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EFFICIENT BLIND RENDEZVOUS SCHEMES FOR COGNITIVE RADIO AD-HOC NETWORKS

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By

ABDULMAJID MOHAMMED AHMED AL-MQDASHI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATIONS

In the name of Allah, Most Gracious, Most Merciful

This thesis is dedicated to:

To the spirit of my beloved father. It was your wish, thus I insisted to make it come true.
To my beloved mother, who endured my absent. Her prayers for me have not stopped.
To my beloved older brother, who stands by me when things look bleak.
To my dear wife, who faithfully supported me and endured a lot for me.
To all of my family members for their unconditional love and support.

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December 2018

Chair : Prof. Ir. Aduwati Sali, PhD
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Cognitive Radio (CR) has been emerged as a promising technology for solving the spectrum scarcity and underutilization issues. The CRs allow unlicensed users, a.k.a. secondary users (SUs), to opportunistically use licensed bands without causing interference to the bands licensed users, a.k.a. primary users (PUs). Channel rendezvous is a fundamental and vital process for exchanging control messages and establishing communications between SUs in CR Ad-hoc networks (CRAHNs). Due to the major drawbacks of the dedicated common control channel (CCC) rendezvous approach, channel hopping (CH) has been emerged as an alternative approach for achieving blind rendezvous without the need of any predefined CCC. However, the absence of clock synchronization and neighborhood information as well as the spectrum heterogeneity among SUs in CRAHNs imposes great and unique design challenges for the blind CH scheme. Further challenges arise from the limitation and fluctuating of channel availabilities which are varied according to the nature, dynamics, and density of PUs that are licensed to use the target spectrum. The previous research works on blind rendezvous have mainly focused on designing the CH sequence for ensuring rendezvous within a finite time while ignoring some practical issues such as the rendezvous in CRAHNs operating under fast PU dynamics or highly-dense PU networks. Besides, most of the existing works still rely on some unpractical assumptions or take long time to establish rendezvous. Therefore, designing blind rendezvous schemes that can cope with the aforementioned challenges and limitations while minimizing the rendezvous latency at the same time is an important and open area that needs to be studied and improved.

In this research, efficient blind schemes are proposed to establish deterministic and fast pairwise rendezvous in different types of CRAHNs. Firstly, three CH schemes are developed for rendezvous in slow-varying CRAHNs where channel availabilities are not varying during the rendezvous process. The first two schemes called,

Slow and Quick CH (QS-CH), and Interleaved Slow, Quick and Fixed CH (IQSF-CH), are designed to provide rendezvous in single-radio CRAHNs where each SU in the network has only a single radio. On the other hand, the third scheme called Multi-Grid-Quorum CH (MGQ-CH) is designed for multi-radio CRAHNs where SUs exploit multiple radios. The three proposed schemes utilize only the unrestricted local available channels for generating their CH sequences which is desirable in distributed heterogeneous CRAHNs. Theoretical analysis and extensive simulations are conducted to demonstrate the proposed schemes efficiency in providing guaranteed rendezvous within bounded and short time-to-rendezvous (TTR). The simulation results show that significant TTR reductions up to 68%, 73%, and 60% can be achieved by the proposed single-radio and multi-radio schemes, respectively, as compared to other related previous works in the literature.

Second, two adaptive nested cyclic-quorum-based CH schemes, called NCQ-CH and MNCQ-CH, are proposed for rendezvous in fast-varying CRAHNs where channel availabilities can vary during the rendezvous process. The proposed schemes are augmented with efficient channel ranking and quorum selection mechanisms for generating and adapting the CH sequence on the fly which make them robust to the fast PU dynamics. The simulations results show that the proposed schemes can reduce the TTR up to 49%, as compared to other existing adaptive CH schemes while providing better PU detection accuracy.

Finally, two blind coprimality-based sector hopping (SH) schemes called, Prime and Even SH (PES-SH), and Interleaved PES-SH (IPES-SH), are proposed to establish sector rendezvous in directional antenna CRAHNs where SUs are equipped with single directional antenna CRs. The proposed SH schemes are then combined with a Ranked Quick and Slow CH (RQS-CH) scheme in order to establish simultaneous sector and channel rendezvous. The theoretical analysis and simulations results demonstrate the developed schemes efficiency where they can reduce the rendezvous delay significantly up to 85% and 55%, as compared to other existing related works. Furthermore, the results demonstrate that the proposed schemes are more resistant to rendezvous failures under high density PU networks, as compared to the omni-directional antenna rendezvous paradigm.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

