RENDEZVOUS IN COGNITIVE RADIO AD-HOC NETWORKS

By
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To my parents, brother, sister

and my lovely wife

Table of Contents

List of Tables

List of Figures

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

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Abstract

Cognitive radio (CR) is a promising technique to enhance the spectrum utilisation by enabling the CR users to opportunistic access the spectrum holes or channels. CR ad hoc network is a multi-channel environment where channel status changes over time depending on primary users' (PUs) activities. Analogous to control channel establishment in traditional multi-channel ad hoc network, rendezvous in CR ad hoc network is one of the most important processes for a pair of unknown CR users to initiate communication. Most of the existing research have utilised a common control channel to achieve rendezvous. This utilization generates channel saturation, extreme transmission overhead of control information, and a point of vulnerability. The traditional designs for rendezvous protocols do not support an ad-hoc CR network model. Therefore, this thesis is focused on improving control channel establishment to solve the rendezvous problem and support further CR ad-hoc networks.

This thesis proposes a new channel hopping (CH) scheme called extended torus quorum channel hoping (ETQCH) for asymmetric and asynchronous pair wise RDV in CR ad-hoc networks. The ETQCH employs channel ranking information for allocating more slots to high-rank channels than low-rank ones. The system dynamically updates the CH sequence by replacing channels from both the licensed and unlicensed bands to protect intermittent PUs.

Channel hopping sequence scheme is a mathematical concept to guarantee overlap between two CR users. A successful RDV establishment depends on successful channel probe or control packet exchange which is a MAC layer issue. Therefore, a new MAC protocol named cognitive radio rendezvous (CR-RDV) MAC is proposed to facilitate the multiuser contention in CR ad-hoc networks. CR-RDV is developed by re-defining the traditional backooff procedure and incorporating a sensing period immediately after the request-to-send; the incumbent PU's transmission is protected and blocking problems are resolved. The analysis and simulation results show the potential to minimise service interruption, block node problems, and efficiently utilise dynamic radio resources. The thesis also provides a guideline for CR system planners to design and deployment of dense networks with active PUs.

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List of Publications

Manuscripts relating to the RDV have been published in the following academic conference proceedings:

1. Hossain, A., and Sarkar, N. I., Cross Layer Rendezvous in Cognitive Radio Ad-Hoc Networks, presented at the International Telecommunication Networks and Applications Conference (ITNAC), UNSW, Sydney, Australia, November 18-20, 2015.

2. Hossain, A., and Sarkar, N. I., Rendezvous in Cognitive Radio Ad-Hoc Networks with Channel Ranking. 18th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), Cancun, Mexico, November 2-6, 2015.

3. Hossain, A., Sarkar, N.I., Rendezvous in Cognitive Radio Ad-hoc Networks with Asymmetric Channel View, IEEE 16th International Symposium on World of Wireless, Mobile and Multimedia Networks (WoWMoM), Boston, MA, USA. pp.1-6, June 14-17, 2015.

4. Hossain, Md Akbar, and Nurul I. Sarkar., Spectrum Management in Cognitive Radio Networks: Modeling and Performance Evaluation. Proceedings of the International Conference on Wireless Networks (ICWN). The Steering Committee of The World Congress in Computer Science, Computer Engineering and Applied Computing (WorldComp), 2012.

5. M. A. Hossain and N. I. Sarkar, Spectrum Handoff Management in Cognitive Radio Networks: Solutions, Modeling and Future Directions. In Meghanathan, N. and Yenumula B. Reddy. Y. B. (Eds.), Cognitive Radio Technology Applications for Wireless and Mobile Ad hoc Networks, IGI Global, Chapter 6, pp 103-123, 2013.

List of Abbreviations and Acronyms

ACK Acknowledgement

ACL Available channel list

AMRCC Adaptive multiple rendezvous control channel

ATTR Average time to rendezvous

BC Back up

BP Beacon period

BS Base station

CA-MAC Concurrent MAC

CCC Common control channel

CCL Common channel list

CH Channel hopping

C-MAC Cognitive medium access control

COL Channel occupancy list

COMAC Cognitive radio MAC

CR Cognitive radio

CRAHNs Cognitive radio ad-hoc networks

CREAM-MAC Cognitive radio enabled multi-channel MAC

CRNs Cognitive radio networks

CR-RDV Cognitive radio rendezvous

CRT Chinese remainder theory

CRSEQ Channel rendezvous sequence

CST Channel state transmitter

CSR Channel state receiver

CTS Clear to send

CSMA/CA Carrier sense multiple access collision avoidance

CUCB-MAC Channel usage and collision based MAC

DAB Direct access based

DC Data channel

DCA Dynamic channel allocation

DCF Distributed co-ordination function

DIFS Distributed coordination function inter-frame space

DOSS Dynamic open spectrum sharing

DRSEQ Deterministic rendezvous sequence

DSA Dynamic spectrum allocation

DSMMAC Difference set based Multichannel MAC

DSP Digital signal processor

DSRM Design science research methodology

DTP Data transmission period

EJS Enhance jump stay

EQOS Extended quorum overlap size

ETQCH Extended torus quorum channel hopping

FCC Federal communication commission

FCS Frame check sequence

gQRDV Grid quorum rendezvous

HC Hardware constraint

IEEE Institute of electrical and electronics engineers

JS Jump stay

LP Linear programming

LSB Least significant bit

MAC Medium access control

MANET Mobile ad-hoc network

MC Modular clock

MMC Modified modular clock

MSC Message sequence chart

MTTR Maximum time to rendezvous

MVCS Modified virtual carrier sensing

NAV Network allocation vector

NTS Not to send

OSA Opportunistic spectrum access

PCL Primary channel list

POMDP Partially observable Markov decision process

PTS Prepare to send

PU Primary user

QoS Quality of service

RA Receiver address

RAT Radio access technology

RC Rendezvous channel

RCP Rotation closure property

RDV Rendezvous

RSS Receives signal strength

RTS Request to send

RW Random walk

SCA Statistical channel allocation

SCL Secondary channel list

SDR Software define radio

SINR Signal to interference noise ratio

SIP Spectrum image of PUs

SIFS Short inter-frame space

SRAC Single radio adaptive channel

SRP Scan result packet

SSB Short sequence based

SSCH Slotted seeded channel hopping

SYN-MAC Synchronize MAC

TTR Time to rendezvous

VCS Virtual carrier sensing

WiFi Wireless fidelity

WiMAX Worldwide interoperability for microwave access

WLAN Wireless local area network

Chapter 1

Introduction

With the increasing demand for new wireless services and applications, as well as the increasing demand for higher capacity, wireless networks become highly heterogeneous. In this context, it is essential to have updated information on the radio environment to enhance the overall network performance. So far, most of the radio spectrum is predominantly assigned by the national authority to several service providers, companies or institutes for exclusive use over national areas on a long term basis. The outcomes of several investigations have shown that the lack of spectrum is not an issue, but the fact that radio resources are used inefficiently. According to Federal Communication Commission (FCC), up to 85% of the assigned spectrum is underutilized in major urban areas due to static spectrum allocation policy [5]. This fixed static spectrum allocation policy is one of the main reasons behind this varying licensed band inefficient spectrum underutilization. On the other hand, the unlicensed portion of the spectrum the ISM 2.4 GHz and 5 GHz band has become overcrowded due to WLAN, Bluetooth, cordless phones, microwave ovens and other devices. In this situation, a new system should be deployed to efficiently utilize available spectrum resources in a dynamic way to fulfil growing bandwidth demands [6].

The new system should be able to sense the spectrum, detect spectrum holes and utilize these spectrum holes to improve overall spectrum utilization. Hence, a promising functionality is required to be built into future terminals that have the cognitive capability to assist with the dynamic spectrum allocation (DSA), which allows more efficient utilization of radio resources by changing the spectrum allocation on demand [7]. The CR approach is one of the most promising concepts to realize DSA which facilitate the flexible usage of radio spectrum [8]. CRs are currently being considered as an alternative to current wireless devices in many applications such as smart grid [9], public safety [10], cellular networks [11–13], and wireless medical networks [14].

1.1 Background and Motivation

Wireless ad-hoc network with CR devices known as cognitive radio ad-hoc networks (CRAHNs), gain importance for envisioned future ubiquitous communication due to their cognitive capability to use the radio resources in an opportunistic manner. CRAHNs is a dynamic multichannel environment where the channel status changes over time depending on surrounding radio users activities. Hence, it is essential for a CR node to detect and identify the neighbors to initiate communication in CRAHNs which corresponds to rendezvous (RDV). In multi-channel wireless ad-hoc environment, RDV is the first key step for CR users to be able to communicate with each other. To achieve RDV, CCC and CH are often used to exchange control information. Despite the advantage of CH over CCC due to single point failure, control saturation and incumbent users protection policy, some challenges have not yet been addressed in the design of a CH protocol:

Asymmetric Channel Information: In multi-channel CRAHNs, different CRs may have different channel information due to relative geographical locations and radio environment. Based on channel information, we can consider two cases: in the symmetric case, all CRs have access to the same subset of the spectrum, and in the asymmetric case, CRs may have access to a different set of channels. Most of the existing research has focused on the symmetric case only, supposing that all the CRs observe the same set of available channels. This leads to an inefficient utilisation of the spectrum and wastes network resources.

Intermittent PUs: Although CRs can enhance the network utilisation by opportunistically utilising the unused spectrum, the effect of intermittent PUs is significant and has been less explored. To minimise the interference with PUs, most of the existing protocols remove the PU-occupied channel from the channel list. However, it may reduce the interference but the channel list becomes progressively shorter and decrease the RDV achievement probability. Moreover, consecutive spectrum handoffs by CRs among different unoccupied channels have a negative effect in terms of delay, and thus an effective solution should be developed.

Spectrum Sharing: In multi-user CRAHNs, multiple CR users are contending for the same channel to establish RDV. Hence, it is necessary to have an efficient MAC protocol to facilitate the channel contention and spectrum sharing. Most of the existing CR-MAC protocols utilise the reactive spectrum handoff policy to cope with intermittent PUs which increase the control overhead and delays in CRAHNs.

To address the above issues and challenges, the following contributions are made.

- Develop a new RDV protocol to achieve RDV on available common channel and minimise performance fluctuation. The system must handle channel asymmetry, asynchrony between CR nodes and sudden appearance of PUs on serving channel.

- Propose a new CR-RDV MAC protocol to handle the multiuser contention in CRAHNs. The most important feature of this protocol is proactive link maintenance with minimum control overhead in the case of PUs appearance.

1.2 Research Problems

In this thesis, RDV in CRAHNs is addressed as a potential research problem. RDV problem as initially described in [15] defines an optimal meeting criteria for two unit-speed players randomly placed in a known region according to known independent distributions. The RDV problem in CRAHNs has some additional requirements such as two players may not have locally known search region i.e. the search region is asymmetric and asynchronous between the players. Let's consider, there are at least two or more CR users in CRAHNs to act as players and the search region can be defined as a set of non-overlapping channels $C = \{C_0, C_1, C_2, ..., C_{N-1}\}$ where N is the number of available channels in the system. Now assume that two players, say user i and user j observe $C_i = \{C^i_0, C^i_1, C^i_2, ..., C^i_{M-1}\}$ and $C_j = \{C^j_0, C^j_1, C^j_2, ..., C^j_{N-1}\}$ set of channels with M and N in size respectively. Hence, the RDV problem can be defined as a search sequence followed by Users i and j, such that User i and User j can meet each other within minimum time.

The search sequence can be written as a tuple of two elements where the first element is time and the second element is the channel on which it searches for the other player at this instant, i.e. $A = \{(0, a_0), (1, a_1), ..., (i, a_i), ..., (t-1, a_{t-1})\}$. Here $a_i \in (0, N-1)$ represent the channel index. To achieve RDV, two search sequence A and B have to have at least one overlap in the search sequence, i.e. $A \bigcap B \neq 0$. The idea is to minimise the average time it takes for pair of nodes to achieve RDV, which can be expressed as a linear optimisation problem as follows:

$$\begin{aligned}
&\text{minimise } \mathbf{T} \qquad (1.1)\\
&\text{subject to } \forall A, B \in C, A \neq B\\
&C(rotate(A,k), rotate(B,l)) = N,\ \forall k, l \in [0, T-1]
\end{aligned}$$

The average time to achieve RDV is a ratio of length of the search sequence and number of overlaps within the search period. Hence Eqn. 1.2 can be written as:

$$\begin{aligned} &\text{maximise } (\mathbf{A} \bigcap \mathbf{B}) \\ &\text{subject to } \forall A, B \in C, A \neq B \\ &C(rotate(A,k), rotate(B,l)) = N,\ \forall k,l \in [0, T-1] \end{aligned} \tag{1.2}$$

The first constraint of the linear problem define the global search region for both A and B and the second constraint consider the time asynchrony between two search sequences.

The work carried out in this thesis is either an improvement made on previous studies in this field with some extensions or existing methods are integrated in a novel way to achieve better performance. The research questions related to RDV establishment in CRAHNs can be formulated as follows:

1. What are the factors that affect RDV performance in CRAHNs?
2. What should be the search strategy to achieve RDV in asymmetric CRAHNs?
3. How to solve the RDV problem in asynchronous CRAHNs?
4. How to minimise the RDV collisions in multiuser CRAHNs?
5. How to minimise the channel access delay in CRAHNs?

The first three questions in particular are related to design of a search sequence in asymmetric asynchronous CRAHNs. The rest of the questions handle the channel contention in multi-user CRAHNs based on the adopted search strategy proposed to answer the former questions. All these question will be answered in the rest of the thesis.

1.3 Research Methodology for Investigation

Wireless communication systems is an applied research discipline, in the sense that it frequently applies theory from other disciplines, such as economics, computer science, engineering and the social sciences, to solve the problems of wireless communication systems. Considerable research currently conducted in the wireless communication areas focuses on understanding phenomena and finding new truths which is generally known as "natural science" research. On the other hand, design science research, focuses on creation: "*how things ought to be in order to attain goals and to function*" [**?**]. The purpose of design is "to change existing situations into preferred ones" [**?**]. Design science research creates an artifact (something created by humans usually for a practical purpose). Two important characteristics of design science artifacts are relevance and novelty. First, an artefact must solve an important problem: i.e. being relevant. Second, to differentiate design science research from routine design, [16] suggest that design science research should address either an unsolved problem in a unique and innovative way or a solved problem in a more effective or efficient way. The main of objective of this thesis is to identify and quantify the key factors influencing RDV performance. To achieve this objective both analytical and simulation methods have been used to estimate the system performance.Fig. 1.1 shows the modified design science research method adopted in this thesis.

To predict the performance of RDV protocols, analytical modelling is widely used in the literature. Interestingly, RDV is a mathematical problem reported in [17–20] whose authors developed several analytical models to find an optimal solution during the search period in the two player environment. Working along this line, researchers from the wireless community have also presented a number of analytical models [21–23] for the same problem. Moreover, channel access in multi-user wireless scenario is well studied in the literature [24–27] using analytical modelling with the help of

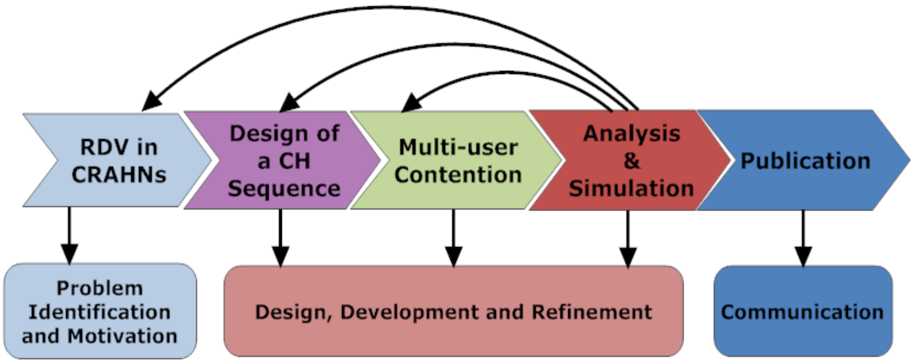


Figure 1.1: Modified design science research method.

probability, Markov chain and queuing theory.

Traditionally, the theoretical models are validated either by simulation or test bed or combination of both. Since it is difficult setting up a real world large scale deployment, simulations are often considered as the optimal approach of studying the performance of ad-hoc networks. There are many open source and proprietary simulators available in practice within the research community that allow users to have a better control of nodes and network environment and parameters.

In this thesis MATLAB is used as a primary tool for the performance study of CRAHNs, including the performance evaluation of a new CH protocol (Chapter 4) and a new MAC protocol (Chapter 6). The combination of analysis capabilities, flexibility, and reusability of the code makes MATLAB the premier software for scientific researchers. Authors in [28] showed that around 31% of the research published in year 2007 to 2009 used MATLAB as a simulation tool in telecommunication studies. The most important feature of MATLAB is its programming capability, which is very easy to learn and to use, and which allows user-developed functions. Another motivation of using MATLAB is that one can compare the proposed approach with the other protocols on a single common and pre-validated platform for simulations. The study carries out in this thesis mostly focuses on control channel establishment which involves channel sensing and initial channel negotiation in a single hop network. Matlab is one of the simplest but efficient simulator, especially for physical and data link layer. Alternatively, $NS-2$ simulation package can be used, however, which is more effective for network layer protocols.

Figure 1.2 shows the map of CR functionalities built in MATLAB. A detailed description of energy detection based spectrum sensing is described in chapter 5. The energy detector based approach is the widely used spectrum sensing because of its low computational and implementation complexities. When the primary user signal is unknown or the receiver cannot gather sufficient information about the primary user signal, the energy detection method is used. Channel ranking is the core of the RDV protocol proposed in this thesis. A linear optimisation based channel ranking method is developed in chapter 3 based on PU and CRs activities in the system. MATLAB has an in-built optimisation function to carry out the channel ranking operation. Finally the MAC process is well studied in the literature based on MATLAB based simulators.

In this thesis, the performance evaluation are presented in chapter 4 for the CH protocol and chapter 6 for the MAC protocol. Chapter 4, evaluates the performance of the proposed ETQCH protocol with existing channel rank based RDV protocols. However, it also compares the results with some non-channel rank based CH protocol in different network configurations. ATTR and degree of overlap are used to quantify the performance. A mathematical closed form formula is derived to estimate the degree of overlap in terms of quorum overlap size. In chapter 6, performance of the CR-RDV MAC protocol is analysed and compared with the well established CSMA/CA protocol. It is considered that both the protocols utilise the same CH scheme for RDV. The verification of the accuracy of the simulation results involves comparison with an analytical model. The proposed ETQCH and CR-RDV protocols were found to be flexible and effective to establish and maintain RDV in CRAHNs.

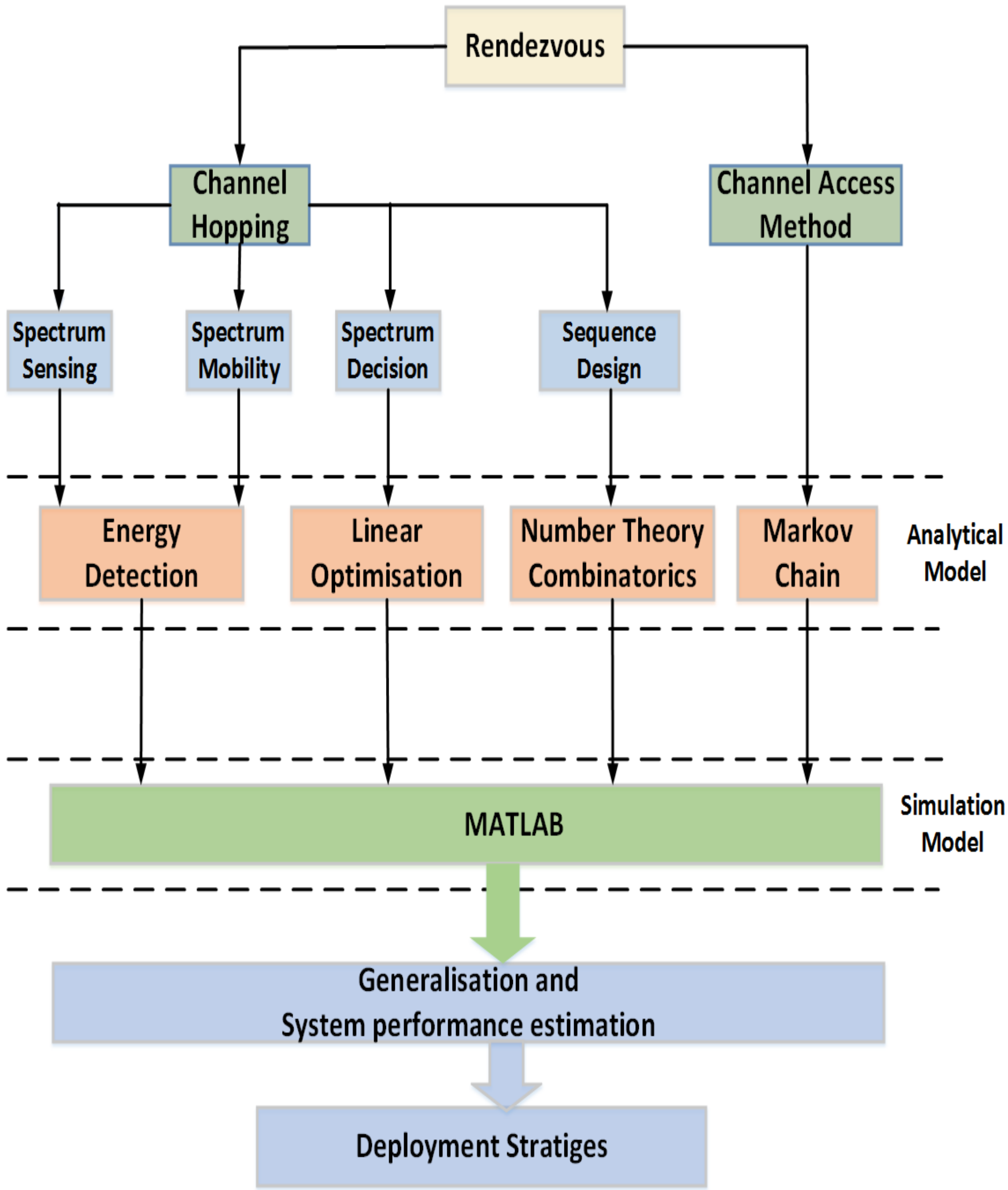


Figure 1.2: Block diagram of the adopted performance evaluation methodology.

1.4 Thesis Contributions

The thesis provides the following main contributions. A CH sequence based on the concept of a torus quorum system to overcome the channel asymmetry and asynchrony challenges is proposed. A MAC protocol is proposed to implement the proposed concept in multi-user CRAHNs.

ETQCH: Extended Torus Quorum Channel Hopping

Rendezvous in CRAHNs is a key measure for a pair of unknown CRs users to initiate communication. Due to the dynamic radio environment, RDV on a predetermined CCC cannot be guaranteed. CH provides an efficient method to guarantee RDV in CRAHNs. To design a CH scheme, assumption of symmetric channel information is widely employed in the literature. Unfortunately, in a dynamic radio environment CR nodes may observe a different set of channels. Moreover, the existing CH based schemes still suffer from high average time to rendezvous (ATTR) and low degree of overlap due to random channel selection for CH sequence design. To enhance the RDV performance, the CH sequences are designed based on channel quantity using different mathematical concepts such as prime number theory, Chinese remainder theory (CRT), quorum system and combinatorial block design and so on. This thesis claims that RDV in CRAHNs can be enhanced by considering channel quality information in CH design. It is assumed that neighboring nodes experience a similar PU activity with high probability which implies that there is a high correlation between their channel ranking [29].

Based on the above assumption, a channel ranking based CH scheme is proposed under blind (i.e. unknown) and asymmetric channel information scenarios. The fundamental idea is to assign more time slots to the channel with higher rank. The proposed approach, which exploits the rotation closure property of a torus quorum system to capture the asynchrony in CH sequence between two users is called extended torus quorum channel hopping (ETQCH). The extension of the torus quorum system is proposed to tackle the asymmetric channel information observed by different CR nodes.

CR-RDV: Cognitive Radio Rendezvous MAC Protocol

The ETQCH is a RDV concept that uses the available spectrum more efficiently based on channel ranking. However, ETQCH is a mathematical concept, and some open issues still exist as mentioned in research question 4 and 5. Thus, a detailed MAC protocol is needed to answer the aforementioned questions.

In order to handle the RDV collision issue mentioned above, the CR-RDV protocol considers a two radio transceiver architecture. During RDV operation, a CR node sends a channel probing packet according to the CH sequence and waits for a reply. Upon reply, RDV will be established. It could happen that some other CR nodes already achieved RDV on the probing channel which causes a RDV collision with the current RDV attempt. To eliminate the RDV collision, a parallel sensing policy is proposed. So when a CR node performs RDV in one channel, the next channel from the CH sequence will be sensed in parallel using the additional radio. If the channel is found to be busy, it will be eliminated from the channel list and replaced by the previously achieved RDV channel or the best channel from the channel list.

To minimise the channel access delay due to channel negotiation or multi-user channel contention for both RDV and data channel, the CR-RDV modifies the carrier sense multiple access (CSMA/CA) protocol. Some modifications are proposed to control messages to make the coordination process between sender and receiver more efficient. For example, extra fields are added to control messages to negotiate DC, BC and RC during the RDV process between the transmitter and receiver.

To cope with sudden PU appearance, the CR-RDV uses the BC concept. The BC is negotiated between the transmitter and receiver prior to the actual data transmission.

Thus, when a PU appears, both sender and receiver switch to the BC without additional control messages which leads to minimising the control overhead required to find a new channel in the case of PU's appearance. Furthermore, neighboring nodes are informed about channel switching to further reduce the collisions.

1.5 Structure of the Thesis

This thesis has eight chapters with the structure shown in Fig. 1.3.

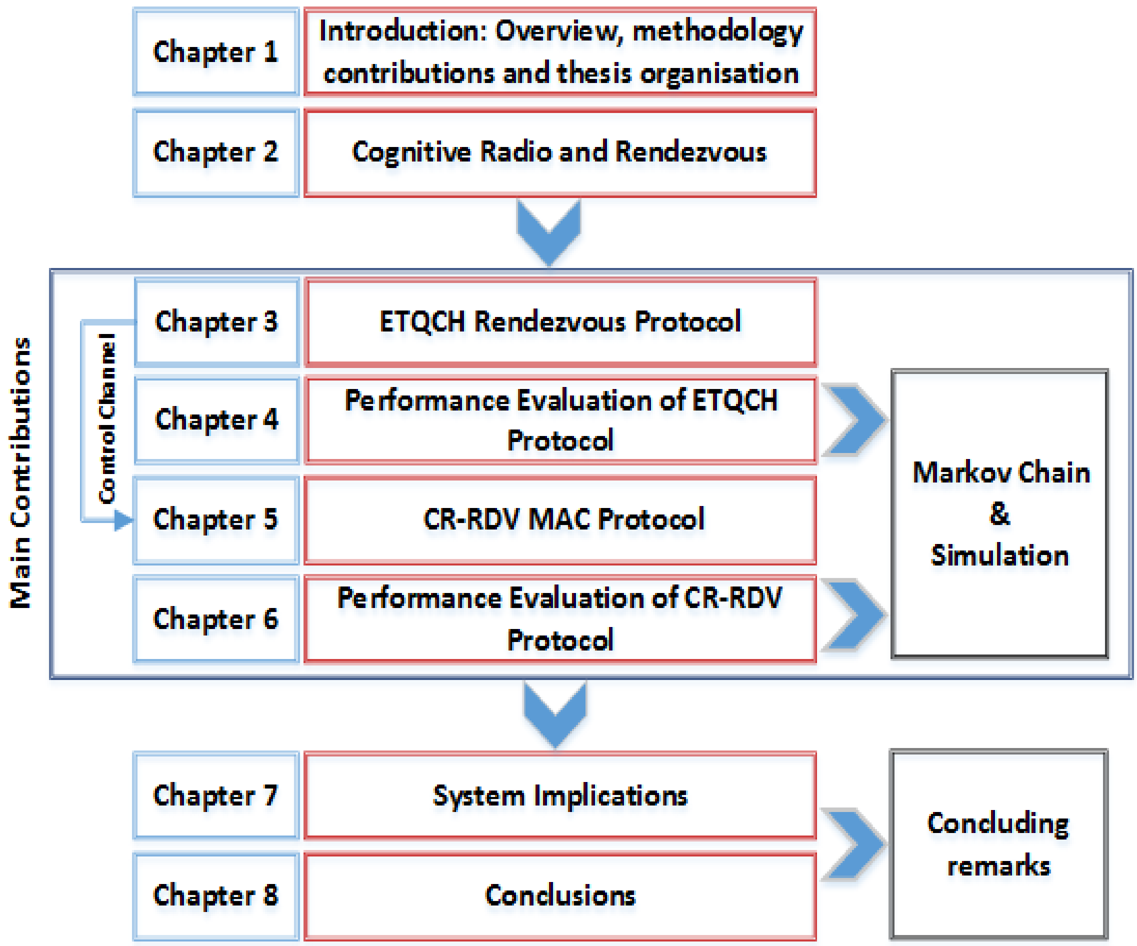


Figure 1.3: Structure of the thesis

Chapter 2 provides a detailed overview of CR technology and its functionalities. Furthermore, RDV in CRAHNs is introduced and discussed the difference with traditional ad-hoc networks. It also contains a review of previous studies on RDV schemes for CRAHNs. In the review, the existing RDV schemes which includes CCC and CH methods are investigated. In the context of CH, various RDV CH approaches are summarised and they are classified based on underlying mathematical concepts. Based on the survey, various performance issues are identified to design a CH RDV scheme.

Chapter 3 presents a new CH RDV scheme, ETQCH, to achieve RDV in asymmetric asynchronous CRAHNs. ETQCH utilises the extended torus quorum structure and maps the channel based on channel ranking. A linear optimisation based channel ranking method is introduced considering both PUs and CRs collision probability. In this chapter, an adaptive ETQCH is described to protect the intermittent PUs transmission.

Chapter 4 reports the performance enhancement achieved by using the ETQCH protocol. A mathematical formulation is derived to estimate the degree of overlap in terms of expected quorum overlap size. A detailed simulation set up and results are presented to verify that the ETQCH performs better than that of both existing channel rank and non-channel rank based CH protocols.

Chapter 5 addresses the issues and challenges in the design of a CR MAC protocol through a brief literature review. A new CR MAC protocol called CR-RDV is proposed to implement the RDV concept in chapter 3. The CR-RDV protocol is developed as a modification of the CSMA/CA virtual carrier sensing (VCS) method that overcomes the blocking problem due to unsuccessful transmission from neighbors node. Moreover, a protocol state machine of the CR-RDV protocol is described to understand the protocol behavior.

Chapter 6 presents the both the analytical and simulation results of the CR-RDV

MAC protocol. A theoretical formulation, based on a Markov chain is discussed in detail to evaluate the performance of the proposed CR-RDV protocol. It is also extensively evaluated using simulation. The simulations are conducted in three different network environments: (i) dense network i.e. number of nodes in the network (ii) large network i.e. network resources (iii) highly active PUs.

Chapter 7 reports the major findings from chapter 3 to 6 from the perspective of system planning and deployment. This relates the key factors influencing RDV performance in CRAHNs to design and deployment in a real environment. Furthermore a number of possible future developments of this research are highlighted in this chapter.

Chapter 8 summaries the contributions and concludes the thesis. The concluding remarks are also drawn from system planner point of view to provide a guideline or study before deployment of a CR based ad-hoc network.

Chapter 2

Cognitive Radio and Rendezvous Protocols

2.1 Introduction

In chapter 1, the motivation for the performance estimation and improvement of RDV establishment in CRAHNs was presented. In a multi-channel wireless ad-hoc environment, RDV is the first key step for CR users to be able to communicate with each other. RDV in CRAHNs is analogous to control channel establishment in traditional multi-channel wireless ad-hoc networks despite fixed channel assignment. Hence, one of the main objectives of this thesis was to identify and quantify the key factors influencing RDV design. To achieve this objective, a brief introduction to cognitive radio and its basic components is required, which is included in this chapter. The chapter also discusses the requirements in the design of CR-related RDV protocols.

In Section 2.2 the basic definition of CR and its cognition cycle is discussed. The cognition cycle includes the control processes of a CR in utilising and analysing the surrounding spectrum knowledge to modify its transmission parameters in an adaptive manner. Section 2.3 presents the RDV concept in CRAHNs and its difference to traditional multi-channel ad-hoc networks. In Section 2.4, a review of the literature considering the design and performance improvement of the CR RDV protocol is described. Further, the well-known RDV protocols for CRAHNs and their main concepts are highlighted in that section. It also describes the CH RDV protocols and classifies them based on the underlying mathematical concepts. In Section 2.5 various performance issues concerning CH based RDV protocols are presented. Three important design issues in CR RDV protocols are discussed in Section 2.6: channel state information, PU activity and time synchronization. Finally, the chapter is summarised in section 2.7.

2.2 Cognitive Radio

Cognitive Radio (CR) is one of the most promising concepts in facilitating the flexible usage of the radio spectrum and enhancing the spectrum utilisation by enabling unlicensed users to exploit the spectrum in an opportunistic manner. The term "cognitive radio" was introduced by J. Mitola in a number of publications (e.g., [8], [30]) including his PhD thesis [31]. According to his definition, cognitive radio can be described as an autonomous radio frequency transceiver which can intelligently detect whether a particular segment of the radio spectrum is in use, and jump into (and out of) the temporarily unused spectrum very rapidly without interfering with the transmission of other authorized users [31]. A much narrower definition was introduced by the Federal Communications Commission (FCC): "*a CR radio is a radio that can change its transmitter parameters based on the environment in which it operates*" [5]. Since the FCC's definition was coined, many studies in the literature have focused on this narrower view. In this context, Haykin [32] defines CR as a radio capable of being aware of its surroundings, learning, and adaptively changing its operating parameters in real-time with the objective of providing reliable anytime, anywhere, spectrally efficient communication.

In general, cognitive radios must be intelligent enough to learn the radio environment and adapt the transmission/reception parameters to meet performance requirements and maximise the spectrum efficiency. Operation of the cognitive radio can be described by the cognitive cycle as shown in Fig. 2.1. The steps involved in the cognitive cycle are discussed below:

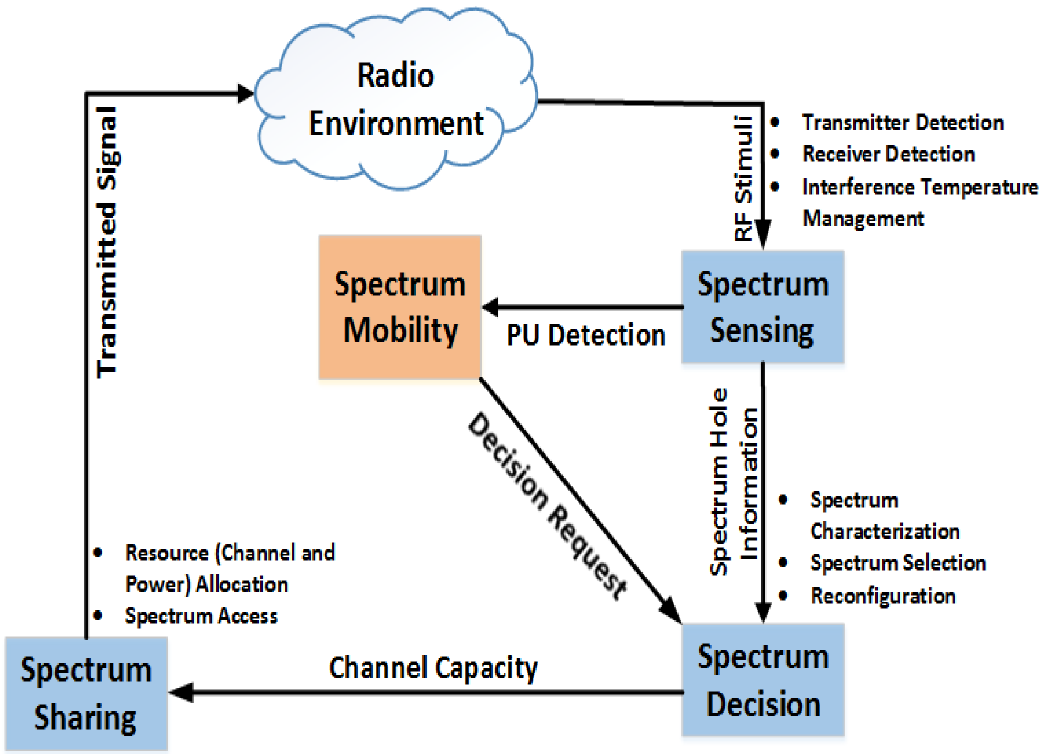


Figure 2.1: Cognitive cycle [1]

Spectrum Sensing

The cognitive cycle starts with sensing the radio environment and analysing the RF stimuli through transmitter detection, receiver detection and level of interference. The sensed spectrum information must be sufficient for the cognitive radio to reach accurate conclusions regarding the radio environment. Furthermore, spectrum sensing must be fast in order to track the temporal variations in the radio environment.

Existing spectrum sensing techniques depend on detecting the activities of the primary transmitters. Such schemes are generally classified as matched filter detection, energy detection, feature detection, and interference temperature measurement. The purpose of spectrum sensing is to classify the frequency bands in its surroundings. There are three categories: black space, grey space and white space. Black space indicates that, this portion of frequency band is occupied by the licence user with a high power signal. Grey space means the frequency band is temporarily occupied by licence user with a low power signal, and if it is free of licence users it is known as white space or spectrum holes. Fig. 2.2 illustrates the concept of spectrum white space.

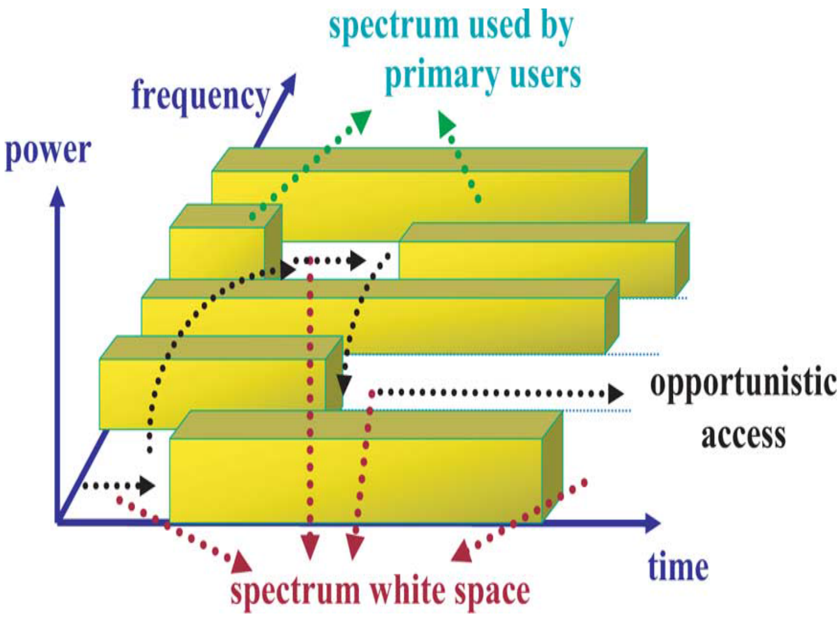


Figure 2.2: Concept of spectrum white space [1]

Spectrum Decision

The result of spectrum sensing process is a list of spectrum holes, which is utilized in the spectrum decision process to select the appropriate spectrum bands according to the user QoS requirements. QoS requirements includes quality of spectrum bands in terms of transmission power and availability(time duration) of the spectrum band. However, none of these qualities can be assured without prior information regarding the statistical behaviors of the PUs. Moreover, if the current serving spectrum band does not support the required QoS, the CR nodes will always search for another spectrum band and reconfigure its transmission or physical parameters to operate. As a consequence, the CR node has to update its routing table in multi-hop communication.

Spectrum Sharing

Based on the channel capacity information gained from the spectrum decision process, CR users will share the available radio resources for transmission. The spectrum sharing issue is raised when multiple CR users are trying to access the spectrum. In infrastructure-based network architecture, this issue can be controlled by the CR base station. However, this issue become more severe in a distributed network, where nodes will make their decisions independently. Hence a set of rules to share and access the available channels among CR users is required. Alongside that, it is necessary to control the transmission power in order to avoid interference with other CR users or PU transmission.

Spectrum Mobility

After completing the contention period, the CR node starts its transmission. However, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users. Hence, a CR node should immediately vacate the spectrum upon detection of a licensed user on the particular frequency band, known as spectrum handoff or spectrum mobility. In spectrum handoff, a temporary communication break is inevitable due to the process of discovering a new available spectrum band. Since the available spectrum is discontiguous and distributed over a wide frequency range, CR users may require the reconfiguration of the operation frequency in its RF front-end, which leads to significant throughput degradation due to communication and switching overheads. Moreover, the protocols for different layers of the network stack must adapt to the channel parameters of the operating frequency and be transparent to the spectrum handoff. Therefore, each time the CR changes its frequency of operation, the network protocols shift from one mode of operation to another. The purpose of spectrum mobility is to make smooth and faster protocol transitions such that the CR user perceives minimum performance degradation during a spectrum handoff. Moreover, it is essential for the mobility management protocols to learn in advance about the duration of a spectrum handoff.

Therefore, a CR device is able to perform spectrum sensing to detect and monitor the surrounding RF environment for interference and access availability. Based on sensing, it will reconfigure its own operating parameters to best utilize the radio spectrum. Hence, cognitive radio communications can be used to increase spectrum efficiency and support the rapidly growing demand for wireless applications at personal and industry level, including public health and safety, smart grid, and broadband cellular applications. However, successful operation of CR based communication depends on the guaranteed RDV achieved by a pair of communication CR devices. The concept of RDV and existing mechanisms to achieve RDV are discussed next.

2.3 Rendezvous in Cognitive Radio Ad-Hoc Networks

A CRAHN is shown in Fig. 2.3 as being composed of three PU base stations (BSs) and a set of PUs and CR nodes distributed randomly within the coverage area of PU BSs. PUs and PU BSs are in general not equipped with cognitive functions. A CR node shares a licensed spectrum band with the primary networks. Besides detecting the spectrum white space and utilising the best spectrum band, the CR node is required to immediately detect the presence of a PU and direct the CR transmission to another available band so as to avoid interfering with PU transmission. Their transmission should not be interfered with by secondary networks. A CRAHN refers to a network composed of a set of CR users without a CR BS. CR users can only access the licensed spectrum when it is not occupied by a PU. The opportunistic spectrum access of CR users is usually coordinated by the CR nodes. Therefore, to establish communication, the CR nodes perform spectrum sensing (local sensing) and identify the available spectrum white spaces or holes. Assume that the output of the spectrum sensing for CR nodes A and B are {1_1,1_2,1_3,3_1,3_2} and {1_3,1_4,1_5} respectively. The issue of channel RDV arises, as the availability of these white spaces is not the same for both users. This information may change dynamically in frequency, time and space. Moreover, the set of available channels depends on its location relative to the PUs. A pair of nodes (node A and B) desiring to communicate with each other has to exchange control information on an unoccupied channel to enable the establishment of a link. To enable reliable exchange of control information, two nodes should RDV in one channel commonly available to them. Here, RDV means that two nodes access a channel during a certain period of time which is long enough to establish a reliable link. Hence, if node A and B wish to communicate with each other, they have to exchange the control information on channel {1_3} as shown in Fig. 2.4.

The RDV channel in CRAHNs differs significantly from traditional multi-channel environments, where one channel is commonly available to all network nodes to exchange and disseminate the control messages. In traditional wireless networks, nodes have symmetric channel information and follow static (global dedicated) or dynamic (local, based on channel hopping) control channel assignment. In contrast, CRAHNs are meant to utilize the heterogeneous wireless networks with asymmetric channel information. The channel availability in CRAHNs depends on PU activity, which varies

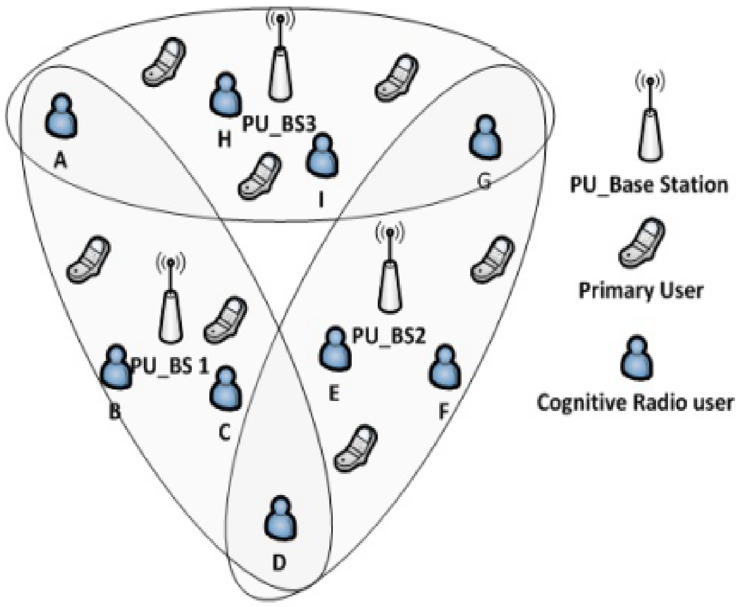


Figure 2.3: Cognitive radio ad-hoc networks

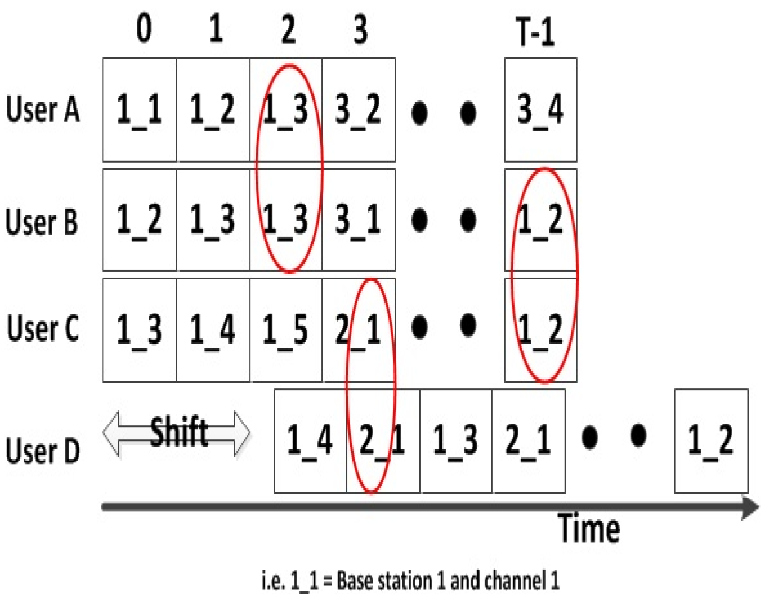


Figure 2.4: Rendezvous problem in CRNs

in time, space and frequency. Therefore, a new control channel has to be established upon PU's return to the current control channel. Unlike multi-channel wireless networks, CR users usually observe different sets of available channels, each of which is a subset of the set of all licensed channels. Due to this spectrum heterogeneity in CR networks, it is unlikely a channel will be found that is commonly available to all users as the control channel. Fig. 2.5 shows the role of the RDV process in the cognition cycle in accessing, updating and maintaining connectivity. It is necessary to establish the RDV prior to spectrum sharing. This is because in distributed ad-hoc networks, spectrum sharing information is carried over the control channel which is only for the RDV process.

Several extensive studies have been performed regarding the RDV design process. In section 2.4, a review of the literature on existing RDV protocols is presented.

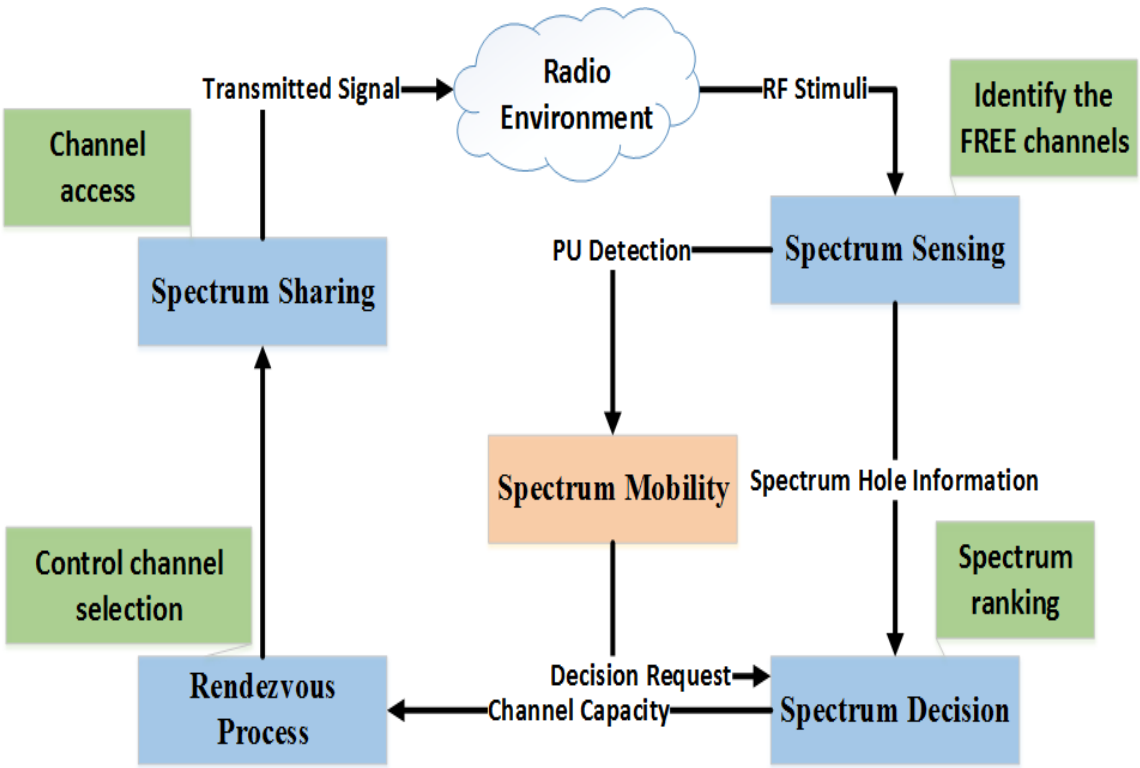


Figure 2.5: Illustration of rendezvous process in cognition cycle

2.4 Rendezvous Protocols: A Review of Literature

The design of RDV protocols in CRAHNs originated from the traditional multi-channel wireless networks. In traditional wireless networks, a common channel is employed in the entire network to serve as a control channel. However, such a dedicated control channel is not feasible in CRAHNs due to the special requirement to protect the license users. Therefore, numerous RDV protocols are studied in the current literature. An efficient RDV protocol should provide a mechanism to establish a link to initiate the communication together with simplicity of operation, protection of the licence users' transmission, and fairness in serving all stations. However, there is no existing RDV protocol which can guarantee all these characteristics. Hence, a variety of RDV protocols have been developed to suit different circumstances where various tradeoff factors are considered [33–38]. In this section, a review of the literature on CRAHNs RDV protocols focuses on: (i) RDV protocol classification, (ii) common control channel versus channel hopping, and (iii) representative RDV protocols.

Rendezvous Protocol Classification

Rendezvous protocols in CRAHNs can be classified in many different ways. For example, the author in [39] categorises RDV protocols based on the availability of information to carry out the RDV process: aided RDV and unaided RDV systems.

In the aided RDV system, the CR node performs the local spectrum sensing and forwards the sensing information to a centralized controller to assist the RDV process. To disseminate the sensing information a pre-selected common channel is considered in both DIMSUMNet [40] and DSAP [41]. However, an exhaustive search-based common channel is considered in [42].

Similar to aided RDV, in unaided RDV the CR node performs the local spectrum sensing and uses it to find the common channel between peer nodes. However, nodes may still share their sensing information by using a network-wide dedicated [43–47] or group wise (local) [48–51] common control channel (CCC), or single, multiple or no control channels. "No control channel" refers to no pre-defined channel, which implies that any channel can be used as the control channel based on availability.

Common Control Channel versus Channel Hopping

In addition to the CRAHNs RDV protocol classification outlined earlier, the existing RDV protocols can be divided into two main categories: (1) common control channel (CCC); and (2) channel hopping (CH). In the CCC based protocol two users tune the radio in the network wide or local common channel to exchange the control information. This common channel can be selected from the unlicensed band or the licensed band. In [45, 52] the authors considered a global CCC that can be used by all users in a decentralised system. In contrast, a local CCC is considered in [53, 54] and forms a cluster based on available channel set. Any time a CR node wants to transmit a packet, it selects a channel from the cluster group channel set and exchanges control information. It is obvious that CCC based RDV schemes are very easy to deploy and efficient in a centralised or coordinated network. Hence, in purely distributed ad-hoc networks (with no coordination and no prior agreement), the performance of CCC based RDV protocols is limited by these factors: (i) single point failure, (ii) vulnerability to PU activity, (iii) channel saturation, and (iv) control channel jamming.

