26, 2005, Philadelphia, PA, USA.

[71] Aruna Balasubramanian, Brian Neil Levine, and Arun Venkataramani. DTN routing as a resource allocation problem. In Proc. ACM SIGCOMM, August 2007.

[72] John Burgess Brian Gallagher, “MaxProp: Routing for Vehicle-Based Disruption-Tolerant Networks”, IEEE infocom, 2006.

[73] Lindgren, A.Doria, A, and Schelen.O, “Probabilistic routing in intermittently connected networks”, In The First International Workshop on Service Assurance with Partial and Intermittent Resources (SAPIR) (2004).

[74] Raj Jain, Chakchai, “System-level Modeling of IEEE 802.16e Mobile WiMAX Networks: Key Issues”, IEEE Wireless Communications , October 2008.

[75] “Multi-hop Relay System Evaluation Methodology (Channel Model and Performance Metric)”, IEEE 802.16 Broadband Wireless Access Working Group, IEEE 802.16j-06/013r3, Feb, 07.

[76] H. Claussen, “Efficient modelling of channel maps with correlated shadow fading in mobile radio systems,” Sept. 2005.

[77] Tapan K.Sarkar, Zhong Ji, A Survey of Various Propagation Models for Mobile Communication, IEEE Antennas and Propagation Magazine, Vol. 45, No. 3, June 2003.
[78] Kejiong Li, Peng Jiang and John Bigham, "Partitioning the Wireless Environment for Determining Radio Coverage and Traffic Distribution with User Feedback", National Conference on Communications (NCC 2011), Jan. 2011.
[79] WiMAX module for the NS-2 simulator: http://www.lrc.ic.unicamp.br/wimax_ns2/.
[80] Ari Keränen, Jörg Ott, "Opportunistic Network Environment simulator", Special Assignment report, Helsinki University of Technology, 2008.
[81] Ari Keränen, Jörg Ott, Teemu Kärkkäinen, "The ONE Simulator for DTN Protocol Evaluation", SIMUTools 2009, Rome, Italy .
[82] Ari Keränen, Jörg Ott, "Increasing Reality for DTN Protocol Simulations", Helsinki University of Technology, Tech. Rep., July, 2007.
[83] Frans Ekman, Ari Keränen, "Working Day Movement Model", MobilityModels'08, May 26, 2008, Hong Kong SAR, China.
[84] Peng Jiang, Bigham.J. Jiayi Wu, "Cooperative Geographic Load Balancing in Hybrid Cellular Networks", Signal Processing, Communication and Networking, Jan.2008.
[85] Wonjong Rhee and John M. Cioffi，Increase in Capacity of Multiuser OFDM System Using Dynamic Sub-channel Allocation，VTC 2000.
[86] Zukang Shen, Jeffrey G. Andrew, Brian L. Evans, "Adaptive Resource Allocation in Multiuser OFDM Systems with Proportional Rate Constraints", IEEE Transactions on Wireless Communications, July 2005.
[87] Joo Heo , Insuk Cha , KyungHi Chang, Effective adaptive transmit power allocation algorithm considering dynamic channel allocation in reuse partitioning-based OFDMA system, Wireless Pers Commun (2007).
[88] Sukumar Ghosh, Mehmet Hakan Karaata, A self-Stabilizing Algorithm for Colouring Planner Graphs, 29th Allerton Conference on Control, Communication & Computing, October, 1991.
[89] Peng Jiang, John Bigham, and M. Anas Khan, Distributed Algorithm for Real Time Cooperative Synthesis of Wireless Cell Coverage Patterns, IEEE Communications Letters, Vol. 12, NO. 9, Sep 2008.
[90] Kwang Mong Sim, Weng Hong Sun, "Ant Colony Optimization for Routing and Load-Balancing: Survey and New Directions", IEEE transactions on systems, man, and cybernetics-Part A: systems and humans, VOL.33, No. 5, Septmeber 2003.
[91] Peter R. Winters, "Forecasting Sales by Exponentially Weighted Moving Averages", Management Science Vol. 6, No. 3 (Apr., 1960), pp. 324-342.

[92] S.Pierrel, T.Erlin, J.Roslof, "A Prototype for Policy Driven Control of Heterogeneous NetworkAccess", 2nd Workshop on Applications of Wireless Communications (WAWC'04).

[93] Dusit Niyato, Ekram Hossain,"Dynamics of Network Selection in Heterogeneous Wireless Networks: An Evolutionary Game Approach ", IEEE Transactions on Vehicular Technology, Vol. 58, No. 4, May 2009.

[94] Haris Pervaiz, Haibo Mei, Enhance Cooperation in Heterogeneous Wireless Networks using Coverage Adjustment, The 6th International Wireless Communications& Mobile Computing Conference-(IWCMC 2010), Caen, France.