SKIM RENDEZVOUS BUTA CEKAP UNTUK RANGKA KERJA AD-HOC RADIO COGNITIF

Oleh

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Radio Kognitif (CR) telah muncul sebagai teknologi yang menjanjikan penyelesaian masalah kekurangan spektrum dan isu-isu kurang penggunaan. CRs membenarkan pengguna tidak berlesen, a.k.a. pengguna sekunder (SU), untuk menggunakan jalur berlesen secara oportunis selagi mereka tidak menyebabkan sebarang gangguan kepada pengguna berlesen band, pengguna utama (PU). Pertemuan saluran adalah proses asas dan penting untuk menukar mesej kawalan dan mewujudkan komunikasi antara SU dalam rangkaian CR Ad-hoc (CRAHNs). Disebabkan oleh kekurangan dalam cara pertemuan saluran kawalan umum dedikasi (CCC) yang dikhususkan, saluran hopping (CH) telah muncul sebagai alternatif untuk mencapai pertemuan buta tanpa memerlukan mana-mana CCC yang telah ditetapkan. Walau bagaimanapun, ketiadaan penyegerakan jam dan maklumat kejiranan serta spektrum heterogen di kalangan SU telah mengenakan cabaran reka bentuk yang tinggi dan unik untuk skema CH buta. Cabaran lebih lanjut timbul daripada batasan dan turun naik daripada ketersediaan saluran yang berbeza-beza mengikut sifat, dinamik, dan kepadatan PU yang dilesenkan untuk menggunakan spektrum tersasar. Kerja-kerja penyelidikan terhadap pertemuan buta sebelum ini telah menumpukan perhatian kepada perancangan urutan CH untuk memastikan pertemuan dalam masa terbatas sambil mengabaikan beberapa isu praktikal seperti pertemuan di CRAHN yang beroperasi di bawah dinamik PU yang cepat atau rangkaian PU yang sangat padat. Selain itu, sebahagian besar kerja yang ada masih bergantung pada beberapa anggapan dan sekatan yang tidak praktikal untuk membimbing pertemuan atau masih menyebabkan kelewatan pertemuan yang sangat panjang. Oleh itu, perekaan skema pertemuan buta yang dapat menampung cabaran dan batasan yang dinyatakan di samping meminimumkan latensi pertemuan pada masa yang sama adalah satu topik kajian yang penting dan terbuka yang perlu dipelajari dan diperbaikkan.

Dalam kajian ini, skim pertemuan buta yang cekap telah dicadangkan untuk mewujudkan pertemuan pasangan yang pantas dan berketentuan dalam pelbagai jenis CRAHNs. Pertamanya, tiga skim CH telah diwujudkan bagi pertemuan dalam CRAHNs yang berlainan-lambat dimana ketersediaan saluran tidak bervariasi semasa proses pertemuan. Skim pertama iaitu Perlahan dan Cepat CH (QS-CH), dan skim kedua iaitu Antara Lembaran Lampat, Cepat dan CH Tetap (IQSF-CH), telah direka untuk menyediakan pertemuan dalam CRAHNs radio tunggal di mana setiap SU dalam rangkaian hanya mempunyai satu radio. Sebaliknya, skim ketiga iaitu Multi-Grid-Kuorum CH (MGQ-CH) adalah direka untuk CRAHN berbilang radio apabila SU mengeksploitasi pelbagai radio. Tiga skema yang dicadangkan hanya menggunakan saluran tempatan tak terhad yang tersedia untuk menghasilkan urutan CH, cara ini sesuai untuk CRAHNs heterogen teragih. Analisis matematik dan simulasi yang luas dijalankan untuk menunjukkan kecekapan skim yang dicadangkan dalam menyediakan pertemuan yang dijamin dalam tempoh masa pertemuan yang singkat dan terhingga. Hasil simulasi menunjukkan bahawa pengurangan TTR yang signifikan sehingga 68%, 68%, dan 60% boleh dicapai oleh skim radio tunggal dan multi-radio yang dicadangkan, berbanding dengan literatur sedia ada yang berkaitan.

Kedua, dua skim CH suai bersarang yang berasaskan kitaran dan kuarza, yang dipanggil NCQ-CH dan MNCQ-CH, dicadangkan untuk pertemuan dalam CRAHN yang cepat berubah di mana ketersedian saluran boleh bertukar semasa proses pertemuan. Skim yang dicadangkan telah ditambah dengan mekanisme pemilihan kedudukan saluran dan kuorum cekap untuk menjana dan menyesuaikan urutan CH dengan serta-merta, dan turut menjadikannya lasak dalam dinamik PU yang cepat. Hasil simulasi menunjukkan bahawa skim yang dicadangkan dapat mengurangkan TTR sehingga 49%, berbanding dengan kerja pertemuan suai yang sedia ada sambil memberikan ketepatan pengesanan PU yang lebih baik.