To overcome this performance instability, a CH or parallel RDV is proposed in [38]. When a CR node wants to transmit a packet to its peers, it switches from one channel to another by following a pre-defined [55] or random hopping sequence [29]. A desirable property of a CH sequence scheme is that it can guide any two users in the network to hop on the same channel in the same time slot as soon as possible. Moreover, it should able to explore the temporal and spatial distribution of the control channel in order to minimise the interference with the licence users.

2.4.1 Representative Rendezvous Protocols

In the last 10 years, a number of RDV protocols have been developed for CRAHNs. However, due to the dynamic nature of licensed users, dedicated CCC is impractical and it suffers from saturation and single point failure problems in high density networks. Moreover, due to spectrum heterogeneity, it is quite complex and expensive in terms of time and cost to obtain and maintain a global or local CCC. Therefore, only CH based RDV protocols are considered in this thesis. Table 2.1 lists the leading research works, assumptions considered for the protocol design, and main concepts in different columns.

Random CH Sequence

Say there are N channels available in the system for all CR users. A pair of nodes that want to establish communication visit the available channels in random order [39]. At each time slot, the intended CR user will select any one of the channels with probability $1/N$. Hence, TTR is computed as a first success of independent Bernoulli trials which is a geometrically distributed random variable. To address these issues, the authors in [29] proposed an adaptive multiple rendezvous control channel (AMRCC) hopping sequence. Upon joining the network, a CR node will perform periodic sensing and rank available channels based on PU activities. Subsequently, a pseudo random hopping sequence is generated to map the channels according to the channel rank list. Based on the length of the sequence, the AMRCC has two variants shown in Fig. 2.7, called (i) Basic AMRCC and (ii) Enhance AMRCC. Basic AMRCC uses the decreasing linear function, and the parabolic decreasing function is used by Enhance AMRCC. A CR node will continue to hop as per the hopping sequence until it achieves rendezvous. However, nodes need to hop continuously even after rendezvous, which accumulates consecutive switching delays. After every sensing period the nodes have to synchronise again to achieve rendezvous, which introduces

Table 2.1: Summary of DSA Common Hopping Algorithms

Protocol	Synchronization	Pre-defined Sequence	Information	Rendezvous	Channel set	Concept
SSCH [38]	Partial	YES	NO	YES	Symmetric	Modular Arithmetic
MCMAC [56]	YES	YES	MAC Address	NO	Asymmetric	Pseudo random hopping based on MAC address.
SYN-MAC [42]	YES	YES	2 Radios	NO	Asymmetric	Time is divided into equal number of channels.
RingWalk [57]	NO	YES	Node ID and Network Size	YES	Asymmetric	visit Channels with different velocities based on node ID.
M-/L-QCH [58]	YES	YES	NO	YES	Symmetric	Majority and Minority cyclic quorum system.
A-QCH [58]	NO	NO	NO	YES (for 2 channels)	Symmetric	Based on Latin square and identical Row Square.
Seq-MRCC [3]	YES	YES	NO	YES	Symmetric	Permutation based CH.
AMRCC [29]	NO	NO	NO	NO	Both (Symmetric and Asymmetric)	Pseudo random CH to map the ranked channels.
CRSEQ [55]	NO	YES	NO	YES	Both (Symmetric and Asymmetric)	Based on triangular numbers and CRT.
MC [39]	NO	YES	NO	NO	Symmetric	Prime modular arithmetic with adaptive rate.
MMC [39]	NO	YES	NO	NO	Asymmetric	Prime modular arithmetic and CRT with adaptive rate.
DSMMAC [59]	NO	YES	NO	NO	Symmetric	Utilize the rotation closure property of difference set.
JUMP-STAY [60]	NO	NO	NO	YES	Both (Symmetric and Asymmetric)	Jump and Stay pattern using modular arithmetic.
gQ-RDV [61]	NO	NO	Channel Ranking	YES	Asymmetric	Grid quorum structure based on available channels
DRSEQ [33]	NO	NO	Channel Ranking	YES	Symmetric	Visits the channels based on channel label and alternate it at each period.
SeqR [3]	NO	NO	Channel Ranking	YES	Asymmetric	Permutation based CH.
EJS [34]	NO	NO	Channel Ranking	YES	Asymmetric	Increase the length of JS protocol.
SSB [35]	NO	NO	Channel Ranking	YES	Asymmetric	visit the channels from the head to end of it and travel back to the starting point in opposite way.

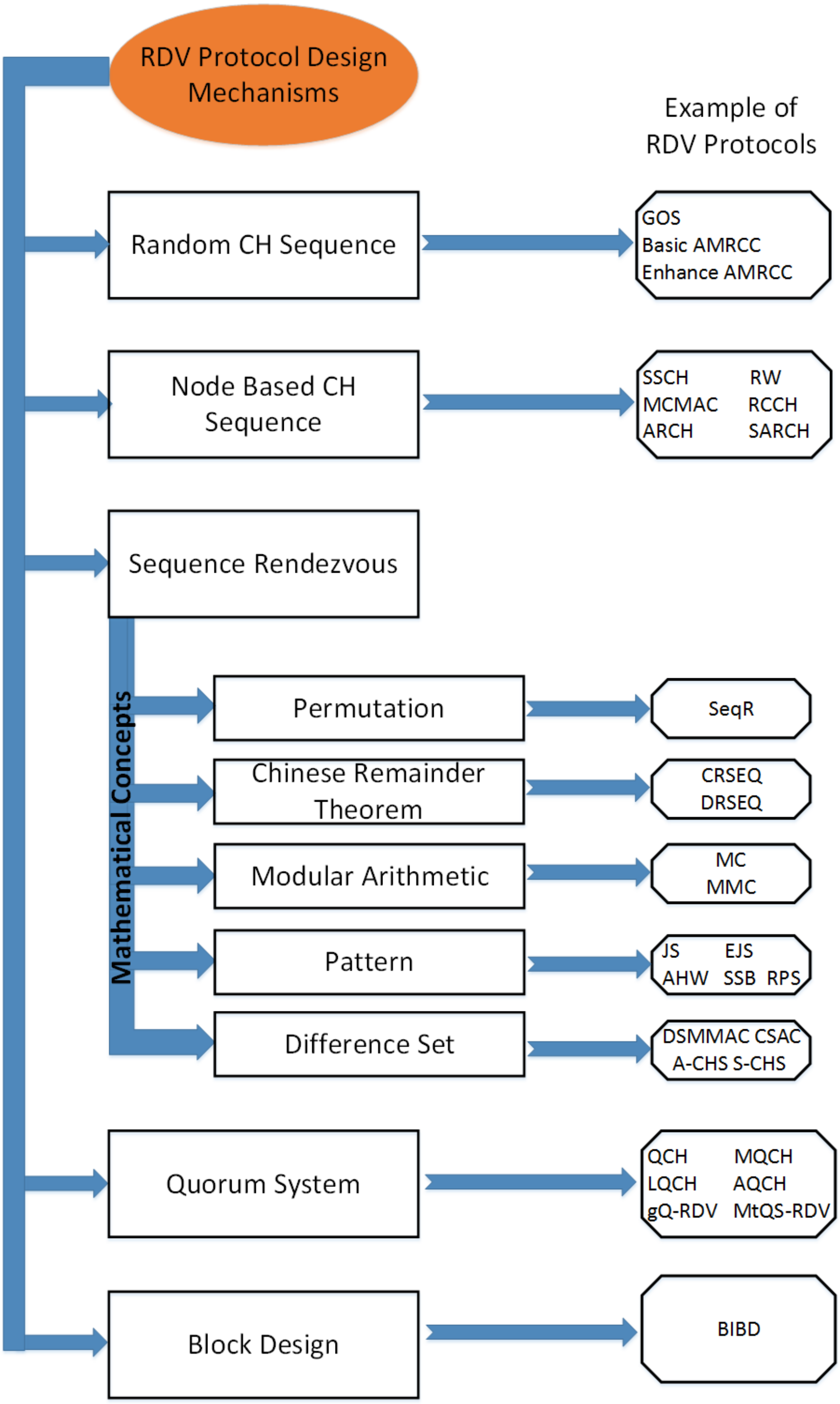


Figure 2.6: Mechanisms used in the design of representative CR RDV protocols.

additional delays.

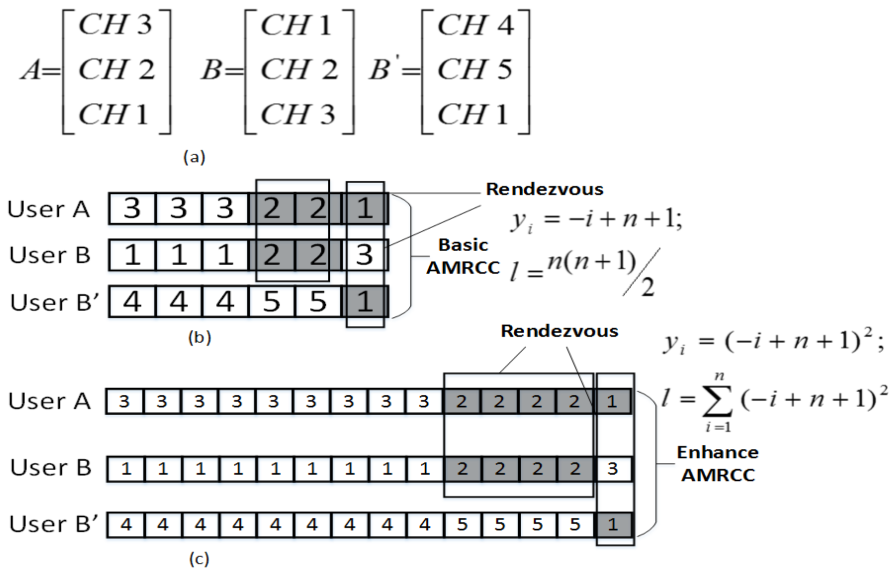


Figure 2.7: (a) Channel ranking list of user A, B and B' Construction of CH sequences by using (b) Basic AMRCC. (c) Enhance AMRCC

Node ID Based CH Sequence

Channel hopping is a process where nodes hop onto different channels based on a predefined or random hopping sequence. To achieve rendezvous, the transmitter and receiver utilize the property of the hopping sequence which can guarantee time to RDV (TTR). The simplest form of hopping sequence for IEEE 802.11 networks is proposed in [38], known as slotted seeded channel hopping (SSCH). SSCH exploits frequency diversity and it produces a channel hopping sequence by using a set of {(channel, seed)mod(number of channel)} pairs to achieve rendezvous at least once in a cycle. The requirement of tight time synchronization is one of its main drawbacks. In addition to that it also imposes extra overhead to maintain the channel schedules of all the other neighbouring nodes. Hence the authors in [56] propose a multi-channel hopping sequence using the sender's own MAC address as the seed to generate a random hopping sequence. During the idle time, the sender listens to the channel based on its sequence and accumulates the information about its one-hop neighbours. Therefore, when a node has data to send, it can predict the hopping sequence of its intended receiver in its one hop neighbours list. However, the proposed protocol does not fit with the concept of cognitive radio where a node needs to redesign its hopping sequence more dynamically due to PU arrival. Moreover, it cannot guarantee the rendezvous for the linear congruential process nor solve the synchronization issue.

Likewise, based on node identification (ID), the authors in [57] proposed a Ring-Walk (RW) channel hopping sequence where each licensed channel is considered a vertex in a ring and generates a CH sequence to visit vertices in the ring. Based on Node ID, a CR node has a distinct velocity of walk, so that nodes with higher velocity can eventually meet with other CR nodes and achieve RDV. The proposed Ring-Walk protocol does not show how to avoid interference when PUs appear in a particular channel. As node ID is static and pre-defined, this protocol is not able to combat the dynamic nature of the radio environment. Moreover, it is impractical to have static node IDs in large, dense, distributed ad-hoc networks.

Sequence Based CH Sequence

In order to achieve guaranteed performance, a designed CH sequence should have two fundamental characteristics [58]: Guaranteed TTR i.e. periodic overlap between sender and receiver CH sequences and a number of rendezvous channels in the hopping cycle.

- **Permutation Method**: Permutation is one of the methods to pose randomness and assign the desired properties in the CH sequence [3]. In this approach, the radio employs a pre-defined permutation of available channels to construct an overlapping channel hopping sequence which can increase the probability of two radios hopping to the same channel. Moreover, to avoid interference with PU users, the hopping pattern is updated by just removing the reclaimed licensed

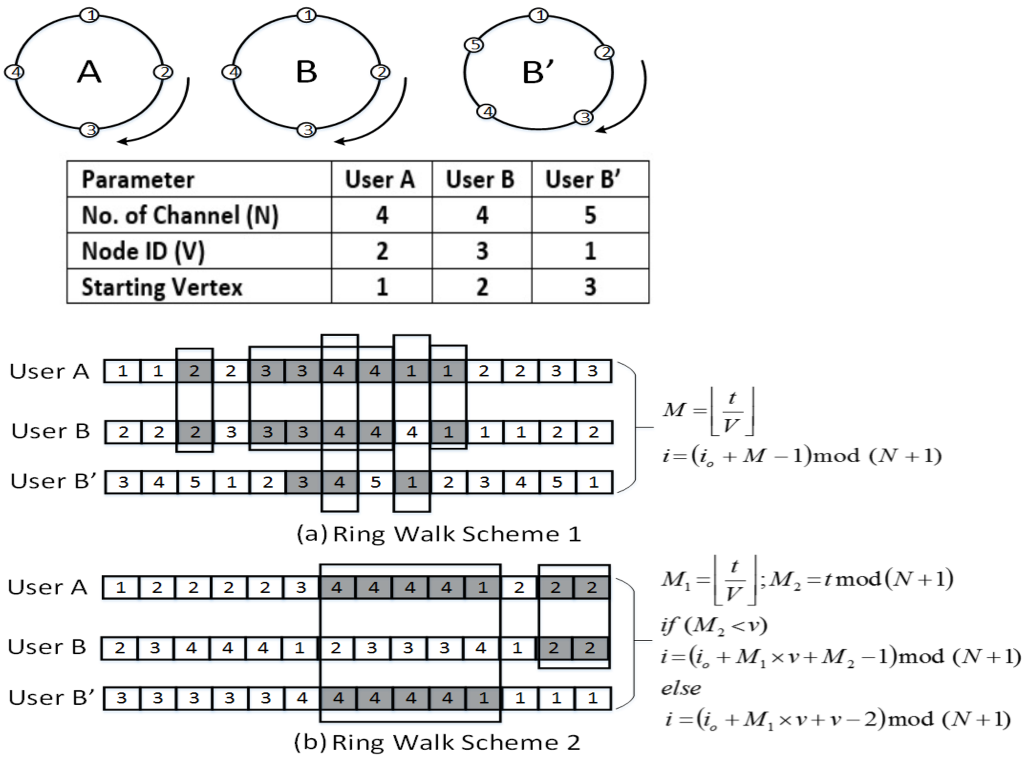


Figure 2.8: Illustration of CH sequence generation based on (a) Ring Walk scheme 1 (b) Ring Walk scheme 2.

channel from the pre-defined sequence. The method shows that the expected TTR is bounded by the quadratic function of the number of available channels. Therefore, the expected TTR increases when the number of available channels is too large for their quadratic relationship. The channel hopping sequence becomes progressively shorter as it cannot adapt to the increasing PU activity and loses diversity in channel usage. A protocol based on similar concepts is presented in [42], where a sequential channel hopping sequence is designed in both frequency and time domain i.e. the number of time slots in each hopping cycle is equal to the number of available channels in the system. This protocol utilizes two separate transceivers for control and data information. Hence, it can easily update and notify the control information such as PU return and channel quality to its neighbour. Unfortunately, it incurs additional delay due to PU arrival in the control slot.

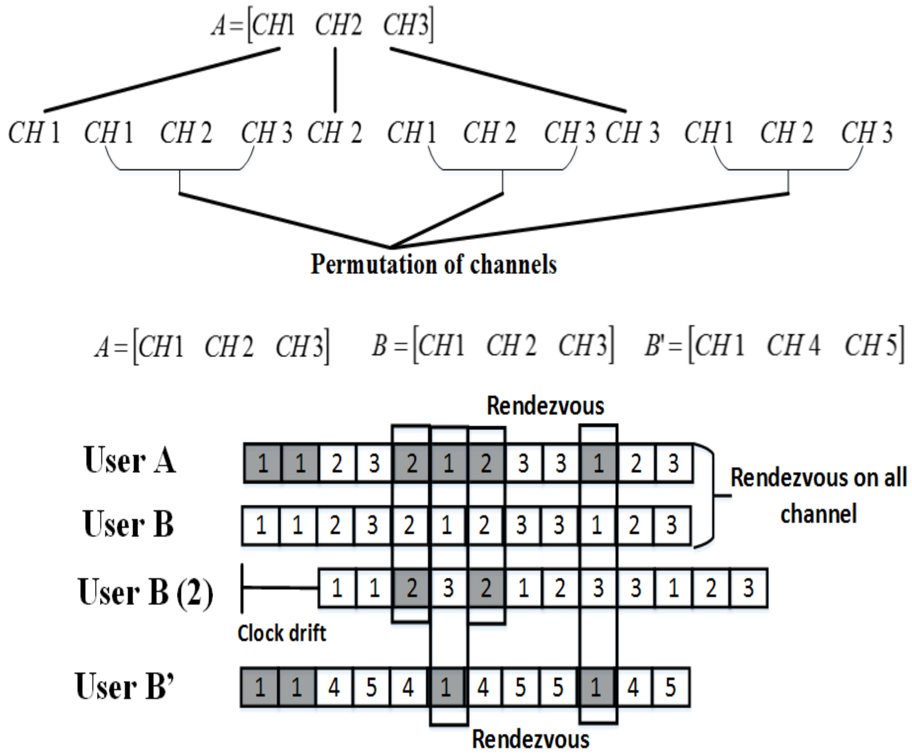


Figure 2.9: Illustration of permutation based CH sequence for a channel set, $N = 3$.

- **Chinese Remainder Theorem Method**: All of these protocols consider that the set of available channels for CR users is the same. Unfortunately, the sensing result for CR nodes is tightly coupled with their geographic locations. Based on this assumption, the authors in [55] proposed a deterministic rendezvous CH sequence protocol called Channel Rendezvous Sequence (CRSEQ). CSREQ is constructed based on the properties of triangular numbers and CRT or modular operation. For the total N number of channels the complete sequence consists of P subsequences where P is the smallest prime number greater or equal to N. Then it shows that for $N \geq 2$ channels, CRSEQ has a K shift RDV property for all $k(=0,1,2,3,...,(M-1))$ so that nodes can achieve RDV within $N(3N-1)$ slots. Further improvement of the CRSEQ protocol is the deterministic RDV scheme in multichannel access networks (DRSEQ) developed in [2] for both symmetric and asymmetric models. For symmetric model it generates identical CH sequences, showing that two nodes can achieve RDV within $2N+1$ slots. However, both of these protocols are unable to manage the dynamic nature of the radio environment, i.e. they do not guarantee to avoid interference with PUs.

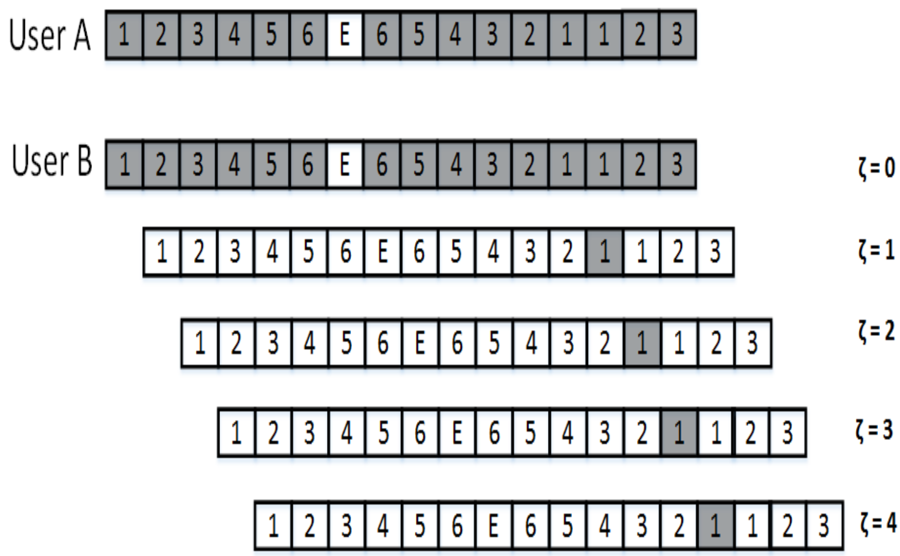


Figure 2.10: Illustration of DRSEQ CH sequence for $N = 6$ [2] with clock drift.

- **Modular Arithmetic and Prime Number Method**:Thies et al in [39] propose two different algorithms called Modular Clock (MC) and Modified Modular Clock (MMC) for symmetric and asymmetric channel information respectively to avoid the interference with PUs. Both of the algorithms are based on prime modular arithmetic such as $C_{i,j} = ((j+r) mod P$ where i, $J \in [0, m_i)$, r, P represent the nodes themselves, nodes available channel list, rate and prime number respectively. If the available channel observation of two CR nodes are symmetric and both nodes use the same prime number with different rates, the MC protocol can achieve RDV within P time slots. If the TTR value is more than $2P$, the nodes will change the rate. The modified version of MC protocol, i.e. MMC, adopts CRT to address the asymmetric case. In this scheme CR nodes will select different prime numbers i.e. $P1$ and $P2$ and perform the same arithmetic algorithm which can guarantee to achieve TTR at most $P1P2$ time slots. However, there is no guarantee of TTR if the CR nodes select the same prime number (P) and rate (r) in the MC and MMC protocols.

- **Pattern Method**:The authors in [60] proposed a jump-stay pattern CH algorithm for both symmetric and asymmetric models without exploiting time synchronization. The jump-stay algorithm consists of two consecutive jump patterns followed by one stay pattern. The total length of the jump-stay pattern for the symmetric model is 3P (2P for the jump and P for the stay pattern) time slots, where P is the smallest prime number greater than M (no. of available observed channel). In the symmetric model with 2 users, the maximum TTR (MTTR) is $3P$ and in the asymmetric model it is $3MP(P - G) + 3P$ where G is the number of common channels. However, MTTR grows dramatically with the number of channels as it does not have any preference to achieve RDV on a particular channel, i.e. channel ranking is not considered during the construction of the hopping pattern. Instead of having a 2 consecutive jump and 1 stay pattern, the authors in [36] proposed an alternate hop-and-wait pattern based on node ID. If the least significant bit (LSB) of the node ID is 0, the CR user performs a single wait pattern with length P (P is the smallest prime number greater than the number of available channel M) followed by $2P$ hop patterns and $3P$ time slots long hop patterns if it is 1. After generating the first set of CH sequence, a CR user will perform the rotate right operation

(ROR) on node ID and generate another set of CH sequence based on LSB. This procedure will repeat until all the bits of ID strings are utilized. Hence the total length of the CH sequence becomes $length(ID)3P$. Based on this protocol, any two CR users can achieve RDV in at most $3P(logN_{node}+1)$ and $3P(logN_{node}+1)(min|M_A|,|M_B|+1-|G_{\_}(A,B)|)$ (where $|M_A|$ and $|M_B|$ is the number of available channels of CR users A and B respectively and $|G_{\_}(A,B)|$ is the number of common channels between A and B) time slots under the symmetric and asymmetric model respectively. In multi-user scenarios, MTTR is $3P(logN_{node}+1)D$ and $3P(logN_{node}+1)(min|M_A|,|M_B|+1-|G_{\_}(A,B)|)D$ for the symmetric and asymmetric models. However, the length of CH sequence is strongly dependent on node ID, which is not realistic in dense networks, as node ID will grow proportionally with the size of the network.

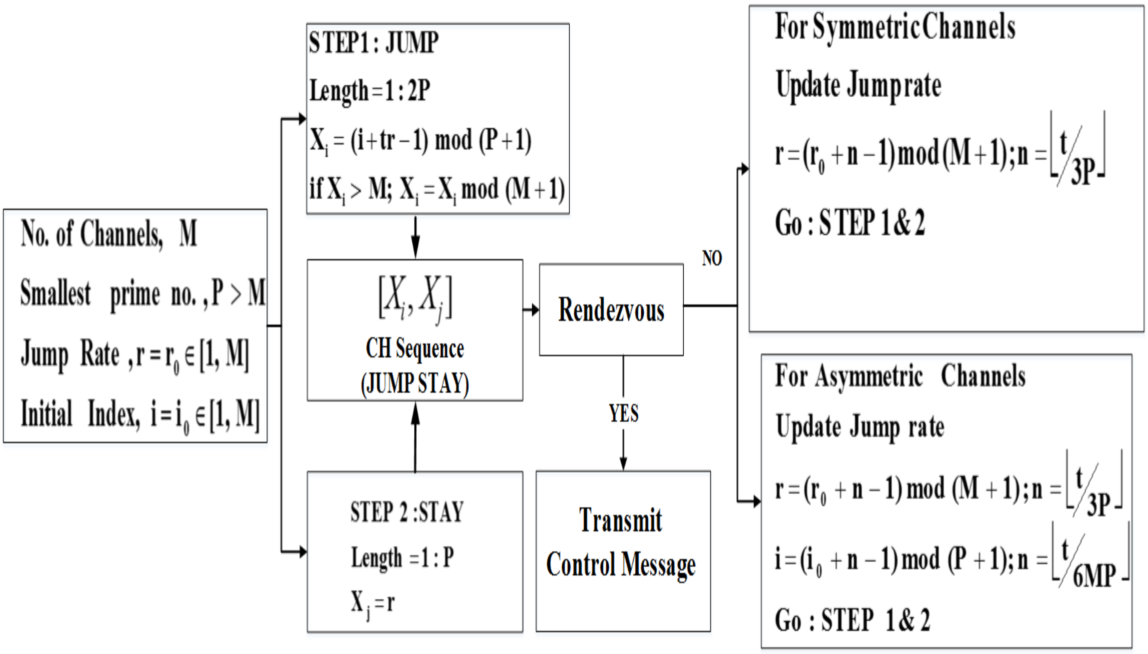


Figure 2.11: Algorithmic flow chart for Jump Stay CH sequence for both symmetric and asymmetric channel observation.

Quorum Based CH Sequence

Based on the quorum system, the authors in [21] proposed a control channel establishment protocol called quorum based channel hopping (QCH), which can guarantee RDV in both synchronous and asynchronous systems. For synchronous networks, two suboptimal algorithms M-QCH and L-QCH are proposed to minimise the MTTR and load of the channel hopping system respectively. The M-QCH system minimises the upper-bound of the TTR by using majority and minimal cyclic quorum systems. In L-QCH, the RDV points (channels) are evenly distributed over different timeslots during CH periods. However, a network-wide synchronization is required to guarantee the RDV within a cycle period. Moreover, time to achieve RDV linearly increases with the number of channels. For time-asynchronous systems, an A-QCH CH sequence is constructed by using a minimal and a majority cyclic quorum system with a rotation closure property. The minimal and majority channel assignments limit the protocol ability of two channels only. Due to the dynamic nature of incumbent users

$$CH_i = \begin{cases} X_j \ \mathit{if}\ (i \bmod k) \in S_i \\ X \ \mathit{if}\ (i \bmod k) \notin S_i \end{cases}$$

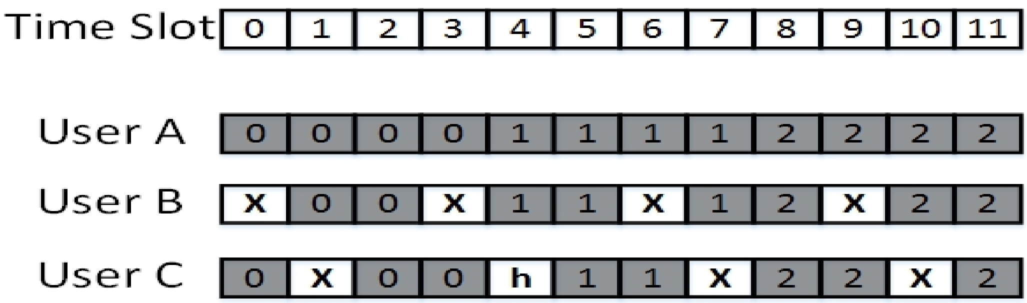


Figure 2.12: Example of quorum based CH sequence with channel set $R = \{0, 1, 2\}$ with $m = 3$ frames. The number inside the box is channel index and X represent the channel randomly chosen from $\{0, \cdot, N-1\}$.

those two RDV channels might be claimed by the incumbent users, which causes the common control channel bottleneck problem. Hence, an asynchronous maximum

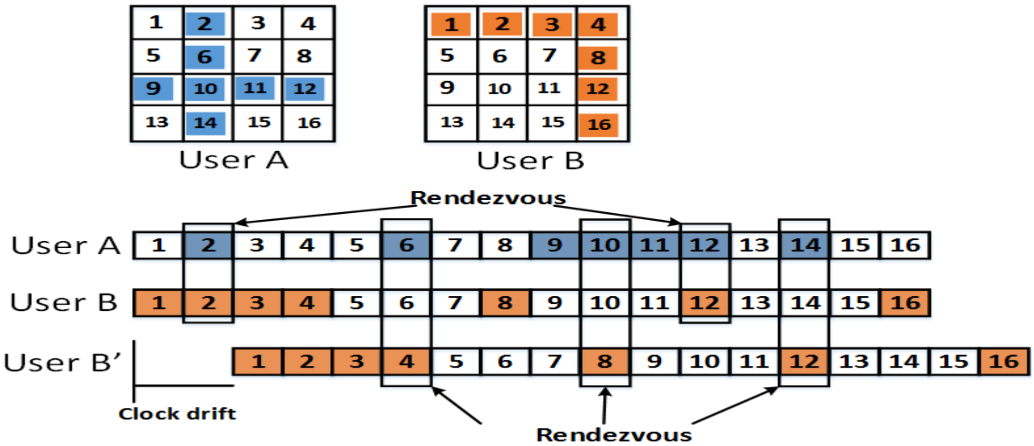


Figure 2.13: An illustration of grid quorum based CH sequence for a channel set, $N = 4$.

overlapping CH system (A-MOCH) is presented, which can achieve RDV in all available channels with $T = N^2$ time. Unfortunately, it does not guarantee the QoS in terms of channel reliability, and channel duration as a consequence suffers from degradation of network throughput. A grid based quorum formation is proposed in [61] to solve the RDV problem in distributed networks without synchronization. A CR node will generate a $n \times n$ grid (where n is the number of available channels) and assign a time slot in each unit of the grid starting from 0 to n^2. Each node then maps its channels according to the channel index. Assume there are 5 channels in the system with an index $\{CH_1, CH_2, CH_3, CH_4, CH_5\}$ and the channels are ranked according to QoS:$CH_5/CH_3/CH_4/CH_1/CH_2$. Hence, all the elements in column 5 and row 5 are assigned to CH_5. Each time a set of elements is chosen, a grid is cut to a sub-grid and repeats the process till it becomes a 2×2 grid, i.e. two channels will remain to be assigned. The last 2 channels are chosen in a diagonal manner. Extension of this work is presented in [62] with an asymmetric channel view called a grid quorum system (gQ-RDV). However, gQ-RDV cannot guarantee RDV on each available common channel between users.

Block Design Based CH Sequence

A balance incomplete block design (BIBD) based on CH sequence is proposed in [37] to achieve RDV in distributed ad-hoc networks relaxing both CCC and synchronization requirements. In the case of two channels, V distinct objects are assigned in b rows (sequence) which contains K different objects in each row and can guarantee RDV in v time slots. If the number of channels is more than two, then the maximum TTR is v^i where $i = log(c)$ and c is the number of channels. However, this protocol introduces extra overhead due to two layers of spectrum sensing i.e. feature detection and energy sensing. Due to the time split fashion of channel access, this protocol incurs extra delays in data transmission.

2.5 Rendezvous Protocol Performance Issues

In this thesis, the two most important RDV performance issues are considered: time to rendezvous (TTR) and degree of overlap. RDV parameters mostly depend on the rendezvous methods used to achieve RDV, such as CCC or CH.

A brief description of each of the performance metrics is given below.

i) **Time-To-Rendezvous(TTR)**:In CRAHNs, to initiate the communication, a CR node has to exchange the control information with its neighbour. It will switch from one channel to another, by following a hopping sequence, until it finds its neighbour. TTR refers to the time needed by a CR node to meet with its neighbour, and it is computed by the number of time slots that elapse from the reference time to the RDV time. In CH based protocols, it is obvious that channel access delay fluctuates highly according to the ATTR value, since the exchange of control information is not possible without RDV. Applications that are delay-sensitive such as voice and video in multi-channel ad-hoc networks require a CH system with a small ATTR value. Fig. 2.14, shows an example of the ATTR calculation in a channel hopping protocol.

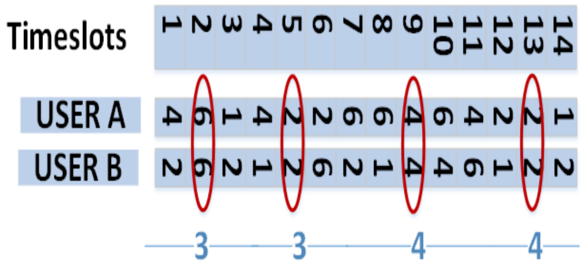


Figure 2.14: An example of TTR calculation.

ii) **Degree of Overlap/Number of Rendezvous**: The degree of overlap or intersection of two CH sequences in a sequence period can be counted in numbers where two users overlapped in the (time, channel) pair. Given two CH sequences A and B shown in Fig. 2.14, they overlap if there is a slot $(i, A[i]) \in A$ and a slot $(i, B[i]) \in B$ that $A[i] = B[i]$. The $i - th$ slot is called an overlapping or RDV slot between A and B, and the channel $A[i] \in 2, 4, 6$ is called an overlapping or RDV channel between A and B. In this scenario, degree of overlap is 4. Therefore, any two sequences can exchange control messages successfully if there is at least one available channel for any two CRs. To avoid interference with PU transmission, a CR node has to vacate the channel upon the PU's arrival and wait until it becomes free. This waiting time is called PU blocking time. Therefore, the CH sequence design should have a higher degree of overlap so that the impact of the PU long blocking time can be reduced and rendezvous probability in high traffic CRNs can be maximised. Moreover, a higher degree of overlap reduces channel access delay.

2.6 Design Issues for CRAHNs Rendezvous Protocol

Channel hopping is an alternative option to CCC in simplifying the RDV problem in CRAHNs. In the CH scheme, control channels are distributed over commonly available channels between CR nodes, thereby alleviating the single point failure and control channel saturation problems. Moreover, due to dynamic change in control channel assignment, the CH scheme is more robust against PU activities and jamming attacks. However, there are still some unsolved problems and research issues to study.

2.6.1 Channel Status Information

Channel status information includes the number of available channels for each user and channel ranking. A CH sequence is typically designed based on available free channels. Most of the existing protocols assume that intended CR nodes experience symmetric channel information i.e.$C_i = C_j = C$. However, in a dynamic radio environment, due to strong shadow, fading effect and geographical distance, CR nodes may sense the availability of different channels. Communication between CR nodes is possible if they have at least one common channel in their channel list, which can be written as $C_i \cap C_j \neq 0$ where i and $j \in 1, ..N$. For a CH sequence, the sequence period is determined by the number of available channels. Therefore, asymmetric channel information results vary in period length, which significantly impacts the RDV performance (i.e. ATTR and degree of overlap) of a CH sequence. Thus, a CH sequence with the same period but different channel ranking experiences miserable performance. Fig. 2.15 illustrates the four different cases: (i) Symmetric channel with different ranking (between User A and B); (ii) Asymmetric channel with asymmetric channel ranking (between User A and c); (iii) Asymmetric channel with symmetric channel ranking (between User A and D); and (iv) Asymmetric channel (number of channels are different) with symmetric channel ranking (between User A and E). It shows that rendezvous is not achieved in case (i) where it has the same channel set but asymmetric ranking. Due to different channel sets, rendezvous is not achieved in case 2, although they have one common channel. In case 3, rendezvous is only achieved on the channels with the same ranking in the channel list. In case 4, users with different (number of available channels) channel sets result in different CH sequence lengths and rendezvous can only be achieved when channels ranked the same.

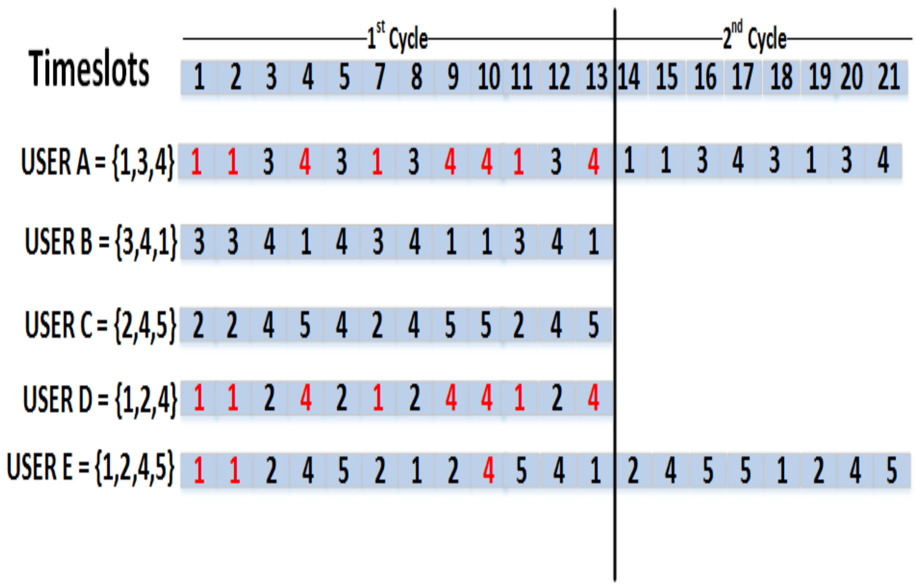


Figure 2.15: Impact of channel status on CH sequence design [3] in terms of degree of overlap.

2.6.2 PU Activity

Most of the existing CH sequences are based on channels observed through local sensing prior to CH construction. Due to the dynamic PU activity, channel availability changes more often. To minimise the interference with PUs, a CH protocol [59] can remove the PU-occupied channel from the sequence. However, it may reduce the interference but at the same time the CH sequence becomes progressively shorter and the probability of RDV being achieved decreases. Therefore, a proactive spectrum management policy is required to switch the channel in case of PU reappearance.

2.6.3 Time Synchronization

The CH sequence in time slotted architecture indicates the time slots on which a node transmits or receives data to or from its neighbours. Two CH sequences are called time synchronized if they start channel hopping at the same time, as illustrated in Fig. 2.16, when $K = 0$. The value of K indicates the time lag between two CH sequences. K can be an integer or fraction. If K is an integer, it is called slot asynchronized, otherwise it is fractional asynchronized. Both slot and fractional asynchronized scenarios are depicted in Fig. 2.17. In the fractional asynchronized case, rendezvous may not be achieved if the overlap duration is smaller than the time required to exchange control information. The performance of a CH sequence depends on time synchronization. Fig. 2.16 shows that the degree of overlap between two CH sequences significantly changes with time asynchronization for different values of K. Consequently ATTR will also fluctuate for the same reason. Hence, the CH sequence that is designed for a time synchronized environment may not suit a time asynchronized environment.

2.7 Summary

In this chapter, the fundamentals of CR were presented together with the basic cognition cycle. In particular, the four main components of CR cognition cycle, which include spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility, were briefly explained. To initiate the communication in distributed ad-hoc networks any two CR nodes have to achieve RDV. The RDV concept in CRAHNs was presented and the distinction from the existing multi-channel environment was

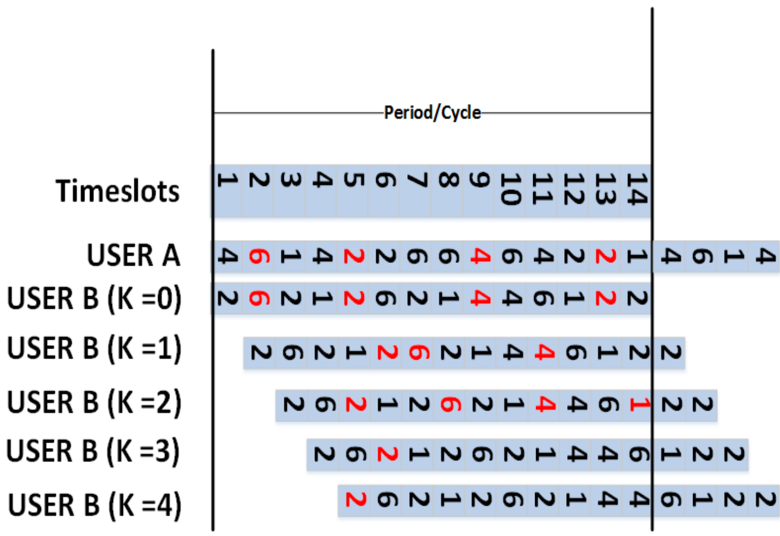


Figure 2.16: Variation of degree of overlap in accordance with time synchronisation.

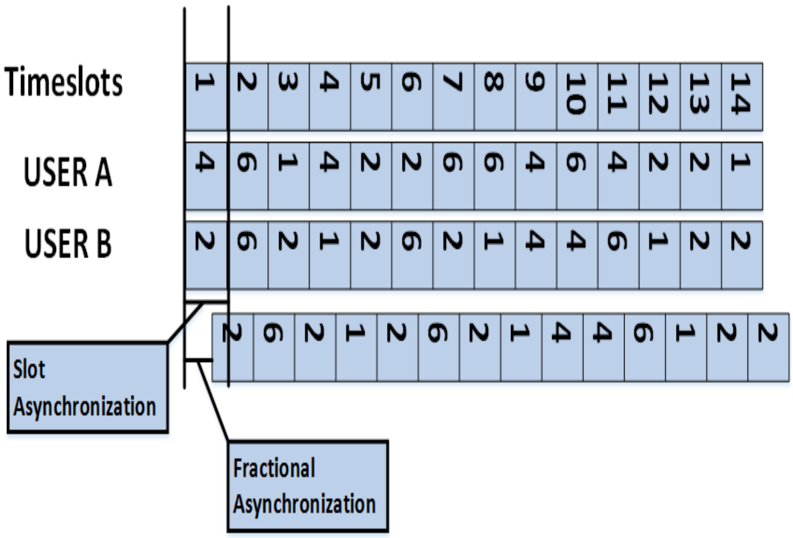


Figure 2.17: Illustration of slot and fractional slot time synchronization

described. RDV protocols in CRAHNs can be classified into two major categories based on available channel information. These are aided RDV and unaided RDV protocols. Through the literature review it was found that aided RDV protocols are used mainly in centralized systems and unaided RDV protocols in decentralized systems. In aided RDV protocols, a server or a central entity negotiates and manages the RDV channels, whereas each individual CR node does the same in unaided RDV protocols. The leading RDV protocols and main concept of the protocols were identified and discussed.

The focus of this thesis is to enhance the performance of the RDV process in an adhoc cognitive radio network. Due to the dynamic behavior of the radio environment, global or local level CCC is not an optimal solution in distributed wireless networks. CCC also suffers from single point failure, jamming attacks and congestion problems. On the other hand, CH fits the rendezvous design approach for distributed networks well. Thereby, only CH based RDV protocols are considered. The well-known CH based rendezvous protocols are reviewed and classified based on mathematical concepts used to build the CH sequence. The design principles of CH based RDV protocols are different to those of traditional multi-channel control channel protocols. The factors influencing CH based RDV protocol performance have been identified and described in detail. In the next chapter, a CH based RDV protocol is presented to enhance the performance of the RDV process in CRAHNs.

Chapter 3

ETQCH: Rendezvous Protocol for Cognitive Radio Ad-Hoc Networks

3.1 Introduction

In Chapter 2, a literature review on the design and performance improvement of RDV protocols was presented. It is noted that previous research extensively used symmetric channel information to design a CH based RDV protocol. In practical scenarios, CR nodes may observe a different set of channels. Moreover, the existing CH based RDV schemes still suffer from high ATTR and low degree of overlap due to random channel selection in CH sequence design. To achieve RDV in the shortest time, most of the CH sequences utilise the family of mathematical concepts such as prime number theory, CRT, quorum system and combinatorial block design. However, user preferences also influence the channel on which RDV will be achieved. As an extension to the previous research, a CH based RDV protocol with an asymmetric channel view is described in this chapter.

Section 3.2 describes the RDV problem in detail from a CRAHNs perspective. In traditional multi-channel ad-hoc networks, a network-wide control channel is often considered to solve the RDV problem. It is also assumed that channel status remains static for the duration of transmission. However, existing RDV schemes are not compatible with CRAHNs due to the dynamic radio environment. To integrate the channel activity and radio dynamics, a Markov chain based channel state transition is explained in section 3.3 to analyse the PU and CR behavior. The concept and construction of extended torus quorum based channel hopping (ETQCH) is described in different subsections of section 3.4. The cognitive cycle of ETQCH protocol is presented in subsection 3.4.1. An extended torus grid formation and channel mapping are explained in subsection 3.4.2 and 3.4.3 respectively. The channel mapping subsection discusses both the symmetric and asymmetric channel status cases. In section 3.5, channel ranking is formulated by using a convex combination of multi-objective linear programming (LP) problem. The objective of the optimisation problem is to maximise the weight, based on channel availability times and sojourn times of the channel in the idle state. In section 3.6 an adaptive CH strategy describes how to capture and protect the incumbent PU transmission in a dynamic radio environment. The features of ETQCH protocol are highlighted in section 3.7.

3.2 Problem Definition

The RDV problem can be illustrated by the telephone coordination game [17], where two players are placed in two separate rooms each with n telephone lines. There is one-to-one matching between the lines in the two rooms, and players can use matched lines to connect to each other. In every round each player can select a line in his room and see whether it connects with the line chosen by another user, provided that users do not have any prior agreement in choosing a line. The goal is to design a strategy for players to get connected while minimising the number of trail rounds. The same coordination game can be applied in CRAHNs to describe the RDV problem with a few additional constraints. Assume there are two CR users A and B in the system and User A has a data packet destined for B. Before initiating data transmission A will exchange the control information with B. It is also assumed that they do not have any prior agreement on which channel to use. In this context, User A will pick up a channel based on its local sensing information and send $HELLO$ packets to user B. if User B is listening to the same channel , it will respond as HI. Otherwise, user A will try the alternative channels from its channel pool and repeat the same procedure. RDV happens when user A receives HI in response to $HELLO$ from user B.

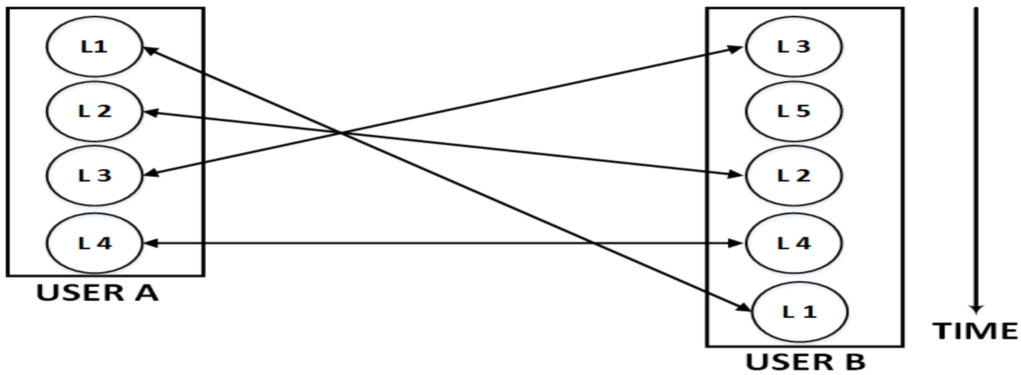


Figure 3.1: An analogy of rendezvous problem using telephone co-ordination game.

In CRAHNs, each CR node performs a primary user detection process to exploit unoccupied channels in its vicinity. An assumption is often made that there is a common set of available frequencies/channels known to all CR nodes. But this information needs to be independently obtained by individual radios through channel sensing. It is not likely that two independently sensed sets of vacant frequencies will be identical. Say there are $P \geq 2$ CR users in the network, who share a set of available licensed channels, such as $X_i \subseteq X; C \in X_0, X_1, X_2, ..., X_{N-1})$ (N is the number of available licensed channels and have labels that are the same for all CRs) that can be used for both control and data information exchange. Before initiating any data transmission, the intended nodes should first exchange control information between them to select common data channels. According to [60], nodes could have identical (i. e. $C_i = C_j$) or different available channel lists with at least one common channel, known as symmetric and asymmetric channel lists respectively. In CH-based solutions, the RDV process can be described as pairwise control channel establishment using sequences X and Y where X and Y are two CH sequences with period T, such as $(0, X[0]), (1, X[1]), ..., (T-1, X[T-1])$ and $(0, Y[0]), (1, Y[1]), ..., (T-1, Y[T-1])$. Hence, RDV sequences must have overlapped property in order to ensure any pair of nodes can establish communication, i.e. $\forall A, B; \mid A \bigcap B \mid \neq 0$.

3.3 System Model

According to the definition of CR, the channel that is currently used for data transmission or RDV process by a CR user becomes unavailable if a PU reappears on that particular channel. Therefore, PU activities have to be considered in designing a CH sequence. Continuous Time Markov Chain (CTMC) is used to model the PU and CR users' activities as shown in Fig. 3.2. It is assumed that there are N CR users operating in $L = f_1, f_2, f_3, ..., f_m$ licensed channels if they are not occupied by PUs. The service request of both PUs and CR users is modelled as a Poisson process with rate λ_P and λ_{CR} and is terminated with rate μ_p and μ_{CR}. A channel cannot be used by more than one user simultaneously. Therefore each channel can be in one of the states shown in Fig. 3.2: Idle state, PU state or CR state. An idle state indicates that the channel is not being used by any users at this time. The channel state will move from idle to PU or CR state if it is used by any PUs or CR_i respectively. In CRAHNs, the PU has a licence to operate in the channel and should not be interfered by CR transmission. Hence, the channel state will move from CR state to PU state but it is not possible to have a transition from PU to CR state. Let $x = 0, P, CR_1, CR_2, ...CR_N$ be the $(N + 2)$ element space vector for the CTMC model and Q be the transition matrix specified in equation 6.11.