Akhirnya, skim sektor hopping (SH) berasaskan comprimality buta yang dipanggil, Perdana dan Genap SH (PES-SH), dan Antara Lembaran Perdana dan Genap SH (IPES-SH), dicadangkan untuk menwujudkan pertemuan sektor dalam antena berarah CRAHN di mana SU dilengkapi dengan CR antena berarah tunggal. Skim SH yang dicadangkan kemudiannya digabungkan dengan skim Cepat dan Lambat Berpangkat CH (RQS-CH) untuk menubuhkan pertemuan sektor dan saluran serentak. Hasil analisis teori dan simulasi menunjukkan kecekapan skema yang dibangunkan di mana ia dapat mengurangkan masa pertemuan dengan signifikan sehingga 85% dan 55%, berbanding dengan kerja berkaitan yang lain. Tambahan pula, keputusan menunjukkan bahawa skim yang dicadangkan lebih tahan terhadap kegagalan pertemuan bagi rangkaian PU berkepadatan tinggi, berbanding dengan paradigma pertemuaan antena omni-arah.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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ACS	Available Channel set
ACHPSs	Asynchronous Channel Hopping Prime Sequences
ASRL	Average Sector Rendezvous Latency
ATTR	Average Time To Rendezvous
A-CHS	Asynchronous Channel Hopping Sequence
BCL	Best Channel List
CCC	Common Control Channel
CH	Channel Hopping
CQS	Cyclic Quorum System
CR	Cognitive Radio
CRT	Chinese Reminder Theorem
CRN	Cognitive Radio Network
CRAHN	Cognitive Radio Ad-Hoc Network
DIR-CRAHN	Directional Cognitive Radio Ad-Hoc Network
DRDS	Disjoint Relaxed Difference Set
D-QCH	Dynamic Quorum Channel Hopping
DS	Difference Set
DSA	Dynamic Spectrum Access
E-AHW	Enhanced Alternating Hop and Wait
EJS	Enhanced Jump Stay
FCC	Federal Communication Commission
FDCH-RB	Full Diversity Channel Hopping
GCS	Global Channel set
GC	Global-Channel based
GQS	Grid Quorum System
GCR	General Construction for Rendezvous
IPES-SH	Interleaved Prime and Even based Sequences Sector Hopping
IQSF-CH	Interleaved Quick, Slow, and Fixed Channel Hopping
ISM	Industrial, Scientific and Medical
JS	Jump Stay
LC	Local-Channel based
MGQ-CH	Multi-Grid Quorum Channel Hopping
MNRDSs	Minimal Nested Relaxed Difference Sets
MNCQ-CH	Minimal Nested Cyclic Quorum Channel Hopping
M-RDS	Minimal Relaxed Difference Set
M-RDST	Minimal Relaxed Difference Sets Table
MSRL	Maximum Sector Rendezvous Latency
MSS	Multi-radio Sunflower-Sets-based
mT-GQS	Mirror torus-in-grid quorum system Channel Hopping
MTTR	Maximum Time To Rendezvous
MTP	Moving Traverse Pointer
NCQ-CH	Nested Cyclic Quorum Channel Hopping

NGQFH	Nested Grid Quorum Channel Hopping
NRDSs	Nested Relaxed Difference Sets
PCH	periodic Channel Hopping
PDP	Padded Dyck Path
PES-SH	Prime and Even based Sequences Sector Hopping
PU	Primary User
QCM	Quorum Channel Mapping
QS-CH	Quick and Slow Channel Hopping
RD	Rendezvous Diversity
RDS	Relaxed Difference Set
RDST	Relaxed Difference Sets Table
RPS	Role-based Parallel Sequence
SARCH	Symmetric Asynchronous Rendezvous Channel Hopping
SCH	Sector and Channel Hopping
SH	Sector Hopping
SJ-RW	Sender Jump-Receiver Wait
SRL	Sector Rendezvous Latency
SRCT	Sector Ranked Channel Table
SSS	Single-radio Sunflower-Sets-based
SU	Secondary User
TTR	Time To Rendezvous
UFH	Ultra High Frequency
UMTS	Universal Mobile Telecommunication System
WLAN	Wireless Local Area Network
WFM	Wait-For-Mommy