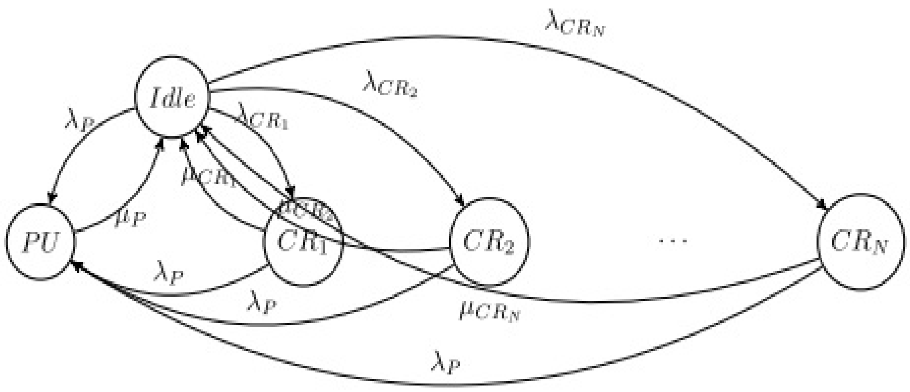


Figure 3.2: Channel state transition diagram

Let $\pi^m(t) = [\pi_1^m(t), \pi_2^m(t), \pi_3^m(t), ..., \pi_N^m(t), \pi_P^m(t)]$ be the steady state distribution for channel m. The i^{th} element of $\pi^m(t)$ is given by $\pi_i^m(t) = P[x(t) = i], \forall i \in X$. To analyse the steady state behavior, it is assumed that the channels are in the ON state for long enough to achieve steady state values. Hence the steady state probability of state i can be written as $\pi^m = \lim_{t\to\infty} \pi_i^m(t)$. Now, the steady state probability vector π can be obtained by solving the following steady state Eqs. 3.2 and 3.3:

$$\sum\nolimits_i \pi_i^m \mathbf{Q}_{ij}^m = 0; \forall j \tag{3.2}$$

$$\sum\nolimits_{\forall i \in X} \pi_i^m = 1 \tag{3.3}$$

where, $\mathbf{Q}_{ij}^m$ is the product of the rate of leaving state i and the probability of transitioning to state j from state i, which is the rate of transition from i to j. By using Eqs. 3.2 and 3.3, a system of linear equation can be derived in Eq.(3.4- 3.6) as follows:

$$\mathbf{Q} = \begin{bmatrix} -(\lambda_1 + \lambda_2 + \cdots + \lambda_N + \lambda_P) & \lambda_1 & \lambda_2 & \cdots & \lambda_N & \lambda_P \\ \mu_1 & -(\mu_1 + \lambda_P) & 0 & \cdots & 0 & \lambda_P \\ \mu_2 & 0 & -(\mu_2 + \lambda_P) & \cdots & 0 & \lambda_P \\ \vdots & \vdots & \vdots & \ddots & \vdots & \\ \mu_N & 0 & 0 & \cdots & -(\mu_1 + \lambda_P) & \lambda_P \\ \mu_P & 0 & 0 & \cdots & 0 & -\lambda_P \end{bmatrix} \tag{3.1}$$

$$\pi_0^m \left(\lambda_1^m + \lambda_2^m + \lambda_3^m + ... + \lambda_N^m + \lambda_P^m\right) + \pi_1^m \mu_1^m + \pi_2^m \mu_2^m + $$

$$+ \pi_3^m \mu_3^m + ... + \pi_N^m \mu_N^m + \pi_P^m \mu_P^m = 0 \tag{3.4}$$

$$\pi_0^m \lambda_i^m - \pi_0^m \left(\mu_i^m + \lambda_p^m\right) = 0, (1 \le i \le N) \tag{3.5}$$

$$\left(\pi_1^m + \pi_2^m + \pi_3^m + ... + \pi_N^m\right) \lambda_p^m - \pi_P^m \mu_P^m = 0 \tag{3.6}$$

After a series of arithmetic manipulations π_i^m can be written as:

$$\pi_i^m = \frac{\lambda_i^m}{\left(\mu_i^m + \lambda_P^m\right)} \pi_0^m; \tag{3.7}$$

$$\pi_0^m = \frac{\mu_P^m}{\left(\mu_P^m + \lambda_P^m\right)\left(1 + \sum_{i=1}^{N} \frac{\lambda_i^m}{\left(\mu_i^m + \lambda_P^m\right)}\right)}$$

$$\pi_P^m = \frac{\lambda_P^m}{\left(\mu_P^m + \lambda_P^m\right)} \tag{3.8}$$

Hence, the design challenge of the CH algorithm is to generate a hopping sequence based on channel availability and activity which can guarantee achieving RDV within a finite time, provided that there is at least one common channel between CR users. In addition to that, the CH algorithm must adapt to avoid or reduce RDV collisions among CR users and regenerate the sequence because of PU activity. The mathematical concept that has been used in this thesis to design a CH sequence is called the torus quorum system. Quorum system can guarantee the intersection between two torus quorum sets. In the following sections, quorum systems and their properties are discussed in relation to CH sequence design.

3.4 Extended Torus Quorum Grid Channel Hopping (ETQCH) Protocol

3.4.1 Overview

The proposed CH protocol described in this chapter differs from the earlier work described in section 2.4.1. It has different goals and capabilities. This is a systematic approach to generate a CH sequence based on the torus quorum system to achieve RDV in CRAHNs without the assumption of global clock synchronization. This proposal integrates the channel heterogeneity (symmetric and asymmetric channel information) between CR users, channel status variation due to PU activity and collision among PU/CR users. The sequence is used by each node to decide the order in which the available channels are to be visited. The proposed approach is called the Extended Torus Quorum Channel Hopping (**ETQCH**) scheme, which is used for implementing RDV protocol in DSA networks and which is robust against link breakage caused by the intermittent appearance of incumbent user signals.The following properties of extended torus quorum structure are the foundation of ETQCH protocol:

- Any two extended torus quorums have at least one intersection.

- No extended torus quorum is a proper subset of another quorum.
- All extended quorums have the same size of $h + 3 \times \left\lfloor \frac{w}{2} \right\rfloor$.
- Each node belongs to exactly $(h + 3 \times \left\lfloor \frac{w}{2} \right\rfloor)\ w^{h+3\times\left\lfloor \frac{w}{2} \right\rfloor - 1}$

Figure 3.3 shows the cognitive cycle of the ETQCH protocol. The ETQCH protocol is tripped when a CR node wants to transmit data to its neighboring node but is unable to find one with its current radio information. To gather radio information, it starts spectrum sensing and prepares the list of available channels which are not being used by PU or CR users. It is assumed that a CR node consists of two radio transceivers: RDV radio (R-radio) and Data radio (D-radio). R-radio is used to establish and maintain RDV for control information exchange and D-radio for data transmission between a pair of CR nodes. It is assumed that a CR node can sense all the available channels (which includes both licensed and unlicensed spectrum) periodically after a time out of T_{out}. For a synchronous case, T_{out} is the CH sequence duration T_{CH} and $T_{out} = 2 \times T_{CH} - 1$ is the sequence duration for a asynchronous case. Based on the sensing outcome, two parallel processes - channel ranking and extended torus quorum grid formation - are executed. The purpose of channel ranking is to rank the channels based on their availability and fluctuation under collision constraints. The extended torus quorum grid is created to assign the time slots for each channel. The dimension of the extended torus quorum grid depends on the number of available channels. Channel mapping integrates the channel ranking and extended torus grid to map the channels in corresponding time slots. The outcome of channel mapping is the desired ETQCH sequence that a CR user follows to establish RDV in CRAHNs. But a problem happens when a PU reappears on the channel currently being used in the CH sequence. To protect the incumbent PU transmission in a dynamic radio environment, ETQCH updates the CH sequence by replacing the busy channel with the best channel from the channel list or previously achieved rendezvous channel. In the following sections, we describe each of the processes in detail except channel sensing. Channel sensing is a research issue in itself, which is out of scope of this thesis.

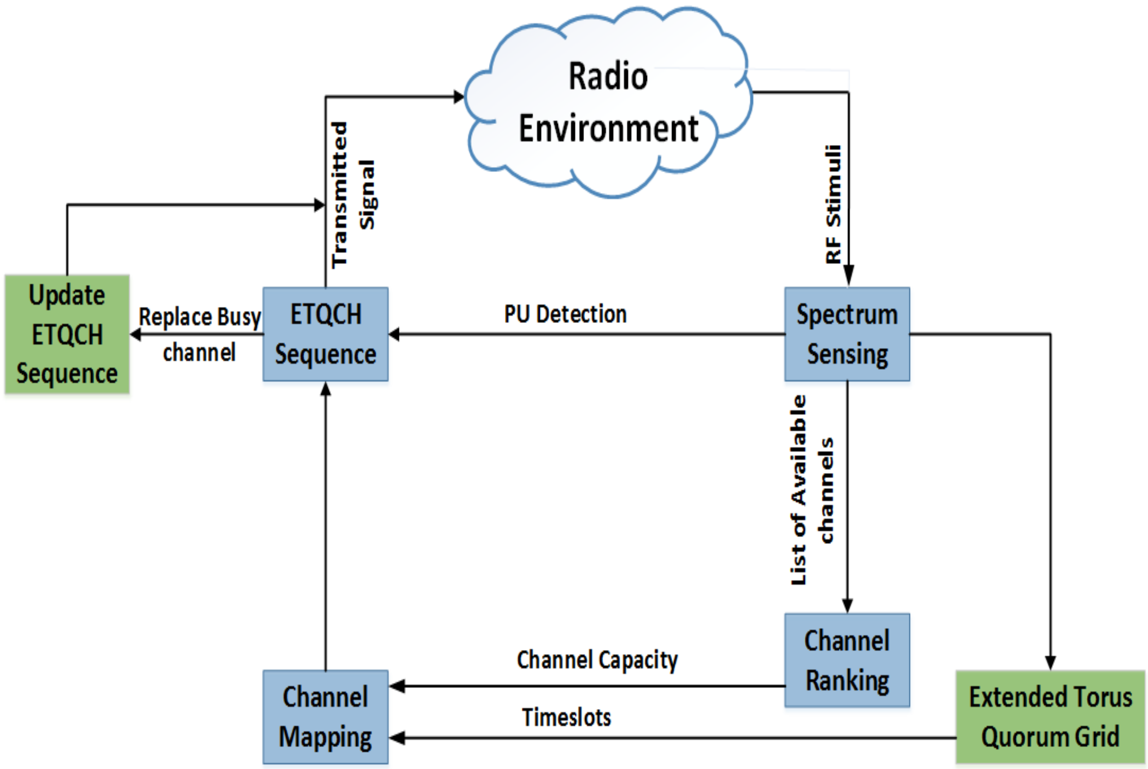


Figure 3.3: Cognitive cycle of ETQCH protocol

3.4.2 Extended Torus Grid Formation

Before getting into further details of ETQCH RDV protocol, concepts of quorum and its mathematical properties are discussed in detail. Quorum is a mathematical concept that has been widely used in distributed systems to solve the mutual exclusion problem [63–66], the agreement problem [67], the replica control problem [68–70] and the power saving problem [71–73] in wireless sensor networks (WSNs). In general, a quorum is a collection of elements in a system. The system may have a couple of quorums. All quorums in a system constitute a quorum system. Any two quorums in the quorum system should have a non-empty intersection (i.e. the intersection property). Hence, the definition of a quorum system is as follows:

Definition 1(Quorum system): Let us assume a finite universal set $S = \{0, 1, ..., n-1\}$ of n elements, where n represents the cycle length. A quorum system Q under universal set S is a collection of non-empty subsets of S, provided that it satisfies the intersection property: $\forall X, Y \in Q : X \bigcap Y \neq 0$. As an example shown in Fig. 3.4 where $Q = \{\{1, 2\}, \{1, 3\}, \{2, 3\}\}$, Q_1,Q_2, and Q_3 chooses quorums $\{1, 2\}$, $\{1, 3\}$ and $\{2, 3\}$ respectively to donate their channel visit sequence. By intersection property, Q_1 and Q_2 will meet each other at time slots 2, 6 and 10. However, due to clock drift problems Q_1 and Q_3 may not meet even though their quorums have the common intersection $'2'$. The same problem happens for Q_2 and Q_3. Therefore, quorum systems that are used for CH sequence design should have the property to hinder the clock drift problem. This is called rotation closure property (RCP), which ensures that two asynchronous users selecting any two quorums have at least one intersection in their quorums [71]. The definition of RCP property is as follows:

Definition 2 (Rotate): For a quorum H in a quorum system Q under $U = \{0, ..., n-1\}$ and a non-negative integer $i \in \{1, 2, ..., n-1\}$, we define $H' = rotate(H, i) = \{(j + i) \ mod \ n \mid j \in H\}$ to be a new quorum H'.

Definition 3 (Rotation Closure Property): A quorum system Q under $U = \{0, ..., n-1\}$ is said to satisfy the rotation closure property if $\forall H', H \in Q, i \in \{1, 2, ...n-1\} : rotate(H, i) \bigcap H \neq 0$ or $H', H \neq 0$.

$Q = \{\{0, 1, 2, 4\}, \{1, 2, 3, 5\}, \{0, 2, 3, 4\}, \{1, 3, 4, 5\}, \{0, 2, 4, 5\}, \{0, 1, 3, 5\}\}$ is a quorum system under $U = \{0, 1, 2, 3, 4, 5\}$. Q_1, Q_2 and Q_3 choose $\{1, 2, 3, 5\}$, $\{0, 2, 3, 4\}$ and $\{0, 1, 3, 5\}$ to denote their quorum intervals, respectively. An example of RCP property is shown in Fig. 3.5, where the clock of Q_2 drifts four units $\{0, 1, 3, 5\}$

$\bigcap rotate(\{0,2,3,4\},4)$ and still satisfies the intersection property. Thus, Q_1 and Q_2 can still meet each other even though their clocks drifted by 4 units. Thus, the rotation closure property holds for Q. Two CR nodes adopting quorums in Q to denote their quorums can meet at the same time even if their clocks drifted. However, the quorum system $Q' = \{\{0,1\},\{0,2\},\{1,2,3\}$ does not satisfy the rotation closure property due to $\{0,1\} \bigcap rotate(\{0,3\},3) = 0$. Hence, this quorum system Q' is not suitable for the asynchronous RDV protocol.

Figure 3.4: Quorum system for rendezvous protocol

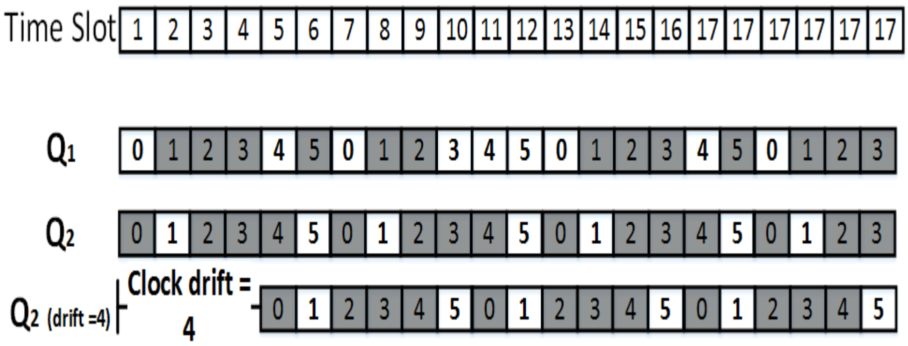


Figure 3.5: Quorum system with rotation closure property

Definition 4 (Torus Grid Quorum System): A torus grid of size $t \times w$ consists of a rectangular array of t rows and w columns, in which for $1 \leq r_i \leq r_{t-1}$, row r_i is followed by row r_{i+1}, and row r_{t-1} is followed by row r_1 using wraparound. Similarly, for $1 \leq c_j \leq c_{w-1}$, column c_j is followed by column c_{j+1}, and column c_{w-1} is followed by column c_1 using wraparound. A torus quorum of $t \times w$ torus grid is a set of $t + \left\lfloor \frac{w}{2} \right\rfloor$ timeslots, consisting of one entire column (say, $column_j$), plus one slot out of each of the $\left\lfloor \frac{w}{2} \right\rfloor$ column following row i and column $j+1$ using end wraparound. The entire column portion c_i of a quorum is called the head, and the rest of the elements - one element from each $\left\lfloor \frac{w}{2} \right\rfloor$ succeeding column - is called the tail. Fig. 3.6 presents the torus grid based CH sequence. As is shown in Fig. 3.6 (a) both of the users A and B have 4 available channels which represent the height of the quorum. The width of the quorums is twice the height. Therefore, the resultant torus quorum becomes a 4×8 grid. The number inside the grid represents the timeslot to access a channel. Let user A select all the elements from column 3 plus one element from four successive columns to access the CH_2. Similarly, user B selects all the elements from any arbitrary column (in this case column 7) plus one element from columns 8, 1, 2, and 3 in a wraparound manner to access the CH_2. Fig. 3.6 (b) shows the CH sequence for both users A and B. According to the definition of quorum system, users A and B meet each other at timeslots 3 and 7. Hence the rendezvous pairs are $\{CH_2, T_3\}$ and $\{CH_2, T_7\}$. In this scheme, RDV is achieved when nodes have symmetric channel information. However, in a dynamic radio environment nodes with asymmetric channel information generate torus grids with different dimensions. Hence, this problem is extended to guarantee RDV in the smallest period. This is a non-trivial task, since nodes do not rely on the same grids (only $n \times n$ grid and $(n+i) \times (n+i)$, where $i \geq 1$). The smaller period also does not contain some of the channels of the larger periods. In other words, the channel mapping algorithm must have a logical relations with grids of different sizes. Moreover, the algorithm should be robust against link breakage caused by the appearance of incumbent user signals. This can be achieved by allowing the CR nodes to have RDV on all available channels within a sequence of a smaller period. Therefore, an extension of the ordinary torus quorum system is proposed in the following subsection called the extended torus grid quorum system.

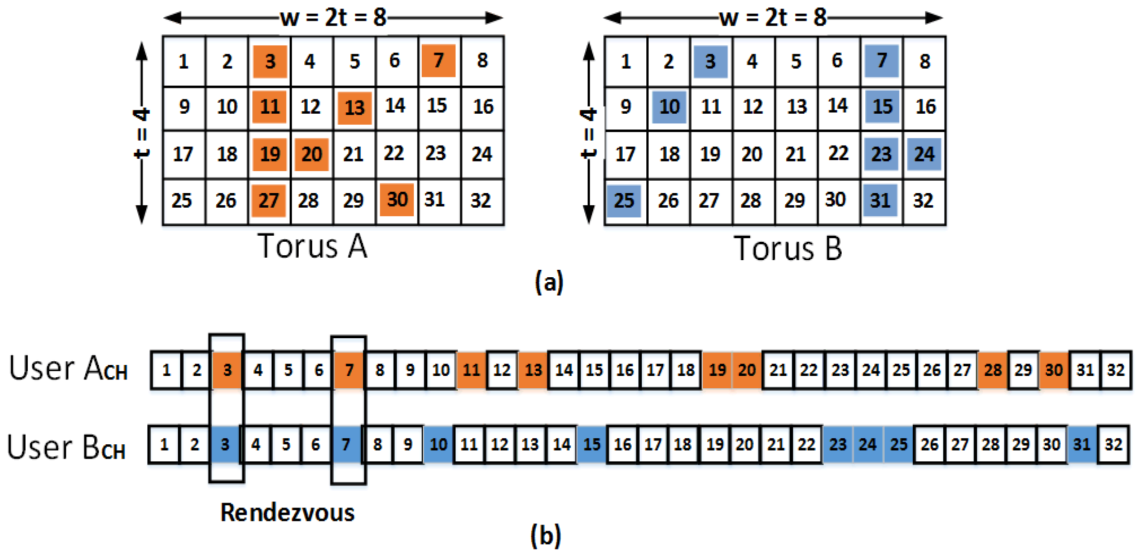


Figure 3.6: (a)Illustration of two torus quorums A and B under $U = \{1, 2, , 3. \cdots, 32\}$ with $t = 4$ and $w = 8$. (b) Construction of CH sequence based on Torus quorums system.

Definition 5 (Extended Torus Grid Quorum System): The extended torus grid quorum system is an extension of the torus quorum system. An extended torus quorum system is also defined as a rectangular array of t rows and w columns (where $w = 2 \times t - 1$) such that $U = \{0, 1, ..., tw - 1\}$. The difference is that it assigns more tails instead of one in the former approach to achieve RDV in the best channels. Hence, it becomes a torus quorum in an $t \times w$ torus grid with a set of $(h + 3 \times \left\lfloor \frac{w}{2} \right\rfloor)$ elements as quorum size. Moreover, a choice of 3 diagonals makes the grid proportional to the number of channels.

- Rational Behind 3 Branches: According to definition 4, all quorums must have size and structure of $t \times w$ (where $w = 2 \times t - 1$). Notice that t represents the number of rows in the torus structure which is the same as the number of available channels observed by a CR node. Consider a CR node that observes

n available channels and forms a torus grid quorum with size $n \times (2 \times n - 1) = 2n^2 - n$. If the number of available channels is $n - 1$, then it becomes $(n-1) \times (2 \times (n-1) - 1) = 2n^2 - 5n + 3$. Therefore, the difference in quorum size with successive torus grids is $2n^2 - n - 2n^2 + 5n - 3 = 4n - 3$. Eqn. 3.9 equates the number of diagonals required to maintain the torus grid structure. For example, 4 channels observed by a CR node form a torus grid with $4 = 28$ elements. The successive torus grid is $5 \times 9 = 45$ elements and has a difference of $45 - 28 = 17$, which is $4 \times 5 - 3$ or $n + x \times \left\lfloor \frac{(n-1)}{2} \right\rfloor$ where $n = 5$ and $x = 3$. Now equate the difference in elements for successive torus grids:

$$\begin{aligned}
& n + x \times \left\lfloor \frac{(n-1)}{2} \right\rfloor = 4n - 3 \\
& x \times \left\lfloor \frac{(n-1)}{2} \right\rfloor = 3(n-1) \\
& x \times \frac{(n-1)}{2} = 3(n-1) \\
& x = 3
\end{aligned} \tag{3.9}$$

Using the above mentioned definition, the ETQCH scheme is discussed in the rest of the chapter. When a CR node receives a packet from an upper layer, it will generate a torus grid quorum as shown in Fig. 3.7 and select a column based on the channel ranking list and three associated diagonals (2 positive and 1 negative diagonal) as described in algorithm 1.

w = 2*h-1

h

1	6	11	16	21	26	31	36	41
42	2	7	12	17	22	27	32	37
38	43	3	8	13	18	23	28	33
34	39	44	4	9	14	19	24	29
30	35	40	45	5	10	15	20	25

Figure 3.7: Time slot assignment in Torus Grid

Now let us consider the number of available channels, $avail_{CH} = 5$ i.e. $t = 5$. Also assume that the channels are ranked (i.e.5/4/2/1/3) based on QoS. Here QoS refers to channel availability and channel fluctuation. The detail of the channel ranking procedure is presented in section 3.5. Hence, a CR node will generate a 5×9 torus grid and assign the time slots as per line 7 of algorithm 1 which is shown in Fig. 3.7. The column and three diagonals are shown in Fig. 3.8. The idea is to assign more time slots for the best channel and decrease gradually. It is highly probable that neighbour nodes experience similar channel quality across the channels, which implies high correlation among their channel ranking tables and consequently their hopping sequences.

3.4.3 Channel Mapping

When a CR node has data to send, it first discovers the intended receiver. Under the discovery process or RDV process the CR node performs spectrum scanning to explore channel information. The channel information might be different for sender and receiver due to the dynamic nature of the radio environment. However, there should be at least one common channel to achieve RDV. In this context, both sender and receiver nodes will create an array of $t \times w$ elements, where t is the number of

Algorithm 1 Extended Torus Grid Formation

Input: (i) Number of available channels, $m8$

(ii) Transmission flag, $Flag_{Tx}$;

(iii) Rescan period, T_{out};

Output:

Extended Torus Grid with 3 diagonals (2 positive and 1 negative).

Begin

while $mod(T, T_{out}) = 0$ **do**
  $[Avail_{CH}]$; ▷ Available Channel Set
  Rank($[Avail_{CH}]$) = $[CH_{List}]$
  $t =\mid Avail_{CH} \mid$
  $w = 2 \times t - 1$
  Generate $t \times w$ Torus Grid
  $T_{slots}(r, c) = ((r \times avail_{CH}) - ((avail_{CH} - 1) * c))\%(avail_{CH} \times (2 * avail_{CH} - 1))$; ▷ Timeslots assignment in the torus grid
end while
while $packetsarrive$ **do**
  $q \leftarrow q + 1$
  $m \in [1 : w]$
  for $Diag = 1 : 3$ **do**
    for $i = \left\lfloor \frac{w}{2} \right\rfloor$ **do**
      $1_{Diag}(i) = [r((i)mod\ t); c((m + i)mod\ W)]$
      if $r\ is\ ODD$ **then**
        $2_{Diag}(i) = [r(t - 2 + i)mod\ t); c((m + i)mod\ W)]$
        $3_{Diag}(i) = [r(\left\lfloor \frac{t}{2} \right\rfloor + i)mod\ t); c((m + i)mod\ W)]$
      else$r\ is\ even$
        $2_{Diag}(i) = [r(t - 2 + i)mod\ t); c((m + i)mod\ W)]$
        $3_{Diag}(i) = [r(\left\lfloor \frac{t}{2} \right\rfloor + i)mod\ t); c((m + i)mod\ W)]$
      end if
    end for
  end for
end while

End

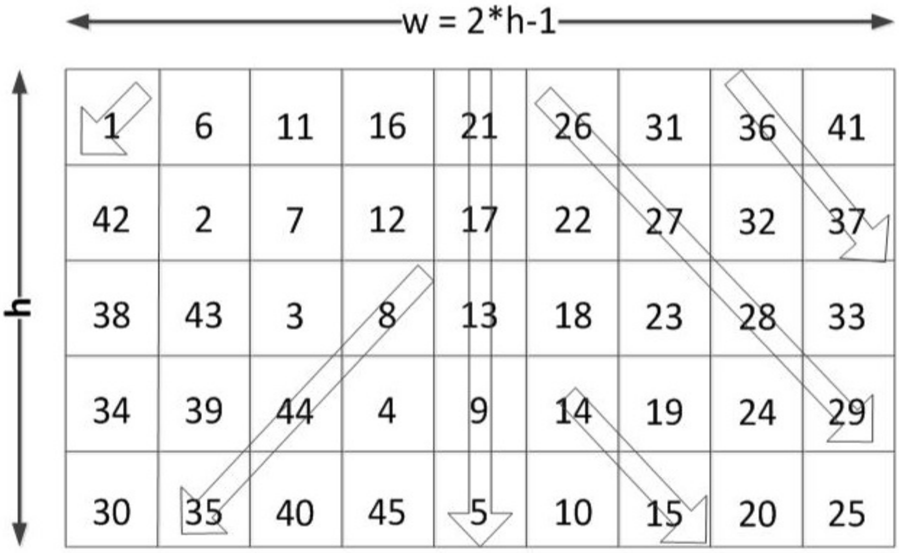


Figure 3.8: Illustration of quorum assignment based on channel rank.

available channels for each CR user and $w = (2 \times t) - 1$. Suppose we have 5 channels available, which would become a 5×9 grid having 45 elements. Each of the elements inside the grid represents the time slot starting from 1 to 45. Each node maps the channel according to the channel ranking, which may not be the same for both sender and receiver. The channel ranking procedure is discussed in section 3.5. Consider that a CR node CR_X observes five channels and ranks them as $C5/C3/C1/C2/C4$, where $C5$ (channel 5) is best, and $C3$ is second best and so on. CR_Y observes the same channels but ranks them in different order $C5/C1/C4/C3/C2$. The idea of the proposed protocol is to spend more time on the best channel and decrease gradually. Therefore, the best channel is mapped in the grid with the highest quorum size. The CR node will select the column according to the channel index as described in line 2 of algorithm 2 and 3-diagonal branches as per algorithm 1. The resulting time slots are assigned to the best channel. In this example node CR_X and CR_Y will both select the same time slots for C5 as it is the best channel for both of them: {1,5,8,9,13,14,15,17,21,26,27,28,29,35,36,37,44}.

Algorithm 2 Channel Mapping

Input:
(i) Available channel $Avail_{CH}$;

(ii) Channel index CH_i;

(iii) Channel list, CH_{List};

Output:
(i) Channel map CH_{map};

(ii) Channel timeslots CH_{t_slots};

Begin

for map = 1:$avail_{CH} - 2$ **do**
    $CH_{t\_slots} = Grid(:, (CH_{List}(map) mod(2 * avail_{CH} - 1)))$
    $Algorithm1$
    $GRID(CH_{t\_slots}) = [\ ]$
    if $avail_{CH} = 2$ **then**
        $CH_{t\_slots} = [Grid(:, CH_i mod(length(column)))'$
                $Grid(CH_i mod(length(row)), :)]$
        $GRID(CH_{t\_slots}) = [\ ]$
    else
        $CH_{t\_slots} = Grid(CH_{t\_slots})$
    end if
end for

End

Number of Channel = 5

1	6	11	16	21	26	31	36	41
42	2	7	12	17	22	27	32	37
38	43	3	8	13	18	23	28	33
34	39	44	4	9	14	19	24	29
30	35	40	45	5	10	15	20	25

Number of Channel = 4

2	3	4	6	7	10	11
12	16	18	19	20	26	27
28	29	30	31	32	33	34
38	39	40	41	42	43	45

Number of Channel = 3

3	4	7	11	12
16	18	26	28	29
32	34	38	40	43

Number of Channel = 2

4	12	16
18	32	40

Number of Channel = 1

4	16

(a)

CH5	CH3	CH3	CH2	CH5	CH5	CH2	CH5	CH3
CH2	CH1	CH3	CH4	CH5	CH3	CH5	CH1	CH5
CH3	CH1	CH1	CH5	CH5	CH3	CH4	CH5	CH3
CH1	CH1	CH5	CH3	CH5	CH5	CH1	CH1	CH5
CH3	CH5	CH3	CH2	CH5	CH1	CH5	CH3	CH3

(b)

Figure 3.9: Example of Channel mapping based on Algorithm 2 with channel ranking $C5/C3/C1/C2/C4$. (a) Timeslots assignment. (b) Resultant CH sequence

Each time a set element is chosen, a torus grid is cut to a sub-grid, together with the already mapped channel. Therefore, $1, 5, 8, 9, 13, 14, 15, 17, 21, 26, 27, 28, 29, 35,$ $36, 37, 44$ total 17 time slots will be cut out from the grid and form a new grid which will become a 4×7 grid with 28 timeslots in it. Interestingly, every time the new sub-grid will be a torus grid with the rest of the time slots. This is the inherent property of our proposed torus protocol and is valid for 3 or more than 3 channels. When the number of available channels is 2, a torus grid is generated based on algorithm 2. For channel mapping, a row and column will be selected based on the channel index. The rest of the time slots are assigned to the remaining channels.

To introduce the asynchronous scenario, we assume CR_X clock is $K < n(n = t \times w)$ times ahead of clock CR_Y but the time slots are aligned. It is very easy to prove that CR_X and CR_Y can achieve RDV within bounded time due to the rotation closure property of the torus quorum system. However, two cases based on channel status observed by the CR nodes are discussed in the following section.

Symmetric Channel Status

In a symmetric case, the CR nodes sense the same number of channels through channel sensing. Therefore, the CR nodes will generate a symmetric extended torus quorum grid to construct the CH sequence. Nevertheless, to guarantee the rendezvous in an asynchronous environment, extended torus quorum systems have to satisfy the rotation closure property.

Definition 6 (Symmetric Rotation Closure Property): For a quorum H in a quorum system Q under $U = \{1, ..., n\}$ and a non-negative integer $i \in \{1, 2, ..., n\}$, we define $rotate(H, i) = \{(j + i)\ mod\ n \mid j \in H\}$. A quorum system Q is said to have the RCP if $\forall H', H \in q, i \in \{1, 2, ...n\} : H' \bigcap H \neq 0$.

For instance, the quorum system $Q = \{\{0, 1\}, \{1, 2\}, \{0, 2\}\}$ under $U = \{0, 1, 2\}$ satisfies RCP. For example $rotate\{\{0, 2\}, 2\} = \{1, 2\}$. Hence $\{0, 1\} \bigcap rotate\{\{0, 2\}, 2\} \neq$

0. However, the quorum system $Q' = \{\{0,1\},\{0,2\},\{0,3\},\{1,2,3\}\}$ under $U = \{0,1,2\}$ has no RCP since $\{0,1\} \bigcap rotate(\{0,3\},3) = 0$.

Theorem 1: An extended (3) torus quorum system with the same dimension satisfies the rotation closure property. The intersection between two extended (3) torus quorum systems is ≥ 3.

Proof: Let Q be a torus formed by a $t \times w$ array and $H \in Q$ be a quorum containing column c. By the definition of extended torus quorum, H also contains another 3 branches of $\left\lfloor \frac{t}{2} \right\rfloor$ elements. Each of the branches consists of $\left\lfloor \frac{t}{2} \right\rfloor$ elements, each from one of the $\left\lfloor \frac{t}{2} \right\rfloor$ succeeding columns of c and wrap around. Hence it is obvious that $rotate(H, i)$ still has the torus quorum structure for an arbitrary i. That means that it follows the rotation closure property $\forall H', H \in q, i \in \{1, 2, ..., n-1\} : A' \cap A \neq 0$. Suppose $A = \{1,3,4,7,8,10,13,17,18,19,21,22,24\}$ is the quorum under $Q = 1 : 28$ and $A' = rotate(A, 2) = \{3,5,6,9,10,12,15,19,20,21,23,24,26,28\}$ which follows the rotation closure property as $A' \cap A = \{3,10,21,24\}$. This is the scenario when two users observe channel information in distributed ad-hoc networks. Moreover, Fig. 3.11 illustrates the RCP of an extended torus quorum system for two different quorums A and B. Users A and B construct a quorum by selecting the elements $\{1,3,4,7,8,10,13,17,18,19,21,22,24\}$ and $\{3,4,6,9,13,14,15,17,18,20,$ $27,28\}$ respectively under Z_{28}.

Asymmetric Channel Status

In an asymmetric case, the channel information in terms of the number of channels observed by the participating CR nodes in communication is asymmetric. As is discussed in the previous section, a CR node generates an extended torus grid structure where the number of rows h is the number of channels and number of columns is $2 \times h - 1$. Therefore, asymmetric channel information leads to an asymmetric torus grid structure. This section shows how two asymmetric torus grid quorums can satisfy

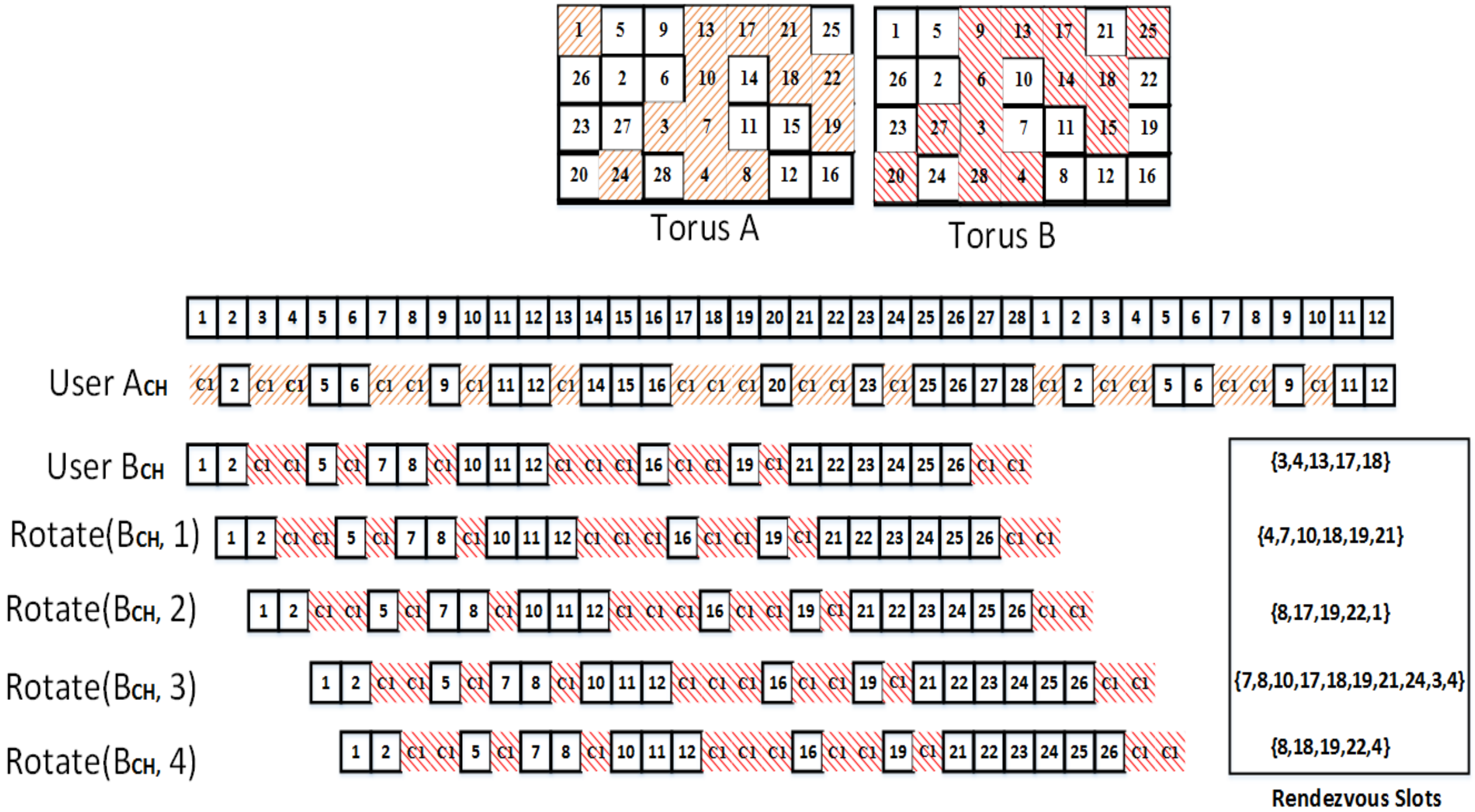


Figure 3.10: Construction of two extended (3) torus quorum systems of dimension 4×7 with 4 rendezvous channels.

the rotation closure property and eventually guarantee RDV.

Definition 7 (Asymmetric Torus Quorum):Given two positive integers n and m, two torus quorum systems x over universal set $U1 = \{0, 1, ..., n-1\}$ and y over $U2 = \{0, 1, ..., m-1\}$ that form a torus of $t \times w$ and $t \times s$ respectively are called asymmetric if $t \neq t$ and satisfy the intersection property i.e. $\forall Q_A \in x$ and $\forall Q_B \in y$; $Q_A \cap Q_B$.

To guarantee RDV in an asymmetric case, it is necessary to prove that the two CR nodes following $EQTCH$ protocol observe asymmetric channels and satisfy the rotation closure property.

Definition 8 (Cycle Augmentation): Assume a torus quorum system x over universal set $U = \{0, 1, ..., n-1\}$ and $Q_A = \{Q_{A_i}, ...Q_{A_k}\}$ is the quorum of x. The cycle augmentation of quorum Q_A is defined as $Q_A^c = (\{Q_{A_i} + j * n\} mod(n * c))$; where $1 \leq i \leq k$ and $0 \leq j \leq c-1$.

For example, $Q_A = \{1, 3, 4, 7, 8, 10, 13, 17, 18, 19, 21, 22, 24, \} \in x(Z_2 8)$. Now $Q_A^2 =$
$\{1, 3, 4, 7, 8, 10, 13, 17, 19, 21, 22, 24, 28, 30, 31,$
$34, 35, 37, 40, 44, 45, 46, 48, 49, 51\}$

Definition 9 (Asymmetric Rotation Closure Property): Two asymmetric extended torus quorum systems x over universal set $U1 = \{0, 1, ..., n-1\}$ and y over $U2 = \{0, 1, ..., m-1\}$ satisfy the asymmetric RCP if

i $\forall\ Q_A \in x$ and $Q_B \in y$, $Q_A \cap (Q_B + i) \neq 0$

ii $\forall\ Q_A^c \in x^c$ and $Q_B \in y$, $Q_A^c \cap Q_B \neq 0$

iii $\forall\ Q_A^c \in x^c$ and $Q_B \in y$, $Q_A^c \cap (Q_B + i) \neq 0$

Theorem 2:The extended torus quorum system satisfies the asymmetric rotation closure property and can guarantee RDV.

Proof:It has been proven in [71] that the torus grid quorum system satisfies the rotation closure property. The extended torus quorum system is a super set of the torus grid system. Hence, RCP also stands for an extended torus quorum system. For example, two users A and B form 4×7 torus grid systems. User A chooses one column and three elements, each of which falls in a diagonal position for successive columns in wrap around manner i.e $Q_A = \{3, 6, 9, 13, 14, 15, 28\}$. User B will choose quorum $Q_B = \{3, 4, 6, 9, 13, 14, 15, 17, 18, 20, 25, 27, 28\}$ based on definition 8. It shows that $Q_B \supset Q_A$.

3.5 Channel Ranking

In this section, the channel ranking problem is formulated as a convex combination of sequential multi-objective linear programming problems. The primary and secondary objective functions are to maximise a weighted sum of the channel average availability times and channel sojourn times in the idle state respectively. Consider that w_m is a weight associated with channel $f_m, m \in \{1, ..., L\}$. The weight is used to rank the channel such that the channel with the largest weight will be considered the best channel. The primary objective function of the linear optimisation problem can be written as Eqn. 3.10:

LP1: Channel Availability

$$w = \underset{(w_1, w_2, \ldots, w_L)}{\text{maximize}} \{\mathbf{C}(\mathbf{w}) \overset{\text{def}}{=} \sum_{m=1}^{L} \pi_1^{(m)} w_m\} \tag{3.10}$$

subject to

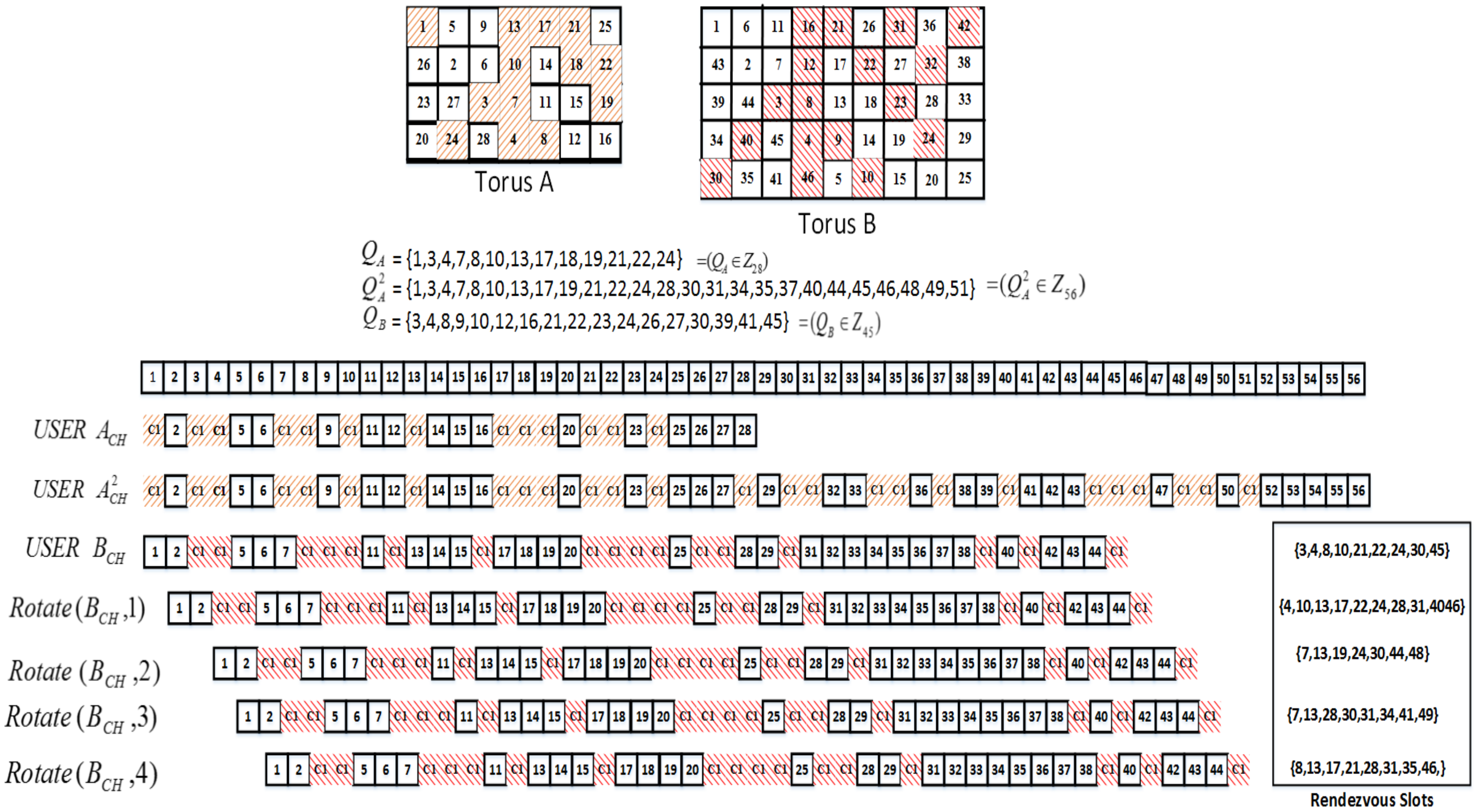


Figure 3.11: Construction of two asymmetric extended (3) torus quorum systems A and B of dimension 4×7 and 5×9 with 4 and 5 rendezvous channels respectively.

$$[1-\prod_{i=1}^{h}\left(1-p^{(m)}_{(n+mi)T}(1,S)\right)\prod_{i=1}^{\left\lfloor \frac{w}{2}\right\rfloor}\left(1-p^{(m)}_{(n+(x(1+i)mod\ h).y((m+i)mod\ w))}(1,s)\right)\cdot$$

$$\prod_{i=1}^{\left\lfloor \frac{w}{2}\right\rfloor}\left(1-p^{(m)}_{(n+(x(1+i)mod\ h).y((m-i)mod\ w))}(1,s)\right)\cdot$$

$$\prod_{i=1}^{\left\lfloor \frac{w}{2}\right\rfloor}\left(1-p^{(m)}_{(n+(x(\left\lfloor \frac{h}{2}\right\rfloor+i)mod\ h).y((m+i)mod\ w))}(1,s)\right)]w_m<\lambda_s^{(m)}col(n) \quad (3.11)$$

$$\forall s\{K,P\},\forall m\in\{1,2,...,L\},K\in\{1,2,3,...,N\} \quad (3.12)$$

$$\sum_{m=1}^{L}w_m=1;0\leq w_m\leq 1,\forall m\in\{1,2,...,L\} \quad (3.13)$$

The probability of collision with PUs and other SUs and channel fluctuation levels are considered to be the constraints in the optimization problem. Eqn. 3.11 described the constraints of the optimization problem for the ETQCH quorum structure. The left side of Eqn. 3.11 has four parts: one for the column and the rest for three different diagonals. $p_u(1,s)$ is the probability that the channel will move from the idle state (i.e. state 1) to state s in quorum slot u. $1-p_u(1,s)$ is the probability that the channel state will not change during slot u. $\prod(1-p_u(1,s))$ is the probability that the channel state will not change during any of the quorum slots of a particular quorum. $1-\prod(1-p_u(1,s))$ is the probability that the channel state will change (i.e., will no longer stay idle) during at least one of the slots that belong to a particular quorum. Hence, $1-\prod(1-p_u(1,s))$ is the probability of collision with a PU (when s = 2) or another CRs (when s = 3). Note that channel sensing occurs at the beginning of a grid. Taking into account the processing time for assigning the probabilities and assigning the channels, this sensing can be used for the next grid, not the current grid. This is why n is added to each index. That means whenever a quorum starts, its channel has already been assigned during the previous quorum. In this work, n is considered to be an individual total time slot rather than a global system parameter like in [74]. Here n is the length of the rendezvous cycle or number of time slots, which depends on the number of available channels. In an asymmetric channel scenario, a node experiences a different number of channels and has a different cycle length. Hence, channel sorting would also be different due to collision probability.

Consider that the sojourn time for channel m in state i is $\mathrm{T}_i^{(m)}$ and return to state i is $\mathrm{R}_i^{(m)}$ after leaving it. Let $\psi_i^{(m)} \stackrel{\text{def}}{=} \mathbb{E}[T_i^{(m)}]$ and $\mathrm{R}_i^{(m)} \stackrel{\text{def}}{=} \mathbb{E}[R_i^{(m)}]$. For $i \in 1, 2, 3$ i.e. idle, PU, CRs the sojourn time for the different states can be expressed as follows:

$$T_1^{(m)} = \frac{1}{\lambda_p^{(m)} + \lambda_p^{(m)}} T_2^{(m)} = \frac{1}{\mu_p^{(m)}} T_3^{(m)} = \frac{1}{\lambda_p^{(m)} + \mu_s^{(m)}} \tag{3.14}$$

The constraint in Eqn 3.11 is used to improve the prediction accuracy by restricting the fluctuation level of the selected channel. Channels with higher fluctuation levels will have higher collision probability and hence receive lower weight. The second objective function is to minimise the effect of channel fluctuation in prediction accuracy by providing higher priority to channels with larger mean sojourn time in the idle state. Hence, the secondary objective function of the linear optimisation problem can be written as in Eqn. 3.10:

LP2:Channel Sojourn Time

$$w = \underset{(w_1, w_2, \ldots, w_L)}{\text{maximize}} \{\mathcal{F}(w) \stackrel{\text{def}}{=} \sum_{m=1}^{L} \psi_i^{(m)} w_m\} \tag{3.15}$$

$$= \underset{(w_1, w_2, \ldots, w_L)}{\text{maximize}} \{\mathcal{F}(w) \stackrel{\text{def}}{=} \sum_{m=1}^{L} \sum_{i=1}^{3} \psi_i^{(m)} w_m\} \tag{3.16}$$

$$= \underset{(w_1, w_2, \ldots, w_L)}{\text{maximize}} \{\mathcal{F}(w) \stackrel{\text{def}}{=} \sum_{m=1}^{L} \psi_1^{(m)} w_m\} \tag{3.17}$$

subject to

$$\mathcal{X}_I^*(1-\epsilon) < \mathcal{X}(w) \tag{3.18}$$

Equation 3.18 limits the influence of sojourn time on channel ranking by adjusting the value of ϵ ($0 \leq \epsilon \leq 1$). If $\epsilon = 0$, the second objective function does not have any control over channel ranking.

To explain the channel selection criteria, an example is presented in tables 3.1 and 3.2. It is considered that user A observes eight available channels. It is also assumed that channel collision probability thresholds are the same for all channels. However, it can vary based on frame length, and frame length increases with the number of channels. There are 2 pairs of channels, each has the same $\pi_1^{(m)}$ but different channel sojourn time $\psi_1^{(m)}$. Here channel availability times and sojourn times are considered for only the idle state. The other two states (PU and CRs) are captured by collision probability constraints. The LP problem is implemented in MATLAB and it is found that the minimum collision probability value that keeps the problem feasible is 0.16 (i.e. $\lambda_{min} = 0.16$). Table 3.2 shows the ranking of the eight channels. Initially ϵ is set to zero, to analyse the behavior of the channel availability linear programming problem in relation to collision constraint probability. It is found that the feasible region of LP1 increases with λ and channels gain higher weight based on $\pi_1^{(m)}$ leaving the other channels with zero weight. In this example, $CH1$, $CH6$ and $CH8$ receive zero weight when $\lambda = 0.18$. A further increment of λ results $CH3$ and $CH5$ down to zero. Interestingly, collision probability increases due to channel transition from the idle state to either PU or CR state and the channel sojourn time is reduced. Hence, the second optimisation stage is used to assign higher weight to the channels with larger mean sojourn time which are subject to constraint 3.18 to restrict the reduction in optimum value of the first objective function. Again see table 3.2, for $\lambda = 0.16$ and $\epsilon = 0$, which shows that $CH6$ gets higher rank over $CH5$ and $CH3$ due to higher $\psi_1^{(m)}$ and lower rate of channel occupancy by PUs. For further increments of ϵ and λ, still channels with larger values of $\pi_1^{(m)}$ dominate the get higher ranking priority however with less available channels having zero weights. An interesting observation is that $CH6$ receives higher rank than the $CH5$ and $CH7$. This is because $CH5$ and $CH7$ have a higher collision probability and lower sojourn time. However, it would be changed with further increments of λ and provide higher weight or rank to the channels with high $\pi_1^{(m)}$.

Table 3.1: Channels with different optimisation parameters

	$\pi_1^{(m)}$	$\psi_1^{(m)}$	$\frac{\pi_2^{(m)}}{\pi_3^{(m)}}$
CH1	0.2544	36.41	25.68
CH2	0.7425	54.18	4.06
CH3	0.4822	26.5	12.44
CH4	0.7425	88.21	1.52
CH5	0.4822	64.89	12.44
CH6	0.2113	97.32	1.003
CH7	0.5411	29.59	1.84
CH8	0.3128	47.18	21.03

3.6 Adaptive CH sequence

Before joining the network, a CR node starts channel sensing and creates a channel list according to the channel ranking. Using algorithm 1, the CR node generates a CH sequence. It is assumed that the CR node has two radio transceivers as described in section 3.4.1. During the network set up phase, the CR node selects the channel from the CH sequence and senses using D-Radio. If the channel is sensed as idle for a distributed coordination function inter-frame space (DIFS) interval, it implies that currently there are no ongoing transmissions over the channel and an RTS transmission is initiated using R-Radio. If no clear-to-send (CTS) is received after a short inter-frame space (SIFS) interval, it continues channel hopping. It is assumed that

Table 3.2: Channel Ranking for ETQCH protocol

Optimisation Parameters		1	2	3	4	5	6	7	8
$\epsilon = 0$	$\lambda = 0.16$	CH4	CH2	CH7	CH6	CH5	CH3	CH8	CH1
	$\lambda = 0.18$	CH4	CH2	CH7	CH5	CH3			
	$\lambda = 0.195$	CH4	CH2	CH7					
$\epsilon = 0.05$	$\lambda = 0.16$	CH4	CH2	CH7	CH6	CH5	CH3	CH8	CH1
	$\lambda = 0.18$	CH4	CH2	CH7	CH6	CH5	CH3		
	$\lambda = 0.195$	CH4	CH2	CH7	CH6	CH5	CH3	CH8	
$\epsilon = 0.1$	$\lambda = 0.16$	CH4	CH2	CH7	CH6	CH5	CH3	CH8	CH1
	$\lambda = 0.18$	CH4	CH2	CH6	CH5	CH7			
	$\lambda = 0.195$	CH4	CH2	CH7	CH5	CH3	CH6	CH8	

RTS/CTS transmission is always successful. In addition, with multiple channels operating in parallel, the collision probability on any of these channels is greatly reduced. Therefore, when a CR node sends an RTS but receives no CTS after an SIFS, most likely the corresponding destination is not accessing the same channel at that time. Thus, the CR node should switch to a different channel. If a CTS is received after an SIFS, it means that the corresponding destination is also accessing the channel at that time. After the successful handshake, the CR node starts data transmissions to its destination using D-Radio. If the channel is sensed to be busy, which implies that the current channel is occupied by other CR node pairs, CR will modify the channel hopping sequence by replacing the busy channel with the last rendezvous channel. If there is no rendezvous achieved so far, the busy channel will be replaced by the best channel from the channel list for the rest of the hopping sequence. Figure 3.12 presented below illustrates the channel access strategy.