CHAPTER 1

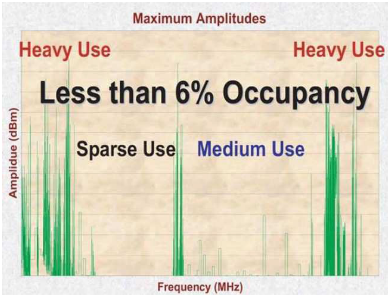
INTRODUCTION

Owing to the rapid development of new wireless services and applications, the number of wireless devices increases exponentially over the last decade, which result in a tremendous demand for the wireless spectrum. However, the radio spectrum which is suitable for wireless communications is a naturally limited and scarce resource. According to the traditional spectrum assignment policy, a large portion of the radio spectrum has been statically licensed by the national authorities and agencies to several wireless communication systems. These licensed spectrum bands are assigned to license holders for an exclusive use on a long-term basis within given geographical regions. Meanwhile, a small portion of the spectrum bands is left as unlicensed such as the ISM bands, which facilitate several short-range and indoor wireless communications such as the WLANs and Bluetooth, among others. However, these unlicensed bands are overcrowded due to the huge bandwidth demand by the applications which utilize them (e.g., voice/video calling, gaming, media steaming, etc).

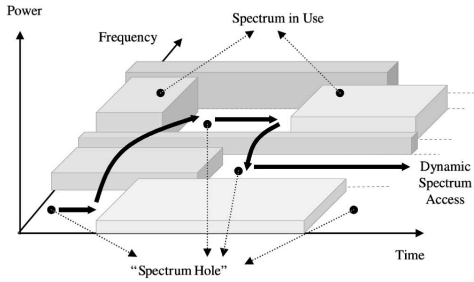
1.1 Overview

Although the spectrum majority have been statically assigned to licensees, several statistical studies and real-life measurements conducted by the Federal Communication Commission (FCC) and other regulatory agencies indicate that most of the licensed spectrum bands are heavily underutilized [1, 2, 3, 4]. This results in a spectrum inefficiency problem as illustrated in Figure 1.1.a. According to FCC, up to 85% of the spectrum that is licensed to existing wireless communication systems are underutilized most of the time even in the crowded urban areas where the spectral usage is intensive. These investigations revealed that the spectrum scarcity problem can be contrasted if the already licensed spectrum is exposed in a more efficient and flexible manner [5, 6]. Therefore, Dynamic Spectrum Access (DSA) has been proposed as a new communication paradigm and alternative policy for spectrum management to solve the spectrum scarcity and underutilization issues [7].

The DSA paradigm enables a dynamic and opportunistic exploitation of the temporarily unoccupied or underutilized portions of the licensed spectrum, a.k.a. Spectrum Holes or White Spaces (see Figure 1.1.b). In DSA, the unlicensed users a.k.a. secondary users (SUs) can opportunistically access and utilize the white spaces to establish their communications. Nevertheless, whenever the licensed users a.k.a. primary users (PUs) reappear on their licensed spectrum, SUs must vacate the reclaimed spectrum holes immediately and move to other spectrum holes for proceeding their transmissions [6, 8]. This is in order to avoid causing interference to PUs since PUs have the absolute priority to access their licensed spectrum. In this situation, Cognitive Radio (CR) has been emerged as the promising technology to realize DSA due to its capability of sensing/capturing the radio spectrum, learning from the interactions with the surrounding environment, and adapting the internal state [9, 10, 11].



(a) Spectrum underutilization [4].



(b) Spectrum hole concept [5].

Figure 1.1: Spectrum underutilization and the spectrum holes.

In Cognitive radio networks (CRNs), SUs are equipped with CRs which allow them to sense the channels of the target licensed spectrum and detect the idle/available ones for opportunistically sharing them with the co-located PUs. A channel is decided to be available for the SU if the channel is idle from any PU activities. However, once the PUs become active on their licensed channels, the SUs must vacate the corresponding channels to avoid causing unacceptable interference to PUs which makes these channels unavailable. Therefore, In CRNs, the channel availability is position-varying (depends on the position of the SU relative to PUs) and time-varying (depends on the appearance time of co-located PU signals) [12]. This spatial and temporal varying channel availability is the main unique trait that distinguishes CRNs from the traditional wireless networks.

Although a lot of research and development efforts have been made in CRNs, these efforts had mainly focused on the physical layer aspects such as spectrum sensing and interference mitigation. However, enabling opportunistic operation through CR technology necessitates the addressing of other aspects in the upper layers such as rendezvous, neighbor discovery, and device coordination in the MAC layer. In this thesis, the rendezvous issue is addressed which plays a crucial role in CRN configuration and connectivity. The research is specially focusing on the distributed CR Ad-Hoc Networks (CRAHNs) due to their challenging features such as self-organizations and heterogeneity, which are derived from the absence of network infrastructure.