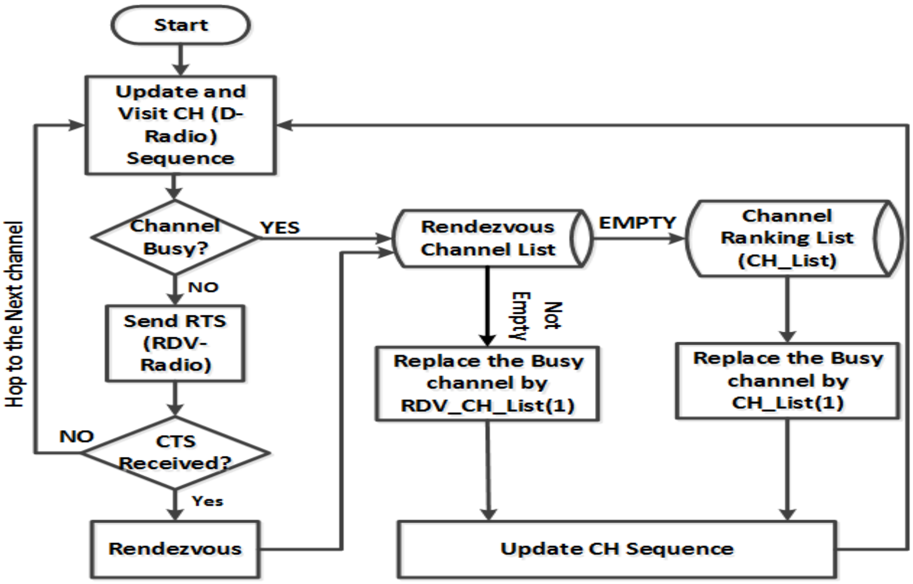


Figure 3.12: Channel hopping update

Assume we have the following channel sequence:

2	2	4	4	4	1	1	3	3	4	2

At any time in the rendezvous process channel 1 may become busy. Then the busy channel will be replaced by channel 2, assuming the CR established RDV in channel 2 in the previous cycle. Therefore, the updated CH sequence would be:

2	2	4	4	4	2	2	3	3	4	2

Otherwise, the busy channel will be replaced by the channel in the top of the channel ranking list. Assuming channel 4 is at the top of the channel rank.

2	2	4	4	4	4	4	3	3	4	2

3.7 Features of ETQCH Protocol

This section outlines the features of the ETQCH protocol, which achieves better performance by dynamically updating the hopping sequence based on PU activity. The features are as follows:

i. ***Synchronization***: Synchronization between sender and receiver is one of the fundamental requirements of existing CH protocols in achieving and guaranteeing RDV in CRAHNs. This assumption may ease the problem but cannot capture the practical scenario where clock drift is evident. In distributed networks, achieving clock synchronization is very difficult unless an external synchronization system is used. In ETQCH, all the CR nodes hop to the channels based on the local clock and CH sequence. Synchronization can only be achieved after RDV through the exchange of a control message. However, synchronization between CR users is captured by the RCP and cycle augmentation property of the ETQCH scheme in both symmetric and asymmetric scenarios. Hence, sender and receiver can achieve RDV if the slot alignment is less than the control message transmission time.

ii. ***Scalability***: There are many CH protocols in the literature that fundamentally rely on the exchange of seed (MAC address or NODE ID) values between neighbors to track the sender CH sequence prior to RDV. However, this information is only received if neighbors are on the same channel or there is a dedicated channel to transfer this information. In CRAHNs, this is impractical as nodes are not aware of neighbor nodes and their transmission. Moreover, CR nodes need to spend a significant amount of time on each channel to get this (seed) information. As a result, further latency and overheads are incurred on link establishment. In contrast to that, the ETQCH protocol is a completely blind rendezvous protocol which does not need to exchange any prior information and consequently reduces the overhead and latency.

iii. ***Load Balancing***: This is one of the classic problems in both infrastructure and ad-hoc wireless networks. Here, load refers to the amount of traffic flow through the channel. Hence channel activity or channel availability times imply the load on the channel. Most of the existing CH RDV schemes map the channel randomly from the available channels set to construct CH regardless of channel availability times or channel activity. As a result, these schemes encounter more collisions and spectrum handoffs, which eventually degrade network performance. In contrast, channel mapping in the ETQCH protocol is fundamentally based on channel quality or channel ranking. To quantify the channel quality, a channel activity-based channel ranking system is embedded in the ETQCH protocol.

iv. ***Robustness***: Robustness refers to protocol behavior against intermittent PU and CR activities which cause a change of channel status. The idea of CR is to opportunistically use the licensed and unlicensed radio spectrum. Hence protocols for CR should be able to update the channel status more often. Existing CH RDV protocols perform spectrum sensing and gather radio information to construct CH sequences. Based on the CH sequence, the CR node visits the channel and performs a RTS/CTS handshake to achieve RDV. However, it may happen that the channel becomes unavailable during the CH operation and causes a collision with either PUs or CRs operating on that channel. In ETQCH, robustness is achieved by monitoring the channels in the CH sequence prior to hopping on that channel using an additional antenna and eventually updating the sequence if there is any change in channel status. A detailed explanation of this update procedure is given in section 3.6.

3.8 Summary

In summary, this chapter presents the novel ETQCH protocol based on channel ranking to guarantee RDV on available common channels. It utilizes the extended torus quorum concept to achieve and guarantee RDV. It also shows that EQTCH can guarantee RDVs for both symmetric and asymmetric channel scenarios without any further modification. The fundamental concept of the EQTCH protocol is to assign more time slots to the best channel and decrease the time slots according to channel ranking. Hence, channel ranking is one of the important components of the ETQCH protocol. Channels are ranked based on channel availability times and sojourn times with the constraint of PU and CR collision probability. A multi-objective linear optimization problem has been discussed to eliminate channel fluctuation levels. Moreover, to avoid collision with any PU and CR transmission during a CH period, an adaptive CH update procedure was explained which utilizes the historical RDV information if available or stays on the best channel. Finally, the features of the ETQCH protocol were presented.

In the next chapter, the performance of the ETQCH protocol is investigated through mathematical analysis and simulation. A detailed mathematical formulation is derived to estimate the expected degree of overlap for ETQCH and gQ-RDV protocols. It also describes the simulation results to compare the ETQCH protocol behavior with existing CH protocols, including channel rank and non-channel-rank based protocols.

Chapter 4

Performance Evaluation of ETQCH Protocol

4.1 Introduction

In Chapter 3, construction of the ETQCH protocol was presented, which integrates channel quality information to assign the priority among the number of channels observed. The fundamental idea is to assign timeslots based on channel quality in terms of availability times and channel fluctuation. In this chapter, the performance of the ETQCH protocol is evaluated in relation to legacy CH RDV protocols. Average time to rendezvous (ATTR) and degree of overlap are used to evaluate the performance of the CH sequence. These are the two widely used performance metrics that quantify the effectiveness of an RDV CH protocol. ATTR measures the time required to achieve RDV, and degree of overlap counts the number of overlaps within a CH period. For comparative analysis, simulation is performed on two groups of channel selection schemes: channel rank-based channel mapping (gQ-RDV [61], Basic AMRCC and Enhance AMRCC [29]); and non-channel-rank-based channel mapping (Jump Stay (JS) [60],Enhance Jump Stay (EJS) [34], DRSEQ [33], Sequence Based Rendezvous (SeqR) [3], Modular Clock (MC) [39], Modified Modular Clock (MMC) [39], and

Short Sequence Based (SSB) [35]) in the CH sequence.

Section 4.2 explains the expected quorum overlap size (EQOS) for ETQCH and gQ-RDV protocols in subsections 4.2.1 and 4.2.2 respectively. EQOS is the measurement of expected degree of overlap. For both of the protocols, different channel mapping strategies are considered to estimate the EQOS or degree of overlaps. Section 4.3 presents the simulation environments and model assumptions in building the MATLAB based simulator. The simulation results are explained in section 4.4 with detailed analysis of the protocols' behavior in different simulation scenarios. The chapter concludes with a brief summary of the main findings in section 4.6.

4.2 Expected Quorum Overlap Size (EQOS)

Definition 4 [75]: For a quorum system Q under $U = \{0, 1, 2, ..., n-1\}$, the expected quorum overlap size of Q can be defined as $\sum_{G,H \in Q} p(G)p(H)|G \bigcap H|$, where $p(G)$ and $p(H)$ is the probability of accessing quorum G and H respectively for a quorum access strategy.

4.2.1 EQOS of Extended Torus Quorum System

Suppose Q and Q' are the torus quorum systems formed according to the quorum formation rule described in section 3.4.2, where Q contains all elements of column C and Q' contains all elements of column C'. We define d, the distance between C and C', as $min((C' - C) mod\ w, (C - C') mod\ w)$. Let $E(h, i, j)$ be the expected number of the common members of two independently chosen subsets of a set of h elements, where the first and the second subsets respectively contain i and j elements. Using combinatorics and applied probability we can derive that $E(h, i, j) = (i \times j)/h^2$ when i and j are equal in size. For an asymmetric scenario, where the number of elements are not chosen from the same universal set, $E(h,k,i,j)$ is the expected number of elements common to both samples. If we assume that $H = \{1, 2, ..., h\}$ and $K = \{1, 2, ..., k\}$, and if i elements are chosen (uniformly and without replacement) from H, and j elements are chosen (uniformly and without replacement) from K, then $E(h,k,i,j) = (i \times j\ min(h,k))/(h \times k) = (i \times j)/(max(h,k))$. This is obtained by adding, for each $n \in 1, 2, ..., min(h,k)$, the probability that n is chosen in both samples. Let $K_r = \left\lceil \frac{K}{2} \right\rceil$, $K_l = \left\lfloor \frac{K}{2} \right\rfloor$, $K'_r = \left\lceil \frac{K'}{2} \right\rceil$, $K'_l = \left\lfloor \frac{K'}{2} \right\rfloor$, $W_r = \left\lceil \frac{W}{2} \right\rceil$, $W_l = \left\lfloor \frac{W}{2} \right\rfloor$, $W'_r = \left\lceil \frac{W'}{2} \right\rceil$, $W'_l = \left\lfloor \frac{W'}{2} \right\rfloor - 1$. According to the proposed extended torus quorum system $K = 3$, hence $K_r = K'_r = 2$ and $K_l = K'_l = 1$.

- *Case 1*: $d = 0$; this means user A and B are on the same column; $L = 0$; $R = 0$, which reflects that user A and B have the same number of channels in the channel list. The expected overlap size between Q_A and Q_B is

$$O_1 = T + E(T, K_r, K'_r).W_r + E(T, K_l, K'_l).W_l \tag{4.1}$$

- *Case 2*: $d = 0; L \geq 1, R \geq 1$; this means user A and B have asymmetric channel information but they are on the same column, hence the expected quorum overlap size is $L = 0$; $R = 0$, which reflects that user A and B have the same number of channels in the channel list. The expected overlap size between Q_A and Q_B is

$$O_2 = min(T, T') + E(T, T', K_r, K'_r).W_r + E(T, T', K_l, K'_l) \cdot W_l \tag{4.2}$$

- *Case 3(1)*: $1 \leq d < W_r$; here $d = (C' - C) mod\ W$; $L = 0$, $R = 0$. The size of the quorum overlap is:

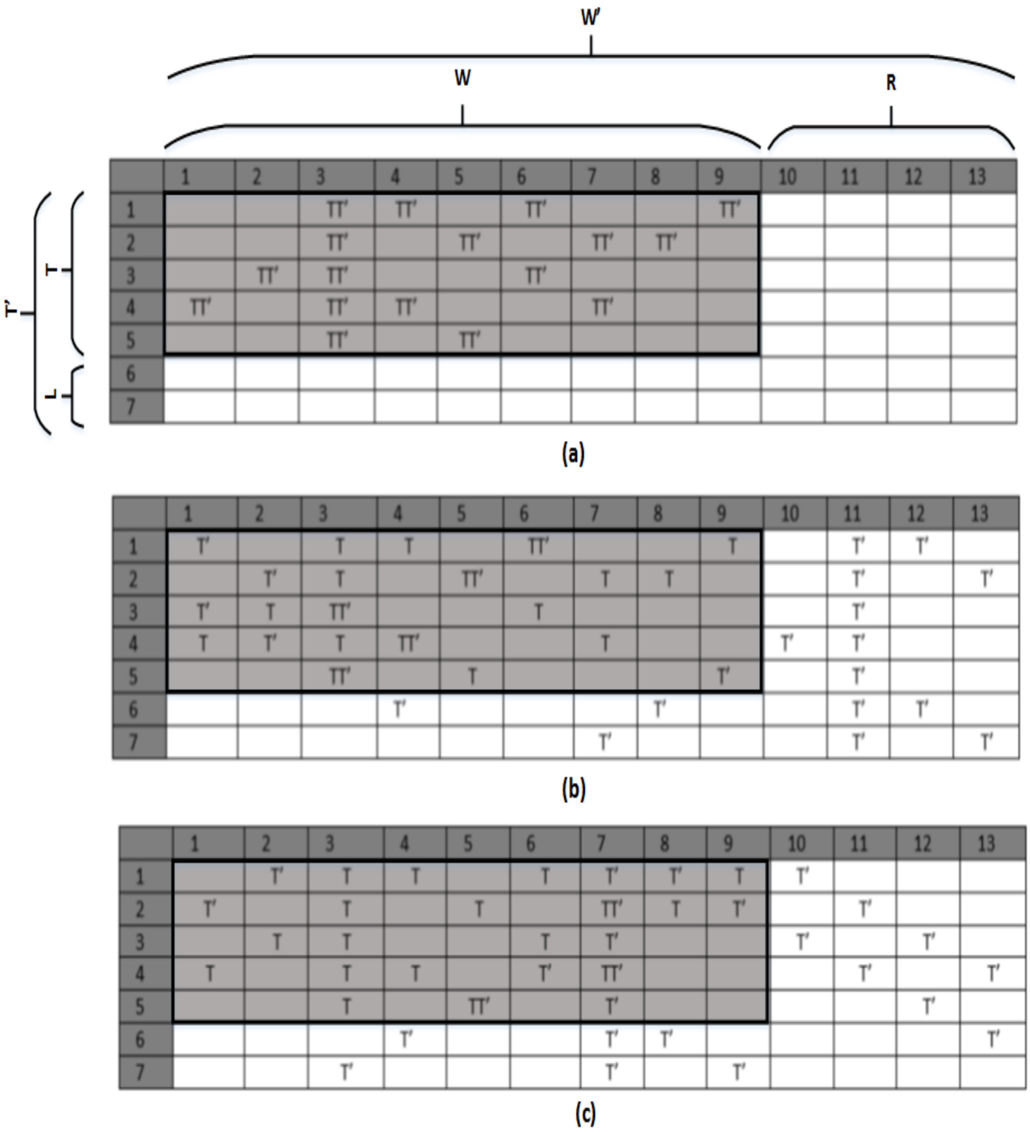


Figure 4.1: Illustration of extended torus quorum system with three different cases: Symmetric channel observation with same channel ranking (at the top); Asymmetric channel observation with different channel ranking (at the middle and bottom).

$$\begin{aligned} O_{31} = (d-1).E(T, K_r, K'_r) + (W_r - d).E(T, K_r, K'_r) + \\ d.E(T, K_l, K'_r) + (W_l - d)E(T, K_l, K'_l) + K'_l + K_r \end{aligned} \tag{4.3}$$

- *Case 3(2)*: $1 \leq d < W_r$; here $d = (C - C')mod\ W$; $L = 0$, $R = 0$. The size of the quorum overlap is:

$$O_{32} = (d-1).E(T, K_l, K'_r) + (W_r - d).E(T, K_r, K'_r) + \\ d.E(T, K_r, K'_l) + (W_l - d)E(T, K_l, K'_l) + K_l + K'_r \tag{4.4}$$

- *Case 4(1)*: $1 : n < d$; here $d = (C' - C) mod\ W$; $n = T - T'$,$L \geq 1$, $R \geq 1$. The overlap size is:

$$O_{41} = (d-1).E(T, T', K_r, K'_l) + (W_r - d).E(T, T', K_r, K'_r) + \\ d.E(T, T', K_l, K'_r) + (W_l - d)E(T, T', K_l, K'_l) + K'_l + K_r \tag{4.5}$$

- *Case 4(2)*: $1 : n < d$; here $d = (C - C') mod\ W$; $n = T - T'$,$L \geq 1$, $R \geq 1$. The overlap size is:

$$O_{42} = (d-1).E(T, T', K_l, K'_r) + (W_r - d).E(T, T', K_r, K'_r) + \\ d.E(T, T', K_r, K'_l) + (W_l - d)E(T, T', K_l, K'_l) + K_l + K'_r \tag{4.6}$$

- *Case 4(3)*: $1 : n < d$; here $d = (C - C') mod\ W$; $n = T - T'$,$L \geq 1$, $R \geq 1$. Assume C' is outside of W but inside W'. The overlap size is:

$$O_{43} = (d-1).E(T, T', K_r, K'_l) + (W'_r - d).E(T, T', K_r, K'_r) + \\ d.E(T, T', K_l, K'_r) + (W'_l - d)E(T, T', K_l, K'_l) + K'_l \tag{4.7}$$

- *Case 5(1)*: $n \leq d < W_r$; here $d = (C' - C) mod\ W$; $n = T - T'$,$L \geq 1$, $R \geq 1$. The overlap size is:

$$O_{51} = (d-1).E(T, T', K_r, K'_l) + (W_r - d).E(T, T', K_r, K'_r) + \\ d.E(T, T', K_l, K'_r) + (W_l - d)E(T, T', K_l, K'_l) + K_r \tag{4.8}$$

- *Case 5(2)*: $n \leq d < W_r$; here $d = (C - C') mod\ W$; $n = T - T'$,$L \geq 1$, $R \geq 1$. The overlap size is:

$$O_{52} = (d-1).E(T,T',K_l,K'_r) + (W_r - d).E(T,T',K_r,K'_r) + \\ d.E(T,T',K_r,K'_l) + (W_l - d)E(T,T',K_r,K'_l) + K_l + K'_r \quad (4.9)$$

- *Case 5(3)*: $n \leq d < W_r$; here $d = (C' - C) mod\ W$; $n = T - T'$,$L \geq 1$, $R \geq 1$. Assume C' is outside of W but inside W'. The overlap size is:

$$O_{53} = (d-1).E(T,T',K_r,K'_l) + (W'_r - d).E(T,T',K_r,K'_r) + \\ d.E(T,T',K_l,K'_r) + (W'_l - d)E(T,T',K_l,K'_l) + K_r \quad (4.10)$$

- *Case 6(1)*: $d = W_r$ and W is **ODD**, here $d = (C' - C) mod\ W$; $L = 0$, $R = 0$. The overlap size is:

$$O_{61} = (W_r - 1).E(T,K_r,K'_l) + W_r.E(T,K_l,K'_r) + K_r + K'_l \quad (4.11)$$

- *Case 6(2)*: $d = W_r$ and W is **ODD**, here $d = (C - C') mod\ W$; $L = 0$, $R = 0$. The overlap size is:

$$O_{62} = (W_r - 1).E(T,K_l,K'_r) + W_r.E(T,K_r,K'_l) + K'_r + K_l \quad (4.12)$$

- *Case 7(1)*: $d = W_r$ and W is **ODD**, here $d = (C' - C) mod\ W$; $L \geq 1$, $R \geq 1$. Assume C' is outside of W but inside W'. The overlap size is:

$$O_{71} = (d-1).E(T,T',K_r,K'_l) + d.E(T,T',K_l,K'_r) + \\ (W'_l - d)E(T,T',K_l,K'_l) + K_l \quad (4.13)$$

- *Case 7(2)*: $d = W_r$ and W is **ODD**, here $d = (C - C') mod\ W$; $L \geq 1$, $R \geq 1$. Assume C' is outside of W but inside W'. The overlap size is:

$$O_{72} = (W_r - 1).E(T,T',K_l,K'_r) + W_r.E(T,T',K_r,K'_l) + \\ K'_r + K_l \quad (4.14)$$

- *Case 8*: $d = W_r$ and W is **EVEN**, here $d = (C - C')mod\, W = (C' - C)mod\, W$; $L = 0$, $R = 0$. W and W' both are even. The overlap size is:

$$O_8 = (W_r - 1).E(T, K_r, K'_l) + E(T, K_l, K'_r) + K_r + K'_l \tag{4.15}$$

- *Case 9(1)*: $d = W_r$ and W is **EVEN**, here $d = (C - C')mod\ W = (C' - C)mod\ W$; $L \leq 1$, $R \leq 1$. Assume C' is outside of W but inside W'. The overlap size is:

$$O_{91} = (d-1).E(T, T', K_r, K'_l) + (W_r - d).E(T, T', K_r, K'_r) + d.E(T, T', K_l, K'_r) + (W'_l - d)E(T, T', K_l, K'_l) + K_l \tag{4.16}$$

- *Case 9(2)*: $d = W_r$ and W is **EVEN**, here $d = (C - C')mod\ W = (C' - C)mod\ W$; $L \leq 1$, $R \leq 1$. Assume C' is inside W. The overlap size is:

$$O_{92} = (W_r - 1).(E(T, T', K_r, K'_l) + E(T, T', K_l, K'_r)) + K_r \tag{4.17}$$

- *Case 10(1)*: $W_r < d < W'_r$, here $d = (C' - C)mod\ W$ and $n = T - T'$ $L \leq 1$, $R \leq 1$. The overlap size is:

$$O_{101} = (d-1).E(T, T', K_r, K'_l) + d.E(T, T', K_r, K'_r) + (W'_l - d)E(T, T', K_l, K'_l) + K'_l \tag{4.18}$$

- *Case 10(2)*: $W_r < d < W'_r$, here $d = (C - C')mod\ W$ and $n = T - T'$ $L \leq 1$, $R \leq 1$. This is similar to the case mentioned in 5(2).

- *Case 11*: $d = W'_r$ and W is **ODD**, here $d = (C' - C)mod\ W'$; $L \leq 1$, $R \leq 1$. The overlap size is:

$$O_{11} = (W'_r - 1).(E(T, T', K_r, K'_l) + W'_r E(T, T', K_l, K'_r))+ \\ K'_l \tag{4.19}$$

- *Case 12*: $d = W'_r$ and W is **EVEN**, here $d = (C' - C) mod\ W'$; $L \leq 1$, $R \leq 1$. The overlap size is:

$$O_{12} = (W'_r - 1).(E(T, T', K_r, K'_l) + E(T, T', K_l, K'_r)) \tag{4.20}$$

There are W occurrences for each of the above-mentioned cases. W,W' are possible permutations of Q and Q'. Therefore, the expected overlap size of the two torus quorum systems can be written as follows. For the symmetric scenario:

$$\begin{aligned} &\frac{W.O_1 + W.\sum_{d=1}^{W_r-1}[O_{31}(d) + O_{32}(d)] + W.(O_{61} + O_{62})}{W^2} \\ &\qquad (W is\ ODD) \\ &= \frac{O_1 + W.\sum_{d=1}^{W_r-1}[O_{31}(d) + O_{32}(d)] + (O_{61} + O_{62})}{W} \\ &= \frac{W.O_1 + W.\sum_{d=1}^{W_r-1}[O_{31}(d) + O_{32}(d)] + W.(O_8}{W^2} \\ &\qquad (W is\ EVEN) \\ &= \frac{O_1 + W.\sum_{d=1}^{W_r-1}[O_{31}(d) + O_{32}(d)] + O_8}{W} \end{aligned} \tag{4.21}$$

For the asymmetric scenario:

When W and W' are ODD

$$\frac{W.O_2 + W.\sum_{d=1}^{n-1}[O_{41}(d) + O_{42}(d)] + W.\sum_{d=n}^{W_r-1}[O_{51}(d) + O_{52}(d) + O_{53}(d)] + W.(O_{71} + O_{72}) + W(O_{10} + O_{11})}{W.W'} \\ = \frac{O_2 + \sum_{d=1}^{n-1}[O_{41}(d) + O_{42}(d)] + \sum_{d=n}^{W_r-1}[O_{51}(d) + O_{52}(d) + O_{53}(d)] + O_{71} + O_{72} + O_{10} + O_{11}}{W'} \tag{4.22}$$

When W and W' are EVEN

$$\frac{W.O_2 + W.\sum_{d=1}^{n-1}[O_{41}(d) + O_{42}(d)] + W.\sum_{d=n}^{W_r-1}[O_{51}(d) + O_{52}(d) + O_{53}(d)] + W.(O_{91} + O_{92}) + W(O_{10} + O_{12})}{W.W'} \\ = \frac{O_2 + \sum_{d=1}^{n-1}[O_{41}(d) + O_{42}(d)] + \sum_{d=n}^{W_r-1}[O_{51}(d) + O_{52}(d) + O_{53}(d)] + O_{91} + O_{92} + O_{10} + O_{12}}{W'} \tag{4.23}$$

4.2.2 EQOS of Grid Quorum System

A grid system can be defined as a collection of elements which are logically organized to form a square. The quorum system based on the grid structure is a union of rows and columns that are associated with a particular element [66]. For example, a set $S = \{1, 2, ..., 16\}$ is organised in a (4×4) square grid to accommodate all of the elements as shown in Fig. 4.2. In order to select element number 11, a union of columns and rows corresponding to element 11 will be selected to form the quorum which is $\{3, 7, 9, 10, 11, 12, 15\}$. In general, the grid quorum system arranges elements of the universal set $U = \{0, 1, ..., n-1\}$ as an $(n \times n)$ array. A quorum can be any set containing a full column plus a full row of elements. Hence, the size of the quorum becomes $2\sqrt{(n-1)}$.

Assume there are two users A and B with quorums Q and Q' respectively. According to the quorum formation rule, user A will select one full column C and row R to form the quorum Q and user B will select C' and R' to form the quorum Q'. A grid quorum system is called symmetric if both users have the same grid dimensions, otherwise it is asymmetric. The EQOS of the symmetric grid system is presented in [75].

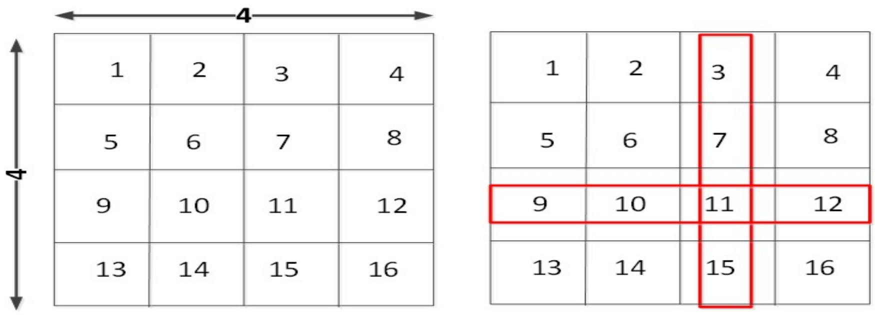


Figure 4.2: Grid structure and quorum system based on grid quorum

In this section, we compute the EQOS for the asymmetric grid quorum system by considering the following quorum selection strategies:

- *Case 1*: $C = C'$; $R = R'$ and $L > 0, R > 0$ (Both users choose same column and row). The expected overlap size between Q_A and Q_B is

$$\begin{aligned} &O_{1\_grid} = 2\big(min(\sqrt{n}, \sqrt{n'})\big) - 1; \\ &Occurance\ of\ event = min(n, n') \end{aligned} \tag{4.24}$$

- *Case 2*: $C = C'$; $R \neq R'$ and $L > 0, R > 0$ (Both users choose same column but different rows). The expected overlap size between Q_A and Q_B is

$$
\begin{aligned}
&O_{2\_grid} = min(\sqrt{n}, \sqrt{n'});\\
&Occurance\ of\ event = n \cdot \big(min(n, n') - 1\big)
\end{aligned} \tag{4.25}
$$

- *Case 3*: $C \neq C'$; $R = R'$ and $L > 0, R > 0$ (Both users choose different columns but same row). The expected overlap size between Q_A and Q_B is

$$
\begin{aligned}
&O_{3\_grid} = min(\sqrt{n}, \sqrt{n'});\\
&Occurance\ of\ event = n \cdot \big(min(n, n') - 1\big)
\end{aligned} \tag{4.26}
$$

- *Case 4*: $C \neq C'$; $R = R'$ and $L > 0, R > 0$ (Both users choose different columns and rows). It has four different subcases as shown on Fig. 4.3

  1. subcase 4.1: Different columns and rows but within the smaller grid

$$
\begin{aligned}
&O_{4.1\_grid} = 2;\\
&Occurance\ of\ event = min(n, n') \cdot \big(min(\sqrt{n}, \sqrt{n'})\\
&- 1\big) \cdot \big(min(\sqrt{n}, \sqrt{n'}) - 1\big)
\end{aligned} \tag{4.27}
$$

  2. subcase 4.2: Column is chosen inside the smaller grid but row is from outside

$$
\begin{aligned}
&O_{4.1\_grid} = 1;\\
&Occurance\ of\ event = min(n, n') \cdot \big(min(\sqrt{n}, \sqrt{n'}) - 1\big)
\end{aligned} \tag{4.28}
$$

  3. subcase 4.3: Column is chosen outside the smaller grid but row is from inside

$$
\begin{aligned}
&O_{4.1\_grid} = 1;\\
&Occurance\ of\ event = min(n, n') \cdot \big(min(\sqrt{n}, \sqrt{n'}) - 1\big)
\end{aligned} \tag{4.29}
$$

  4. subcase 4.4: Column is chosen outside the smaller grid but row is from inside

$$
\begin{aligned}
&O_{4.1\_grid} = 0;\\
&Occurance\ of\ event = \mid n - n' \mid \cdot \big(\mid (\sqrt{n}, \sqrt{n'} \mid -1\big)
\end{aligned} \tag{4.30}
$$

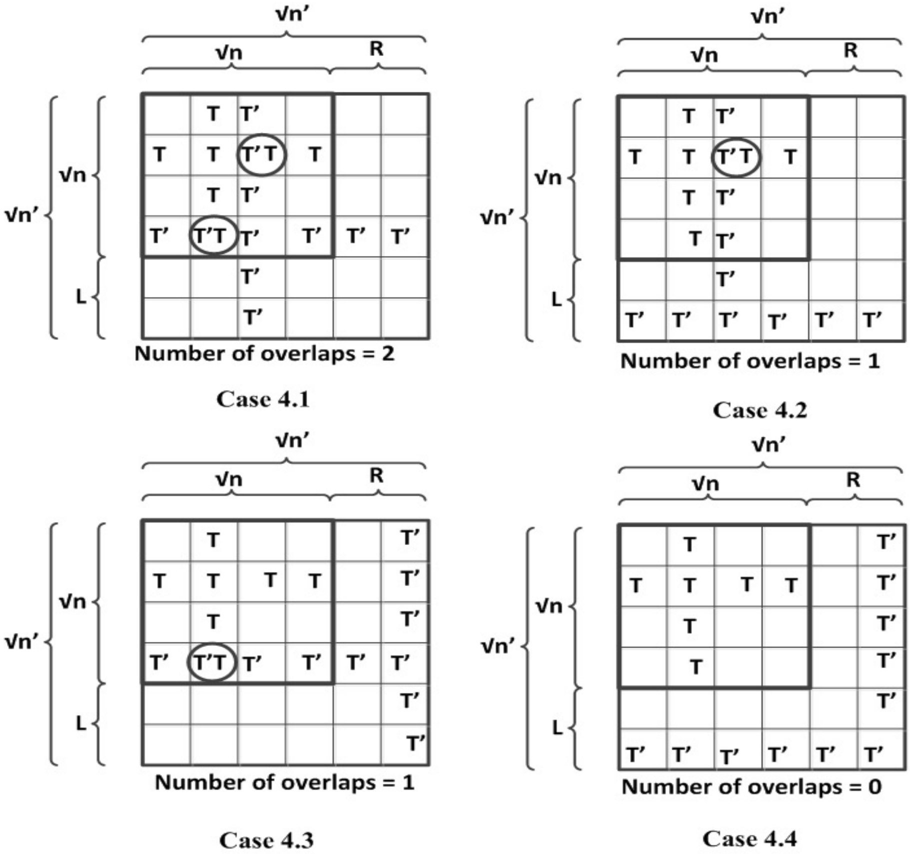


Figure 4.3: Quorum selection strategies in asymmetric grid quorum system

Therefore, the EQOS of the two grid quorum systems can be written as follows. For the symmetric scenario:

$$\frac{2n\cdot\big(\sqrt{n}-1big\big)\cdot\big(\sqrt{n}-1big\big)+2\sqrt{n}\cdot\sqrt{n}\cdot\big(\sqrt{n}-1\big)+\big(2\sqrt{n}-1\big)\cdot n}{n^2} = \frac{4n-4\sqrt{n}+1}{n} = \frac{\big(2\sqrt{n}-1\big)^2}{n} \tag{4.31}$$

For the asymmetric scenario:

$$
\begin{aligned}
&\frac{\big(min(\sqrt{n},\sqrt{n'})-1\big)\cdot min(n,n')+2\cdot min(\sqrt{n},\sqrt{n'})\cdot n\cdot \big(min(n,n')-1\big)+2\cdot min(n,n')\cdot \big(min(\sqrt{n},\sqrt{n'})-1\big)\cdot \big(min(\sqrt{n},\sqrt{n'})-1\big)+2\cdot min(n,n')\cdot \big(min(\sqrt{n},\sqrt{n'})-1\big)}{n\cdot n'} \\
&=\frac{\big(2\cdot\sqrt{n}-1\big)\cdot n+2\cdot n\cdot\sqrt{n}.(n-1)+2\cdot n\cdot(\sqrt{n}-1)\cdot(\sqrt{n}-1)+2\cdot n\cdot(\sqrt{n}-1)}{n\cdot n'} \\
&=\frac{\big(2\cdot\sqrt{n}-1\big)+2\cdot\sqrt{n}.(n-1)+2\cdot(\sqrt{n}-1)\cdot(\sqrt{n}-1)+2\cdot(\sqrt{n}-1)}{n'} \\
&=\frac{2\cdot\sqrt{n}(n-1)+2n}{n'}
\end{aligned}
\tag{4.32}
$$

4.3 Simulation

The effectiveness of the ETQCH protocol was extensively evaluated by a MATLAB based simulation. ETQCH was evaluated in relation to the existing channel rank and non-channel rank based channel mapping. Table 2.1 lists the protocols and the corresponding descriptions. The gQ-RDV [61], Basic AMRCC [29], and Enhanced AMRCC [29] protocols use channel ranking information to construct the CH sequence and rest use random channel selection to map the channels in hopping sequence.

4.3.1 Simulation Environment

A MATLAB based simulation was used to evaluate the performance of the ETQCH protocol. A network with varying CR nodes was considered with the number of available channels ranging from 2 to 40 in a $800m\times800m$ area, where each of the nodes had an equal transmission radius of $100m$. In this work both licensed and unlicensed channels were considered with equal priority. CR nodes were considered asynchronous, which was implemented by imposing a random delay at network initialization. During the simulation, the CR nodes may synchronize themselves after achieving RDV. Each CR node starts with spectrum sensing. The sensing duration was set at $25ms/channel$ and $\leq 1ms/channel$ for fine and fast sensing respectively [76]. Fast sensing is performed by selecting samples of the PU Poisson traffic within its sensing period and later on performing fine sensing before jumping into a channel. The ranking table of CR nodes is based on channel availability and channel activity observed locally by a CR user. It is assumed that, if a packet arrives during the spectrum sensing or handshaking process, it is enqueued and remains in the queue till RDV is achieved. In this chapter, collision among control or handshake packets is not considered; however, in case of collision between a CR user packet and a PU packet, the CR user packet is dropped instead of being retransmitted after a backoff.

All the results presented in this chapter are averaged over 10000 iterations [36]. The simulation covered both symmetric and asymmetric models with channel ranking starting from zero (zero means the channels between users A and B are completely out of order) to 1 (1 means CR users A and B have the same channel ranking list). Each PU is randomly assigned a channel when a new packet needs to be transmitted and packet arrivals follow the Poisson distribution with exponentially distributed inter-arrival times. Table 4.1 lists the parameters used in the simulation.

Two parameters were introduced to analyse the protocol behavior in relation to the number of channels and number of commonly available channels: (a) Degree of common channel, and $\theta(0 < \theta \leq 1)$ and (b) Channel ranking similarity factor $\alpha(0 \leq \alpha \leq 1)$. The available channel set CH_{avail} was randomly selected from the whole set CH_{list}, which is equivalent to $k \cdot CH_{list}$, where k is the factor to control the available channel set in the system. It is assumed that k is very small, varying from 0.1

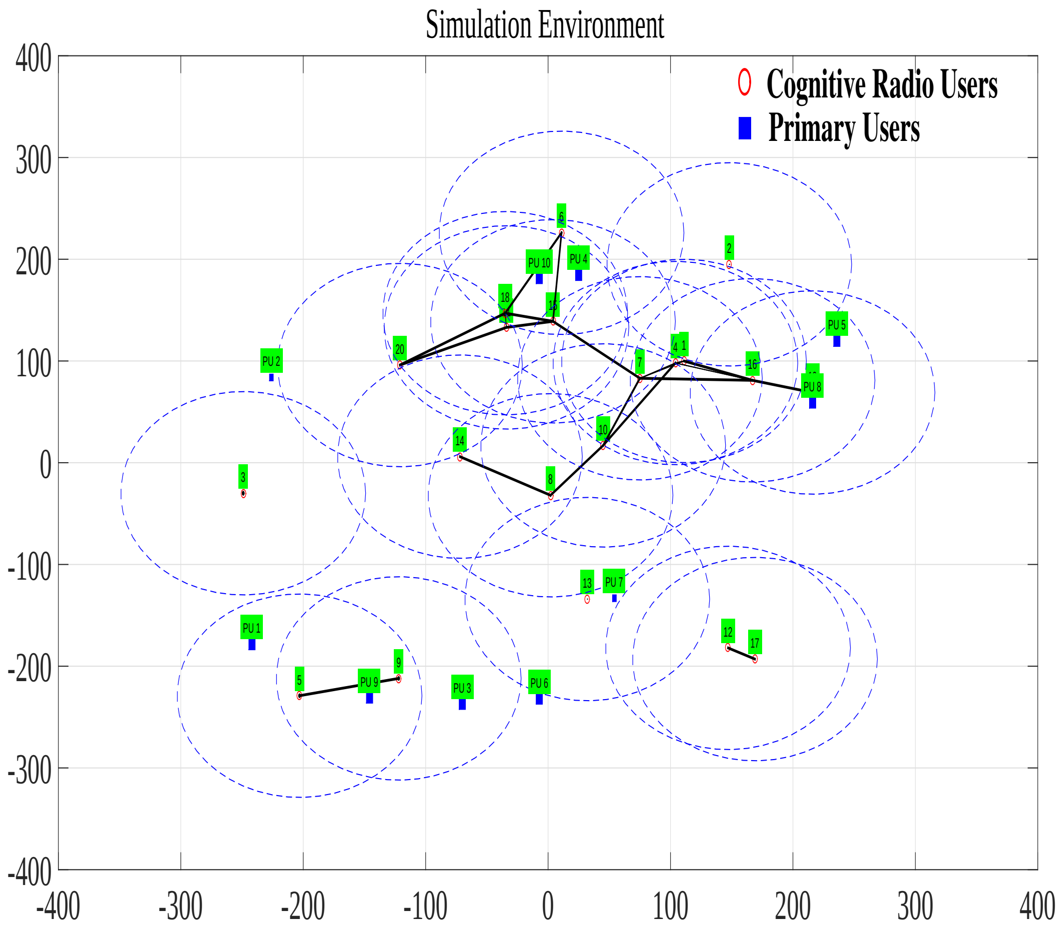


Figure 4.4: Simulation Environment with 10 PU and 20 CR nodes

Table 4.1: Simulation Parameters

Number of CRs	20
Number of PUs	10
Number of channels, M	2 to 40
PU packet size	50 slots
Simulation time	10000 slots
Simulation area	$500 \times 500\ m^2$
PUs and CRs sensing range	100 m
Channel date rate	2 Mbps
T-RTS	192+160/r*
T-CTS	192+112/r*
r*	1 Mbps

to 0.3 [77]. This is an important factor because channel availability is directly related to PU activity or traffic rate. A higher traffic rate implies that CR channel availability fluctuates at a high rate. In order to capture the dynamic radio environment, it is assumed that θ portion of channels are commonly available between CR users. The value of θ can vary from 0 to 1. $\theta = 0$ implies that there is no channel that is commonly available. $\theta = 1$ reflects the symmetric scenario, i.e. two CR users observe the same set of available channels.

4.3.2 Modeling Assumptions

To simplify the simulation model, the following assumptions are made.

A.1 A single hop scenario was considered in the simulation model; i.e. A node can only communicate within its single hop neighbors.

A.2 For the sake of simplicity, network wide common spectrum labeling was assumed.

A.3 It was assumed that all CR users could detect the primary users' activity.

A.4 The delay in switching from one channel to another channel was assumed to be negligible with respect to the hopping slot time.

A.5 A fully heterogeneous radio environment was considered, which includes GSM, WiMAX and UMTS as licensed users, and any device having cognitive capability but which does not have the right to access the licensed channel is considered a cognitive radio user or secondary user.

A.6 As an ad-hoc network is completely distributed in nature, time synchronization was not considered in this paper. Hence, different nodes may start channel hopping at different times.

A.7 The packet arrival process for PUs, CRs was assumed to follow Poisson distribution with rates λ_{PU}, and λ_{CR} respectively.

A.8 The CRs under consideration were all homogeneous, i.e. statistically identical and independent.

A.9 Collision among control or handshake (i.e.RTS/CTS collision) packets was not considered.

A.10 The time in the developed simulator was divided into small slots. The same slot duration was used for all the CR nodes. Each time slot was enough to exchange the RTS/CTS packets.

A.11 The channels were noise-free, so that packets were lost only because of collisions.

A.12 It was assumed that all nodes in the networks were static.

4.4 Results and Discussion

Based on the simulation results, the proposed ETQCH protocol is compared to different channel rank and non-channel rank based CH protocols. The performance of the ETQCH protocol is investigated by changing the channel order, number of channels, asymmetric channel information and number of common channels for both the symmetric and asymmetric scenarios.

4.4.1 Impact of Channel Order/Rank

Figure 4.5 shows the network performance in terms of ATTR (Fig. 4.5(a)) and degree of overlap (Fig. 4.5(b)) with changing channel order/rank. For comparative analysis, channel rank based CH protocols such as AMRCC, gQ-RDV, basic and Enhance AMRCC protocols were selected. It was observed that ATTR decreased for all protocols with similar channel rank factors. Rapid growth in ATTR was observed when none of the channels were in the same rank as the peer CR nodes. The ATTR for both ETQCH and gQ-RDV showed almost identical performance when a CR node observed channels with similar rank. The ETQCH outperformed as the channel rank similarity factor decreased. Fig. 4.5(a) shows that a 50% performance enhancement can be achieved at $\alpha = 0$, i.e. asymmetric channel rank. α represents the similarity between intended communicating CR nodes. The performance of basic AMRCC and enhance AMRCC is dominated by the pseudo random assignment of time slots. Moreover, in Enhance AMRCC the length of CH sequence increases exponentially with the number of channels, which results in higher ATTR.

Figure 4.5(b) shows the degree of overlapping or the number of intersections of two sequences within the hopping period. The number of RDVs per cycle depends on cycle size, which is a design choice in each protocol. Therefore, to compare the performance of different protocols we defined the normalized degree of overlap per 100 time slots. As expected, all the protocols showed an upward trend with the degree of channel order. However, ETQCH outperformed compared to both Basic and Enhance AMRCC. Significant performance enhancement could be observed in the worst case scenarios where channel order was below 60%. This is due to the inherent property of the ETQCH protocol, whereby two torus quorums with 3 branches are spread evenly over the trunks of the quorum's structure and detect each other more often compared to gQ-RDV. Random quorum (i.e. time slots) distribution was considered in both AMRCC protocols, which failed to achieve RDV as the channel order decreased.

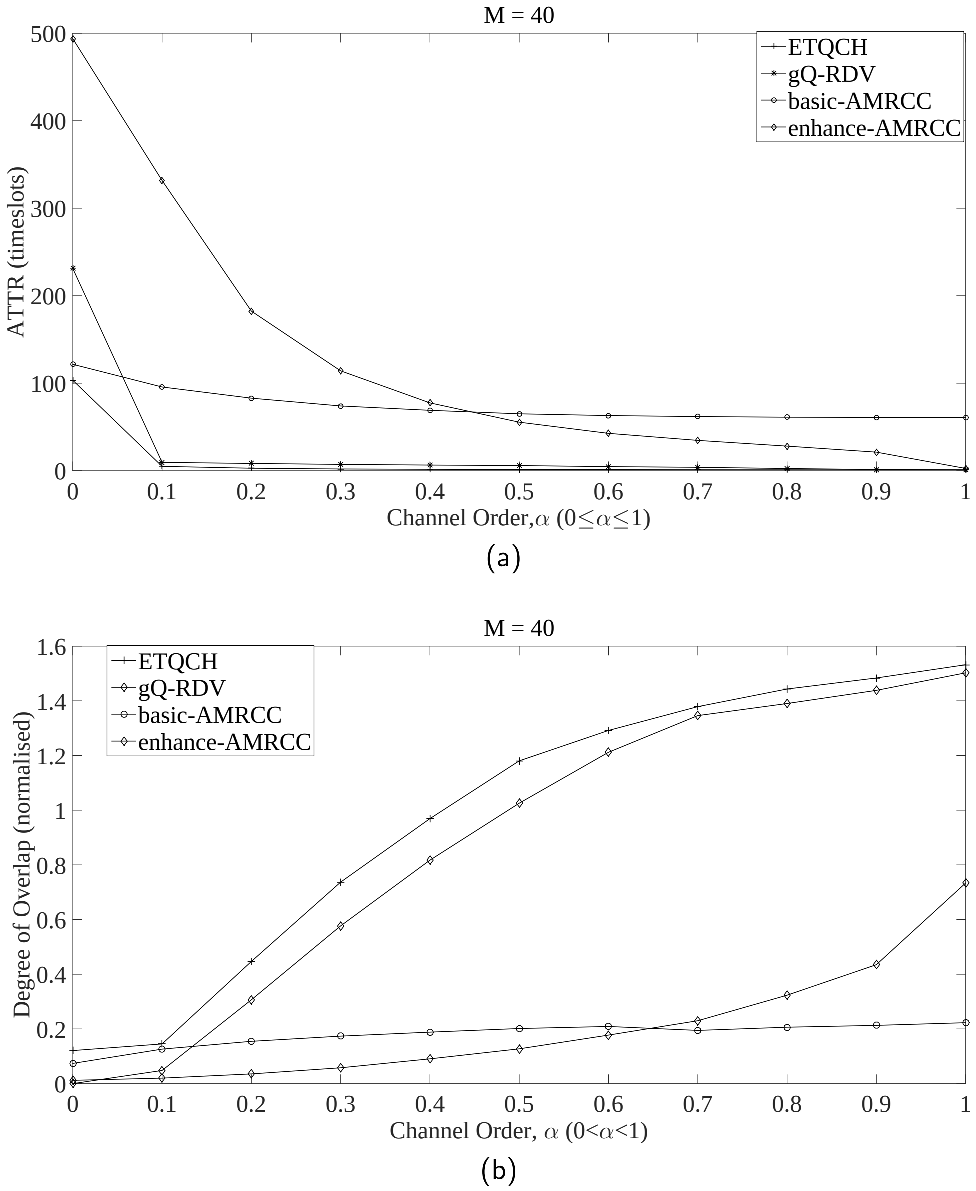
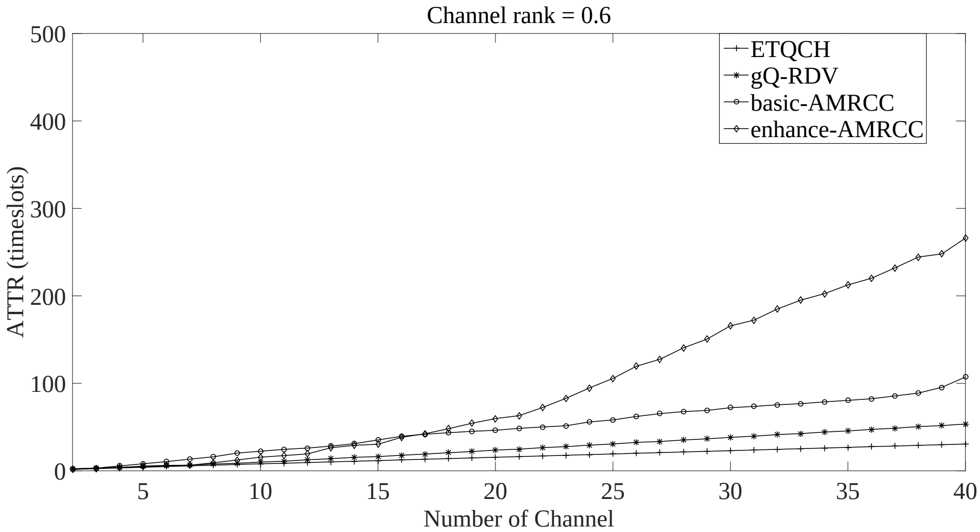


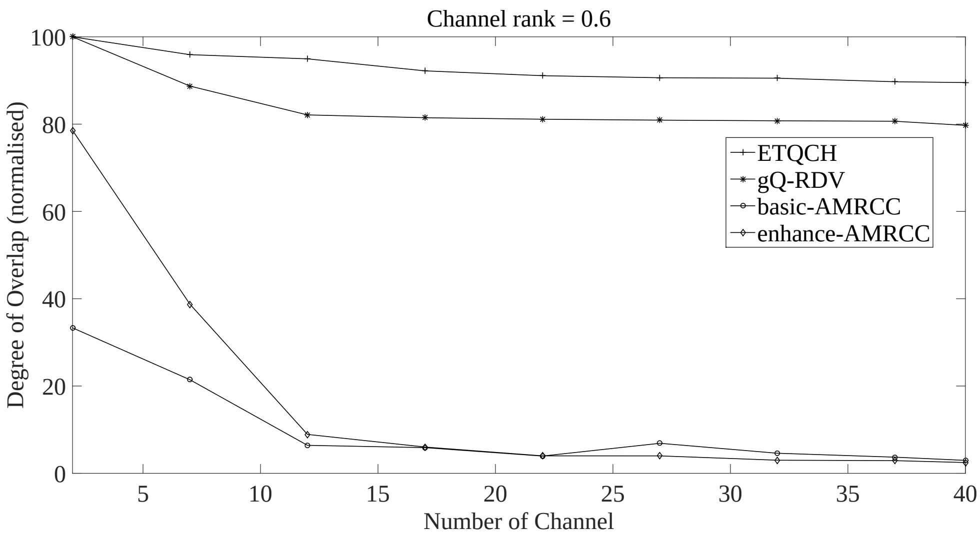
Figure 4.5: Comparison of ATTR and degree of overlap with channel rank similarity factor: (a) ATTR (b) Degree of overlap

4.4.2 Impact of Number of Channels

The impact of the number available channels on network performance is obvious as the length of the CH sequence depends on the number of available channels. Fig. 4.6 manifests the variation of ATTR and degree of overlap with the number of channels. In this scenario, it was assumed that there were 40 channels (which includes licensed and unlicensed) available to use as RDV channels. Moreover, a channel ranking similarity factor of 0.6 between two users was considered. Fig. 4.6(a) exhibits that ATTR increased with number of channels due to the dependency on the CH cycle length. The proposed ETQCH protocol performed better compared to the other protocols as it could facilitate higher number of intersections in a given RDV cycle. The ATTR of ETQCH protocol was 1.174 time slots with 22 channels whereas it was 54% higher for gQ-RDV, and the difference in performance was observed with the number of channels. Moreover, an exponential increment of ATTR for enhance AMRCC is shown in Fig. 4.6(a), as the length of CH is a quadratic function of the number of available channels. According to the definition (presented in subsection 4.4.1) ATTR can only be minimized by increasing the number of RDVs, which is illustrated in Fig. 4.6(b). For instance, when there are 22 channels in the system, the degree of overlap achieved by ETQCH is 91.1 while it is 81.1, 5.88 and 4 for gQ-RDV, basic-AMRCC and enhance-AMRCC respectively. For all CH based RDV techniques, RDV cycle length increases with the number of available channels, which incurs higher ATTR and a lower normalized degree of overlaps. Therefore, one of the design aspects is to hop on channels more often, which can provide higher QoS and distribute the channels over the RDV cycle.