1.2 Rendezvous in Cognitive Radio Networks

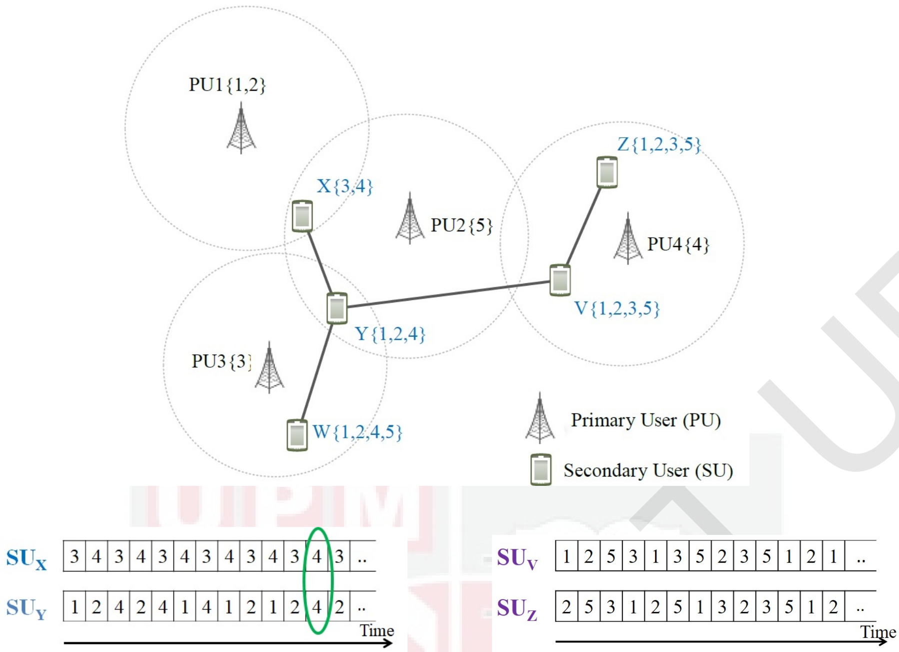
In CRAHNs, every SU has its own available channel set which is determined after the spectrum sensing stage. To start data transmissions, SUs need to meet each other on a commonly-available channel in order to exchange control messages and setup their data communication links. This process is called *channel rendezvous*, which is a fundamental and a vital process for initiating the connection of SUs data communications. However, implementing rendezvous on available channels is non-trivial and challenging. The difficulty mainly comes from the fact that before rendezvous, SUs are oblivious of each other's information and even they might unaware of each other existence. According to that and since SUs may reside in distinct channels, they have no consensus about which common channel they have to switch into simultaneously for achieving rendezvous.

A simple approach that is widely-adopted in the literature to achieve rendezvous is the dedicated common control channel (CCC) e.g., [13, 14, 15, 16, 17, 18]. In this approach, one of the licensed channels which is assumed to be a globally available for all SUs is assigned as the CCC for exchanging the control messages. Although this approach can simplify the rendezvous process, it has several drawbacks. Firstly, the maintaining of a channel that is a globally available to all SUs is infeasible in practical CRAHNs. This is due to the spectrum heterogeneity among SUs which is caused by the spatial and temporal variations of the channel availabilities. Secondly, the CCC is susceptible to long-time blocking by PUs where PUs may continuously occupy/block the CCC for a long time [19, 20]. Thirdly, the CCC is also susceptible to early saturation by SUs where it may become congested under heavy loads. Finally, the CCC is vulnerable and easy target for jamming attacks [21, 22, 23].

To overcome the drawbacks of CCC, Channel hopping (CH) has been emerged as an alternative approach in the literature for blind rendezvous which require neither CCC nor prior knowledge of the other SUs available channel sets. In the CH approach, each SU generates its CH sequence independently and keeps hopping on the channels in a time-slotted manner according to the generated CH sequence for achieving rendezvous with its potential neighbors. The rendezvous occurs between a pair of neighboring (i.e., in-range) SUs when they hop simultaneously during the same time slot on a channel that is a commonly-available for both of them. At that time, SUs can perform a three-way handshake to exchange different control messages and set up their data transmission links.