(a)



(b)

Figure 4.6: Comparison of ATTR and degree of overlap with increasing number of available channels: (a) ATTR (b) Degree of overlap

4.4.3 Impact of Asymmetry

Under the asymmetric model, different users may have different cardinality of the available channel set, which is defined by degree of asymmetry, β, where $\beta = \frac{|C\_A|)}{|C\_B|}$; $\mid C\_A \mid$ and $\mid C\_B \mid$ is the cardinality of the available channel set of users A and B respectively. In this case, the ATTR and degree of overlap of ETQCH and gQ-RDV protocols was considered. Basic AMRCC and Enhance AMRCC algorithms were excluded from this analysis as they do not support an asymmetric channel view. Fig. 4.7(a) exhibits the ATTR of ETQCH, gQ-RDV for $\beta = 0.8$ and $\beta = 0.6$. For both cases, the number of common channel between users was 4. However, at each run the common channels were selected randomly from the available channel set. Based on Fig. 4.7(a), the ATTR of both protocols increased with degree of asymmetry, as the node had to spend more time on the channels out of rendezvous facility. The ETQCH protocol performed better than gQ-RDV. For instance, when the number of available channels was 50, the ATTR of ETQCH was 52% and 60% less than gQ-RDV at $\beta = 0.8$ and $\beta = 0.6$ respectively. Moreover, it became more severe with further increases in the number of available channels. The same statistics were collected for 80 channels and show that ATTR reached 76% and 68% for $\beta = 0.8$ and $\beta = 0.6$ respectively. Figure 4.7(b) illustrates the comparison of degree of overlap between the ETQCH and gQ-RDV protocols. It shows that with the increase in degree of asymmetry, the number of overlaps increased. However, for both of the protocols, the degree of overlap dropped continuously with the number of channels for the same degree of asymmetry.

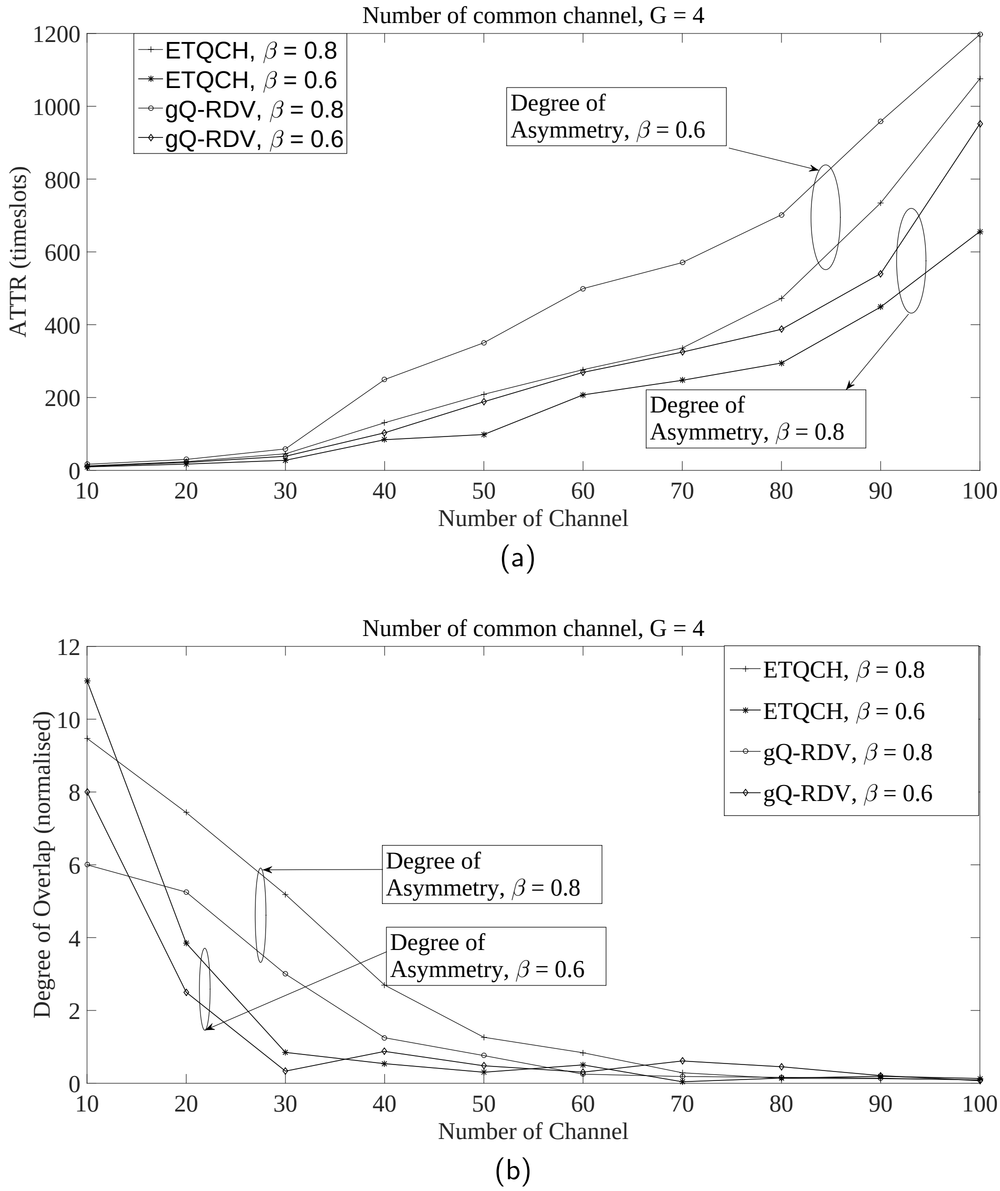


Figure 4.7: Comparison of ATTR and degree of overlap when two users experience asymmetric set of channels: (a) ATTR (b) Degree of overlap

4.4.4 Impact of Number of Common Channels

The number of common channel between CR users plays an important role in minimizing ATTR. It is natural that two CR nodes should have at least one common channel to establish communication. To make the communication more robust against service interruptions due to sudden PU reappearance, the CR node should have guaranteed overlaps with all common channels. Therefore, the CR node should continue channel hopping even if it achieves RDV in one channel, which requires at least two transceivers at each node to maintain and update the RDV channels. In this section, different CH protocol behaviors are analysed and compared with the proposed ETQCH protocol. We consider that there are 40 channels in the system. The term "degree of common channel", θ refers to the degree of common channels between users. These common channels can be arranged based on symmetric channel ranking or asymmetric channel ranking. In symmetric channel ranking, two CR nodes observe the same channel rank, otherwise it is asymmetric channel ranking. The impact of the number of common channels with both symmetric and asymmetric channel ranking is described in the following subsections.

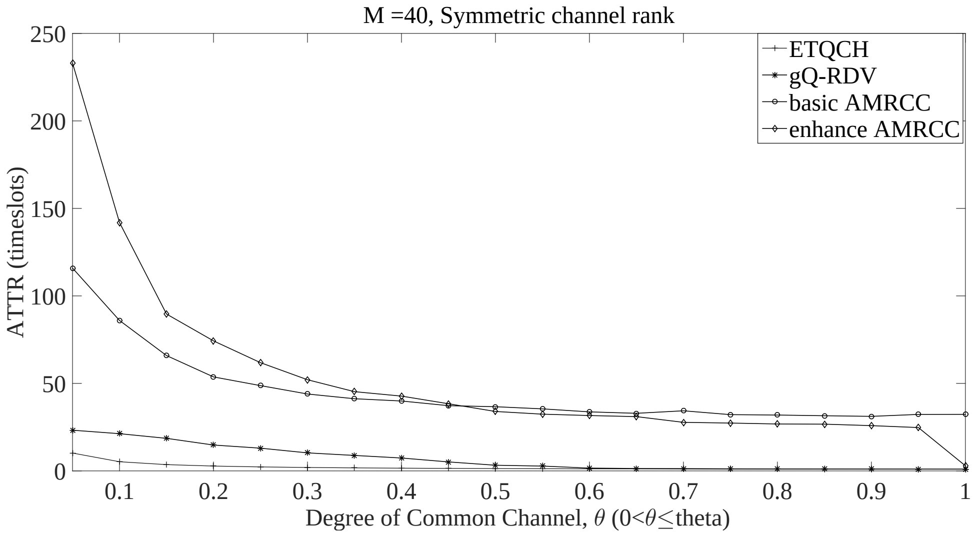
Symmetric Channel Ranking

Figure 4.8(a) shows that the ATTR performance of ETQCH, gQ-RDV, Basic AMRCC and Enhance AMRCC with degree of common channels θ varied from 0.05 to 1 for the symmetric channel rank scenario. The ATTR for all of these protocols showed same trend as the number of common channels. However, ETQCH outperformed when the number of common channels was less than 50% and converged with gQ-RDV as it increased further. The same behavior can also be observed in Fig. 4.8(b) for degree of overlap with degree of common channel. For instance, when 27% channels were commonly available, the normalized degree of overlap of ETQCH was approximately

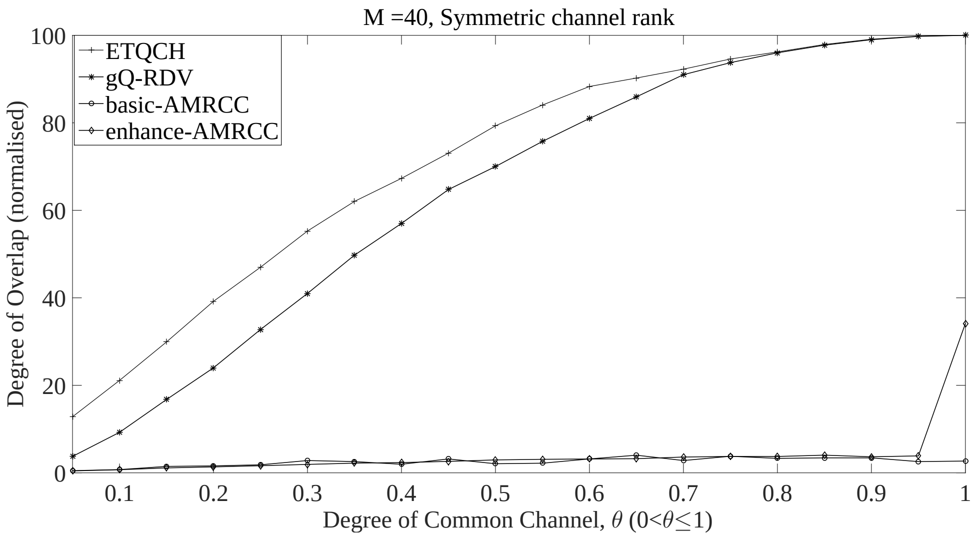
47 while it was 32.75, 1.82 and 1.61 for gQ-RDV, basic AMRCC and enhance AMRCC respectively. In both AMRCC protocols, time slots and channels are not mapped deterministically but rather are assigned more time slots for higher rank channels in a biased pseudo random fashion. However, this bias cannot guarantee to achieve RDV and incurs higher ATTR and lower RDV.

Asymmetric Channel Ranking

Figure 4.9(a) illustrates the ATTR behavior with asymmetric channel ranking. It shows that overall ATTR was higher compared to the symmetric channel rank scenario. In this scenario, it was considered that 50% common channels would have the same order. As an example, two CR users had a total of 40 channels with 50% common channels in between (i.e. both users had 20 common channels). Out of these 20 common channels 50% i.e. 10 channels were in the same order in terms QoS. Based on Fig. 4.9(a), the ATTR decreased with the increase in common channels. However, the rate was significantly slower compared to symmetric channel rank due to missed opportunities. In CH protocols, time slots assignment is based on channel ranking; hence channels that are not common but have higher rank can occupy more time slots. However, still ETQCH performed better compared to any other protocol, especially in a worst case scenario when the degree of common channels was only 5%. The ATTR in the worst case (i.e.5% common channel) was 57.75 for ETQCH, whereas it was 320, 198.34 and 299.19 for gQ-RDV, basic-AMRCC and enhance-AMRCC respectively. Fig. 4.9(b) depicts the normalized degree of overlap for the different protocols. The slope of all the considered protocols is very nominal up to 60% of common channels and exhibits a gradual increase thereafter. Performance of the ETQCH algorithm was very close to that of gQ-RDV under the symmetric channel rank model. However, there was a significant performance gap between ETQCH and gQ-RDV protocols, shown in Fig. 4.9(b), in terms of the normalized degree of overlap.



(a)



(b)

Figure 4.8: Comparison of ATTR and degree of overlap in varying number of common channels with symmetric channel rank: (a) ATTR (b) Degree of overlap

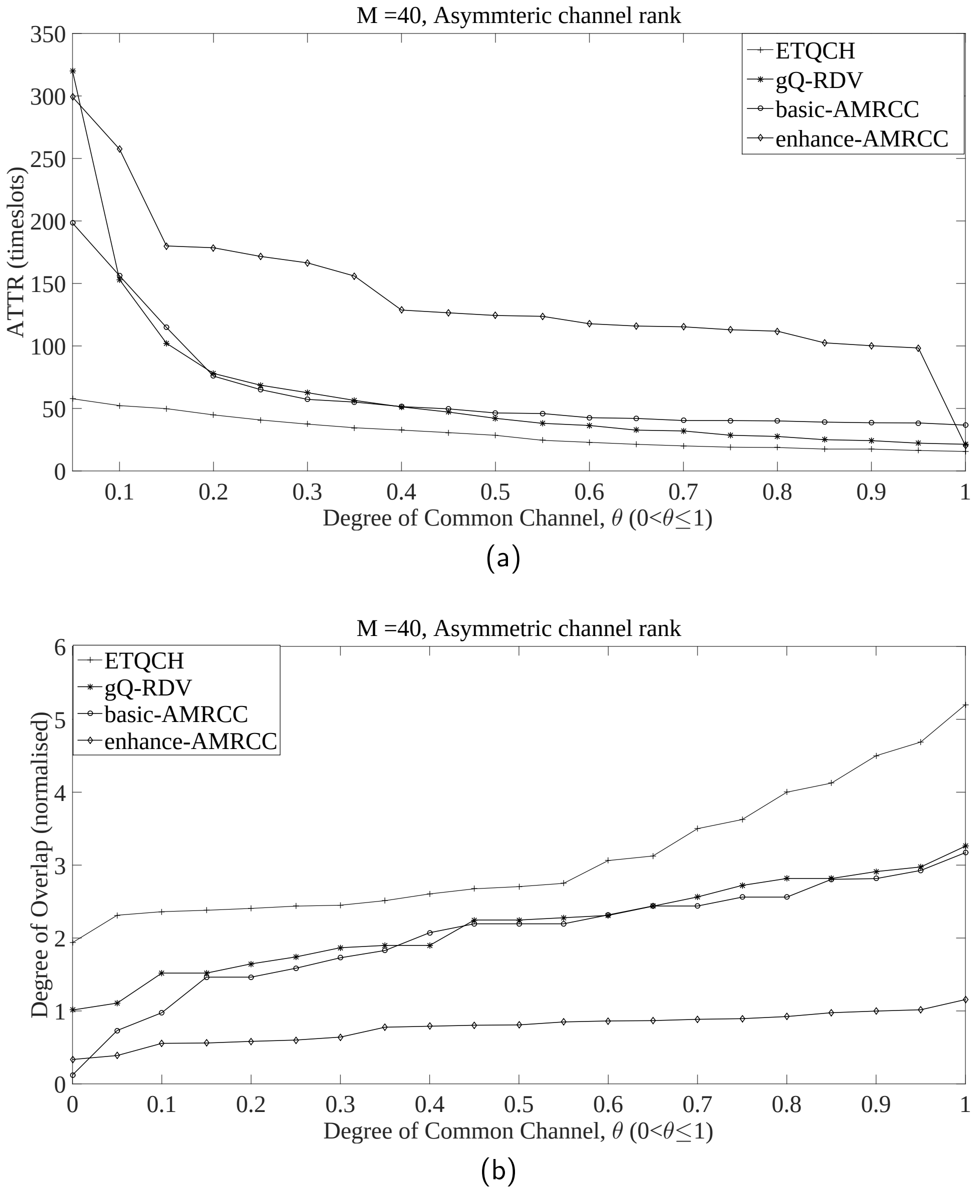


Figure 4.9: Comparison of ATTR and degree of overlap in varying number of common channels with symmetric channel rank: (a) ATTR (b) Degree of overlap

4.4.5 Comparison with Non-Channel Rank CH Protocols

In this scenario, different non-channel rank based legacy CH protocols were considered to compare the performance of the ETQCH protocol. All the protocols use symmetric channel information in terms of the number of channels. All the protocols use random channel selection to map the channels in a time slot, except the DRSEQ and SSB protocols. For DRSEQ and SSB protocol channels are continuously visited based on a channel index. In this section, number of channels varied from 2 to 40 and at each run a simulation was performed to compute the ATTR. Fig. 4.10(a) illustrates the ATTR performance of different legacy CH sequences. Due to the polynomial relationship between ATTR and the number of channels, sequence RDV (SeqR) showed very high ATTR compared to other CH protocols. Interestingly the rest of the protocols showed a similar trend of ATTR progression with the number of channels. The zoom section in Fig. 4.10(a) shows the difference in performance between the protocols. It shows that ETQCH performed better than MMC. This is because ETQCH utilizes channel quality information and has a shorter period of sequence period than MMC. ATTR performance improves even more compared to MMC when the number of available channels is increased, and surpasses the other schemes by a significant amount. It is worth mentioning that channel ranking was performed based on PU activity and channel fluctuation, which eventually reduced the probability of spectrum mobility. As a result, significant performance could be observed for ETQCH.

Next, degree of overlap was measured to compare the performance of ETQCH with existing non-channel rank based CH protocols. Figure 4.10(b) shows that the performance of the ETQCH scheme outclassed other legacy protocols due to the integration of channel quality information in the CH sequence design. Moreover, the torus quorum with extended diagonals facilitated in distributing the channel mapping over the CH period, which minimised the performance gap caused by time asynchronization. Nevertheless, with the number of available channels, it was obvious there was performance degradation. This is because the period of the CH sequence increased with the number of channels and asynchronous behavior became more dominant. To distinguish the performance of the different protocols, a close-up from 31 to 40 is shown inside the figure.

Next, to evaluate the asymmetric behavior, the number of common channels (G) was varied from 1 to 20 out of a fixed number of channels (i.e. $M = 40$) and the ATTR for the protocols that supported asymmetric channel hopping was computed. Fig. 4.13(b) shows that out of all the non-channel rank based protocols, SSB achieved the nearest performance to ETQCH when G was more than 17. But ETQCH exhibited prodigious performance when the number of common channels was decreased. This is because ETQCH utilizes the channel ranking information together with channel availability and results in RDV more often in a CH period. However, SSB performed better than the Jump Stay and MMC protocols due to shorter CH sequence length.

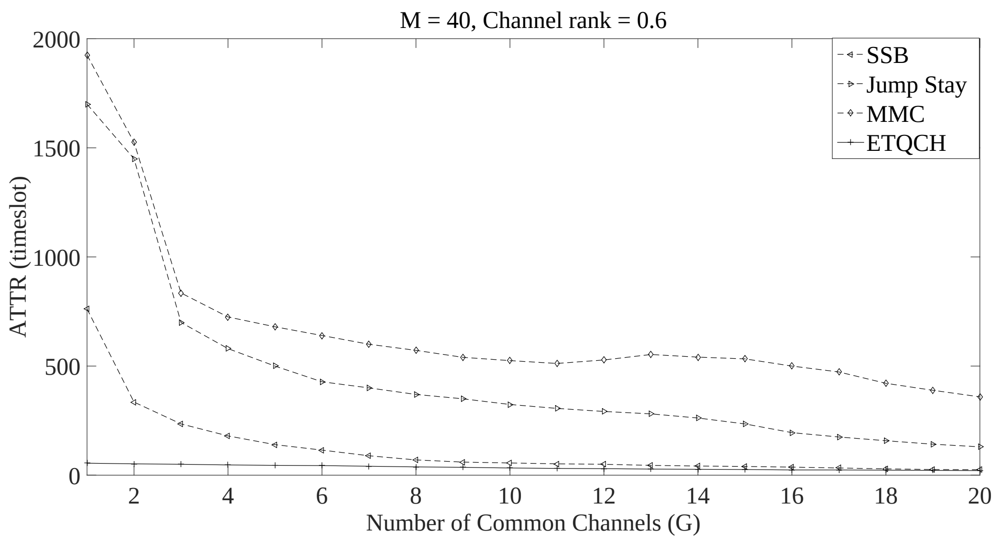
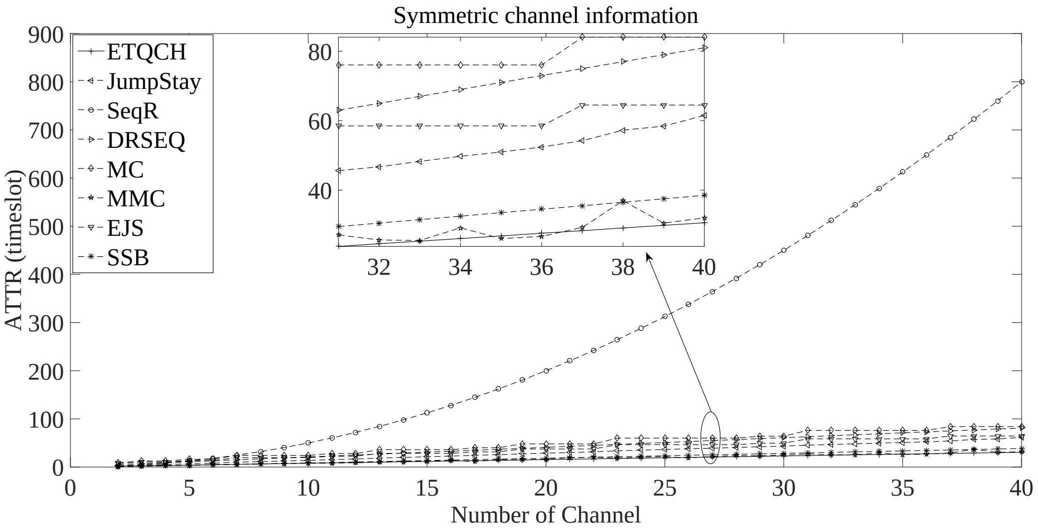


Figure 4.11: ATTR performance of different protocols with number of common channel



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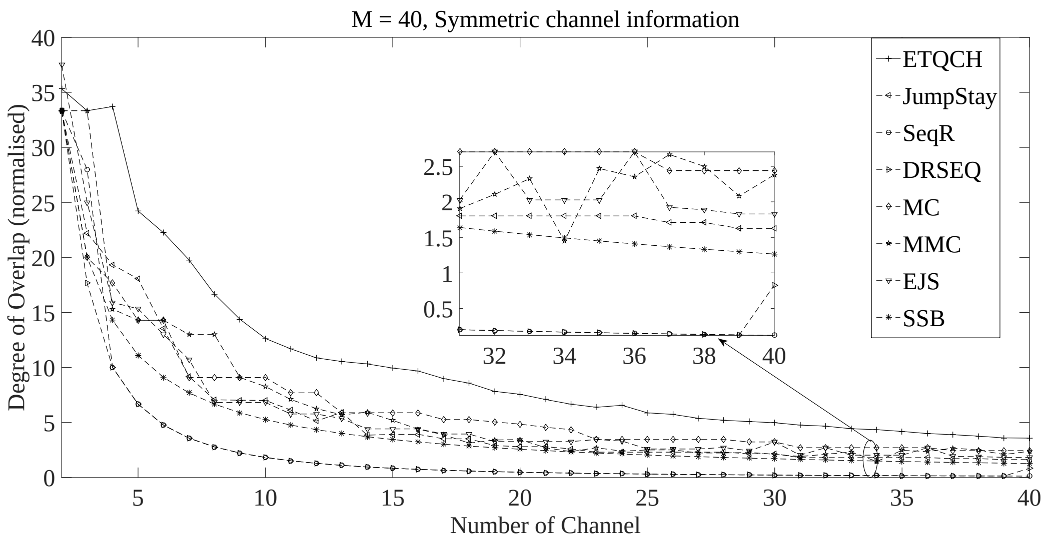
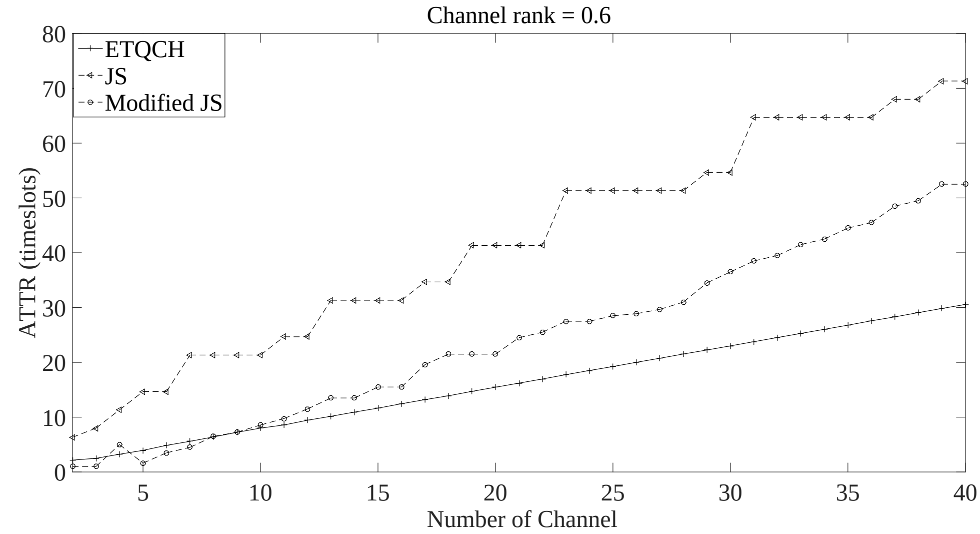


(b)

Figure 4.10: Illustration of performance difference between ETQCH and non-channel rank based CH protocols: (a) ATTR (b) Degree of overlap

4.4.6 Performance Enhancement Using Channel Ranking

In this section, further investigation was performed to compute the impact of channel ranking in CH sequence design. For this, JS and Enhance JS (EJS) protocols were modified to integrate the channel ranking information. The random starting index and channel stay patterns were replaced by a channel based on ranking. A CR node always starts with the best channel from the list and if no RDV is achieved then it uses the second best channel and so on. Moreover, further modification was made to change the channel visit rate. In this simulation, the number of channels varied from 2 to 40 and the nodes always had 60% channels in same rank. Figure 4.12(a) and Fig. 4.13(a) show that for both JS and EJS protocols respectively, ATTR performance improved significantly. ATTR for the JS scheme with channel rank dropped by 20 time slots when there were 40 channels. The overall performance increased in the range of 30% to 70% for the JS scheme. The same behavior was seen for the EJS scheme and 25% to 57% of performance enhancement was achieved with channel ranking. Same as before, the degree of overlap was measured and is illustrated in Fig. 4.12(b) and Fig. 4.13(b) for both JS and EJS protocols respectively. Modified JS and modified EJS outperformed JS and EJS with random channels. It is interesting to observe the change in performance gap with number of channels for both modified JS and modified EJS compared to JS and EJS respectively. In JS and EJS, the starting index is randomly selected from a window of $(1, p)$ where p is the smallest prime number greater than the number of channels. The change in window size due to the number of channels eventually reduces the probability of selecting the same starting index between peer CR nodes. As a result, the CR nodes experience a smaller degree of overlap with the increase in the number of channels.



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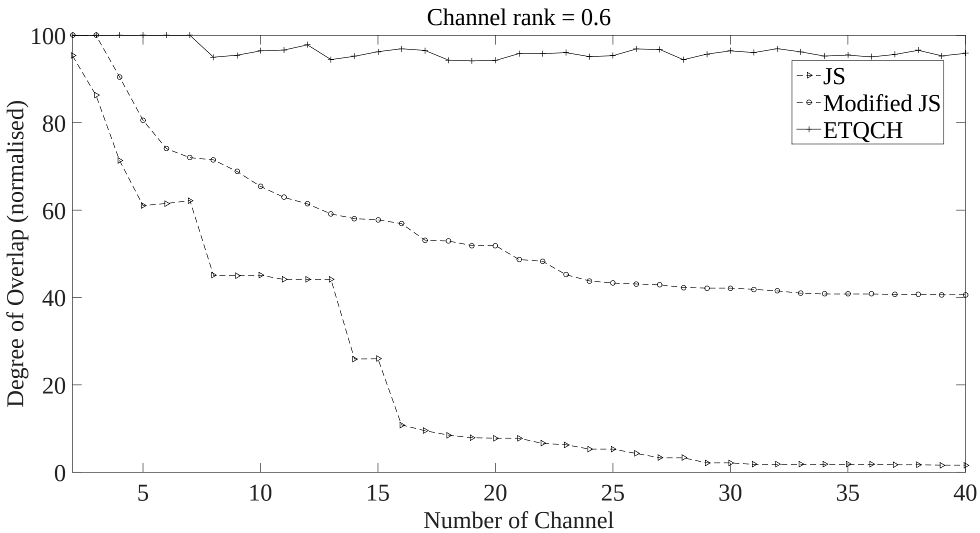
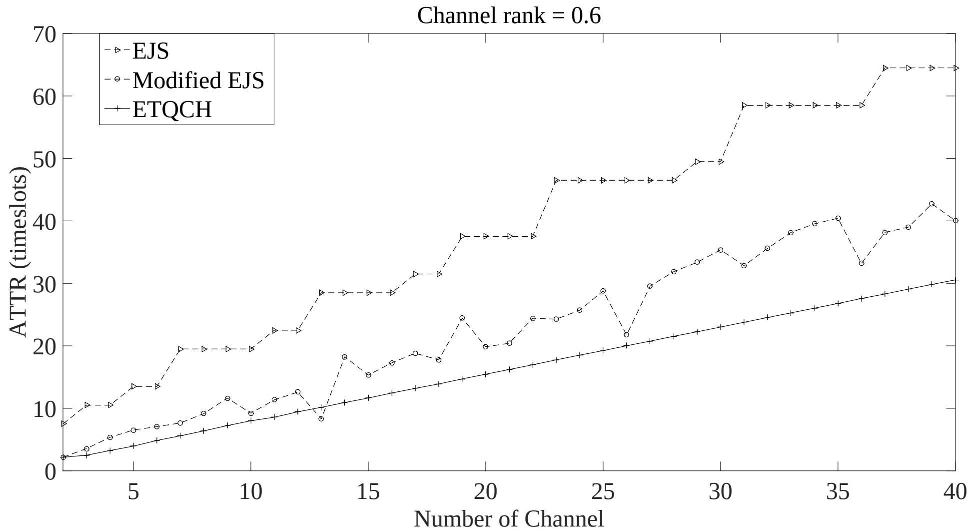


(b)

Figure 4.12: Performance comparison of Jump Stay and Modified Jump Stay protocols: (a) ATTR (b) Degree of overlap



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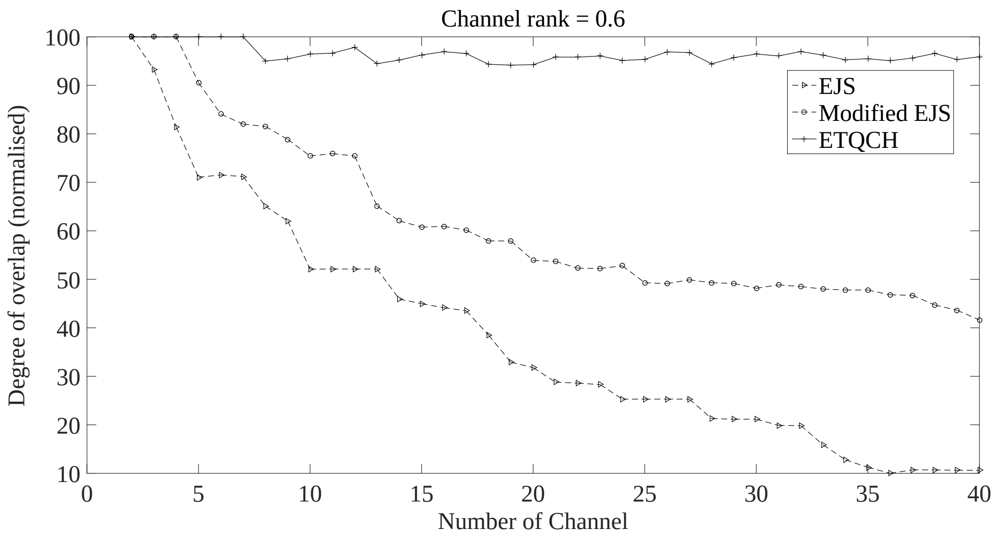


(b)

Figure 4.13: Performance comparison of Enhance Jump Stay and Modified Enhance Jump Stay protocols: (a) ATTR (b) Degree of overlap

4.5 Validation of Simulation Results

In this chapter MATLAB simulation was used to quantify the performance gain. However, the credibility of the simulation results may questioned if the simulation parameters were not correctly configured. Therefore model verification was an important part of the simulation study. The MATLAB simulation model presented in this chapter was verified by comparison to the other simulation models and the correctness of the data relationship [78]. The simulation results presented in this chapter were compared with the results reported by other scientists to ensure the correctness of the simulation model [3, 29, 33–35, 39, 60, 61]. Moreover, the data relationship between different types of data, such as the number of channels with ATTR, number of channels with degree of overlap, and ATTR with degree of overlap validated the correctness of the simulation results.

4.6 Summary

In this chapter, the performance of ETQCH was presented and compared with the existing channel ranked and non-channel ranked based CH protocols. To estimate the degree of overlap, the expected quorum overlap size was formulated for symmetric and asymmetric scenarios for both the ETQCH and gQ-RDV protocols. Analysis shows that gQ-RDV cannot guarantee the degree of overlap in a asymmetric scenario due to the different dimensions of the grid structure. Details of the simulation setup and model assumptions were discussed in this chapter.

Simulations were performed to quantify the performance enhancement that can be achieved by the ETQCH protocol. As ETQCH is a channel rank based CH protocol, performance was analysed compared to existing channel rank based CH protocols. It showed that ETQCH outperforms other channel rank based CH protocols. In the worst case scenario, when channels were not in order ($\alpha = 0$), at least 50% performance (i.e. ATTR) enhancement could be achieved using the ETQCH scheme. Interestingly, all the protocols exhibited similar behavior with the number of available channels. However, the ATTR increment rate of ETQCH with number of channels was significantly smaller than for other protocols. For the degree of overlap, ETQCH maintained a higher overlap ratio with the number of channels. For a system with 22 channels, the degree of overlap achieved by ETQCH was 91.1, whereas it was 81.1, 5.88 and 4 for gQ-RDV, basic-AMRCC and enhance-AMRCC schemes respectively. Next, channel cardinality asymmetry was considered to analyse the performance comparison. Basic-AMRCC and enhance-AMRCC cannot be used while users experience a different set of channels, hence only gQ-RDV was considered for the performance comparison. The simulation results showed that ATTR of ETQCH was 52% and 60% less than that of gQ-RDV protocol for degree of asymmetry (β) = 0.8 and 0.6 respectively. Similar performance was observed for degree of overlap. Later on, the impact of number of common channels was considered in evaluating the performance comparison. This is an important parameter in an asymmetric channel scenario. The results showed that for a higher degree of common channels gQ-RDV and ETQCH presented better performance than basic-AMRCC and enhance-AMRCC. It is important to note that even in cases of $\theta > 0.6$ onwards, the ATTR of the ETQCH protocol was slightly better than that of gQ-RDV. When the degree of common channel decreased, the performance of ETQCH improved marginally for symmetric channel ranking and was prodigiously high for asymmetric channel ranking. Besides the channel rank based CH sequence, a performance comparison was also performed with non-channel rank-based legacy CH RDV sequences. In this context, the performance of different protocols (e.g. JS, SeqR, DRSEQ, MC, MMC, EJS, and SSB) was evaluated using number of available channels and number of common channels. In both scenarios, ETQCH showed better performance in terms of ATTR and degree of overlap. Finally, the impact of channel ranking was evaluated by modifying the JS and EJS protocols. The simulation results showed that almost 75% performance improvement was achieved with modified JS and EJS, which utilized the channel rank information to select the initial starting index.

In the next chapter, a cognitive radio MAC protocol is presented to capture RTS/CTS collisions, PU activity and CRs which incorporate the proposed ETQCH protocol for control channel establishment.

Chapter 5

CR-RDV: A Cognitive Radio Rendezvous MAC Protocol

5.1 Introduction

In the previous chapter, an ETQCH RDV protocol was evaluated under different network configurations and compared with existing CH based RDV protocols. A significant performance gain was observed in the simulation. A successful RDV is not only a mathematical concept to guarantee overlap between two CR users, but a medium access issue to solve in multiuser ad-hoc environments. In the previous chapter, it was assumed that channel probe packets were always received successfully when two users were on the same channel at the same time. But in a multi-user scenario, channel probing may not be successful due to simultaneous transmission. Moreover, CRAHNs are prone to multi-channel hidden terminal problems, as neighbouring nodes may be operating on another channel during channel negotiation. Thus, it is necessary to have an integrated RDV and CRAHNs MAC protocol. In this chapter, a new MAC protocol called CR-RDV MAC protocol is developed.

The remainder of this chapter is organised as follows. In section 5.2, a survey of CR-MAC protocols is presented and the functional requirements for a new MAC protocol design are identified. Arising from this survey, three performance issues are outlined in section 5.3: rendezvous collision, handshake collision and blocking problem. In section 5.4, the CR-RDV MAC protocol is described to address the identified issues in CRAHNs. The control packet exchange message sequence chart (MSC) is presented in section 5.5. CR-RDV MAC protocol state machine is presented in section 5.6. Finally, the chapter is summarized in section 5.7.

5.2 Cognitive Radio MAC Protocols: A Review of the Literature

Medium access protocols (MAC) protocols for CRAHNs should provide an efficient mechanism for the opportunistic sharing of wireless resources, high bandwidth utilization and fairness in serving all stations. The MAC protocol for CRAHNs is similiar to the multi-channel MAC protocol for traditional wireless ad-hoc networks except for the following essential functional requirements:

- *Channel Coordination*: In CRAHNs, channel coordination is required to update the surrounding radio information and share this information with neighbours. In Chapter 3, a channel coordination/RDV scheme was presented for CRAHNs. However, to accomplish the channel coordination, a CR node has to adopt a reliable channel access method for channel probing. Moreover, the same coordination is required for data transmission upon successful channel negotiation.

- *Incumbent User Protection*: One of the most essential requirements for a CR-MAC protocol is to protect the PU's transmissions under any circumstances. Hence, a CR node should always be aware of PU activity in its vicinity and react accordingly, either by handoff to another channel, changing the power level, or resuming the transmission after the PU is finished.

- *Spectrum Efficiency*: Due to the dynamic radio environment and intermittent PU activities, the availability of the radio spectrum changes with time and space. Thus, a CR node should always have updated spectrum usage information to efficiently and opportunistically utilize the radio resources.

5.2.1 CRAHNs MAC Classification

Wireless MAC protocols for CRAHNs can be classified in different ways. For example, based on the channel access method, CRAHNs is classified in three categories [79]: i) random access, ii) time slotted, and iii) hybrid access. Random access MAC protocols are fundamentally based on the CSMA/CA principle and hence synchronization is not required. Examples of random access MAC protocols include SRAC-MAC [80], HC-MAC [81], DOSS [82], and DCA-MAC [83] and [25, 84–100]. In random access, data and control channels are considered in the same way, i.e. there is no separate strategy for control and data channel selection. In a time slotted protocol, the control and data channels are separated by time, hence they require network-wide synchronization. Protocols that belong to this category include OSA-MAC [46], and CR-ALOHA [84] and [101–109]. Hybrid protocols utilize both time slotted and random access methods for control and data transmission respectively. Examples of hybrid protocols include C-MAC [110], OS-MAC [44], Opportunistic MAC [111], SYN-MAC [112] and POMDP based MAC [113].

Further, based on resource optimisation [114], MAC protocols for CRAHNs are categorised in two main groups: i) direct access based (DAB), and ii) dynamic spectrum allocation (DSA). Protocols belonging to DAB optimise the use of network resources at the local level during the handshake procedure [44, 49, 54, 76, 81, 82, 91, 94, 110, 112, 115, 116]. The computational cost and latency of DAB protocols is lower than for DSA protocols because of its simple protocol architecture. DSA protocols utilize more advanced algorithms to achieve global optimisation [117–121]. Hence, the performance of DSA is significantly better than the DAB scheme. However, protocols belonging to this class suffer from low scalability, high negotiation delay and operational cost.

5.2.2 Representative MAC protocols

In the last 10 years, numerous MAC protocols have been developed for CRAHNs. Table 5.1 lists the leading research works, assumptions considered for the protocol design and the main concept in different columns for CRAHNs.

Cognitive MAC (C-MAC)

C-MAC [110] is a distributed multi-channel MAC protocol for CRAHNs. In C-MAC, a CR node is equipped with a single half duplex radio transceiver which performs in-band and out-band spectrum sensing during network-wide quiet periods. It is assumed that each channel is organised in a logically divided recurring superframe structure which has two parts: i) beacon period (BP), and ii) data transmission period (DTP). The outcome of sensing information is exchange through beacons transmitted during BP. It is also assumed that the nodes are synchronized to broadcast beacons without overlapping across all the available channels. For synchronization and coordination in different channels, a CR node periodically visits the common channel, called the rendezvous channel (RC). However, the strong dependency on network-wide tight synchronization is a performance issue in CRAHNs.

Multi-channel MAC Cognitive Radio (MMAC-CR)

In [91], the authors proposed a multi-channel MAC protocol for CRAHNs. It is assumed that there is a network-wide CCC which is free of PU interference. CCC is used for synchronization and control information exchange. To manage the available spectrum information, this protocol uses two data structures: i) spectrum image of

Table 5.1: Summary of CR MAC protocols

Name of the Protocol	Access Method	Number of Radios	Rendezvous	Synchronization	Concept
HC-MAC [81]	CSMA/CA	1	CCC	No	Optimal spectrum sensing to enhance spectrum utlization
DOSS [82]	CSMA/CA	2	CCC	No	Adaptively use an arbitrary channels and use busy tone to solve hidden node problem
C-MAC [110]	Hybrid	1	CCC	Yes	Dynamic RC is used for channel negotiation and BC is used to make RC robust against PUs activity
OSA-MAC [46]	Time Slotted	1	CCC	Yes	Predetermined window periods for coordinating the choice of spectrum among the CR users
CR-CSMA/CA [25]	CSMA/CA	1	CCC	No	Three way handshaking using dedicated period for channel sensing
su2007cognitive [85]	CSMA/CA	2	-	Yes	Utilize different sensing policies to identify the free channels
CA-MAC [122]	Time Slotted	2	Split Phase	Yes	Reserve a data channel which is least common to all member nodes
CUCB-MAC [103]	Time Slotted	1	Spectrum Manager	Yes	Channel are selected based on collision count and channel ideality
WBMM MAC [109]	Time Slotted	2	CCC	Yes	A centralized spectrum broker is used with weighted bipartite graph matching for spectrum allocation
SCA-MAC [90]	CSMA/CA	1	-	No	Statistical channel allocation and dynamically change the spectrum range to search spectrum opportunities
COMAC [94]	CSMA/CA	>2	CCC	-	Channel selection is based on SINR which is adjustable based on PUs activity
MMAC-CR [91]	CSMA/CA	1	-	Yes	CCC is used to exchange SIP and SCL channel data structure
CREAM-MAC [95]	CSAM/CA	1	CCC	No	Integrates the cooperative sequential spectrum sensing and packet scheduling
SYN-MAC [112]	Hybrid	2	Without CCC	Yes	Time is divided into time slots and each slot represents a particular data channel.
POMDP [113]	hybrid	1	No CCC	Yes	Utilize the partially observed Markov decision process together with past spectrum usage history

PUs (SIP), and ii) secondary user channel load (SCL) for channel usage by PUs and SUs respectively. The operation of the protocol consists of four phases: i) beacon contention, ii) scan result packet (SRP) phase i.e. after scanning the node tries to send an SRP to initiate cooperative detection, iii) channel negotiation phase through the handshake procedure based on CSMA/CA, and iv) data transmission. By using a single transceiver an alternating control and data phase solves the multi-channel hidden terminal problem, which is an energy efficient solution. However, protocol performance strongly depends on synchronization and is limited by the availability of a reliable control channel.

Cognitive Radio based Multi-channel MAC Protocol

Su and Zhang [85] proposed a multi-channel MAC protocol for CRAHNs which utilizes different channel sensing policies and integrates sensing information for packet scheduling. It is assumed that there are two radio transceivers, one that operates on a dedicated control channel and another that is used for data transmission. This protocol introduces two channel sensing policies: i) random sensing, and ii) negotiation based sensing. It shows that if the number of SUs is higher than the number of available free channels, the random sensing policy outperforms negotiation based sensing and vice versa. Using the proposed sensing policies, a SU can efficiently detect the unused spectrum for ongoing/upcoming data transmission. However, the performance of the proposed protocol depends on the existence of a dedicated CCC, which is not realistic in dynamic CRAHNs.

Statistical Channel Allocation-MAC (SCA-MAC)

To minimise the interference with PU transmission while using the unused/under-utilized spectrum, a SCA-MAC is proposed in [90]. The operation of SCA-MAC consists of three phases: i) environmental sensing and learning, ii) CRTS/CCTS exchange over control channel, and iii) data transmission and acknowledgement (ACK) over data channels. To reduce the interference with neighbouring nodes, an optimum operating range is introduced whereby each node dynamically adjusts the spectrum sensing range to find spectrum opportunities. Based on spectrum usage statistics, an efficient channel aggregation is proposed to increase the successful transmission rate and reduce PU interference.

Synchronized MAC (SYN-MAC)

To avoid control channel saturation and single point failure, a multi-channel MAC protocol is proposed in [112] which does not need a CCC but an additional transceiver is used to listen on the channel for the control message. SYN-MAC is a hybrid access protocol where a control signal is exchanged in time slotted fashion and data transmission is based on random access. In SYN-MAC, time is divided into timeslots equal to the total number of channels, hence the dedicated radio is tuned to the channel in accordance with timeslots to send/receive a beacon. However, this protocol cannot guarantee PU protection as the arrival of PUs is only notified in specific timeslots.

Cognitive Radio MAC (COMAC)

Hythem *et al,* [94] proposed a distributed CSMA/CA based MAC protocol without any online interaction with primary radio networks. Each CR node maintains a list of locally available channels and exchanges this information with the intended receiver to select the set of data channels based on dynamically adjusted SINR. COMAC provides a soft guarantee on PU performance without considering a predefined interference power mask.

Cognitive Radio Enabled Multi-channel MAC (CREAM-MAC)

To overcome the multi-channel hidden terminal problem, CREAM-MAC integrates cooperative sequential spectrum sensing at the physical layer and packet scheduling at the MAC layer [95]. It is assumed that each SU is equipped with a single radio transceiver that can dynamically utilize one or multiple channels to communicate and has multiple sensors to simultaneously observe multiple channel activity. This protocol utilizes a four-way handshake procedure i.e. RTS/CTS and CST/CSR to prevent collision between CRs and PUs respectively.

Concurrent Access MAC (CA-MAC)

A concurrent access MAC protocol is proposed in [122], where multiple pairs can transmit concurrently on multiple channels. To minimise collision, a communication pair reserves a channel which is least common to all member nodes. For this, it uses two channel data structures: i) sorted channel list (SCL) and ii) common channel list (CCL). SCL is a global list to rank the channels based on availability to other nodes, and CCL is local list to maintain the common channel between communication pairs. CA-MAC also uses two radio transceivers - one for listening to the control signal and the other for data transmission.

Cognitive Radio CSMA/CA (CR-CSMA/CA)

In [25], the authors proposed a CR-CSMA/CA protocol for both single and multiple channel scenarios. However, for control message exchange it considers a network-wide CCC. Moreover, it introduces a three-way handshake procedure called PTS/RTS/CTS where PTS (prepare to send) is used to notify other nodes that the current time interval is reserved for spectrum sensing. CR nodes that overhear the PTS packet will update the network allocation vector (NAV) value accordingly. However, this extra NAV value may prolong the false blocking problem.

Channel Usage and Collision Based MAC (CUCB-MAC)

Based on collision count and channel ideality, a CUCB-MAC protocol is proposed in [103]. Moreover, it excludes the channel based on the probability that it will be used by neighbouring PUs or SUs. However, this protocol assumes that there is a central spectrum manager to disseminate the channel reallocation information in the network.

5.3 Performance Issues in CRAHNs MAC Protocols

To achieve RDV, a CR node transmits an RTS packet and waits for a CTS packet. Upon receiving CTS, RDV is established. However in CRAHNs, CTS may not be received if RTS/CTS is lost in an error-prone wireless channel or there is a collision between different RTS/CTS packets. In this scenario RDV cannot be guaranteed, even if the sender and receiver are on the same channel at the same timeslot. Therefore, the current setting of the RTS/CTS mechanism has to be reviewed. In this section, different performance issues in current RTS/CTS implementation are investigated from a CRAHNs point of view.

5.3.1 Rendezvous Collision

Rendezvous collision refers to the problem when transmission from a CR node on a channel in the CH sequence collides with another CR's transmission. Let us consider a scenario where two users CR_A and CR_B generate CH sequences based on local spectrum sensing as $\{1, 2, 3, 4\}$ and $\{1, 5, 6\}$ for their corresponding receiver. It is assumed that the CR nodes are not synchronized i.e. channel hopping depends on packet availability in the queue. As depicted in Fig. 5.1, CR_B starts channel hopping 4 timeslots before CR_A and achieve rendezvous on channel 1 while CR_A performs channel probing in another channel. Thereby channel 1 becomes unavailable for CR_A. Since CR_A does not perform sensing during or before hopping on a channel, it will transmit an RTS on channel 1 and cause a collision. This is called RDV collision. The probability of this event can be calculated as the probability that at least one of the $(n-1)$ remaining CR users are in transmission on the same channel:

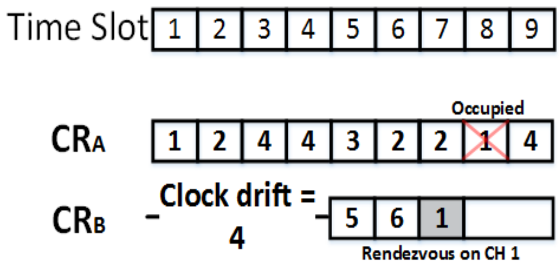


Figure 5.1: Illustration of rendezvous collision. At the 8th timeslot, CR_A hops on channel 1 and transmits an RTS packet which collides with CR_B transmission.

$$p_r(collision) = 1 - (1 - \tau)^{n-1} \tag{5.1}$$

where τ is the probability of transmission at any random slot and can be defined as $\rho_s . \frac{TTR}{TTR+T_{Data}} . \frac{\alpha}{2}$ [123]. Here $\rho_s = \frac{\lambda_s}{\mu_s}$, α is the channel location correlation coefficient in [0 to 1] and T_{Data} is the time to transmit unit data packet. However, α is very close to 1 [124].

5.3.2 Handshake Collision

Upon achieving rendezvous on a CH sequence, a CR node has to contend for the channel. RTS/CTS/DATA/ACK is an optional four-way handshake mechanism by which distributed coordination function (DCF) 802.11 is adopted to exchange the control information [125]. The RTS and CTS packets are exchanged before data transmission between a pair of source and destination nodes so that data frame collisions caused by the hidden terminal problem can be minimized. An RTS packet comprises the destination address and the expected data duration information. It is worth noting that nodes which overhear the RTS refrain from transmitting for that period. Upon receiving an RTS, the destination node responds with a CTS packet. Therefore, with the aid of the RTS/CTS mechanism, other nodes within the range of both the source and the destination defer from accessing the channel by setting a timer known as

NAV. Problems arise when the RTS or CTS packet is not correctly received or collides at the receiver or sender node respectively, known as (i) RTS/RTS collision and (ii) RTS/CTS collision.

RTS/RTS collision is illustrated in Fig. 5.2 where two senders A and C hop on to the same channel and simultaneously transmit an RTS packet to B and D respectively for channel contention. It is assumed that they are not in sensing range and the RTS messages collide as both nodes B and D are in transmission range of A and C. Therefore, CR receivers in the overlap region cannot decode the RTS message and no CTS reply will be sent. In this scenario, rendezvous cannot be achieved even though the senders have hopped onto the same channel at the same time.

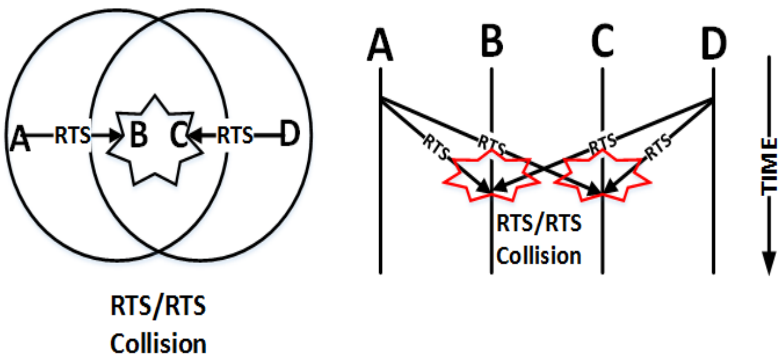


Figure 5.2: RTS/RTS collision due to simultaneous transmission on the same channel.

The RTS/CTS collision scenario is illustrated in Fig. 5.3 where the CTS packet from user C collides with the RTS from user A. Even sense-before-access cannot prevent this collision as both senders (A and D) are outside of each other's transmission range. Hence, rendezvous between A-B cannot be achieved even though their transmission is completely disjoint with C-D. The reason it is called "disjoint" is transmission from D will not interfere with reception of B from A and vice versa.

The handshake collision probability at the time t, between the senders, sender and receiver, receiver and receiver in the overlap region is the same as the probability

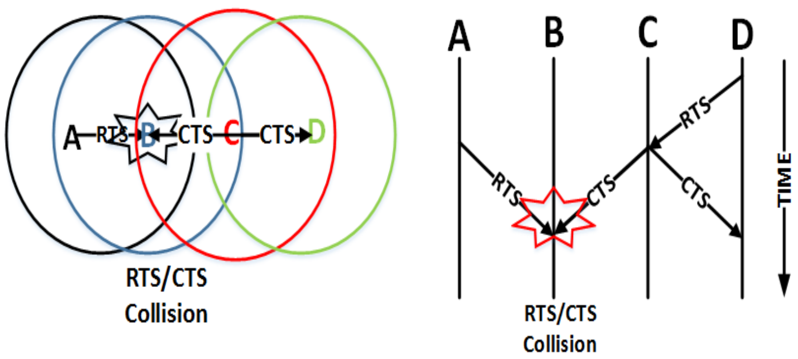


Figure 5.3: Illustration of RTS/CTS collision.

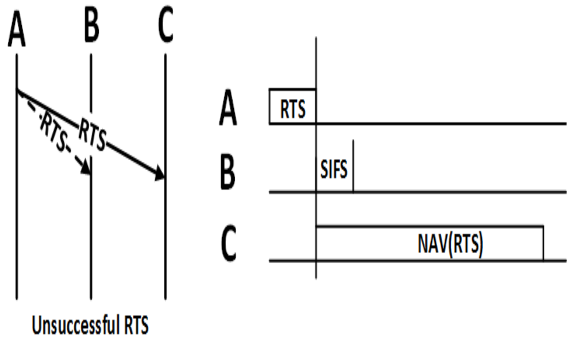
that the sender successfully achieves rendezvous with the receiver within the overlap region. The probability of this event in the overlap region occurring during the time t is $P_{handshake} = \frac{t}{ETTR}$.

5.3.3 Blocking Problem

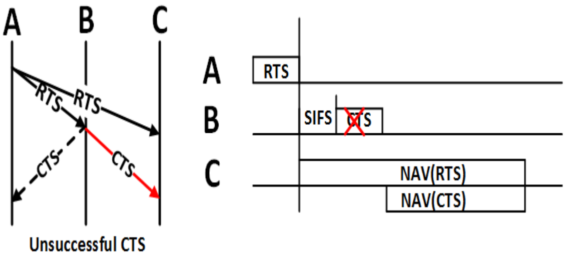
A CR node is said to be blocked if it is not allowed to transmit data at a given time instant. Let us consider a scenario illustrated in Fig. 5.4 where user A wants to transmit a packet to user B. Assume that user C is in the transmission range of both users A and B. As a part of the channel contention process, user A transmits an RTS packet to B and B sends back a CTS packet to A. Notice that the RTS and CTS packets can be decoded by neighbouring nodes. All the neighbours that overhear either the RTS or CTS update their NAV for that duration of time in which the channel will remain busy and the nodes defer their transmission for the NAV duration. This mechanism is known as virtual carrier sensing (VCS) and it effectively reserves the channel for the ongoing transmission. However, it is possible that a CTS packet is not initiated or not successfully transmitted due to unsuccessful reception of the RTS packet, a channel error, RTS/RTS collision or RTS/CTS collisions. In all cases transmission from A to B is not established and the neighbour's users remain blocked.

This scenario is illustrated in Fig. 5.4 for a single hop scenario. It is assumed that A, B and C are in transmission range and A wants to transmit a packet to B. Fig. 5.4(a) shows that RTS transmission from A to B is not successful but it is successfully received by C. C will update the NAV value and defer the transmission based on the duration field in RTS. Fig. 5.4(b) exhibits that RTS is received successfully by both B and C. As B is the destination, it will reply CTS packet. It is assumed that the CTS packet is successfully received at C but not at A. As the CTS reply from B to A is not successful, the channel remain idle but wasted as C cannot use it as well. In both cases, the channel contention process has failed and no actual data transmission takes place. However, in a multi-hop scenario, the blocking problem also arises regardless of whether transmission from A to B is successful or not. Fig. 5.5 illustrates the propagation of the blocking problem. It is assumed that user C receives both the RTS and CTS and updates the NAV value accordingly. Hence an RTS from user D will not reply by C. Moreover, this RTS is also received by user E which updates its NAV value. Hence any request from F to E will not reply by user E, even though transmission from user F will not interfere with D or A-B's transmission.

From the above discussion it is evident that a mathematical design of the rendezvous CH sequence cannot guarantee that RDV will be achieved in a practical scenario. For example, when a sender sends an RTS and no reply is received during the listening period, the sender cannot confirm whether an RTS collision has happened or the sender and receiver are on different channels. If they are on different channels, it is absolute that they will not have RDV. However, even for hops on the same channel, but rendezvous collision, handshake collision, and the blocking problem can render the result in an unsuccessful rendezvous.



(a)



(b)

Figure 5.4: Illustration of single hop blocking problem.

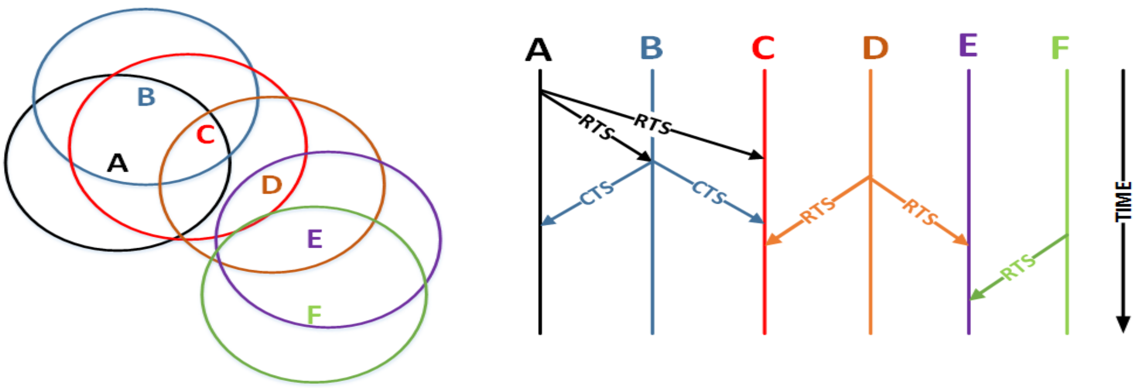


Figure 5.5: Illustration of multihop blocking problem.

5.4 CR-RDV MAC Protocol

As discussed in chapter 3, the CRs use the ETQCH protocol for RDV to exchange control information. ETQCH is a mathematical concept to achieve RDV and establishment of RDV depends on a successful channel probe packet or RTS/CTS exchange, which is a MAC layer issue. In section 5.2.2, different multi-channel CR-MAC protocols are discussed and classified into three groups based on channel access: i) random access, ii) time slotted, and iii) hybrid. Time slotted and hybrid protocols require network wide synchronization, which is not feasible in CRAHNs. Therefore, a random access based protocol is proposed in this section. The cognitive cycle of the CR-RDV MAC protocol is shown in Fig. 5.6. The cycle consists of five major functionalities. It starts with spectrum sensing to gather surrounding radio information. This information is then analysed by the spectrum allocation unit and the channels are ranked based on the channel ranking procedure discussed in Chapter 3. The outcome from the spectrum allocation unit is forwarded to the RDV unit to exchange the information with the intended receiver. Upon RDV establishment, the node decides on the data channel to transmit the packets. To avoid a collision due to simultaneous transmission on the data channel, a CSMA/CA with modified RTS/CTS handshake mechanism is used by the spectrum sharing unit. If the current RDV channel is selected as the data channel, the CR node will transmit instantaneously on the RDV channel. Otherwise, DC is selected from the CTS frame. In this case, the sender has to send an additional control packet to inform its neighbours regarding the new selected data channel. If a PU appears on the serving data channel, spectrum mobility is triggered to move the current data transmission to another available data channel or backup channel.

5.4.1 Spectrum Sensing

Spectrum sensing is one of the most essential elements of CR ad-hoc networks. It is used to exploit the unoccupied portion of the radio spectrum and includes both the licensed and unlicensed spectrum. Moreover, it aims to forecast future idle times in PU traffic to be used by CR transmission. The CR collects information about

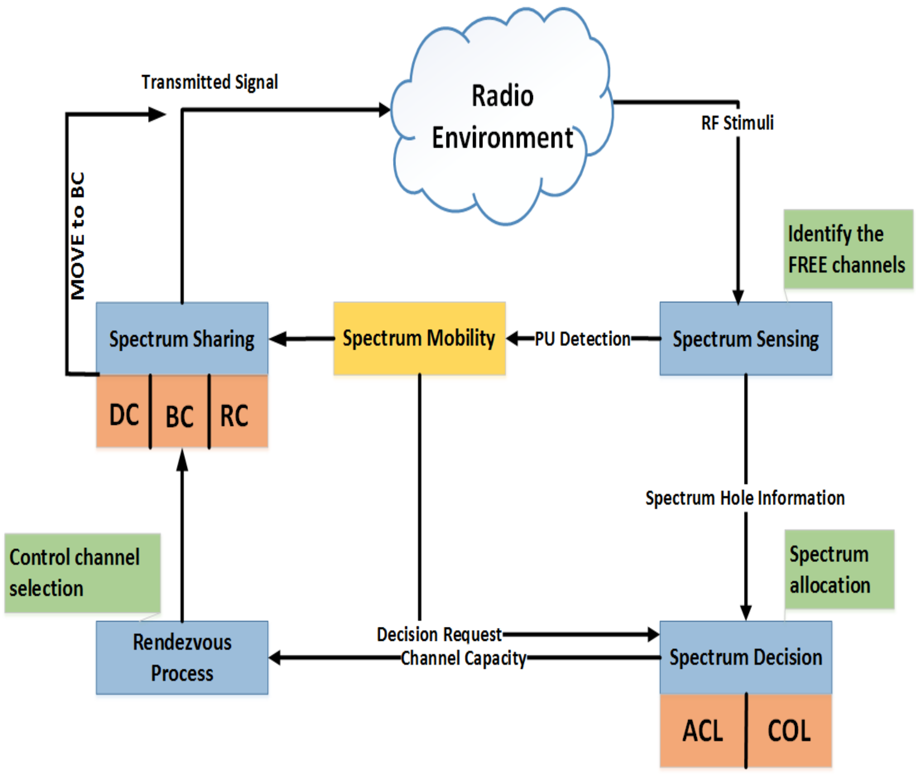


Figure 5.6: Cognitive cycle of CR-RDV MAC protocol

spectrum usage through spectrum sensing and stores this information in a channel history database in a binary format. Hence, spectrum sensing involves two subtasks: (i) PU behaviors, and (ii) sensing method.

The Primary Users' Behaviors

It is considered that there are n licensed channels available in the network in which PUs operate in an asynchronized manner. Moreover, it is assumed that the channel usage patterns of the PUs follow an independent and identity distributed ON/OFF renewal process [126]. An ON period can be considered as a time period in which PUs are present. An OFF state indicates that the channel is currently vacant and can be used opportunistically by SUs. The channel usage model is depicted in Fig. 5.7. Suppose i is the channel index and X_t^i denotes the number of channels i at time t

such that:

$$X_t^i = \begin{cases} 1 & \text{if channel is ON (BUSY),} \\ 0 & \text{if channel is OFF (FREE).} \end{cases} \tag{5.2}$$

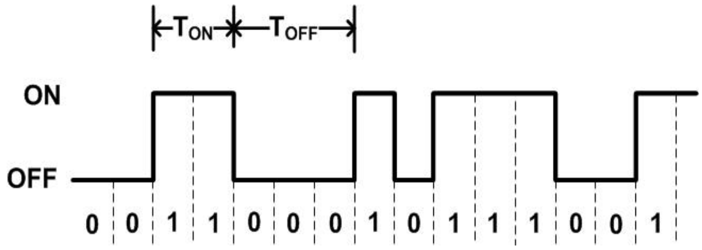


Figure 5.7: Binary channel model [4].

For an alternating renewal process, let $f_{T_{ON}}(X)$ be the probability density function (pdf) of the ON duration and $f_{T_{OFF}}(X)$ be the pdf for the channel's OFF duration. Hence, the channel utilization μ is the expected fraction of time when the channel stays in its OFF state:

$$\mu = \frac{E[T_{OFF}]}{E[T_{ON}] + E[T_{OFF}]} \tag{5.3}$$

Since each licensed user arrival is independent, each transition follows the Poisson arrival process. Hence the length of ON and OFF periods can be expressed using an exponential distribution [4, 127] with pdf $f_X(t) = \lambda_X \times e^{-\lambda_X t}$for ON state and $f_Y(t) = \lambda_Y \times e^{-\lambda_Y t}$ for OFF state. Therefore, channel utilization μ in equation 5.3 can be written as:

$$\mu = \frac{\lambda_X}{\lambda_X + \lambda_Y} \tag{5.4}$$

Where $E[T_{ON}^i] = \frac{1}{\lambda_X}$ and $E[T_{OFF}^i] = \frac{1}{\lambda_Y}$ are the rate parameter for exponential distribution. $E[T_{ON}^i]$ and $E[T_{OFF}^i]$ are the mean of distribution. Let $P_{ON}(t)$ be the probability of channel i in ON state at time t and $P_{OFF}(t)$ be the probability of channel i in OFF state at time t. The probabilities of $P_{ON}(t)$ and $P_{OFF}(t)$ can be calculated as:

$$P_{ON}(t) = \frac{\lambda_Y}{\lambda_X + \lambda_Y} - \frac{\lambda_Y}{\lambda_X + \lambda_Y} e^{-}(\lambda_X + \lambda_Y)t \tag{5.5}$$

$$P_{OFF}(t) = \frac{\lambda_X}{\lambda_X + \lambda_Y} + \frac{\lambda_Y}{\lambda_X + \lambda_Y} e^{-}(\lambda_X + \lambda_Y)t \tag{5.6}$$

Thus by adding equation 5.5 and equation 5.6, we can get

$$P_{ON}(t) + P_{OFF}(t) = 1 \tag{5.7}$$

Hence, it is necessary to have a spectrum sensing process to gather statistical information about PU activities in an effort to predict when the channel will be idle.

Spectrum Sensing Model

As mentioned in the previous section, each CR user only accesses the channel when the channel is in the OFF state. However, detecting the "OFF" state accurately is subject to a sensing model employed in the CR system. There are several spectrum sensing methods that can be used, such as energy detection [126, 128–135], cyclostationary feature detection [126, 136–138], matched filter [139], waveform [140–142] and radio identification [143]. In this thesis, the energy detection approach is considered for its simplicity of implementation and its efficiency. Moreover, it does not require knowledge of the PU's signal features. The purpose of spectrum sensing in this thesis is to identify the channel status and doesn't impose any limit on the generalisability of the result and conclusions of this thesis. However, in realistic situations, spectrum sensing is imperfect and can be characterized by the probabilities of misdetection (p_{md}) and false alarm (p_{fa}). p_{md} represents the probability of falsely detecting an active PU as being idle, and p_{fa} is for the probability of a CR detecting a PU when the PU does not exist. The relationship between p_{md} and p_{fa} for an energy detector can be written as [144]:

$$p_{fa}(\xi) = \mathcal{Q}(\sqrt{2\gamma + 1}\mathcal{Q}^{-1}(1 - p_{md}) + \sqrt{\tau f_s}\gamma) \tag{5.8}$$

where ξ is the sensing time, γ is the signal to noise ratio (SNR) of the PUs at the CR receiver, f_s is the channel sampling rate and $\mathcal{Q}(\cdot)$ is the complementary distribution function of a standard Gaussian variable. According to Eqn. 5.9, the accuracy of spectrum sensing depends on sensing time (ξ), which can be derived from Eqn. 5.9 as:

$$\xi = \frac{1}{f_s \gamma^2}[\mathcal{Q}^{-1}(p_{fa}) - \sqrt{2\gamma + 1}\mathcal{Q}^{-1}] \tag{5.9}$$

Hence sensing time should be large enough to sense the channel with $p_{md} = 0$ and $p_{fa} = 0$. IEEE 802.22 standard specifies that [145] the required time for perfect sensing is much larger than the slot duration $T_s = 10ms$. Optimal spectrum sensing is out of the scope of this thesis.

5.4.2 Spectrum Allocation

Based on the gathered spectrum sensing information, each CR node creates two channel lists: (i) available channel list (ACL) and (ii) channel occupancy list (COL). The ACL is used by CR node i to keep the record of available channels and their status at any time t. Algorithm 3 shows the pseudo code to find the available channel. It considers the geographical constraints imposed by regulatory authorities to protect pre-defined incumbent license users using the incumbent database. Moreover, the CR utilizes the knowledge of previous scanning results to estimate the $P_{OFF}(t)$ in the current channel selection. The selection criteria for being an available channel is shown in line 5 of the Algorithm 3 i.e. estimated OFF state duration has to be equal or greater than the minimum time required to send the smallest packet. In this case priority goes to the license channels. If the CR is not successful in finding a license channel, an unlicensed channel will be used and evaluated with the same conditions. The data structure of the ACL consists of two sub-lists: (a) primary channel list (PCL) and (b) secondary channel list (SCL). Both the PCL and SCL are constructed based on a similar data structure. There are three fields for both lists:

- PCL/SCL.ch: channel index of the channel.
- PCL/SCL(ch).time: time PCL/SCL.ch has to be released.
- PCL/SCL(ch).rank: rank of the PCL/SCL.ch. The ranking of PCL/SCL.ch is dynamically updated based on PU and CR activities.

Algorithm 3 Available Channel List with Proactive Channel prediction

Load:Licensed User Database
K = Number of Licensed Users (Protected by Regulation)
for $i = 1$ to $N - K$ **do**
    Calculate $P_{OFF}(t)$
    if $E[T_{OFF}] \geq E[T_{MIN}]$ **then**
        $Avail\_ch\_list \leftarrow Channel(i)$
    else
        $Avail\_ch\_list \leftarrow Channel(unlicensed)$
    end if
end for

The COL is maintained by each CR node based on local observations and overhearing neighbouring nodes. Nodes that are neighbours of the transmitter may overhear and update the database by themselves. The data structure for the COL can be described as follows:

- COL(i).node: represents the neighbouring node x of node y.
- COL(i).ch: the channel that is using by node x.

Table 5.2: Example of ACL data structure

PCL.ch index	PCL.time	PCL. rank	SCL.ch index	SCL.time	SCL.rank
ch 5	20ms	2	ch 2	10ms	1
ch 6	10ms	2	ch 3	15ms	3
ch 4	15ms	4	ch 1	25ms	2
ch 7	10ms	3	ch 8	10ms	4

Table 5.3: Example of COL data structure

COL(i). node	COL(i). ch	COL(i), type	COL(i). time
X	5	L	30ms
W	6	UL	25ms
Z	7	L	10ms

- COL(i).types: a licensed channel is indicated as L, or UL for an unlicensed channel.
- COL(i).time: estimated duration of channel occupancy.

The COL is used for triangulation i.e. to identify the common neighbours of the transmitter and receiver. It will also help to design the handshake procedure in order to minimise collisions on both the control and data channels.

Upon receiving the ACL and the COL, the next logical step is to select: (i) data channel (DC) (ii) backup channel (BC), and (iii) rendezvous channel (RC). The selection of the DC is determined by the receiver based on ACL received from the transmitter and its own local sensing information. This is because interference and decoding are handled by the receiver. In the case of PU re-appearance on the serving data channel, a CR node must switch to the another channel to continue data transfer, which corresponds to spectrum handoff. To minimise the interruption (delay) during spectrum handoff, a BC list is considered in this protocol. The BC is selected like the DC from the list of available channels from the transmitter and its own ACL. The preference goes to an unlicensed channel only when a licensed channel is unavailable. The RC is very important in maintaining the communication link and needs to be updated very frequently, including when there is a change in ACL. The RC is used to establish and maintain the RDV between the CR users. Hence, the availability of RC will be checked frequently through fine sensing. If it is occupied, the CR node uses the RDV radio to re-establish RDV. Moreover, anytime there is a change in ACL or COL it has to be communicated to the receiver through the RC.

It is important to note that the proposed **CR-RDV** MAC utilizes both licensed and unlicensed channels based on channel availability, which eventually speeds up link establishment in cases of PU appearance on the current sensing channel. This information is discussed in the following subsection.

5.4.3 Spectrum Sharing

In the previous sections, the spectrum sensing and spectrum allocation processes were discussed to identify and classify the available spectrum. However, how to share the sensing information among different CR nodes is a network architectural issue. Thereby different spectrum sharing schemes are studied in [146] and the basic comparison between centralized and distributed methods is discussed. In centralized architecture, spectrum sharing is performed by CR users with the help of CR base station. In contrast to centralized architecture, the information is carried by the CR node itself in a decentralized system. In this thesis, an ad-hoc environment is considered. Therefore, a reliable control channel establishment procedure is required to exchange or share the channel information that corresponds to the RDV problem. A detailed RDV protocol called ETQCH is discussed in Chapter 3. To achieve RDV, each node follows the CH sequence based on the ETQCH protocol and carries the control information in RTS/CTS packets. Therefore, the spectrum sharing process discussed in this section includes two parts: (i) control packets format, and (ii) handshake process.

Control Packets Format

The proposed **CR-RDV** MAC protocol utilizes the similar RTS/CTS control packet format proposed in the MACA protocol [125]. Moreover, it introduces an additional conditional control packet which is only sent if the serving channel is different to the selected data channel, called the not-to-send (NTS) packet. The traditional RTS/CTS scheme proposed in MACA mainly provides the handshake procedure for a single channel environment. As CR is a multi-channel environment, the existing RTS/CTS scheme is extended by integrating the channel information. Figure 5.8 shows the fields in the RTS and CTS control packet. Every time a CR node jumps on a channel during the RDV process, it sends an RTS packet which contains two additional fields of two bytes longer than that of the basic RTS frame. The additional fields are ACL and COL channel lists. In the basic RTS frame there are five fields, including frame control (2 bytes), duration ID (2 bytes), receiver address (RA) (6 bytes), transmitter address (TA) (6 bytes), and frame check sequence (FCS) (4 bytes).

A CR node that receives the RTS and is a valid recipient replies by CTS packet. The packet format of CTS has three additional fields, each of which is one byte longer than the basic CTS frame. The additional field contains the DC, BC, and RC for the transmitter. Hence, the CTS packet length duration is the sum of frame control, duration of data packet, RA, DC, BC, RC and FCS length.

Now, if the current RC is not the same as the selected DC, the sender will send an NTS packet to inform its neighbours regarding the new DC. The frame format of NTS is the same as the CTS except the transmitter address is used instead of receiver address.

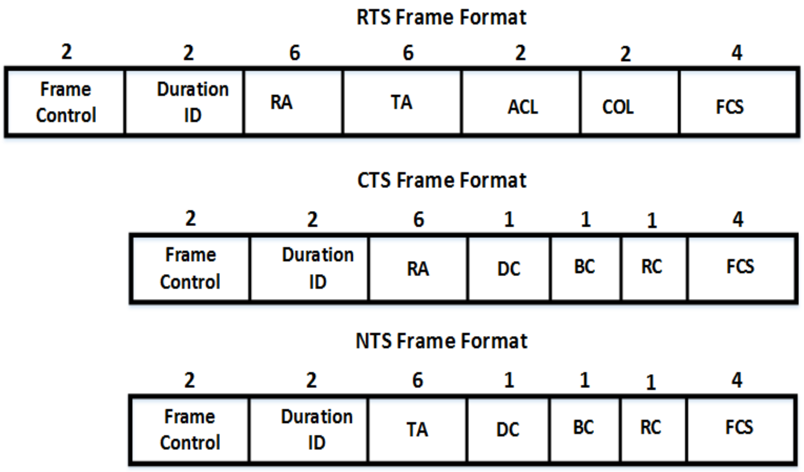


Figure 5.8: Illustration of proposed RTS/CTS/NTS frame format.

Handshake Process

This is the process of facilitating the exchange of local view of spectrum usage between the transmitter and receiver. As CRAHNs is a distributed multi-user multi-channel environment, it is necessary to have a reliable handshake scheme to avoid collisions during channel negotiation. The handshake process proposed in this thesis consists of three subprocesses as follows: (i) channel access method (ii) backoff counter, and (iii) network allocation vector.

i. *Channel Access Method:* In this thesis, CSMA/CA is considered for the channel access method with some modification. The channel access process is started during RDV establishment in CRAHNs where the CR node wants to establish a control channel to exchange control information prior to data transmission. To do this, a CR node sends RTS/CTS based channel probing packets to the intended receiver. Upon successful channel probing, data transmission, rendezvous and backup channels are established.

ii. *Backoff Counter:* According to the CSMA/CA protocol, a CR node uses random backoff after successful packet transmission. However, it is required to refine the backoff procedure based on packet length in order to protect the incumbent PU's transmission and minimise packet error. Therefore, a CR node transmits packets with variable length depending on the remaining time of the current transmission, so that no concurrent transmission will take place. Hence, the modifications are:

   (a) Before each transmission, the CR node will evaluate the remaining time of the transmission session (T_R).

   (b) If $T_R \geq T_{packet}$; packet transmission will take place. Provided that $T_{packet} = T_{RTS} + T_{3SIFS} + T_{CTS} + T_{DATA} + T_{ACK}$.

   (c) If $T_R < T_{packet}$; defer the packet transmission till the next slot is unoccupied by PUs.

   (d) To reduce the packet error, a CR node evaluates the remaining time after each backoff value is counted. The backoff counting down process becomes frozen when the remaining time is smaller than that of the packet size.

iii. *Network Allocation Vector (NAV):* CSMA/CA uses the NAV to indicate the duration of data transmission. However, this NAV value causes a RTS blocking problem in ad-hoc networks which is explained in section 5.3.3. In order to solve this problem VCS is modified, which is called modified virtual carrier sensing (MVCS) and the following amendments are made:

(a) Upon overhearing the RTS packet, a CR node defers the transmission until the data transmission is expected to begin.

(b) Perform the spectrum sensing on particular channel, if it is found

- *Busy*: continue deferral till end of data transmission.
- *Idle*: Access the channel immediately.

According to traditional VCS, the NAV value is (when current RC is the same as selected DC):

$$T_{VCS}^{RTS} = T_{3SIFS} + T_{CTS} + T_{DATA} + T_{ACK} \tag{5.10}$$

$$T_{VCS}^{CTS} = T_{2SIFS} + T_{DATA} + T_{ACK} \tag{5.11}$$

And based on MVCS, it becomes:

$$T_{MVCS}^{RTS} = T_{2SIFS} + T_{CTS} \tag{5.12}$$

$$T_{MVCS}^{CTS} = T_{2SIFS} + T_{DATA} + T_{ACK} \tag{5.13}$$

If the selected DC is different to the current RC, it will follow the same NAV value of T_{MVCS}^{CTS}. The timing diagram of the proposed NAV modification is illustrated in Fig. 5.9. It is considered that A has a data packet for B and C is in transmission range of both A and B. In this case both MVCS and VCS perform the same. Now consider that D has a data packet for C but RTS/CTS exchange fails. However, the VCS mechanism causes node E to defer any sort of transmission/response from the neighbours. MVCS is the solution to prevent this situation by shortening the NAV (RTS) and sensing the channel to update the channel status. If the channel is found busy, it continues to defer or otherwise responds or initiates data transmission.

Now, consider a network scenario shown in Fig. 5.10 to describe the spectrum sharing process of **CR-RDV** MAC. The transmission ranges of the PUs are shown as a dotted

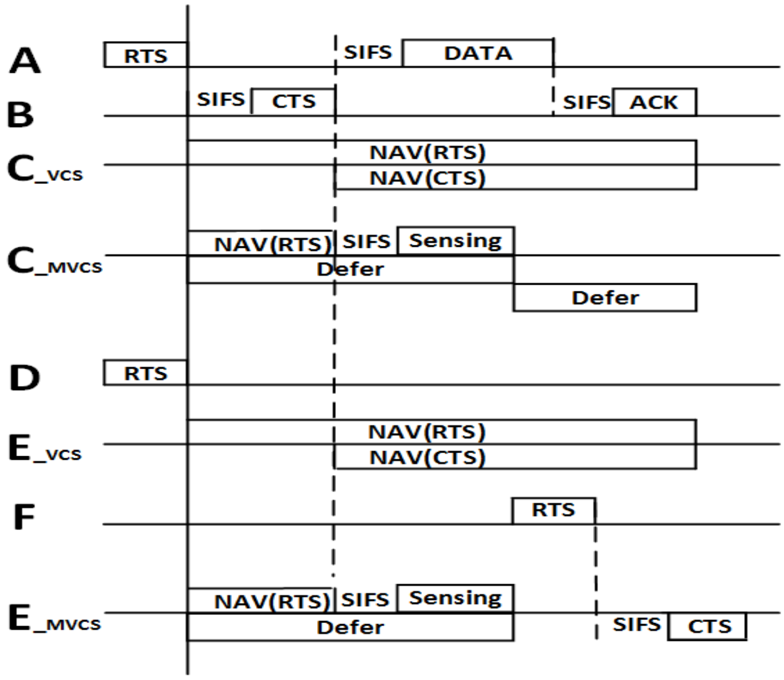


Figure 5.9: Timing diagram for modified virtual carrier sensing.

circle. It is assumed that A wants to transmit a data packet to B. User A follows the standard CSMA/CA protocol with a 4 way handshake mechanism for channel contention. Since C is within the transmission range of A and B, it will receive both the RTS and CTS packets and become blocked. Assume the channels are error free. Therefore RTS from D to C will not be replied to. Similarly E will not reply to F's RTS packet as it is blocked by D's RTS packet. And this blocking problem propagates through the network. It is assumed that there are 6 licensed channels and 4 unlicensed channels available in the system. All the PUs are distributed in the network and their channel usage is listed in table 5.4. According to **CR-RDV** MAC, each CR constructs the ACL and COL during the spectrum sensing process. The outcome of spectrum sensing is presented in table 5.5, provided that the channels are listed according to channel rank.

Table 5.4: Channel Usage by PUs

PU	PU1	PU2	PU3	PU4
Channel	2	3	4	1

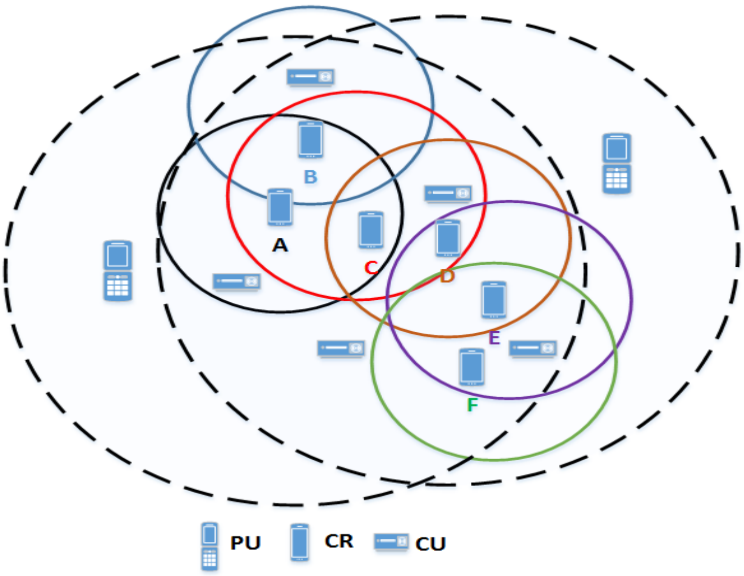


Figure 5.10: The transmission range of A, B, C,D, E and F are shown in circle with different colors.

For further explanation, it is considered that there are two simultaneous data transmission attempts from A to B and D to C. To send a packet from A to B, the node can use the traditional RTS/CTS or modified RTS/CTS handshake method. For a single channel network scenario, either method of RTS/CTS gives the same result. However, in multi-channel CRAHNs, communicating nodes have to decide on both the control and data channel. It is also assumed that there is a packet to transmit from D to C. Based on RTS/CTS transmission success, two cases can be observed:

***Case 1*:** An RTS from A to B is successfully received and B replies with a CTS packet. If the RTS packet from A to B was overheard by C, there would be an

Table 5.5: Channel Observe by CRs

Node	**ACL**	**COL**
A	L3, L4,L5,L6,U1,U2,U3,U4	L1,L2
B	L2,L4,L6,U1,U2	L1,L5,U3,U4
C	L2,L3, L4,L6,U1,U3	L1,L5,U2
D	L3,L5,L6,U2,U4	L1,L2,U1
E	L1, L2,L4,L6,U1,U2,U3	L3,L5
F	L1,L3,L6,U2,U4	L5,L4

RTS-RTS collision at node C due to simultaneous transmission from D, and C will not reply to D's RTS.

***Case 2*:** An RTS from A to B is not successful due to channel error, or an RTS from A to B is successful but CTS from B to A is in collision. Both of these relate in failure to channel establishment. As node C is in the transmission range of node A, it will receive the RTS from A and defer the transmission for the entire duration even though A and B are not using the radio resource.

Using modified RTS/CTS cannot avoid case 1, as it is due to concurrent transmission. However, it can prevent the false RTS blocking for nodes E and F. As C is blocked due to $A's$ and $B's$ transmission, no CTS will be received by D. The RTS from D is also received by node E, which eventually blocks the communication between E and F. In this context, the MVCS can solve this issue by allowing node E to serve the channel after T^{RTS}_{MVCS} time to evaluate the deferral period. If the channel is busy it will continue deferral or otherwise initiate communication with node F. For case 2, the same MVCS can improve the performance by deferring the transmission only for T^{RTS}_{MVCS} duration and sensing the channel. If the the channel is free it follows the backoff procedure, otherwise deferral continues. The next section provides the flow of information during the MAC process.

5.5 Message Sequence Chart (MSC)

In this thesis, the traditional RTS/CTS based handshake [125] method is used with the integration of some additional fields such as ACL, COL, DC, BC, and RC. To establish communication, the nodes exchange RTS/CTS packets with the intended receivers. Fig. 5.11 depicts the MSC for two scenarios with and without reappearance of the PUs on the serving DC. The MSC is really important in studying the flow of information and influence of strategies based on overhearing information. Here, the purpose of RTS/CTS is to serve as a channel probing packet to establish RDV between the intended communicating devices. In this thesis, two radio transceivers are considered. One is used for data transmission and the other is to maintain RDV, channel updates and any other changes in the radio environment during data transmission. The topology of the scenario is shown in Fig. 5.10. It is assumed that A has data to send to B, D has data to send to C and F has data to send to E. The simultaneous transmission of A and D to B and C are considered respectively. According to IEEE 802.11 CSMA/CA, both A and D sense the channel to be idle for DIFS time and select a random backoff. As A and D are outside each other's transmission range, the RTS of the nodes cannot be overheard. The entire communication follows the following message exchange:

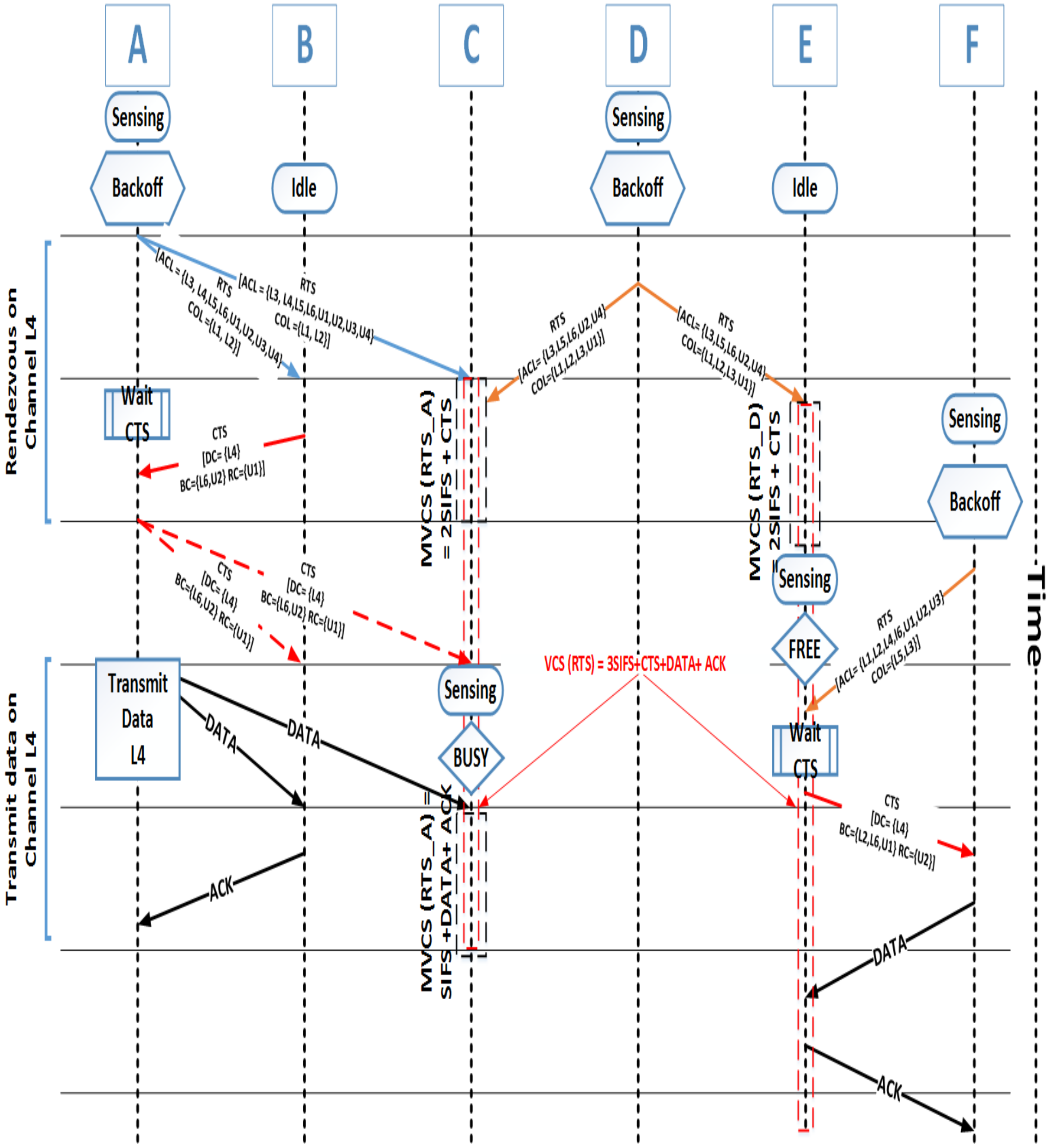
i. A and D both send RTS to receivers B and C respectively. The RTS of node A: $ACL_A = \{L3, L4, L5, L6, U1, U2, U3, U4\}$ and $COL_A = \{L1, L2\}$. For node D: $ACL_D = \{L3, L5, L6, U2, U4\}$; and $COL_D = \{L1, L2, U1\}$ additional fields compared to traditional RTS/CTS.

ii. The RTS from A is received by B and can be overheard by C, which causes collision with RTS from D to C. Hence C will not reply to any CTS.

iii. The RTS from D is also received by E the NAV value is updated as $T_{MVCS}^{RTS} = T_{2SIFS} + T_{CTS}$.

iv. Upon receiving the RTS from A, node B checks its own ACL_B and COL_B to decide on DC, BC and RC. For B, the DC, BC, and RCs are $\{L4\}$, $\{L6, U2\}$ and $\{U1\}$ respectively. Neighbouring nodes which can overhear node B can update the ACL and COL.

v. Upon receiving the CTS from B, node A matches the current RC with the DC field in the CTS. If both of them are the same, node A starts data transmission immediately. Otherwise, the selected DC will sense using the fast sensing method [76] and, if it is free, an additional control packet NTS will transmit before the data transmission is initiated.


A
B
C
D
E
F
Sensing
Backoff
Idle
Rendezvous on Channel L4
Transmit data on Channel L4
RTS
Wait CTS
CTS
MVCS (RTS_A) = 2SIFS + CTS
MVCS (RTS_D) = 2SIFS + CTS
VCS (RTS) = 3SIFS+CTS+DATA+ ACK
FREE
BUSY
Transmit Data L4
DATA
ACK
Time

(a)

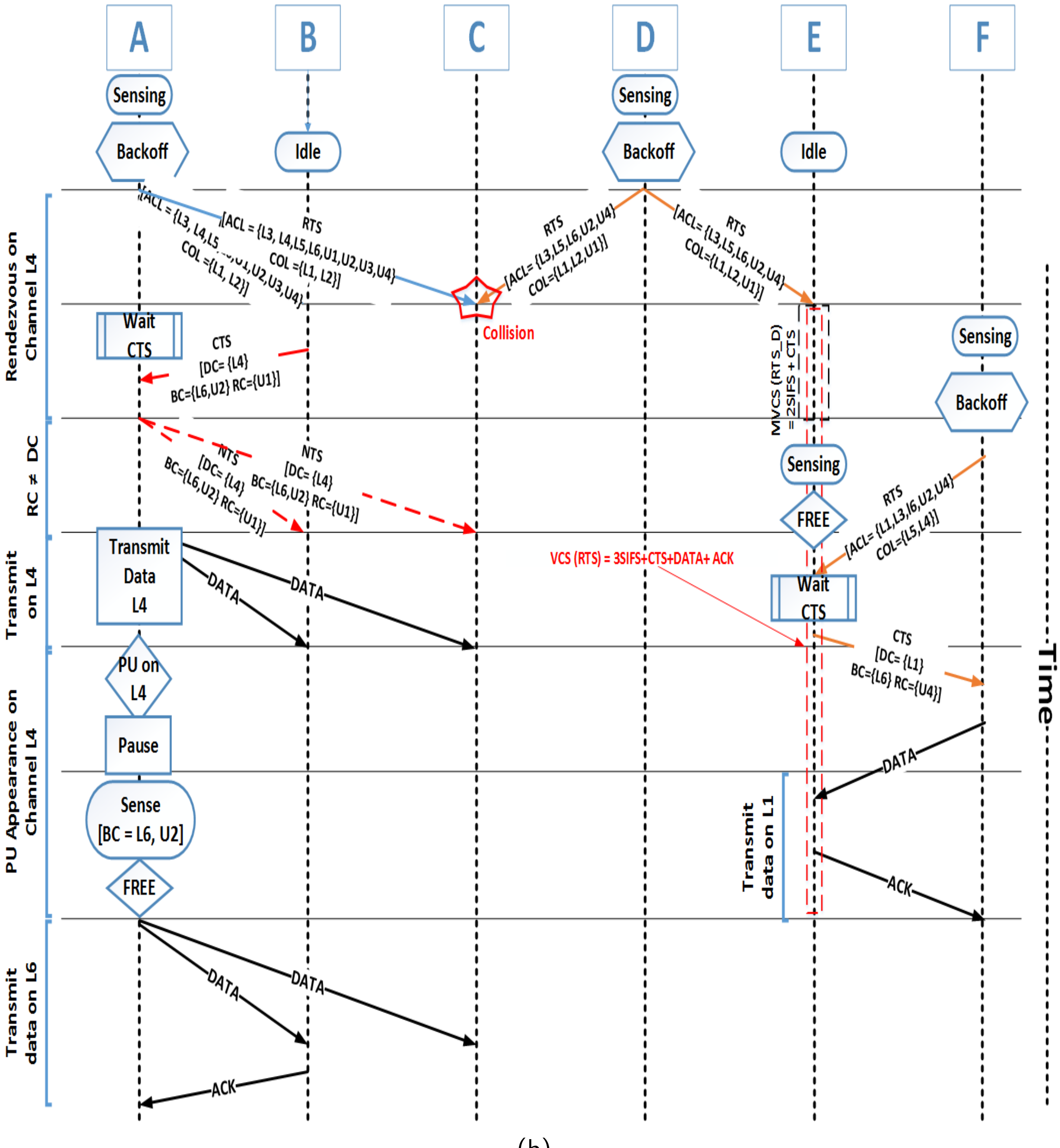


Figure 5.11: Message sequence chart for modified RTS/CTS handshake to establish communication between A to B and F to E. (a) Without PUs (b) With PUs.

vi. If no PUs reappear on the serving DC, the CR node continues to use the DC for the entire data transmission which is shown in Fig. 5.11(a) for A and B's transmission.

vii. Figure 5.11(b) illustrates the scenario of intermittent PU appearance on the sensing data channel. In this case, node A pauses the current transmission and senses the channel from DC. If there is no channel available to serve as DC in the DC list, it senses and selects a channel from the BC list. If the channel from the BC is free, data transmission will resume on the new channel which is $L6$ in this case.

viii. Now for node E, which has previously received RTS from D and updated the NAV value according to the MVCS method. After expiring the NAV value node E senses the channel to evaluate the channel status. If the channel is sensed to be free and receives an RTS from F, the CTS will reply to initiate the data transmission on the selected DC.

5.6 Protocol State Machine

Figure 5.12 illustrates the different states of the CR-RDV protocol, MAC process and transmission condition between the states. The entire protocol behaviour can be divided into two parts based on functionalities: i). Transmitter and ii). Receiver. The two states init and idle are common for both transmitters and receivers. The init state is used for variable initialization, attributes received from the upper layer and NAV. The entry and exit conditions of the states are designed as follows:

5.6.1 Transmitter

IDLE STATE: In the idle state, a node waits for incoming data, either from its own upper layer or from the receiver. If the data is coming from its own upper layer, the transmission of the idle state is triggered to the channel sensing state. After successful data reception, the node becomes idle if there is no other data to transmit. Moreover, a node in this state can overhear the CTS packet from other nodes and update the NAV value.

Channel Sense: To initiate the data transmission, a CR node first establishes RDV with its intended receiver. Hence a CR has to perform channel sensing to gather the channel state information. Moreover, channel sensing is performed if the DC channel is different to the RDV channel. In the case of a PU appearing on the current serving DC, the CR node has to switch the channel from DC to BC. Before resuming the transmission on BC, the BC has to be sensed using the fast sensing method.

Backoff State: The purpose of the backoff state is to reduce the collision probability in distributed ad-hoc networks. After sensing the channel is idle for DIFS time, a random amount of time is chosen by each node independently to further sense the channel. If the channel is sensed to be idle after the expiry of the backoff time, the CR node initiates the RTS packet and transmits to send RTS state.

Send RTS: In this state, the RTS is sent to the intended receiver after the backoff expires. The RTS frame contains two additional fields, which are ACL and COL as explained under spectrum sharing. The successful transmission of RTS can only be confirmed by CTS reply. However, CTS failure and RTS failure are treated as RTS failure as it is not possible to identify whether the CTS has not been received due to unsuccessful RTS or CTS transmission. The transition to send RTS is followed by the wait CTS state.

Wait CTS: Transition to wait CTS happens after sending the RTS packet. In this state, the CR node waits for the CTS packet from its intended receiver. There are two transitions possible from wait CTS based on successful CTS reception. If the CTS is received within the waiting time, a transition will occur from wait CTS state to send data state if the serving channel is the same as DC, otherwise it transits to send NTS state. In contrast, if the timer expires and no CTS is received or it has collided with another RTS/CTS transmission, wait CTS transits to backoff state and doubles the contention window.

Send NTS: Upon receiving CTS and finding that the current serving channel is not the same as the selected DC, the NTS packet is transmitted to inform of the change. Upon successful transmission of NTS, the state transits to send DATA state.

Send Data: In this state, data is transmitted on the selected data channel. Based on the selected data channel it has two transitions. If the selected DC is the same as the current RC, the data transmission will continue. Otherwise it will select a channel from the DC and sense it before transmitting on the DC.

Wait ACK: After successful data transmission on the selected channel, a CR node reaches wait ACK state and waits for an acknowledgement (ACK) from the intended receiver. If the ACK is received successfully and there are no other packets to send, it will transit to idle state and reset the contention window (CW). On the other hand, if an ACK is not received before the timer expires, the CR node transits to backoff state and transmits the data pack again.

MOVE: Due to a PU appearing on the current DC, a CR node has to select another DC from the DC list. If the list is empty, it will select a DC from the BC list. Channels in the BC list are arranged based on channel ranking. Hence, a channel from the head of the BC list is selected as the new DC and senses the channel using the fast sensing method. If the channel is sensed to be busy, the second channel will be selected from the BC list and will perform the same sensing operation until a new DC is selected. However, it may happen that all the channels from the BC list are occupied either by PUs or CR nodes. In this case, a channel from the RC is used as the DC. The

CR node initiates the RDV process immediately and updates the DC, BC and RC lists. If none of the channels is found idle, the transmission will pause and perform spectrum sensing.

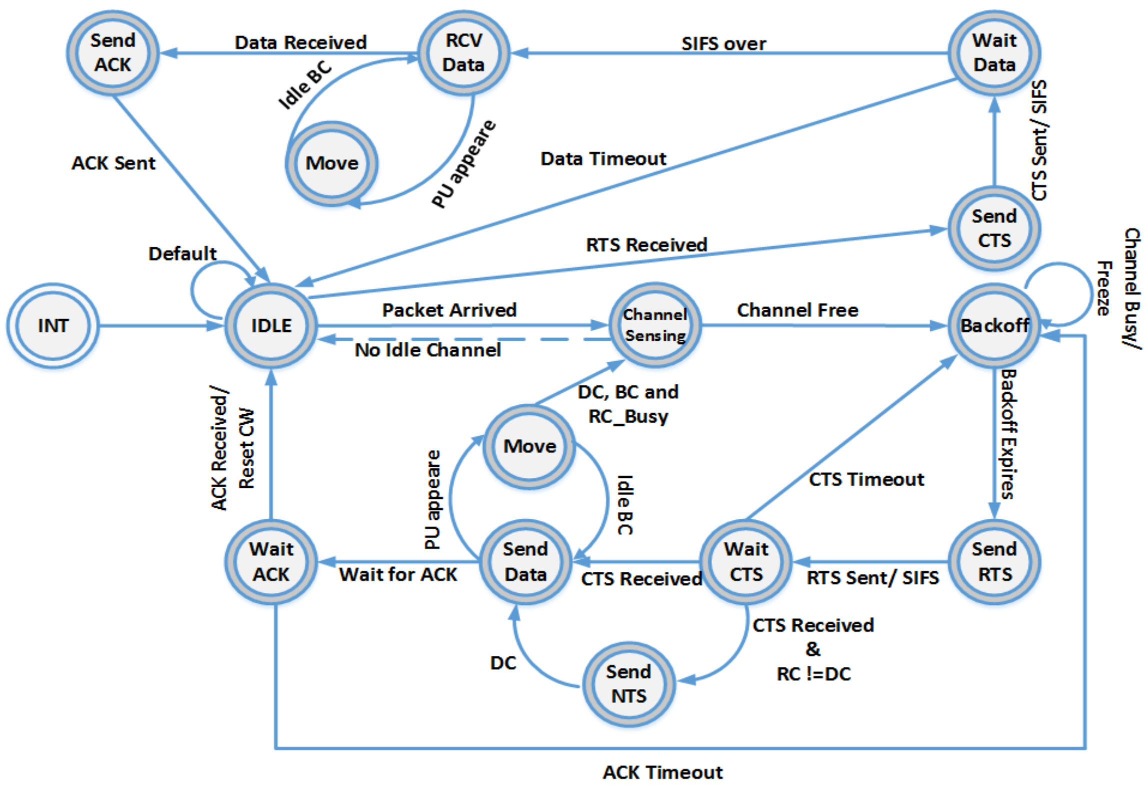


Figure 5.12: State transition diagram for CR-RDV MAC protocol

5.6.2 Receiver

Usually a CR node stays in the idle state and receives an RTS packet which expects to eventually receive a data packet. The receiving mode operation of a CR node is described as follows:

Send CTS: Upon receiving the RTS packet, a CTS replies on the current DC after SIFS time. In this state, a CTS packet is formed with three additional fields, namely

DC, BC, and RC. DC is formed by comparing ACL in the RTS packet and its own channel sensing outcome. If the current channel is the best channel for both sender and receiver, data communication will continue on the current DC. Otherwise the sender will switch to the proposed DC in the CTS. After CTS transmission, there is a state transition to wait data state to receive the data.