Take Figure 1.2 as an example, where there is a licensed spectrum of five channels that are owned by PUs. Meanwhile, there are several SUs which can only utilize the licensed spectrum channels in an opportunistic fashion (i.e., without causing interference to the co-located PUs). Suppose that PU_1 occupies channels $\{1, 2\}$, PU_2 occupies channel $\{5\}$, PU_3 occupies channel $\{3\}$, and PU_4 occupies channels $\{4\}$. It can be seen that not all the channels are available for the SUs. The local available channel set (ACSs) for each SU, as shown by the adjacent blue lists, is determined according to the channels idleness from any co-located PUs' activities. Now, consider the pair of neighboring SUs (SU_X and SU_Y) which have only one common channel between their ACSs (channel 4) and suppose they perform the CH scheme in [24] for generating their CH sequences. As shown in Figure 1.2.a, SU_X and SU_Y can achieve rendezvous on channel 4 After 11 time slots. On the other hand, consider the pair of neighboring SUs (SU_V and SU_Z) which have identical ACSs and which hop on the channels randomly. As illustrated in figure 1.2.b, the rendezvous between SU_V and SU_Z may not be achieved within a finite time. This demonstrate that if the CH scheme is not designed properly, it may not ensure rendezvous between SUs even if they have identical ACSs.

The blind CH scheme can be designed by following either asymmetric or symmetric role approach. In the asymmetric-role approach, SUs are assumed to have pre-assigned roles (either as a sender or a receiver) before starting the rendezvous process where they follow different methods to generate the CH sequences. On the other



(a) Rendezvous is achieved between SU_X and SU_Y when performing the CH scheme in [24]

(b) Rendezvous not occur between SU_V and SU_Z when perform random CH

Figure 1.2: An illustrative example of channel hopping in CRAHNs.

hand, the symmetric-role approach have no pre-assigned roles where SUs generate their CH sequences using the same method. While the former approach can significantly minimize the rendezvous delay, its role-based design limits its applications, for example, the SU can not work as a forwarder (i.e., receive packets from one SU and then forward it to another SU) due to the pre-role assignment.

To work properly in a practical CRAHN, the blind rendezvous scheme should satisfy the following properties:
(i) Asynchronous Scenario: In CRAHNs, each SU may start its CH at different instant of time. Therefore, the blind rendezvous scheme must support both synchronous and asynchronous scenarios.

(ii) Homogeneous and heterogeneous channel availability models: In multi-channel CRAHNs, two models are often considered to describe the channel availability for neighboring SUs; the homogeneous model and the heterogeneous model. In the homogeneous model, SUs have the same set of available channels. Meanwhile, the SUs have different sets of available channels in the heterogeneous model, but there must be at least one commonly-available channel between SUs in order to ensure rendezvous. The blind rendezvous scheme is required to work under both models due to their importance in practice [25]. The homogeneous model is applicable when SUs are located close to each other in a small geographical area (relatively smaller than their distances to PUs). Meanwhile, the heterogeneous model is applicable when the

SUs geographical locations are far from each other. However, establishing rendezvous under the heterogeneous model is more difficult due to the fewer commonly-available channels between SUs.

(iii) Guaranteed Rendezvous: Due to the failure of the random CH in ensuring rendezvous, most of the existing blind rendezvous schemes construct their CH sequences based on different mathematical tools, trying to achieve deterministic rendezvous within a finite time. The performance of the rendezvous scheme is generally evaluated by the time-to-rendezvous (TTR) which is defined as the number of time slots required for SUs to rendezvous once they have started the rendezvous process. However, in the asynchronous environment, SUs may start the rendezvous process at different times and hence the TTR is usually in-equable. Thus, the Average TTR (ATTR) and maximum TTR (MTTR) are considered as the primary metrics to evaluate the TTR performance. The MTTR indicates the required TTR for a guaranteed rendezvous in the worst case which is important to prove the deterministic rendezvous provided by the CH scheme.

1.3 Problem Statement

Due to its advantages over the CCC approach as well as its more feasibility in practice, the CH-based rendezvous approach is one of the significant research directions in CRNs that got more and more attention recently. However, designing distributed CH rendezvous schemes that can support the three fully-blind requirements mentioned before (i.e., asynchronous, heterogeneous, and deterministic) while minimizing the TTR performance metrics is a very difficult and challenging task. In the literature, there has been a proliferation of different CH-based schemes that were proposed to provide blind rendezvous in CRNs. The majority of these schemes were mainly designed for slow-varying CRAHNs where channel availabilities are usually stable after the sensing stage and will not change during the rendezvous process. However, the existing blind schemes have at least one of the following limitations:

(i) Limited local available channels: To ensure rendezvous within a finite time, most of the existing asymmetric and symmetric role CH-based rendezvous schemes generate their CH sequences based on the whole global channel set (GCS) in the network. However, due to the spatial and temporal variations in channel availabilities as well as the limitation of SUs sensing capabilities, the local available channel set (ACS) for each SU in practice is usually a small subset of the global set [26, 24, 27]. Thus, by following the global-based generated CH sequences, SUs would waste a lot of time attempting rendezvous on uncertain channels (i.e., the unavailable or even the randomly-replaced[1] channels). This can result in extensively long TTR especially when the number of unavailable channels is large. Even though some recent works were designed based on the local ACS, they failed to solve the issue efficiently where they either impose some unpractical restrictions or still produce relatively

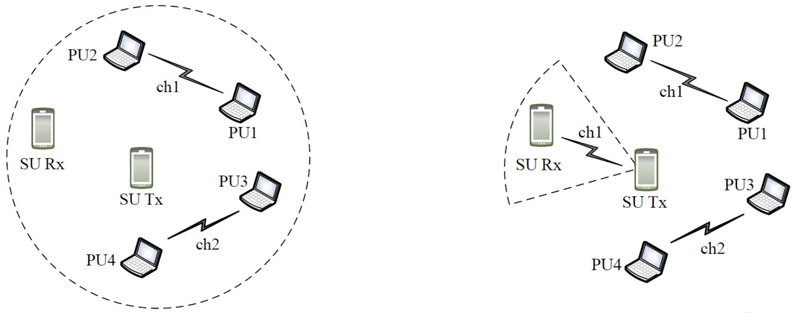
[1]Some of the global-channels-based schemes try to enhance their performance by randomly replacing the unavailable channels in the frames of their CH sequence with available ones. This replacement strategy is not effective and still results in high MTTR.

long TTR. In light of this, it is necessary to develop new blind asymmetric and symmetric role CH schemes which generate their CH sequences efficiently based on the unrestricted local ACSs only for better rendezvous performance.

(ii) Multi-radio rendezvous: Most of the existing CH schemes have been focusing on the single-radio rendezvous where each SU is equipped with a single CR that can only access one channel during each time slot. However, due to the sharply dropping cost of the wireless RF transceivers, equipping SUs with multiple cognitive radios can significantly accelerate the rendezvous process and improve the performance with an acceptable slight increase in the cost [28, 29]. In the literature, only few works have been designed to address the multi-radio rendezvous problem in CRAHNs. However, these works failed to solve the issue efficiently since some of them still generate long global-channel-based CH sequences while others adopted inefficient mathematical tools to generate their local-channel-based CH sequences. Therefore, it is desirable to develop a new blind and efficient multi-radio CH scheme that generate sequences based on the local ACSs only and which can establish faster rendezvous in multi-radio CRAHNs.

(iii) Fast PU dynamics: The majority of existing CH schemes were not designed or tailored for CRAHNs operating under fast PU dynamics, where channel availabilities can vary during the rendezvous operation itself. Ignoring these channel variations by the existing schemes when applied in such dynamic environments can produce an extremely long TTR and high collisions with PUs [30, 31]. Thus, it is desirable to develop an efficient CH-based scheme that is robust to the rapid PU dynamics in such fast-varying CRAHNs for establishing rendezvous with short TTR and high PU detection accuracy.

(iv) High density PU networks: All the existing CH-based rendezvous schemes were designed with omni-directional antennas relaying on a common assumption for their success to achieve rendezvous, which is the existence of at least a single commonly-available channel between the pair of communicating SUs. However, relaying on such assumption would not be precise for CRAHNs that are highly crowded with PUs. In such networks, the large number of active PUs can vary the channel availabilities dramatically among the neighbouring SUs especially when the total number of channels in the network is small. This may lead to the non-existence of any common available channel between a pair of neighboring SUs and hence the failure of their rendezvous process. For example, consider the simple CRAHN in Figure 1.3a which consist of two SUs that are coexisting with four PUs over a licensed spectrum of two channels. As the SUs are equipped with omni-directional antennas, if the sender SU performs channel rendezvous with its intended receiver, the rendezvous message is scattered towards all the directions. Thus, it can cause interference to all the surrounding PUs within its transmission range which is represented by the dashed circle. However, due to the interference restriction imposed by the CR concept, this is not acceptable since SUs can use only the channels that are idle from any PU activities within their transmission range. Accordingly, it is obvious that the probability of having at least one commonly-available channel between a pair of SUs under omni-directional antennas is very low since the transmission range is wide and large.



(a) Unsuccessful channel rendezvous under omni-directional antennas.