Wait Data: In this state, a CR node sets up a timeout timer for the data reception waiting time. Based on the timer expiration, two state transitions can be observed. If a data packet is received before the timeout timer expires, it will transit to the RCV Data state. Otherwise it is assumed that data transmission failed due to collision and goes back to idle state for a new RTS to be received.

RCV Data: If the data packets are received before the timeout timer expires, a CR node is reached in RCV Data state. In this state, the node starts to receive data on the DC. Due to intermittent PU appear on sensing the DC may interrupt the current data transmission. To reduce the service interruption, a CR node transits to MOVE state to select the DC from the BC list and resume the data transmission on the new DC. After successful data transmission, it transits to send ACK state.

MOVE: The switch state on the receiver side behaves the same as on the transmitter side. In this state, it performs fast before selecting a channel from the BC to serve as the DC on sudden PU appearance.

Send ACK: The last state of the protocol state machine is send ACK to acknowledge free data reception. It also include the missing packet information in the data transmission. No matter whether ACK is received or not, a state transition to idle state occurs. If ACK is received successfully, the transmitter starts the DCF procedure again. Otherwise it is assumed that data transmission has failed and the CR node starts to retransmit the data packet.

5.7 Summary

In this chapter, a distributed multi-channel random access CR-MAC protocol called CR-RDV MAC was proposed. The proposed protocol utilizes both licensed and unlicensed channels to initiate and maintain communication in an ad-hoc environment. To exchange the control information, the RDV process is integrated with the CR-RDV MAC protocol. The channel sensing information is exchanged through modified RTS/CTS. The ACL and COL data structures are embedded in the RTS packet. Based on ACL and COL, CTS replies with DC, BC and RC information where DC is used for data transmission, BC is a list of backup channels in case of PU reappearance on the current DC, and RC is used for the RDV process. Moreover, the traditional backoff procedure is redefined based on packet length in order to protect the incumbent PU transmission. To avoid concurrent transmission with PUs, a CR node transmits the packet with a length that is determined by the remaining time in the current transmission. At the last stage, to protect the blocking problem due to unsuccessful transmission from neighbouring nodes, the traditional VCS is modified by introducing sensing after RTS time, and if it is found free, the node will initiate the transmission or otherwise continue the deferral to protect the ongoing transmission. Hence, it can minimise the RDV, handshake collision and blocking problems. In the following chapter, the performance of the CR-RDV MAC protocol is evaluated using both mathematical analysis and simulation.

Chapter 6

Performance Evaluation of CR-RDV MAC Protocol

6.1 Introduction

In Chapter 5, a literature review on the design and performance improvement of CRAHNs protocols was presented. Based on this information, a novel CR-RDV MAC protocol was also proposed to mitigate the service interruptions due to intermittent PUs and consequently enhance overall network performance.

Although various MAC protocol performance models have been extensively studied [113, 147–149] in the context of CRAHNs, the approach taken in this research is simple and does not change the existing Bianchi model significantly, so the same model can be used without major changes. Moreover, none of the existing protocols consider performance issues regarding link establishment i.e. performance fluctuations due to the RDV process. Therefore, in this chapter a joint analytical model is proposed to capture both transmission probability and RDV success using a two-dimensional Bianchi model and an absorbing Markov model respectively.

The remainder of this chapter is organised as follows: the proposed analytical model is described in detail in section 6.2. It consists of three major subsections to explain saturated throughput, packet drop probability and mean packet delay. An absorbing Markov chain model is presented to analyse the probability of capturing channel access (i.e. RDV success) in the throughput analysis subsection. The performance of the CR-RDV protocol is evaluated via simulation in section 6.3. This section also has three subsections in which the simulation and analytical results are compared. An additional subsection is included in the simulation section to compare the performance of the CR-RDV protocol with the channel rank based CH RDV process using the same CR-RDV MAC process. The implementation aspects of the CR-RDV are discussed in section 6.4, and the chapter concludes with a brief summary of the main findings in section 6.5.

6.2 Markov Model for CR-RDV MAC Protocol

In this section, an analytical model is proposed to evaluate the performance of the **CR-RDV** MAC protocol under saturated load conditions. To simplify the mathematical model, the following assumptions are made:

(i) Finite number of stations

(ii) Saturated load i.e. there is always a packet in the transmission queue

(iii) Channel is error free

(iv) No hidden terminals

(v) Packets are destroyed only through collisions exceeding the retry limit

(vi) Packets are of equal length

The proposed model also takes into consideration the RTS/CTS handshake (four-way)-based channel access schemes. Developing a Markov model to evaluate the DCF performance of wireless networks was first shown in the Bianchi model [24] under saturated loads with ideal channel conditions. Unfortunately the Markov models developed for 802.11a/b/g are not substantial enough to explain **CR-RDV** MAC behaviour, which has distinct features such as modified backoff and virtual carrier sensing based on remanning time after each transmission.

The operation of the **CR-RDV** protocol consists of two phases: i) RDV phase, and ii) data exchange phase. When a CR node wants to transmit a packet, it first exchanges the control information through the RDV process. In the RDV phase, a CR node follows the CH sequence according to ETQCH protocol discussed in chapter 3. During RDV, the CR node sends an RTS packet to the intended receiver. If the RTS is successfully transmitted and the intended receiver is listening to the same channel as the RTS is sent on, a CTS will reply to the sender. The fundamental access method of the **CR-RDV** is called the distributed coordination function (DCF), which is based on carrier sense multiple access with collision avoidance (CSMA/CA). For a CR node to transmit, it senses the medium to determine if another CR is in transmission. According to the DCF, there must be a minimum time gap in order to identify contiguous frame sequences. Therefore, a transmitting CR must ensure that the medium is idle for this period before attempting to transmit. If the medium continues to be busy, the CR defers until the end of the current transmission. After deferral, or prior to transmitting again immediately after a successful transmission, the CR selects a random backoff interval and decrements the backoff interval counter while the medium is idle.

Let $b(t)$ and $s(t)$ be the stochastic processes representing the backoff counter and backoff stages at time t respectively. Hence, according to the DCF, the $b(t)$ value is decremented at the start of every idle slot and a contending station wins the channel when it reaches zero. After successful transmissions, if the STA has more data to send a new value will be set for $b(t)$. As the counter value of $k = b(t)$ is chosen to be uniformly distributed over $k \in [0, CW_i]$, where CW_i stands for the contention window size, there is a chance that two STAs end up with the same $b(t)$ values and will transmit data simultaneously. This is called a collision. In order to avoid further collisions, the collided STAs will generate new $b(t)$ values determined by:

$$CW_i = \begin{cases} 2^i CW_{min}; 0 \leq i \leq m, \\ 2^m CW_{min} = CW_m; i > m \end{cases} \tag{6.1}$$

Where CW_i is an initial size for the contention window and m is the maximum number by which the contention window can be doubled. In this model, m is used to resemble the maximum backoff stage. If the maximum is reached, the backoff exponent is fixed at maximum. The two-dimensional process $(s(t), b(t))$ is analyzed with an embedded Markov chain (in steady state) at the time instants at which the channel state changes. To avoid packet overlap with PUs in an asynchronous environment, the backoff counter for all CRs is frozen if the remaining time to end of the slot is $T_{packet} - 1$ and resumes at the next slot unoccupied by PUs. Let (i, k) denote the state of this process. At each stage the CR is described by i, k where i stands for the backoff stage and k stands for the backoff delay, which takes any value in the range of $[0, CW_i - 1]$. Hence, with a homogeneous backoff counting down process with modified embedded points, the transmission probability τ_{CR} can be calculated by directly applying the result of the Markov chain model for IEEE 802.11 DCF in [24].

$$\tau_{CR} = \frac{2(1 - 2p_f)}{(1 - 2p_f)(CW + 1) + p_f CW(1 - (2p_f)^m)}; \tag{6.2}$$

Here p_f denotes the total frame failure transition probability from one stage to another. A frame can fail due to simultaneous transmission of multiple users, or although the frame was sent successfully the receiver was not on the same channel. Frame failure due to simultaneous transmission can be written as $p_c = 1 - (1 - \tau)^{n-1}$, which means at least one of the $(n-1)$ remaining stations transmit with tagged CR station. Here n denotes the number of CRs in the current channel. The success of the frame transmission is $p_s = (1-\tau)^{n-1}$ i.e. $(n-1)$ CR nodes are not transmitting. However, this will not guarantee that the packet is received by the receiver, as the receiver may be in the another channel, which is called RDV failure. Thereby frame failure due to failed RDV is $p_{fr} = p_s(1-p_{rdv})$; where p_{rdv} is the RDV probability, which is equivalent to $\frac{1}{ATTR+1}$. Hence, the total frame failure probability can be written as:

$$\begin{aligned} p_f &= 1-(1-\tau)^{n-1}+(1-\tau)^{n-1}(1-\frac{1}{ATTR+1}) \\ &= 1-\frac{1}{ATTR+1}(1-\tau)^{n-1} \end{aligned} \tag{6.3}$$

6.2.1 Throughput Analysis

The saturation throughput of CRs can be defined as the ratio of the total available time for CRs unused by PUs to the whole time used for transmitting packets successfully. Let P_{tCR} be the probability that at least one CR transmits a packet in a randomly selected time slot with probability τ_{CR} and P_{sCR} is the conditional probability that an occurring packet transmission is successful. Hence, for n CR density per channel with N PUs in the system:

$$P_{tCR} = P_{tP}(1-(1-\tau_{CR})^n) \tag{6.4}$$

$$P_{sCR} = \frac{(1-\phi\tau_P)^N n\tau_{CR}(1-\tau_{CR})^{n-1}}{P_{tCR}} \tag{6.5}$$

Here, $P_{tP} = 1-(1-\phi\tau_P)^N$ is the probability that PU initiates transmission in a randomly selected slot and follows the same access method as the CR [150]. ϕ denotes the load on the primary networks. Hence, the transmission probability τ_P can be expressed using the Bianchi model:

$$\tau_P = \frac{2(1-2p_P)}{(1-2p_P)(CW+1)+p_P CW(1-(2p_P)^m)} \tag{6.6}$$

The term p_P refers to collision probability that at a randomly selected time two or more PUs will initiate transmission, which is $P_{tP}(1-P_{1p})$. P_{1p} denotes the probability that exactly one PU will start transmission on the channel, which can be expressed as:

$$P_{1p} = \frac{N\phi\tau_P(1-\phi\tau_P)^{N-1}}{P_{tP}} \tag{6.7}$$

Let S denote the normalised saturation throughput for the CRAHNs, which can be defined as a ratio of successfully transmitted payload size over a randomly chosen slot duration.

$$S = \frac{P_{tCR}P_{sCR}P_{CCA} \cdot L}{(1-P_{tCR})\sigma + P_{tCR}P_{sCR}P_{CCA} \cdot T_S + P_{tCR}(1-P_{sCR}P_{CCA})T_C} \tag{6.8}$$

where P_{CCA} is the probability of capturing channel access, which represents the channel contention on the RDV channel. The calculation of P_{CCA} is presented in the next subsection. σ is the backoff slot duration, T_S is the average time that the channel is captured for successful transmission and T_C is the average time that the channel is captured by a CR node which collides with other CR transmissions or is unable to capture the channel for successful transmission. Hence the data burst duration T_S and T_C are given as:

$$T_S = \begin{cases} T_{DIFS} + T_{RTS} + T_{CTS} + T_{3SIFS} + T_{DATA} + T_{ACK}; \\ \text{current RC} = \text{DC} \\ T_{DIFS} + T_{RTS} + T_{CTS} + T_{4SIFS} + T_{DATA} + T_{ACK} + T_{NTS}; \\ \text{current RC} \neq \text{DC} \\ T_{DIFS} + T_{RTS} + T_{CTS} + T_{3SIFS} + T_{DATA} + T_{ACK} + T_{MOVE}; \\ \text{current RC} = \text{DC and PU appeares} \\ T_{DIFS} + T_{RTS} + T_{CTS} + T_{4SIFS} + T_{DATA} + T_{ACK} + T_{NTS} + T_{MOVE}; \\ \text{current RC} \neq \text{DC and PU appears} \end{cases} \tag{6.9}$$

$$T_C = T_{RTS} + T_{DIFS} \tag{6.10}$$

Now, to evaluate successful channel access on the RDV channel, another probability measure is considered, called capture the channel access probability (P_{CCA}). A CR node may achieve RDV based on the CH sequence but be unable to capture channel access as multiple CR nodes are achieving RDV on the same channel.

Probability of Capturing Channel Access

It is assumed that each slot subdivides in M number of minislots at n steps as $1 \leq k_n \leq M$. A CR node initiates the transmission if the remaining time is higher than the packet transmission time T_p. If it is higher than T_p, a packet will transmit otherwise transmission will be deferred till the next available slot. Thus the effective time for attempting the transmission is $(T - T_p + \sigma)$, which is equivalent to $(M - k_p + \sigma)$. Then k_n can be represented as a discrete time Markov chain model with two absorbing states (e.g. transmission and defer) and $M - k_p + \sigma$ transient states i.e. $\{k_n : n = 0, 1, 2, ..., M - k_p, t, d\}$. The one step transition probability is given by:

$$\mathbf{P} = \begin{bmatrix} Q & R \\ 0 & I \end{bmatrix} \tag{6.11}$$

where Q is a $(M - k_p + \sigma) \times (M - k_p + \sigma)$ matrix representing the probability of transitioning from one state to another and R is for transitioning from one transient state to either of the absorbing states. Let $\overline{p_{idle}}$, $\overline{p_t}$, $\overline{p_{fc}}$ denote the probability of idle, true and false collisions by the tagged CR in each backoff minislots with the duration of $\overline{t_{idle}}$, $\overline{t_{tc}}$, and $\overline{t_{fc}}$ respectively. Here

- $\overline{p_{idle}}$ denotes the probability that no CR transmits a packet in the minislot of duration $\overline{t_{idle}} = \sigma$
- $\overline{p_{tc}} = 1 - \overline{p_{idle}} - n\tau(1-\tau)^{n-1}$ denotes the probability that there is a true collision in the minislot of duration $\overline{t_{tc}} = t_{rts} + DIFS$ and finally

- $\overline{p_{fc}} = (n-1)\tau(1-\tau)^{n-2}(1-p_{rdv})$ denotes that transmission is successful but unable to achieve RDV with the duration of $\overline{t_{fc}} = t_{rts} + t^{rts}_{MVCS} + DIFS$

In each backoff minislot from 0 to $M - k_p$, the CR will reach either of the absorbing states based on the remaining time. If the remaining time is higher than the T_p and the tagged CR successfully transmits the RTS packet, then it will reach transmission state with the following probability:

$$p_t = n\tau(1-\tau)^{n-1} \tag{6.12}$$

In contrast, if the remaining time is not higher than T_p, the CR node will fall into defer state with the following probability:

$$p_d = \begin{cases} p_{d1} = (n-1)\tau(1-\tau)^{n-2}p_{rdv}; \\ \text{for } X \in [0, M - k_p - k_{fc}] \\ p_{d2} = (n-1)\tau(1-\tau)^{n-2}p_{rdv} + \overline{p_{fc}}; \\ \text{for } X \in [M - k_p - k_{fc}, M - k_p - k_{tc}] \\ p_{d3} = p_{d2} + \overline{p_{tc}}; \\ \text{for } X \in [M - k_p - k_{tc}, M - k_p] \\ p_{d4} = 1 - p_t; \\ \text{for } X = M - k_p \end{cases} \tag{6.13}$$

The primary parameter of the absorbing Markov chain model is the quantity N_{ij}, called the fundamental matrix, which is the mean number of times the process is in the transient state j before reaching an absorbing state, given that it starts in the transient state i. It is assumed that at j^{th} backoff minislot the tagged CR reaches the absorbing state "t" i.e. $S_k = j$; $(0 \leq j \leq M - k_p)$ from the initial state $S_0 = 0$.

Hence, the fundamental matrix can be written as:

$$\begin{aligned} N_{0j} &= \sum_{k=0}^{M-k_p} Q_k \\ &= ([I-Q]^{-1})_{oj} \end{aligned} \tag{6.14}$$

It is worth noting that the tagged CR user reaches the absorbing state if it is not absorbed by either of the absorbing states prior to the j^{th} backoff minislot. Hence the probability of capturing channel access is given by:

$$\begin{aligned} P_{CCA} &= \sum_{j=0}^{M-k_p} P_{CCA}^{j} \\ &= \sum_{j=0}^{M-k_p} Pr\{S_k = j, E_{X=j}^{\{t\}} | E_{X<j}^{\{t,d\}} = 0, S_0 = 0\} \\ &= \sum_{j=0}^{M-k_p} N_{0j}\ p_t \prod_{k=0}^{j-1} (1 - N_{0k}(p_t + p_d)) \end{aligned} \tag{6.15}$$

6.2.2 Packet Drop Probability

The packet drop probability is the probability that a packet is dropped when the retry limit is reached. Moreover, a packet may be dropped when the sending queue is full. Hence, the total packet drop probability is the sum of both of these events.

Packet Drop Due to Retry Limit

A packet is found in the last backoff stage m if it encounters m collisions in the previous stages and it is eventually discarded or dropped. Thus, the packet drop probability due to reaching the retry limit can be written as a function of the last backoff stage:

$$P_{drop} = \frac{b_{m,0}}{b_{0,0}} p_f$$
$$= p_f^m . p_f$$
$$= p_f^{m+1} \tag{6.16}$$
$$= [1 - (1 - p_f)(1 - \tau)^{n-1}]^{m+1}$$

Packet Drop Due to Queue

Let us consider the $M/M/1/K$ queue system, where there are K frames in the system shown in Fig. 6.1. Now, by using one of the balanced equations, the steady state probability can be written as

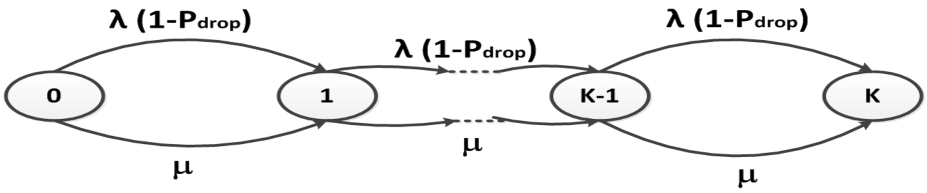


Figure 6.1: M/M/1/K Queue Model

$$\lambda(1 - p_{drop})p_0 = \mu p_1$$
$$p_1 = \frac{\lambda(1 - p_{drop})}{\mu} p_0$$
$$p_1 = \rho p_0;\ where, \rho = \frac{\lambda(1 - p_{drop})}{\mu}$$

Similarly it can be shown that

$$p_n = \rho^n p_0;\ n = 0, 1, 2, ...K$$
$$\sum_{n=0}^{K} p_n = 1 \Rightarrow p_0 = \frac{1 - \frac{\lambda(1-p_{drop})}{\mu}}{1 - \left(\frac{\lambda(1-p_{drop})}{\mu}\right)^{K+1}}$$

Note that not all the frames arriving at the queue enter the queue, because frames are not allowed into the queue when there are already K frames in the queue. Therefore, the frames are dropped with probability

$$P_k = \rho^k p_0 = \left(\frac{\lambda(1-p_{drop})}{\mu}\right)^K \cdot \frac{1-\frac{\lambda(1-p_{drop})}{\mu}}{1-\left(\frac{\lambda(1-p_{drop})}{\mu}\right)^{K+1}} \tag{6.17}$$

Thus, the total probability of packet loss is

$$P_{loss} = P_{drop} + P_K = [1-(1-p_f)(1-\tau)^{n-1}]^{m+1} + \left(\frac{\lambda(1-P_{drop})}{\mu}\right)^K \cdot \frac{1-\frac{\lambda(1-P_{drop})}{\mu}}{1-\left(\frac{\lambda(1-P_{drop})}{\mu}\right)^{K+1}} \tag{6.18}$$

6.2.3 Mean Delay

The delay D can be defined as the time elapsing from the instant the frame is inserted in the MAC buffer to the time in which it is successfully transmitted by receiving an acknowledgement for this frame. From this definition, it is obvious that delay is associated with two factors: a medium access delay due to the number of contending stations, and a queueing delay for load conditions and frame processing rates at the queue. So, the average delay is

$$D_{avg} = D_{MAC} + D_Q$$

MAC Delay

The MAC delay for a successfully transmitted packet is defined to be the time interval from the time the frame is at the head of the MAC queue ready for transmission until an acknowledgement for this packet is received. As per [151], the average MAC delay is given by

$$E[D_{MAC}] = E[X]E[slot]$$

Here $E[X]$ is the average number of slots spent on a successful transmission. Let STA be in the i backoff stage and have a channel access probability of c_i. The average number of slots utilized by the STA in the i backoff stage is $(CW_i + 1)/2$, $i \in (0, m)$ and the probability that the frame reaches the backoff stage i and is not discarded is $\frac{p_f^i - p_f^{m+1}}{1-p_f^{m+1}}$, $i \in (0, m)$. Hence,

$$\begin{aligned} E[X] &= \sum_{n=0}^{m} \left[\frac{(p_f^i - p_f^{m+1})((CW_i + 1)/2)}{1 - p_f^{m+1}} \right] \\ E[slot] &= (1 - p_{tCR})\sigma + P_{tCR}P_sP_{sto}T_s + P_{tCR}(1 - P_sP_{sto})T_c \\ E[D_{MAC}] &= \sum_{n=0}^{m} \left[\frac{(p_f^i - p_f^{m+1})((CW_i + 1)/2)}{1 - p_f^{m+1}} \right] \cdot (1 - p_{tCR})\sigma + P_{tCR}P_sP_{sto}T_s \\ &\quad + P_{tCR}(1 - P_sP_{sto})T_c \end{aligned} \tag{6.19}$$

Queueing Delay

By using Little's formula [152], the expected time spent in the queue (i.e.queueing delay) can be calculated as

$$D_Q = \frac{E[N]}{\lambda(1 - P_{drop})} \tag{6.20}$$

Here $E[N]$ is the expected number of packets in the queue given by

$$\begin{aligned} E[N] &= \sum_{n=0}^{K} nP_n = \sum_{n=0}^{K} n\rho^n P_0 \\ &= \rho P_0 \frac{\mathrm{d}}{\mathrm{d}\rho} \left(\frac{1 - \rho^{K+1}}{1 - \rho} \right) \\ &= \rho P_0 \left(\frac{1 - \rho^{K+1} - (1 - \rho)(K + 1)\rho^K}{(1 - \rho)^2} \right) \\ &= \left(\frac{\rho(1 - \rho^{K+1}) - (1 - \rho)(K + 1)\rho^{K+1}}{(1 - \rho)(1 - \rho^{K+1})} \right) \\ E[N] &= \left(\frac{\rho(1 - (K + 1)\rho^K + K\rho^{K+1})}{(1 - \rho)(1 - \rho^{K+1})} \right) \end{aligned}$$

Now, using equation 6.20, D_Q becomes

$$D_Q = \left(\frac{\rho(1-(K+1)\rho^K + K\rho^{K+1})}{(1-\rho)(1-\rho^{K+1})} \right) \times \frac{1}{\lambda(1-P_{drop})} \tag{6.21}$$

Therefore the mean delay is given by

$$D = \sum_{n=0}^{m} \left[\frac{(p_f^i - p_f^{m+1})((CW_i+1)/2)}{1-p_f^{m+1}} \right] \cdot (1-p_{tCR})\sigma + P_{tCR}P_sP_{sto}T_s + P_{tCR}(1-P_sP_{sto})T_c + \left(\frac{\rho(1-(K+1)\rho^K + K\rho^{K+1})}{(1-\rho)(1-\rho^{K+1})} \right) \times \frac{1}{\lambda(1-P_{drop})} \tag{6.22}$$

6.3 Simulation Results

The performance of CR-RDV was studied using both analytical and simulation models using a MATLAB-based simulator, as discussed in Chapter 4. The network topology, number of CRs, PUs and channels were considered, the same as before. However, the CR-RDV required some amendments in order to implement the proposed MAC. For this, $T-RTS$ and $T-CTS$ were changed to $(192+\frac{192}{r^*})$ and $(192+\frac{136}{r^*})$ respectively to integrate the channel status in the control packet. Moreover, selection of the DC was notified to the neighbours, and a new control packet called NTS was introduced having the same duration of CTS. The time required to move from one channel to another was $40\mu s$ [76]. Finally, channel contention was integrated in the study as both the RDV and data channels may encounter collisions.

Three widely used performance metrics were considered in this study: (i) saturation throughput, (ii) packet drop probability, and (iii) mean delay. The results are given as a function of the number of CRs to evaluate multi-user channel contention, the number of available channels, and PU traffic load, since PU behaviour is the most significant event impacting on CRAHNs performance. To evaluate the effectiveness of the proposed protocol, both versions $MVCSCR-RDV$ and $VCSCR-RDV$

were compared, where $MVCSCR - RDV$ amends all the proposed changes and $VCSCR-RDV$ follows the same RDV protocol (i.e. EQTCH) with basic CSMA/CA parameters. For the benchmarking, all the results are compared with CSMA/CA protocol. Moreover, some of the existing channel rank-based CH RDV protocols were integrated with the proposed MAC protocol to compare the performance of the proposed CR-RDV MAC protocol based on the ETQCH RDV mechanism.

To validate the results, both the analytical and simulation results are presented for each of the metrics. In this chapter, the performance enhancement achieved by CR-RDV MAC protocol is quantified using analytical and simulation methods. The outcomes of the analytical model are validated through operational validity [78] by comparing with simulation results. The same approaches as in Chapter 4 are used to validate the correctness of the simulation results.

6.3.1 Saturation Throughput

Figure 6.2 shows the saturation throughput of the proposed MAC as a function of the number of CRs for both MVCS and VCS schemes. The maximum number of available channels that can be used by the CR nodes is 20. However, this number significantly changes based on PU activities. Here, the traffic load (ϕ) for PUs is 0.5. One can observe that in both cases throughput initially increases with the number of CRs, but further increments of network size significantly reduce the network throughput. After the maximum throughput is achieved at 7 for both MVCS and VCS, the throughput decreases as the number of CRs increases. This is very obvious in wireless networks, as collision probability increases with network size. However, it is observed that the slope of the throughput degradation is steeper for VCS compared to MVCS. On average, the CR-RDV MAC with MVCS exhibits 25% higher throughput than VCS. Collision and false blocking are the dominant factors causing this difference in performance.

In MVCS, a CR node defers transmission only for RTS time and senses the channel again, and if it is found free it initiates the transmission, or otherwise continues to defer. Hence, the insertion of an additional sensing period inside the NAV eventually enhances network performance significantly, especially in dense networks. The results for both the analytical and simulation models are closely matched to each other.

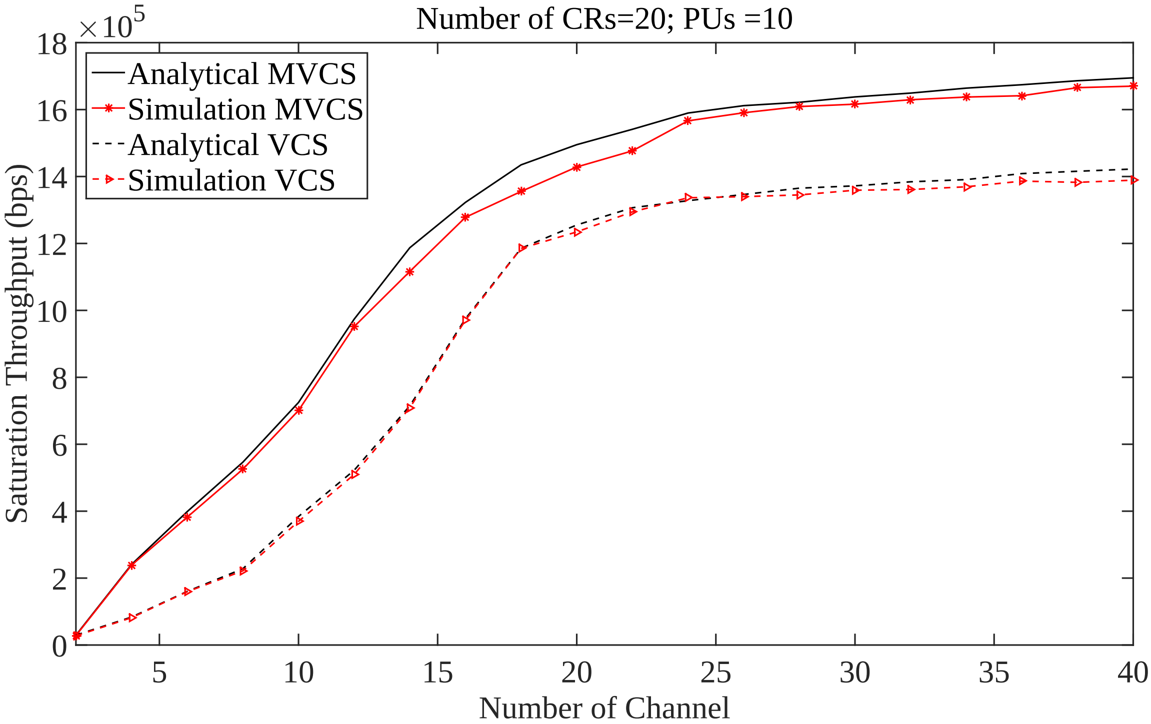


Figure 6.2: Saturation throughput as a function of number of CRs with PU traffic load = 0.5

Next, CR-RDV protocol performance is evaluated with a varying number of channels. Obviously, increasing the number of channel results in an increase in throughput for both the MVCS and VCS schemes as shown in Fig. 6.3. However, MVCS performs better compared to VCS as it can effectively suppress the increased trend of channel access delay with every increment in channel number. Moreover, it minimises the access delay in the case of false blocking due to unsuccessful RDV from a neighbour's node. The results show that approximately 30% performance enhancement can be achieved by adopting a MVCS scheme.

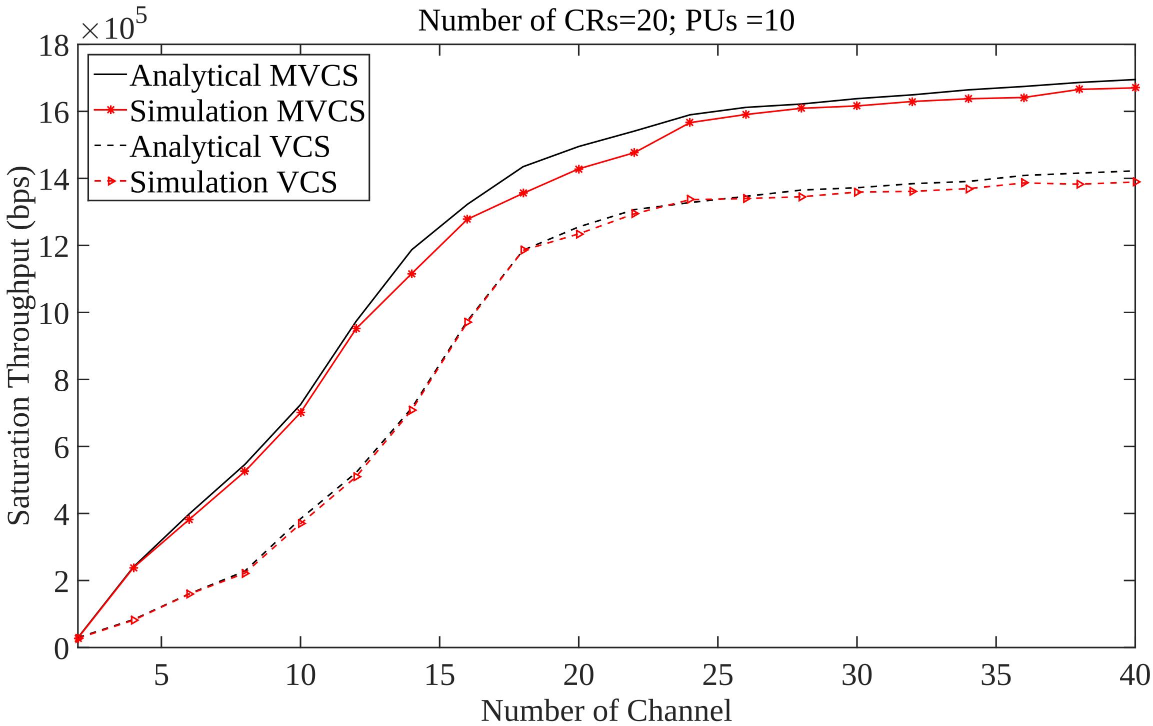


Figure 6.3: Saturation throughput of CRs as a function of number of channels.

Fundamentally, the performance of CRAHNs is greatly impacted by the activity of PUs in the vicinity. This is because a channel that is occupied by a CR should vacate if a PU appears on that channel. In this situation, to maintain and continue current communication a CR node has to find another free channel. Figure 6.4 depicts the saturation throughput of the CR-RDV MAC for both MVCS and VCS schemes as a function of PU traffic load ϕ, where $\phi = \frac{\lambda}{C\mu}$. C is the number of PUs. The result shows that as the PU traffic load increases, the throughput decreases gradually for both VCS and MVCS. However, there is a sharp drop in throughput when ϕ is above 0.5, which is the critical arrival rate of a PU's packet. It is worth noting that there is a significant performance gap between MVCS and VCS schemes due to their underlying channel access methods. In MVCS, a channel is only accessed if it is free and the remaining slot time is sufficient to transmit the data packet. This provides an extra protection against collision with PUs. Moreover, in MVCS neighbours using the NTS control frame, the neighbour's nodes are informed prior to data transmission in order to avoid further collisions on the data channel, which is different to the RDV channel.

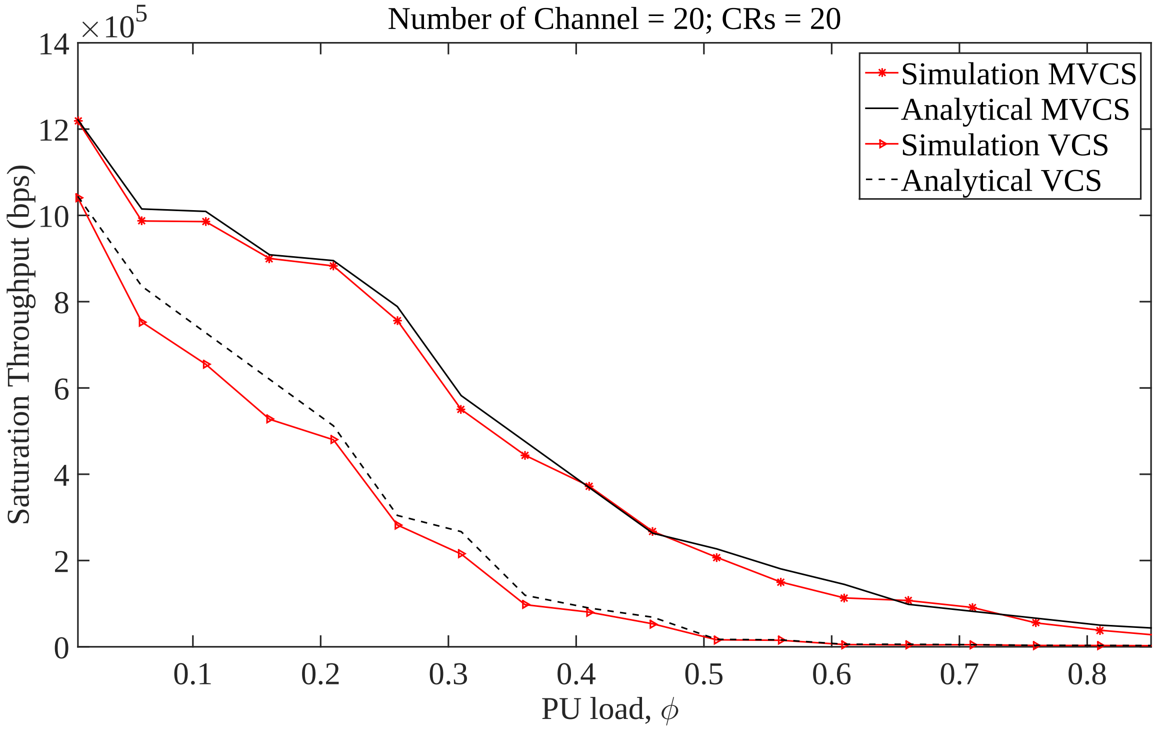


Figure 6.4: Saturation throughput of CRs as a function of PU load, ϕ.

The main conclusion that can be drawn from the above discussion is that CR-RDV with MVCS is significantly better than that of VCS, especially under medium to high network size and PU traffic loads.

6.3.2 Probability of Packet Drop

The probability of packet drop refers to packet drops due to unsuccessful transmission from sender to receiver. A packet may drop due to (i) retry limit, and (ii) queueing capacity. As the number of CRs increases, the node density per channel is increased and causes more collisions. After a collision, the CR node increases the contention window and retries the packet transmission. A packet is dropped if it is not transmitted successfully after maximum retry. Figure 6.5 provides a visual depiction of the above mentioned behaviour. The result shows that increasing the retry limit can significantly reduce the probability of packet drop. However, it always increases with the number of CRs. It also depicts that CR-RDV with MVCS exhibits 30% better performance than that of VCS.

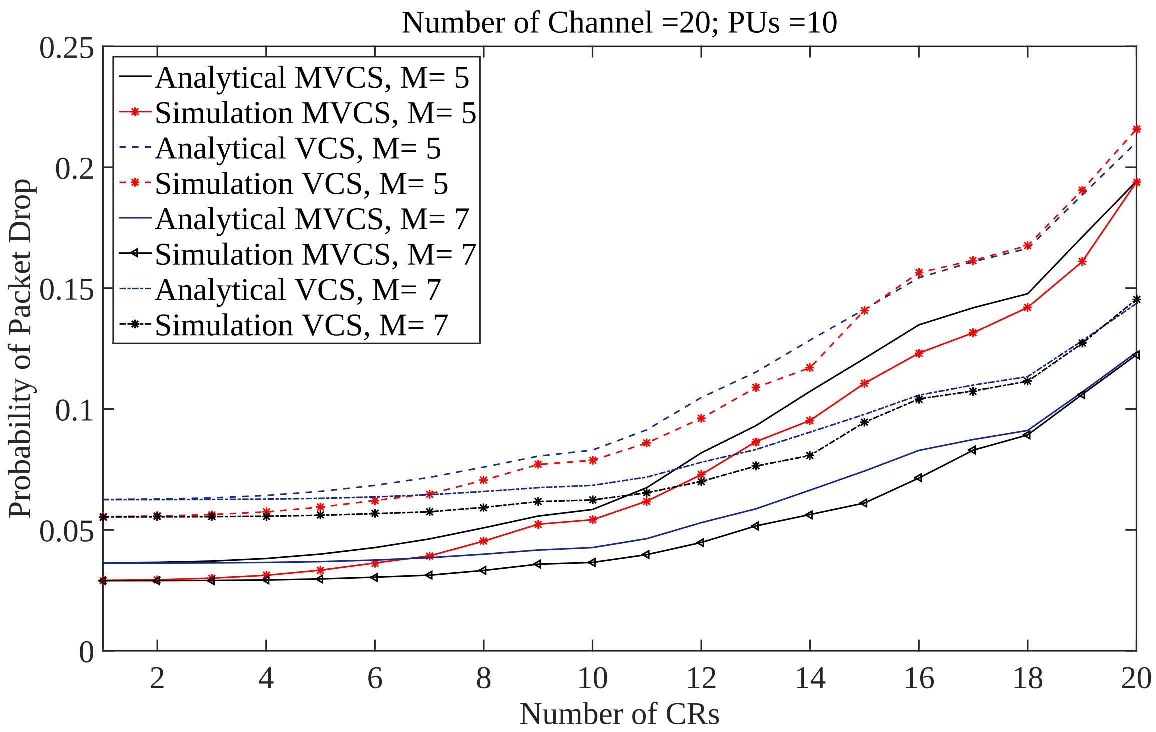


Figure 6.5: Probability of packet drop as a function of CRs for both m =5 and 7.

Figure 6.6 illustrates the probability of packet drop versus the number of available channels. It is obvious that packet loss decreases as node density per channel decreases with an increase in the number of channels. The result shows that the probability of packet drop decreases with the number of channels and becomes mostly flat after 30. This part of packet loss mainly results from queueing capacity. It also shows that there is a performance gap of 20% between MVCS and VCS when the number of channels is below 15 and the gap gradually develops with the number of channels.

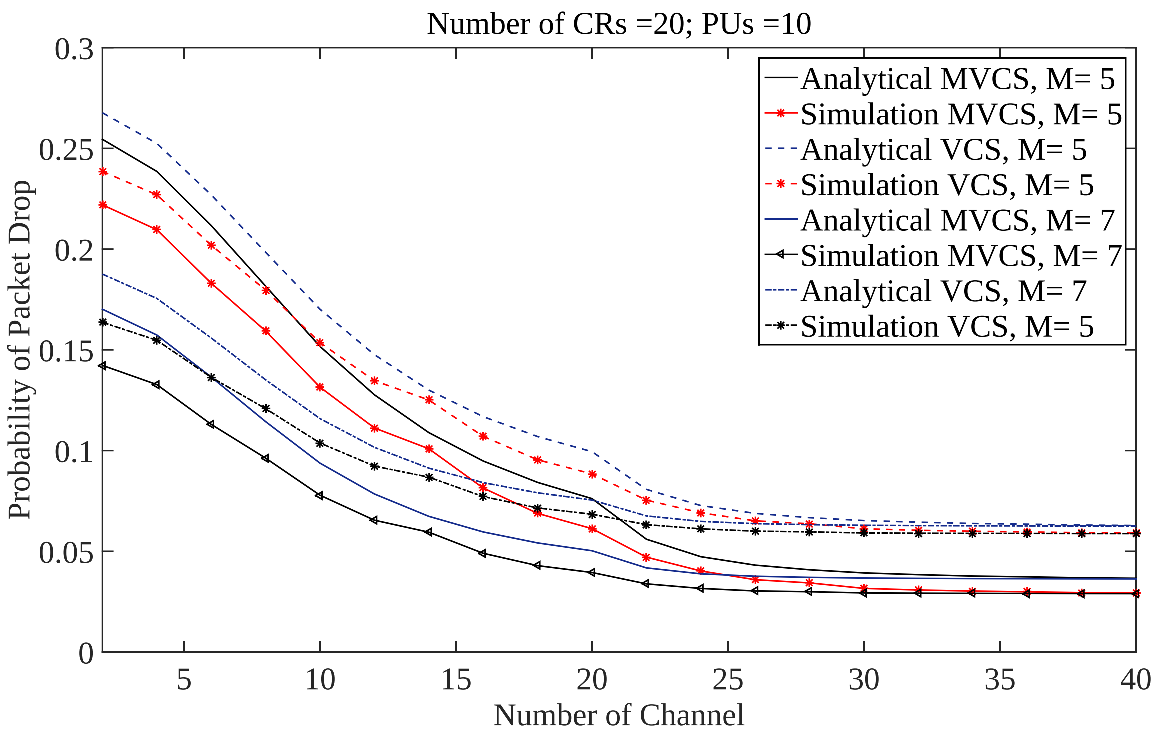


Figure 6.6: Probability of packet drop of CRs as a function of number of channels.

Figure 6.7 shows the impact of PU traffic load on packet drop. One can observe that for both cases the probability of packet drop remains constant when PU traffic is below 0.5. A significant rise in packet drop is observed for PU traffic loads above 0.5. This is because the PUs become more active in the network and mostly have a packet to transmit. This causes the primary networks to become saturated. Hence, P_{tp} becomes large and hinders opportunity for CR users.

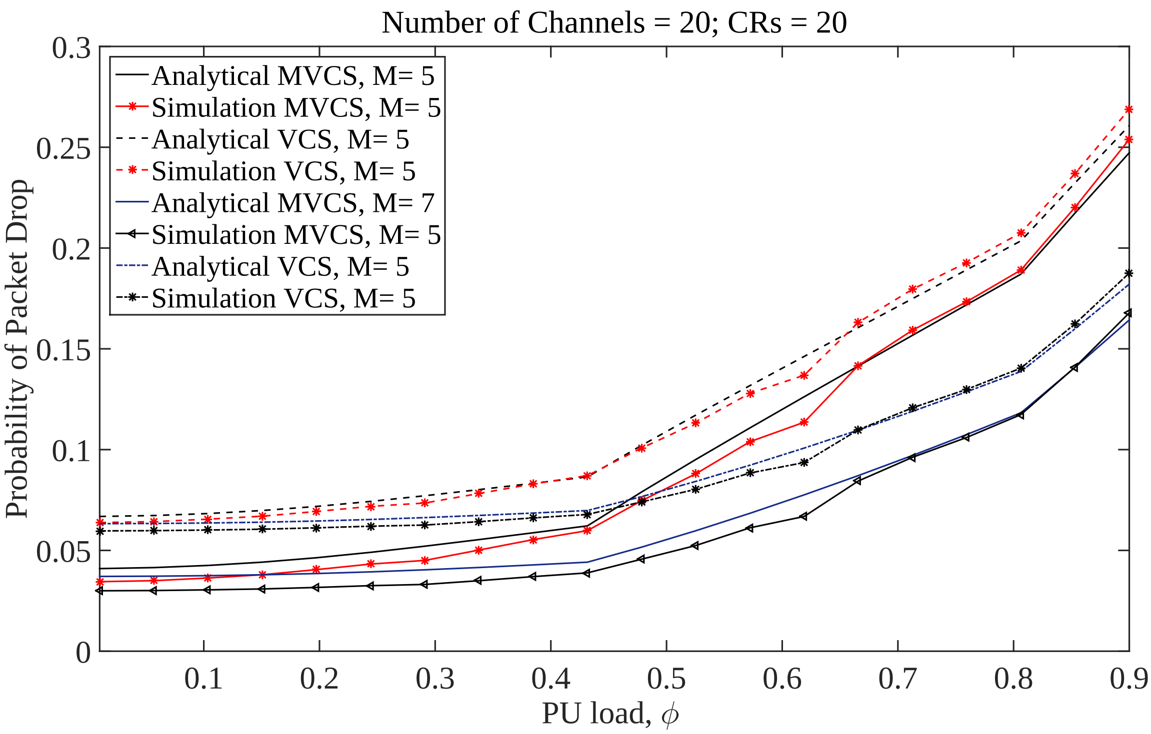


Figure 6.7: Probability of packet drop of CRs as a function of PU load, ϕ.

From the above analysis, it can be concluded that packet drop is highly influenced by the number of retry limits used in the MAC protocol and PU activity. Moreover, CR-RDV with MVCS significantly reduces packet drop probability due to intermittent PU activity.

6.3.3 Mean Delay

Mean delay is the summation of delay associated with accessing a channel and the time a packet has to wait in the queue before being served. Fig. 6.8 depicts the change in mean delay with the number of CRs. The delay increases for both cases as the network size grows and causes a high number of collisions. The results show that MVCS and VCS experience mostly the same delay in a small size network. As the network size increases, VCS experiences on average 42% higher delay than that of the

MVCS scheme of the CR-RDV protocol due to true collisions and the false blocking problem. In a dense network a large number of CRs attempt to access the channel, which leads to a high number of collisions and retransmission attempts and results in longer delays. However, the overhead of the MVCS scheme is slightly higher than VCS because of having an additional control packet (i.e. NTS), introduced by the MVCS scheme to mitigate the false blocking problem.

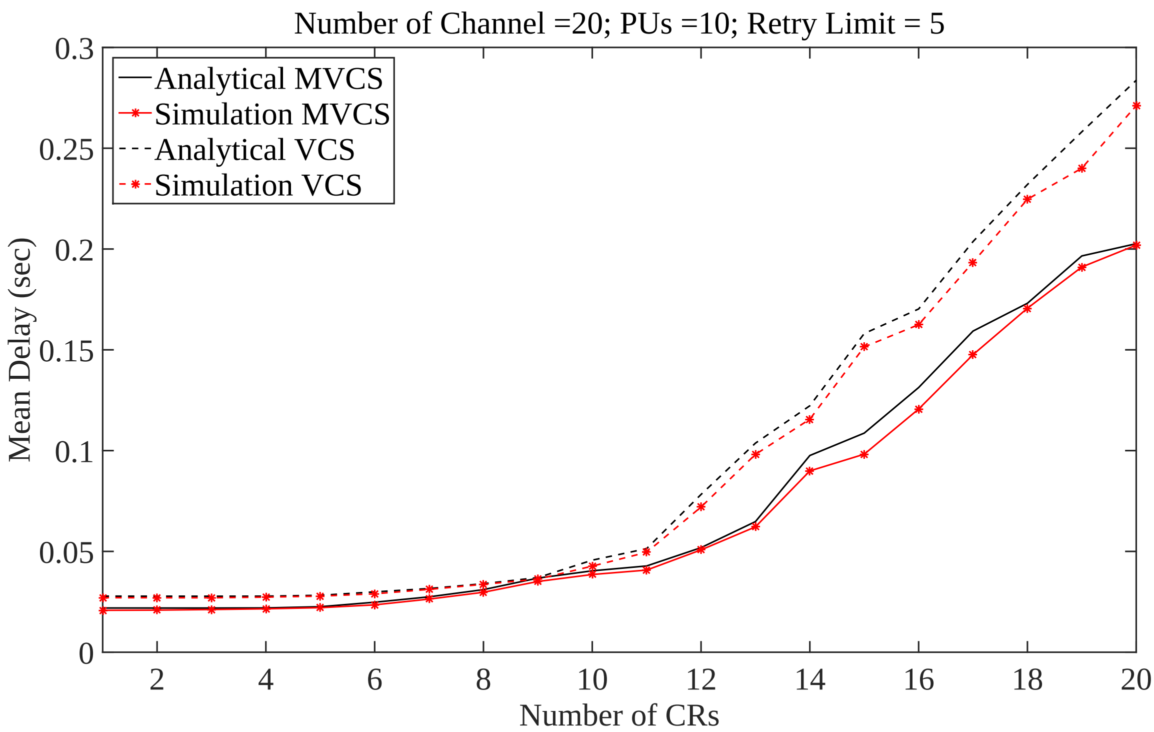


Figure 6.8: Variation of mean delay as a function of number of CRs.

Figure 6.9 illustrates mean packet delay versus number of channels. In this case, delay is mostly injected from the RDV process as ATTR increases with the number of channels. Moreover, MVCS shows better performance than VCS which is approximately 48%.

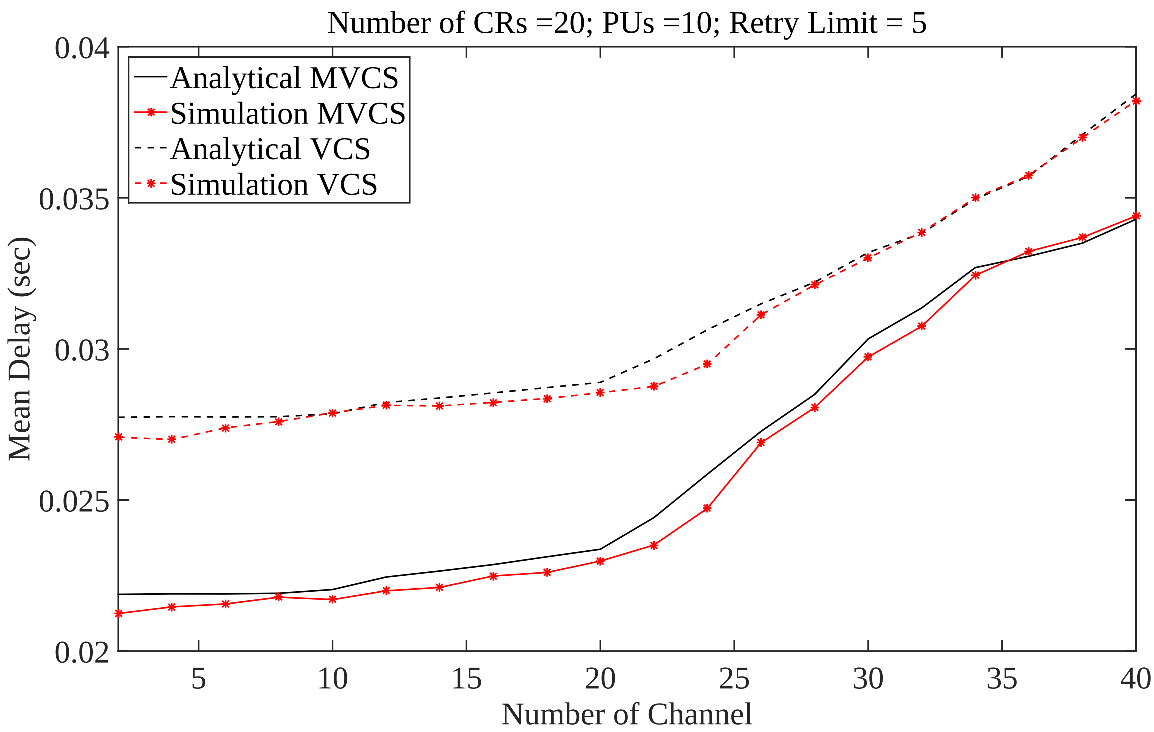


Figure 6.9: Variation of mean delay as a function of number of channels.

The impact of PU activities on CR performance in terms of delay in transmitting a packet is shown in Fig. 6.10. It shows that packet delay increases with PU traffic load as CRs experience more channel switching. Moreover, as PU load increases, the number of available channels for CRs decreases and consequently there is more delay due to channel contention. In addition to that, the CR node experiences longer delays in capturing channel access on the RDV channel. The results show that VCS experiences 45% higher delay when PU load is under 0.5 and more than 75% when the load goes over 0.5. To evaluate the efficiency of the proposed CR-RDV protocol against PU appearance, the operating curve is shown in Fig. 6.11. According to [153], the lower the curve, the better the protocol. One can observe that CR-RDV with MVCS outperforms VCS as it requires less time to perform the handshake procedure.

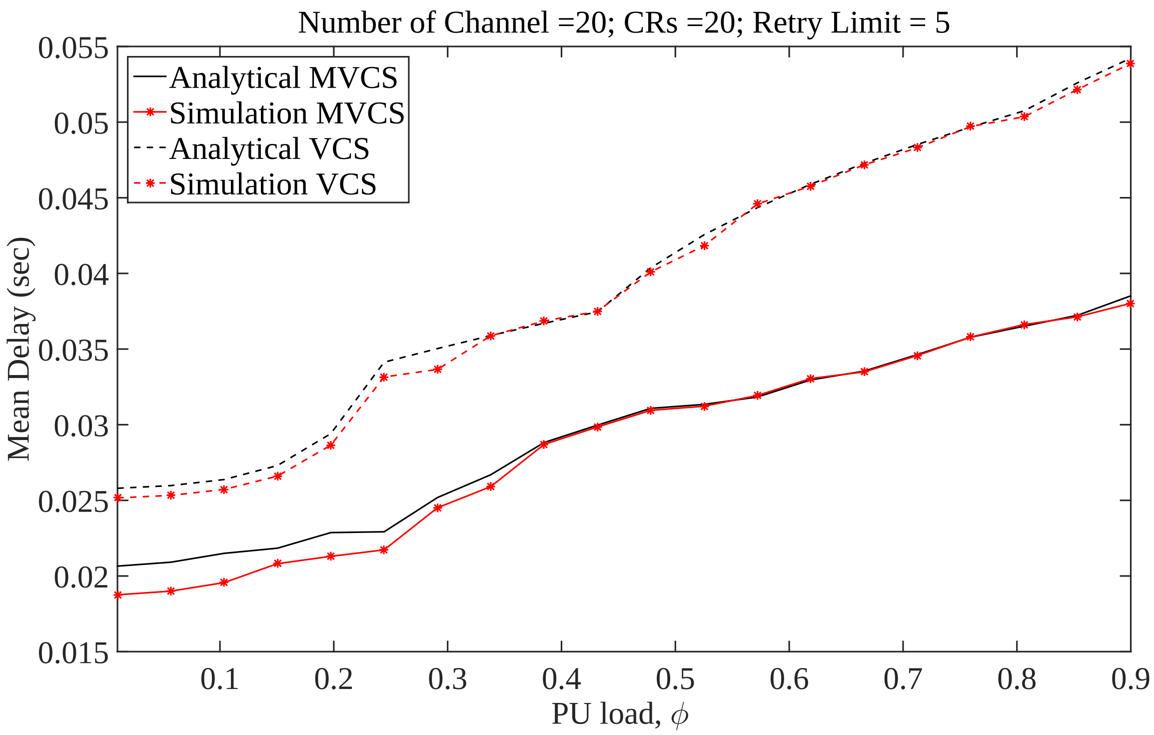


Figure 6.10: Variation of mean delay as a function of PU load, ϕ.

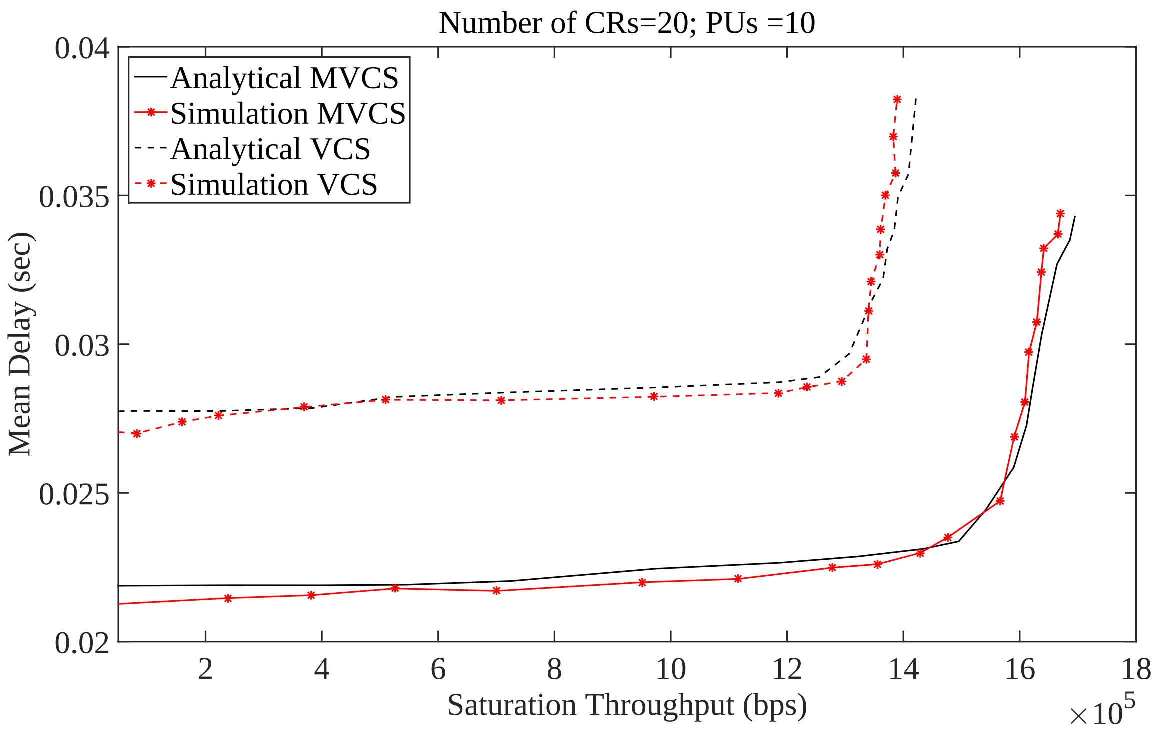


Figure 6.11: Operating curve for CR-RDV MAC protocol.

The main conclusion is that CRs using CR-RDV with MVCS have substantially lower mean delay than CRs using VCS, especially in the context of high PU loads, number of channels and network size.

6.3.4 Comparison with Channel Rank based CH MAC Protocols

In the previous subsections, a detailed comparative analysis was presented using different network settings. From the above studies it can be concluded that CR-RDV with MVCS has the potential to improve network performance by efficiently utilising network resources.

Since there is no other protocol that can be used for comparative analysis, the same MAC protocol with different channel rank-based CH methods was presented in Chapter 4. Fig. 6.12 depicts saturation throughput versus number of channels for the different CH based MAC protocols. Obviously increasing the number of channels leads to increased throughput for each of them. However, CR-RDV with ETQCH outperforms gQRDV, Basic AMRCC, Enhance AMRCC in average 25%, 80% and 45% respectively. The dynamic updating of the CH sequence used in ETQCH facilitates maintenance and re-establishment of RDV in cases of PU appearance. In contrast, the other protocols only eliminated the channel that was claimed by the PUs and resulted in a progressively shortened CH sequence. This shortened sequence encountered more RDV collisions and control channel saturation problems. Fig. 6.13 shows the probability of capturing channel access with PU load for the different CH based MAC protocols. It shows that P_{CCA} is a monotonically decreasing function with PU load. One reason is that every increment of PU load causes CRs to achieve RDV on the same channel with higher probability which increases RDV collisions, $\overline{p_{tc}}$. This means that nodes may achieve RDV but may not capture channel access due to multiple CRs achieving RDV on the same channel.

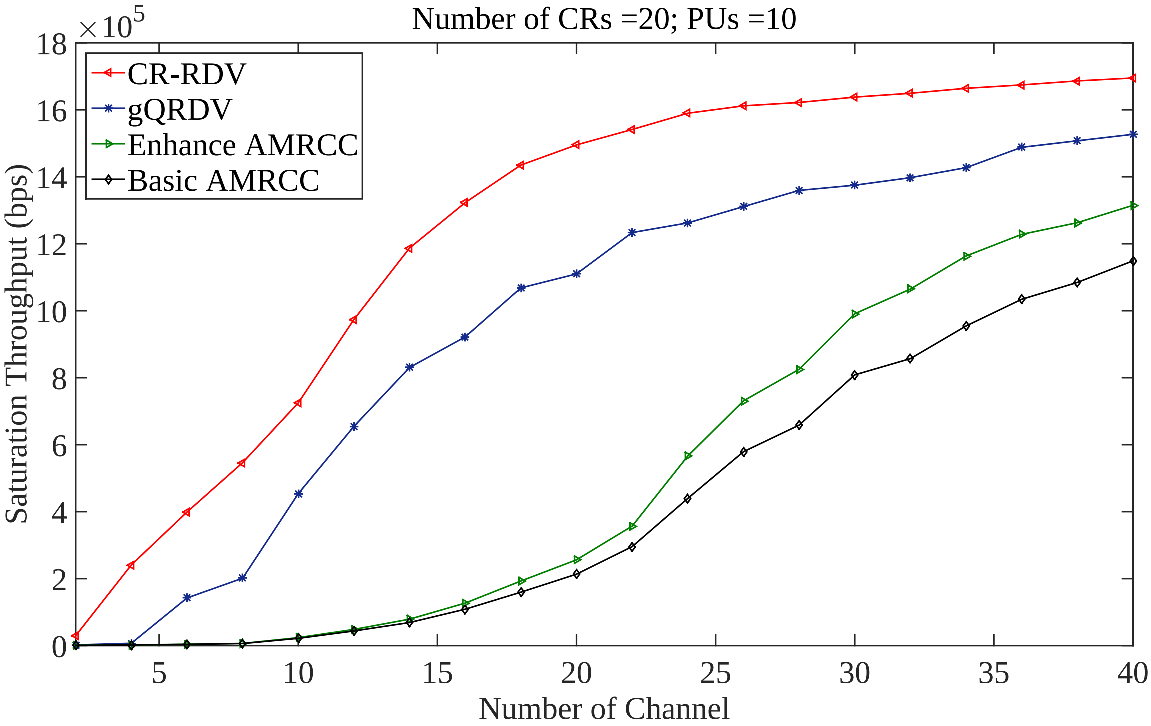


Figure 6.12: Saturation throughput as a function of number of channels.

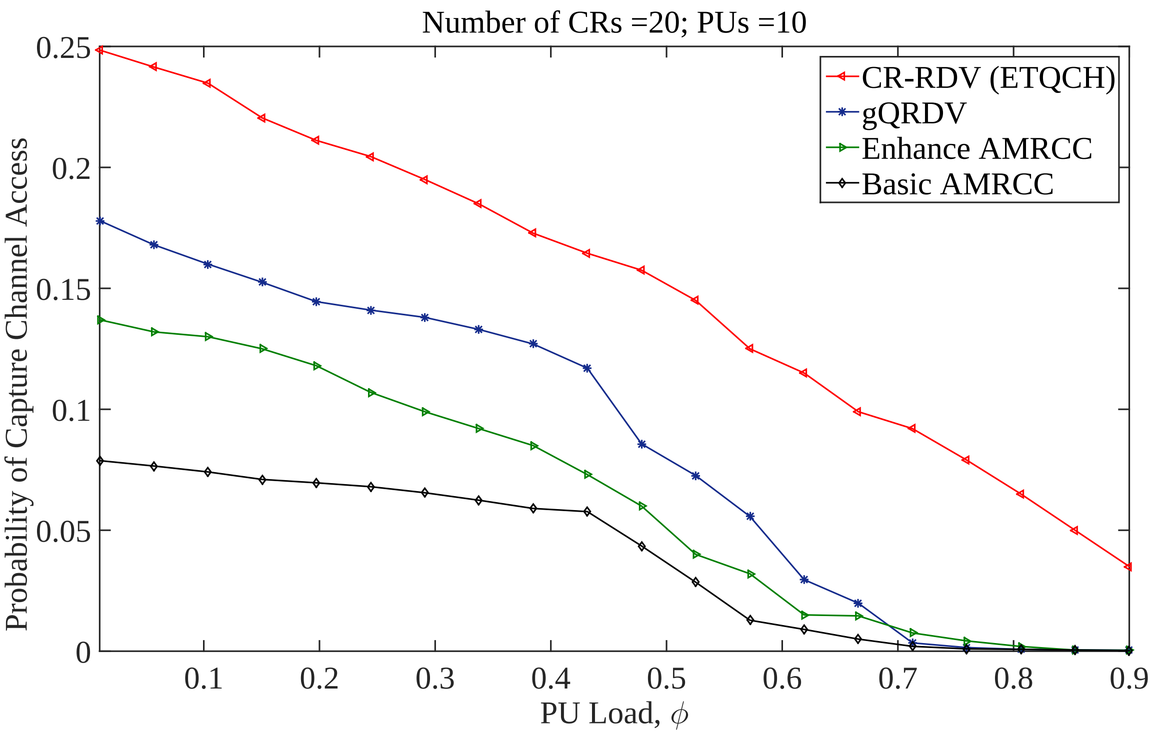


Figure 6.13: Impact of PU activity on successful RDV channel access

6.4 Implementation Aspects

The CR-RDV MAC protocol is easy to implement and provides a low cost solution for improving the performance of CRAHNs. Fundamentally, the CR-RDV MAC protocol considered a CR with two radio transceivers, where radios are used for both sensing and transmission. With the advances in current technology, an additional radio transceiver is a cost effective solution in helping to reduce the number of failed transmissions and time due to collision and channel access respectively. The mechanism of detecting PU activity, slot synchronization, packet transmission and reception can be implemented by CARMEN [154] based IEEE 802.11 wireless devices. Promising SDRs such as GNU radio and USRP can be used to implement channel selection and CH algorithms. The packet format of CR-RDV has to be modified based on the proposed frame format in Chapter 5 and can reuse some of the source code used in the 802.11.

6.5 Summary

In this chapter the performance of CR-RDV MAC was investigated in a saturated transmission scenario for single hop multi-user CRAHNs based on the ETQCH RDV scheme. An analytical model jointly with bi-directional Bianchi model and an absorbing Markov model was used to analyse the protocol's performance. Finally, the model was validated by MATLAB based numerical and simulation studies.

The simulation studies show that CR-RDV using MVCS is an effective solution to mitigate intermittent PU appearance because of the insertion of an additional sensing period to evaluate channel occupancy. In CR-RDV, both licensed and unlicensed channels are utilized based on channel ranking to explore transmission opportunity. Through the simulation, it was observed that MVCS with CR-RDV can increase throughput by up to 80% compared to VCS. This is due to the integration of modified RTS/CTS and RTS/CTS/NTS handshake methods in the MVCS scheme. In low dense networks both VCS and MVCS mostly showed behavior; however, a significant performance difference could be observed as the network size grew. Moreover, CR-RDV with MVCS exhibited more than 75% and 65% better performance than the VCS scheme for packet drop probability and mean packet delay respectively.

The performance of the CR-RDV MAC protocol was further investigated using existing channel rank-based CH RDV schemes which utilise the CR-RDV MAC process. The analysis results showed that the RDV scheme is a key processes that has significant influence on MAC performance. For example, CR-RDV with ETQCH achieved up to 25%, 80% and 45% better performance than gQRDV, Basic AMRCC and Enhance AMRCC protocols respectively.

Next, in Chapter7, the implication for system planning and deployment are discussed.

Chapter 7

Implications for System Planning and Deployment

7.1 Introduction

Rendezvous in CRAHNs is one of the most important processes in initiating communication in CRAHNs. The primary objective of this thesis was to develop techniques to achieve RDV in CRAHNs for improved system performance and deployment. This chapter provides a set of recommendations for system planners based on analysis of the results presented in the previous chapters.

In section 7.2 an evolutionary path for the deployment of a CR technology is presented. The CRAHNs deployment issues in dense, large and PU-active wireless environments are discussed in section 7.3. Possible future research directions are identified and discussed in section 7.4.

7.2 An Evolutionary Path for Adopting CR Technology

Recent studies have shown that CR technology can be used to solve the spectrum scarcity and spectrum under-utilisation problems [8]. Fig. 7.1 shows an evolutionary path for adopting CR technology in wireless networks and the complexity associated with each level. The idea of CR technology was inherited from different radio access technologies (RATs) using different protocols coexisting in the same band provided they did not interfere with each other. To achieve coexistence, different levels of cognition were applied based on the surrounding radio environments. The first coexistence technique was introduced in the WiMAX network (i.e.IEEE 802.16.2). It had a minimum cognition level that used power spectral flux density values to notify other broadband operators [155]. Later on, 802.15.1 standards introduced a dedicated communication link between 802.15.1 and 802.11b networks to exchange the control information so that they could negotiate a spectrum band in a collaborative way. For non-collaborative scenarios, different clear channel access schemes were also introduced. This was more complex than the previous approach that had been used in 802.16.2, as the performance of coexistence depended on channel sensing and energy detection methods. Hence, complexity in achieving coexistence increased as higher levels of cognition were used. It is obvious that this higher level of cognition enhanced spectrum utilisation.

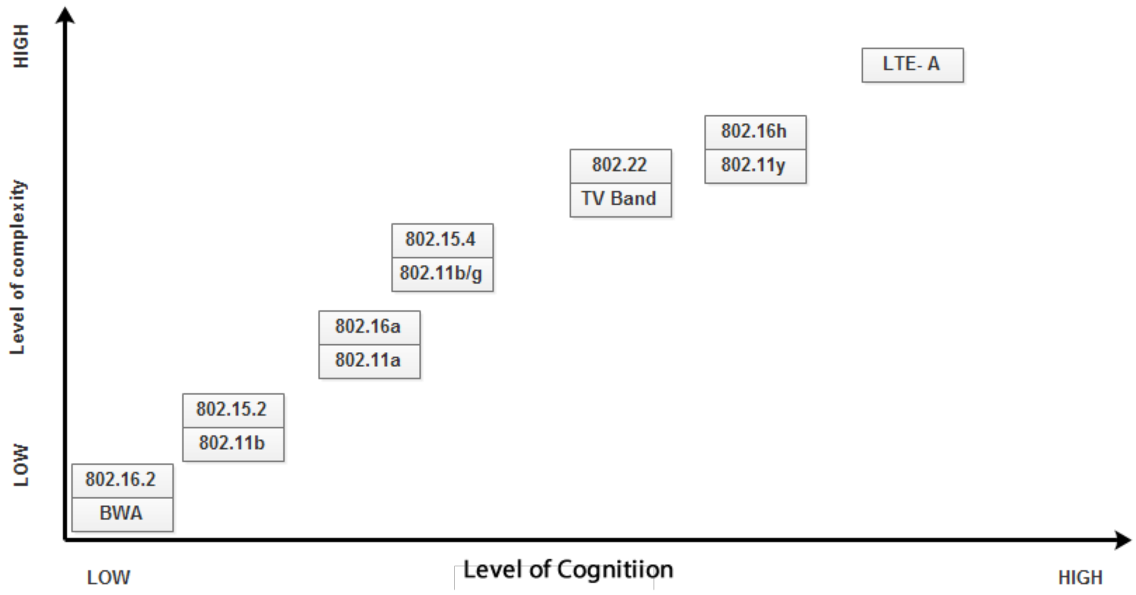


Figure 7.1: An evolutionary path of various coexistence techniques with different levels of cognition

The first cognitive radio standard was introduced in 802.22 to facilitate coexistence with the TV band whereby customer premises equipments (CPEs) could use the unused TV space. Previously, different coexistence techniques were used to share radio resources where there were no issues of proprietorship. Therefore existing coexistence techniques could not be directly applied to the recent concept of CR technology, where CR nodes do not have the right to access licensed channels during ongoing transmission among licensed users. They can only use a licensed channel if it is free. This requires a higher level of cognition capability to identify the unused radio spectrum and vacate the channel upon reappearance of a licensed user. However, with the advancement of technology, a higher level of cognition may be achieved, but the deployment of such technology has become an issue in ad-hoc networks.

7.3 Deployment of CRAHNs

Ad-hoc wireless networks are attractive for mainly two main reasons: i) time, and ii) cost in deploying and maintaining the networks. However, deploying CRAHNs is a new challenge, even for experienced system planners, due to features that are distinct from traditional ad-hoc networks. In traditional ad-hoc networks, network initialisation time is almost negligible due to its relatively fixed channel assignment strategy. In CRAHNs, the initial link establishment consumes significant time due to different channel statuses being observed by different nodes. Spectrum mobility due to PU reappearance results in changes in channel usage in the network. Moreover, in dense and large networks, resource sharing becomes a significant performance issue for CRAHNs. This thesis has investigated the above-mentioned design issues and challenges in CRAHNs. Throughout this study, it has been found that RDV establishment in CRAHNs has a notable impact on overall CRAHNs performance in different network scenarios. This section provides some practical guidelines for deploying CRAHNs in dense, large and PU-active environments.

Dense Network Scenario

Node density is a critical parameter to be considered when deploying CRAHNs. In an ad-hoc network, node deployment strategies can be deterministic or random based on application. A deterministic strategy is widely used when the number of nodes in the network is small. As network grows, it is very hard to follow the deterministic node deployment strategy and consequently random deployment is used. No matter what strategy is used, network performance degrades significantly with a high number of users. In this thesis, uniform node distribution was used. Analysis of the results in section 6.3.1 shows that throughput degraded about 57% as the number of CRs increased from 2 to 20. In addition to throughput, packet drop probability and mean delay also increased, as described in section 6.3.2 and section 6.3.3. The results presented in Chapter 6 confirm that node density has a dramatic effect on system performance.

Large Network Scenario

The term "large" is used in terms of network resources, especially the number of channels in the network. In contrast to traditional ad-hoc networks, the number of channels is higher in CRAHNs as it can utilise the unlicensed spectrum as well as the licensed spectrum if it is free. Increasing the number of channels in CRAHNs reduces the node density per channel, thus helps to improve channel contention. The results show that throughput increased dramatically with the addition of further channels. However, for system planners it is important to know that the more the channels there are in the system, the more time a node has to spend on the RDV process, which is shown in subsection 4.4.2. This is because the length of the CH sequence is increased with the number of channels and results in higher delay. The results in section 6.3.3 confirm similar behavior and show that about 8ms delay is injected into the system when the number of channels is increased from 5 to 40. To deploy CRAHNs in a large wireless network, system planners should consider the number of channels to be used in building the CH sequence to minimise mean delay.

High PU active Networks

Prior to deploying CRAHNs, a system planner has to ensure the protection of PU transmissions. Hence, it is necessary to quantify the performance fluctuation due to PU activity in the vicinity. This thesis has investigated the impact of PU activity for CRAHNs. The results of the analysis from section 6.3.1 show that there is about 83% drop in throughput with the increase in PU load from 0 to 0.5 (note that the maximum is 1). Further increases in the PU load do not affect performance a lot, as the CR node mostly utilises the unlicensed spectrum at this stage. This throughput degradation is only due to collision among CR users and other unlicensed devices

Table 7.1: Impact of network parameters on RDV process in CRAHNs

Change in Performance			
		Low to Medium	Medium to High
Number of CR	Throughput	10%	57%
	Packet Drop	15 17%	30%
	Mean Delay	6%	25%
Number of Channel	Throughput	Very High	Low
	Packet Drop	40%	18%
	Mean Delay	7%	72%
PU Load	Throughput	83%	30.6%
	Packet Drop	15%	25%
	Mean Delay	60%	35%

operating in that spectrum.

Table7.1 summarises the results of evaluating the impact of various network configurations on the RDV process in CRAHNs. Here except for throughput, the rest of the metrics show increasing function with the corresponding increase in input.

7.4 Recommendation for Future Developments

The aim of this thesis was to provide an efficient RDV establishment mechanism in an asynchronous asymmetric radio environment. Based on the proposed RDV mechanism, a MAC protocol was discussed to enhance system performance in distributed CRAHNs. However, there are some research issues that could be investigated in the future.

RDV extension for multi-hop CRAHNs

The thesis has focused on RDV establishment and performance estimation for CRAHNs in single hop networks. The assumption of a single hop network helped to simplify the analytical and simulation model. However, wireless ad-hoc networks in real environments use mostly multi-hop communication. Some RDV protocols exist for multi-hop communication that consider piece-wise single hopping for multi-hop communication [57, 60]. Hence, it is desirable to develop an RDV process for multi-hop networks which can increase network connectivity on the RDV channel.

Extension of ETQCH protocol for mobile CRAHNs

The thesis investigated CRAHNs by assuming that CR nodes are stationary at all times. To apply the proposed RDV sceme in a real environment, one of the concerns is the mobility of a CR node. Designing a CH sequence to establish RDV in mobile CRAHNs is still an open research challenge. The development of a robust RDV scheme where ATTR and node mobility are jointly optimised for better system performance is a logical extension to the work presented in chapter 3.

Development of an energy constrained RDV scheme

The thesis has focused on establishing RDV while minimising the mean time to achieve RDV and maximising the degree of overlaps. However, the performance of wireless ad-hoc networks is heavily influenced by the energy consumption of the adopted protocols [156, 157]. In this thesis, a homogeneous duty cycle is assumed in the entire network. The development of an RDV scheme with guaranteed RDV in all available common channels for a heterogeneous duty cycle setting for different nodes would be an important extension to this research.

Extension of PU behavior in CR-RDV MAC protocol

This thesis investigated the performance of the CR-RDV MAC protocol by assuming the same access scheme for both PUs and CRs. This assumption essentially simplified the analytical models for performance analysis. In reality, different primary networks have different access methods that limit the performance of CRAHNs. Although some protocols have been developed to facilitate the coexistence of PUs and CRs based on heterogeneous access methods [158, 159], a complete framework to study the impact of PU access methods on CRAHNs performance could be a useful contribution.

7.5 Summary

In this chapter the deployment of CRAHNs in different network environments was described to provide concrete guidelines for system planners. First, a brief development history of CR technology was presented. The development trend shows that system complexity increases with the level of cognition, which helps the system planner to adopt the correct level of cognition. Detailed guidelines were derived from the analysis of the results presented in chapters 4 and 6. The guidelines outline three factors that influence the system performance of CRAHNs: CR node density, network size, and PU activity. With CR node density, system performance changes dramatically due to collisions. It is interesting to observe system performance in relation to network size. As network size grows, the number of channels increases, so more CR nodes can be accommodated in the system, but the CR node has to spend longer achieving RDV.

Finally, recommendations for future research were identified, which include extension of the RDV scheme for multi-hop networks, integration of node mobility and energy consumption, and a MAC protocol with different PU activity models.

Chapter 8

Conclusions

In cognitive radio ad-hoc networks, CR users coexist with PUs and continuously monitor their activity to identify the spectrum holes. When two or more nodes want to communicate with each other, it is essential to establish RDV so that they can exchange the control message on the available spectrum holes that are common between them.

The thesis has focused on quantifying the key performance-limiting factors of the RDV process in CRAHNs. In dynamic distributed networks, the RDV process is quite challenging due to spatial and temporal variations in channel availability. While there are several factors affecting the performance of the RDV process, asymmetric channel information, degree of common channels and spectrum sharing processes are the most significant. To achieve RDV and to improve system performance, a channel ranking-based CH sequence was developed in this study and investigated through simulation to quantify the performance gain achieved over existing CH protocols. However, the RDV process without an efficient MAC protocol does not guarantee channel access in multi-user CRAHNs. The performance of CRAHNs with a novel MAC protocol was studied through the use of both analytical and simulation models. This thesis has made a number of original contributions, which are reported in chapters 3 to 6. A summary of the contributions is outlined below.

Rendezvous is the very first step in establishing communication in CRAHNs. Several research works were presented in the literature that considered RDV based on CCC. Due to the dynamic radio environment, RDV on a predetermined CCC cannot be guaranteed. Moreover, existing CH-based schemes suffer from high ATTR and a low degree of overlap due to random channel selection in CH sequence design. To overcome these problems, this thesis developed a simple but effective CH protocol, ETQCH, based on channel ranking. ETQCH utilises an extended torus quorum structure and rotation closure property to achieve and guarantee RDV on available common channels. The quorum selection and channel mapping are decided according to channel ranking. Moreover, to protect the incumbent PU transmissions, an adaptive CH sequence update procedure was introduced. The performance of the ETQCH protocol was evaluated using the MATLAB simulation package.

Simulations were conducted to measure well-known performance metrics for RDV problems, such as ATTR and degree of overlap under various network configurations. The analysis results showed that ETQCH could offer a significant performance gain over other channel rank-based protocols such as gQRDV, basic AMRCC and enhance AMRCC. In the worst case scenario (when sender and receiver observed channels with different rankings), ETQCH reduced the ATTR by at least 50%. Moreover, the change in ATTR with number of channels was significantly lower than for other protocols. For degree of overlap, ETQCH achieved 10%, 85.22% and 87% better results than gQRDV, basic AMRCC and enhance AMRCC respectively for the system with 22 channels. In an asymmetric scenario, similar performance gain was also observed. For example, ETQCH achieved up to 52% and 60% less ATTR than gQRDV for degree asymmetry of 0.8 and 0.6 respectively. ETQCH performs better because more time slots are allocated to the channels with higher rank, which increases the probability of RDV. Moreover, the ETQCH protocol dynamically updates the CH sequence by replacing the channel claimed by a PU with either the best channel from the list or the channel that previously achieved RDV.

Cognitive Radio ad-hoc network is a multi-user environment, where multiple CR users are contending for the same channel on which to establish RDV. Hence, it is necessary to have an efficient MAC protocol to facilitate channel contention and spectrum sharing. In Chapter 5, a distributed multi-channel CR MAC protocol, CR-RDV, was developed based on the random access method. The CR-RDV protocol is an extension of the CSMA/CA protocol, but CR-RDV modifies two components. First, the traditional VCS scheme is modified by adding a sensing period right after RTS. In the CR-RDV protocol, a CR node transmits a packet if the channel is found free after RTS time, otherwise it continues to defer transmission until the end of VCS. This strategy can reduce performance degradation due to false blocking. Secondly, the packet transmission policy is modified based on the remaining channel availability time. A CR node transmits the packet if the remaining time of the channel "OFF" period is greater than the required packet transmission time, otherwise it will defer the transmission to the next available free slot. By adopting this strategy, a CR node can avoid concurrent transmission with PUs and provide additional protection for PU transmissions.

Moreover, the way the CRs negotiate or select the RC, DC and BC, with or without the presence of PUs, is one of the most important features of the CR-RDV protocol. The RC is established through the ETQCH protocol. If the RC is the best channel for both sender and receiver it can serve as the DC. Otherwise, a list of DCs is constructed based on negotiation between sender and receiver. Besides that, a list of BCs is also constructed as a counter measure against service interruptions due to intermittent PUs. Both the DC and BC are negotiated prior to the actual data transmission.

In Chapter 6, the performance of the CR-RDV protocol was investigated through both analytical and simulation studies. The results obtained showed that CR-RDV with MVCS increased the performance of CRs by 80% compared to VCS. This is not only due to the insertion of additional sensing in the NAV, but also the modified control packets used for the handshake process. Moreover, the results show that the ETQCH RDV protocol is another important tool in driving the superior performance of the CR-RDV MAC protocol over other CH-based protocols. This is due to the dynamic updating of ETQCH in cases of sudden PU appearance. In addition, every increment of PU load results in higher probability of RDV collision, as CRs tend to achieve RDV on the same channel.

The work presented in this thesis has provided the basis for system planners to design and analyse CRAHNs. The results indicate that this work can be used to estimate RDV performance in dense, large environments that have a high degree of PU activity.

Finally, a number of recommendations relevant to the ongoing development of the RDV scheme and MAC protocol have been suggested. Extension of the RDV protocol for energy constrained multi-hop mobile CRAHNs has been identified as an area for future research together with different PU activity models.

In light of the results reported above, it can be said that RDV is the most important component in establishing and enhancing the performance of CRAHNs by dynamically updating the CH sequence based on channel availability and channel ranking in both the licensed and unlicensed band.

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Appendix A

Additional illustration for Extended Torus Quorum System

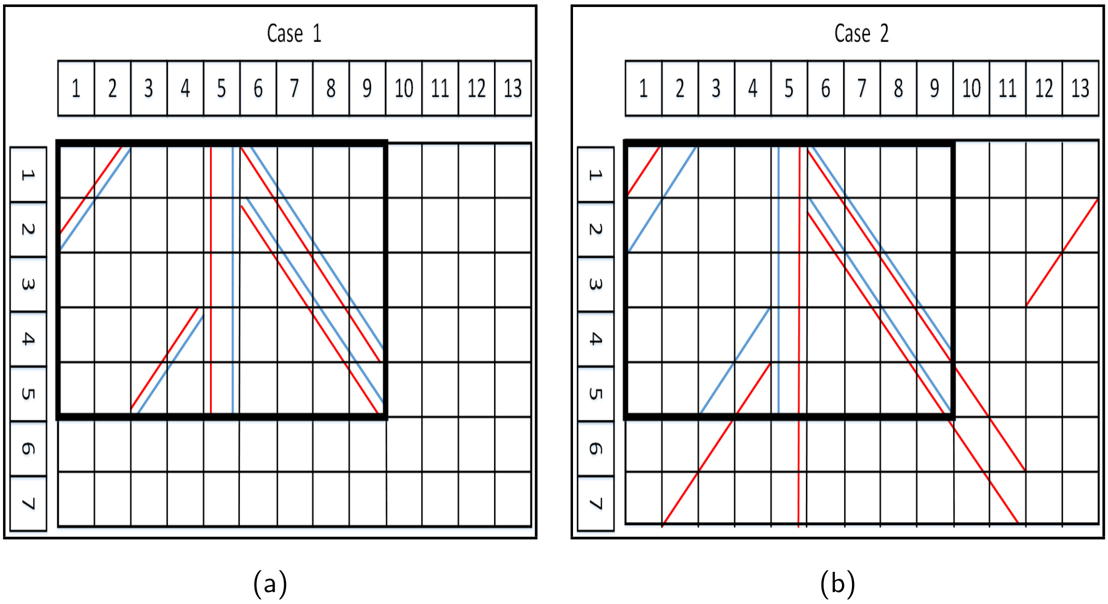
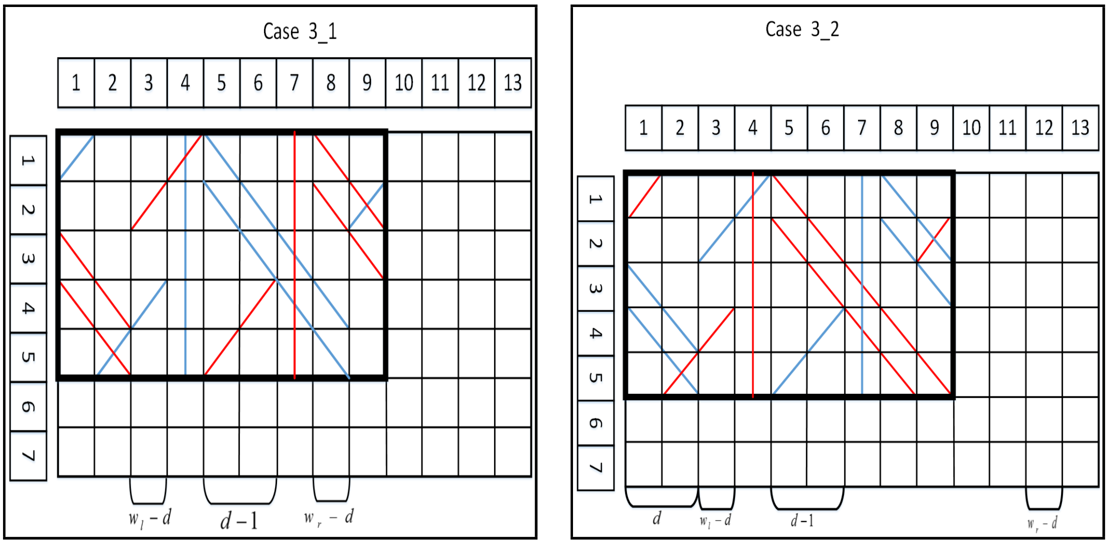
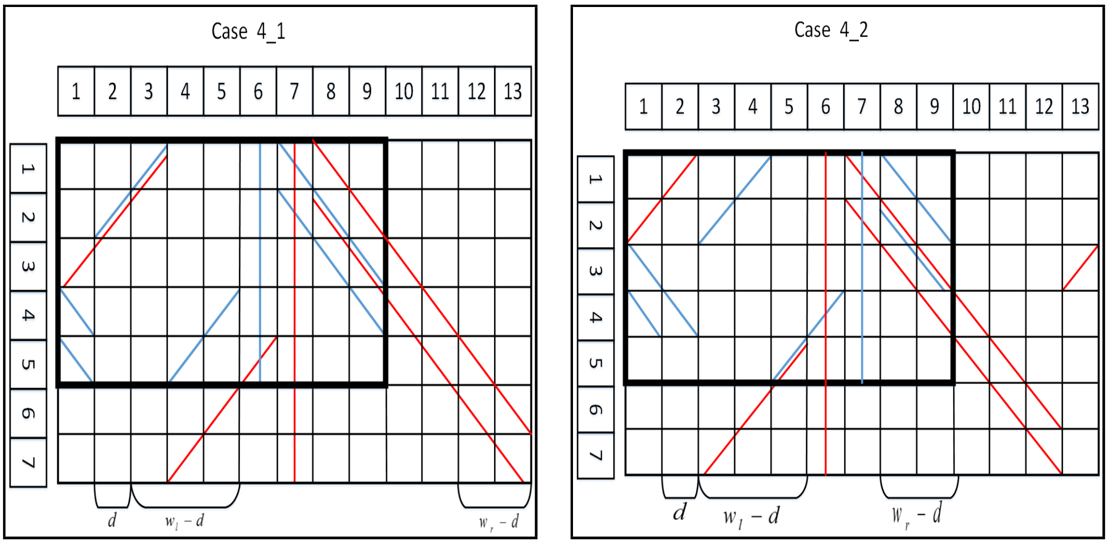


Figure A.1: (a) Case 1 (b) Case 2



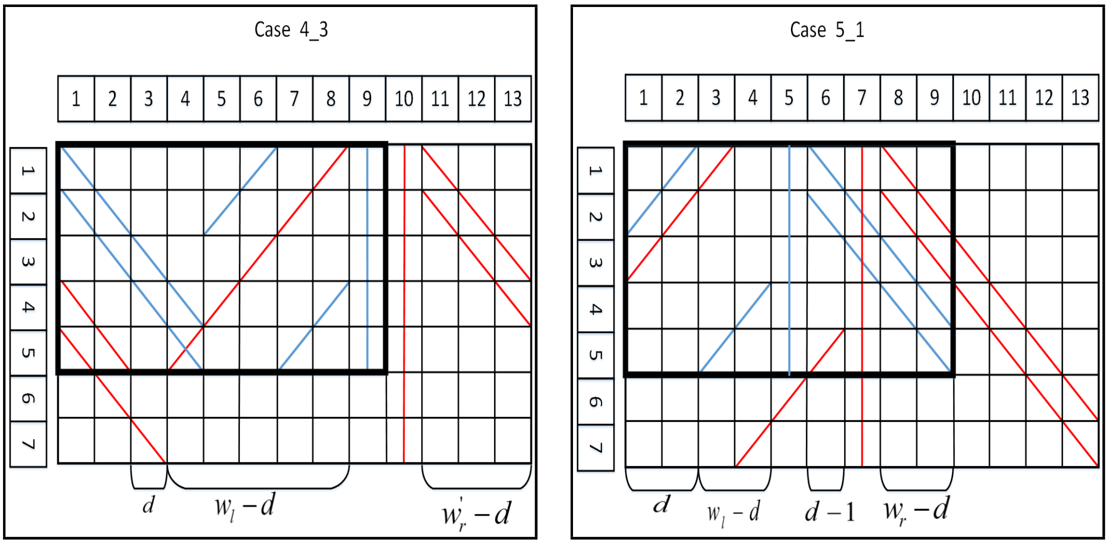
(a) (b)

Figure A.2: (a) Case 3_1 (b) Case 3_2



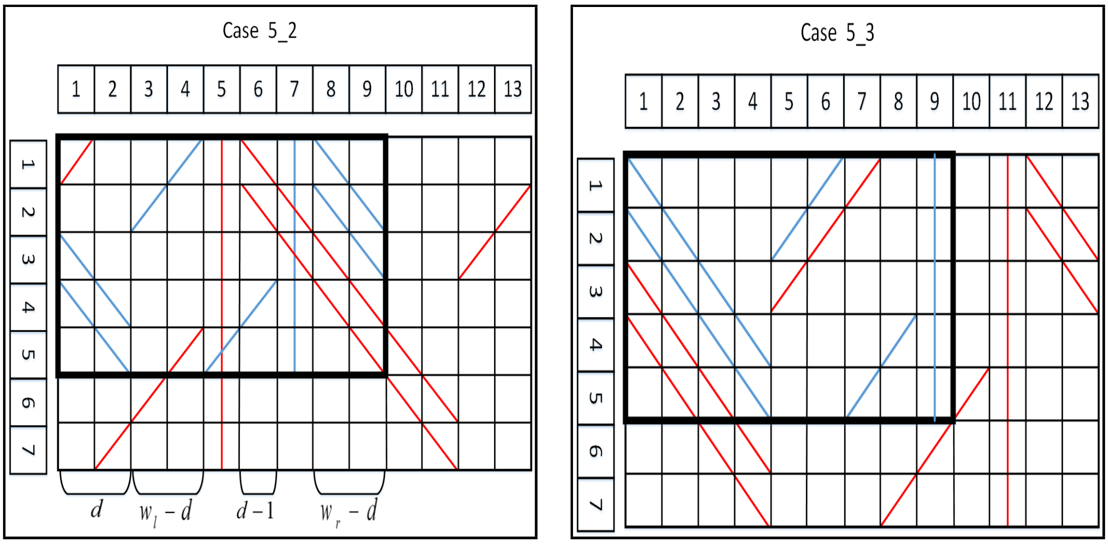
(a) (b)

Figure A.3: (a) Case 4_1 (b) Case 4_2



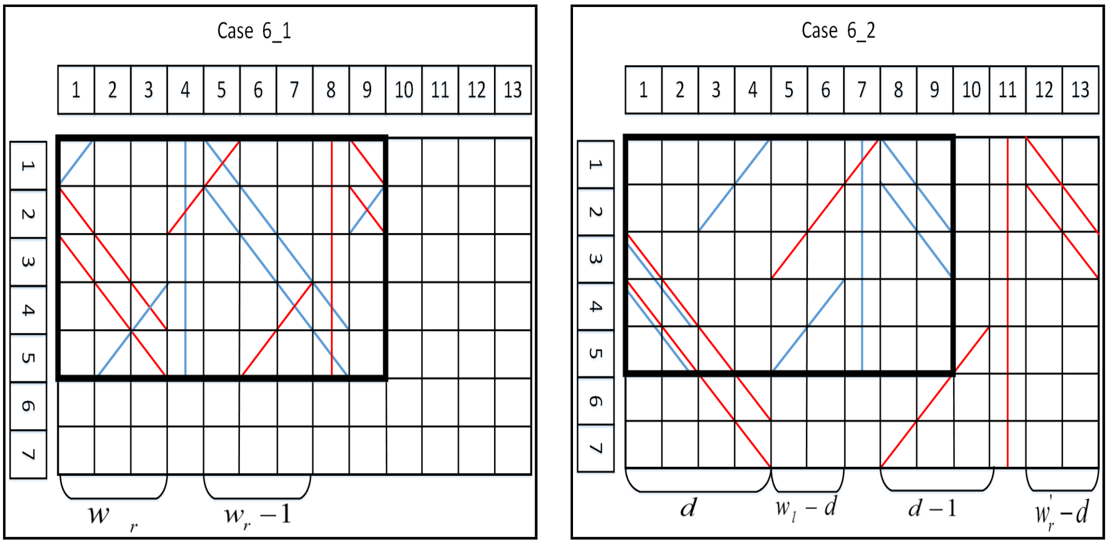
(a) (b)

Figure A.4: (a) Case 4_3 (b) Case 5_1



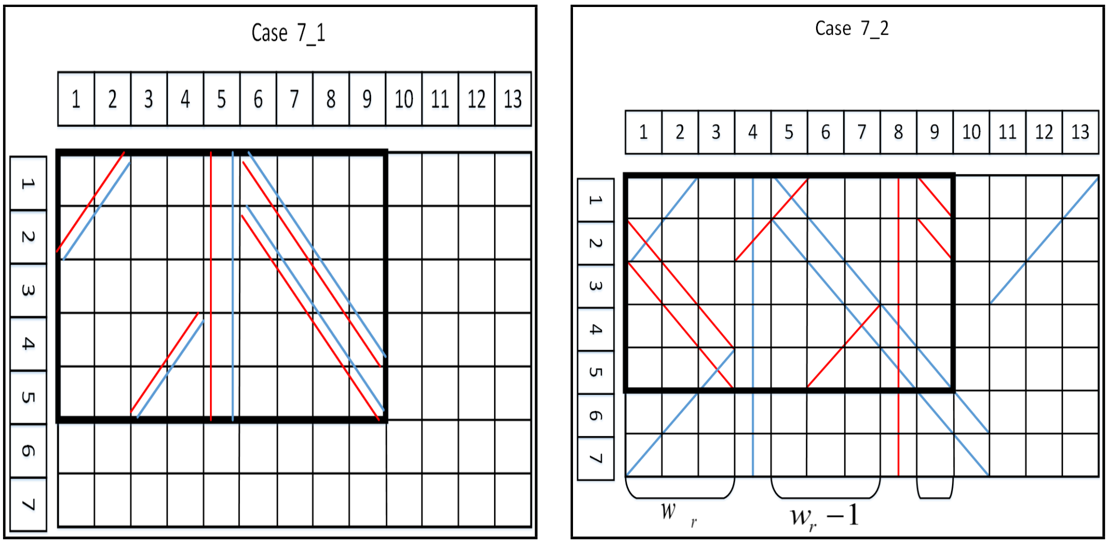
(a) (b)

Figure A.5: (a) Case 5_2 (b) Case 5_3



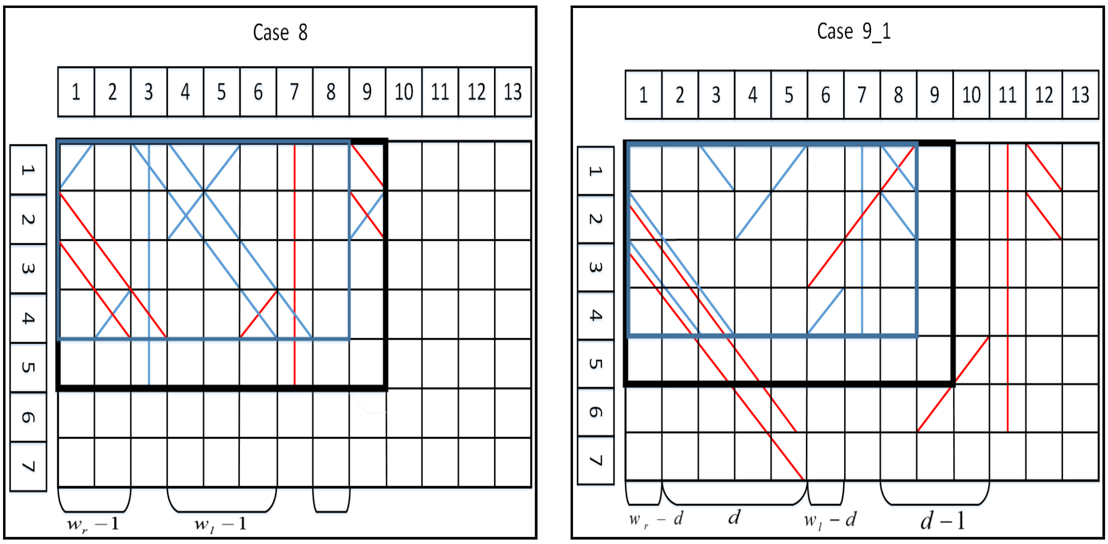
(a) (b)

Figure A.6: (a) Case 6_1 (b) Case 6_2



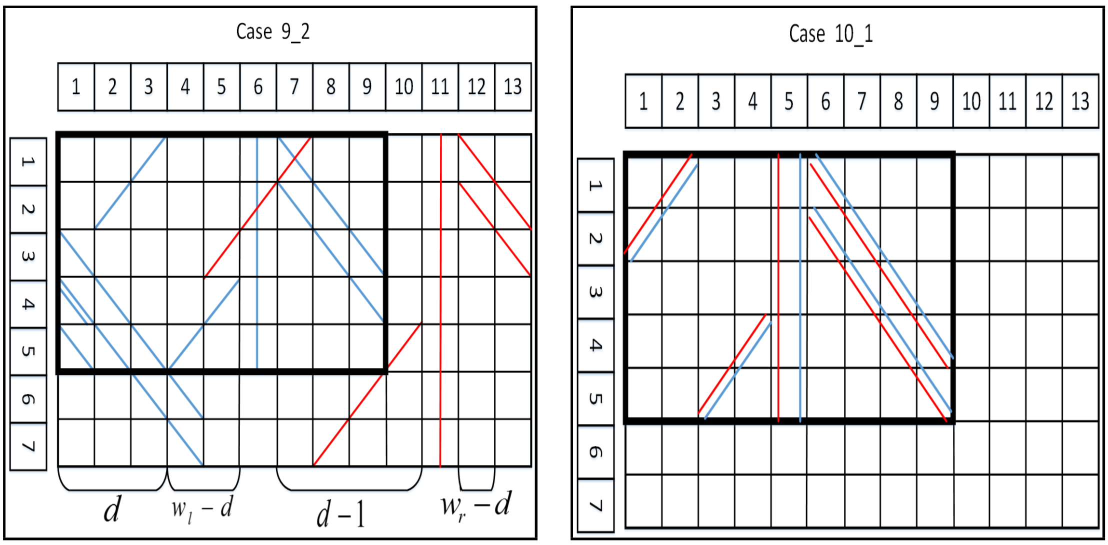
(a) (b)

Figure A.7: (a) Case 7_1 (b) Case 7_2



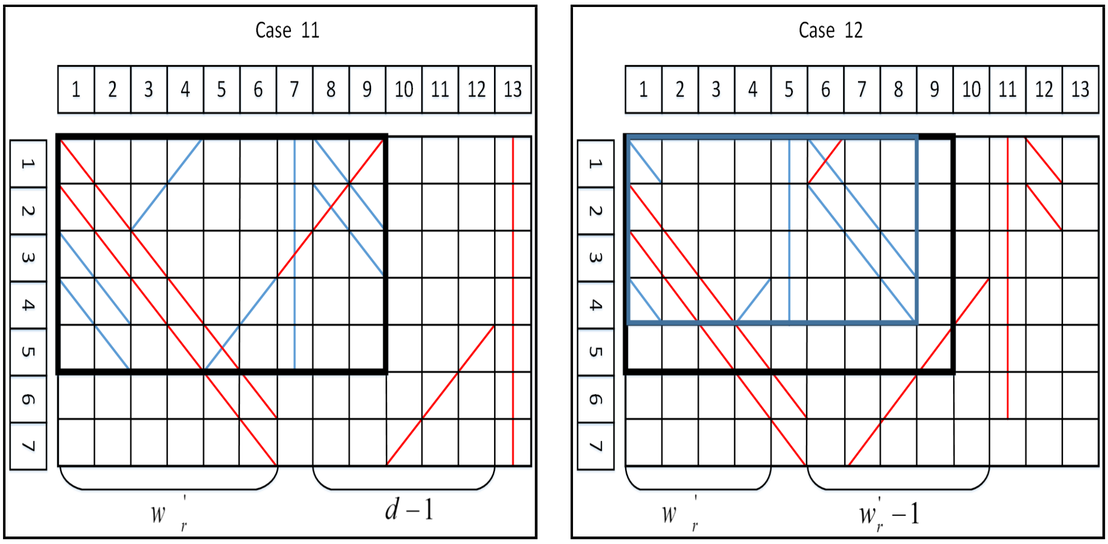
(a) (b)

Figure A.8: (a) Case 8 (b) Case 9_1



(a) (b)

Figure A.9: (a) Case 9_2 (b) Case 10_1



(a)

(b)

Figure A.10: (a) Case 11 (b) Case 12