(b) Successful channel rendezvous under directional antennas.

Figure 1.3: Scenarios for pairwise channel rendezvous in a CRAHN of two channels.

One approach to overcome this serious rendezvous problem is by equipping SUs with directional antennas instead of the conventionally used omni-directional ones due to their inherent capabilities in extending the transmission range while limiting the interference [32]. In such scenario, if the sender SU performs channel rendezvous using directional antennas as shown in Figure 1.3b, its rendezvous message is only sent towards a specific direction. This indicate that directional antenna can limit the interference to PUs better than the omni-directional antenna due to its narrower and directed transmission range. Therefore, the probability of having commonly-available channels between SUs is higher which consequently enhance the probability of successful channel rendezvous significantly.

A thorough search of the existing literature yielded that the works in [32, 33] are the only proposals that address the rendezvous problem in Directional CRNs (DIR-CRNs). However, these works failed to solve the issue efficiently where the former assumes that neighboring SUs have pre-knowledge of each other's information before rendezvous (i.e, not blind) while the later incur very long rendezvous delay. Furthermore, these works were only designed for asymmetric-role environment where SUs have pre-assigned roles (i.e., SU is either a sender or receiver). Therefore, it is necessary to develop new efficient and blind asymmetric-role as well as symmetric-role schemes that are able to achieve fast and guaranteed rendezvous in DIR-CRAHNs.

1.4 Research Objectives

The aim of this thesis is to develop distributed and blind rendezvous schemes that are capable of providing guaranteed and fast rendezvous in different types of CRAHNs. The research specific objectives are as follows:

- To design and develop efficient single-radio CH rendezvous schemes for slow-varying CRAHNs where each SU is equipped with a single cognitive radio.
- To design and develop an efficient multi-radio CH rendezvous scheme for slow-varying CRAHNs where each SU is equipped with multiple CRs.

- To design and develop efficient adaptive CH rendezvous schemes that are robust to rapid PU dynamics in the fast-varying CRAHNs.

- To design and develop efficient rendezvous schemes for DIR-CRAHNs where each SU is equipped with a directional antenna CR.

1.5 Research Scope

This thesis is mainly focusing on the problem of enabling a pair of SUs to rendezvous in a commonly-available channel within a finite and short time for the purpose of link establishment in CRAHNs. The follow-on tasks after initial rendezvous such as the handshaking [34] and channel contention procedures [35] as well as the transmission of data packets [36, 37] are outside the scope of this thesis. Moreover, the developed schemes in this research assumed that SUs can detect their local available channels sets based on spectrum sensing. However, the spectrum sensing technique [38, 39] is a research issue in itself which is beyond the scope of this thesis.

While the main focus of this thesis is on the pairwise rendezvous, it is worthy to point out that multicast rendezvous (i.e,. rendezvous of multiple SUs) can be achieved easily through establishing a series of pairwise rendezvous processes that consequently allow all the SUs in the multicast group to follow a common hopping sequence for establishing rendezvous.

1.6 Main Contributions

The contributions in this thesis address the pairwise rendezvous problem in different types of CRAHNs. The main contributions can be summarized as follows:

- **Single-radio Matrix-based Channel Hopping rendezvous schemes for slow-varying CRAHNs**
  Two matrix-based CH schemes are proposed to provide asynchronous channel rendezvous in slow-varying CRAHNs; one asymmetric-role approach, called QS-CH, and one symmetric-role approach, called IQSF-CH. The proposed schemes utilize only the unrestricted local ACSs for generating their CH sequences which is desirable in distributed heterogeneous environments. Theoretical analysis for the MTTR upper-bounds of the proposed schemes have been carried out to prove their guaranteed rendezvous under the homogeneous and heterogeneous channel availability models. Furthermore, extensive simulations are conducted to study the performance of the developed schemes and illustrate their superior performance as compared to other existing single-radio CH-based rendezvous schemes.

- **A multi-radio Quorum-based Channel Hopping rendezvous scheme for slow-varying CRAHNs**
  An efficient multi-grid-quorum CH scheme, called MGQ-CH, is proposed to provide asynchronous channel rendezvous in multi-radio slow-varying CRAHNs. The guaranteed rendezvous provided by the developed scheme is proved by deriving the theoretical upper-bound of its MTTR under the homogeneous and

heterogeneous channel availability models. Furthermore, extensive simulations are conducted to evaluate the developed scheme performance and illustrate its efficiency as compared to other existing multi-radio CH-based rendezvous schemes.

- **Adaptive Quorum-based Channel Hopping rendezvous schemes for Fast-varying CRAHNs**
  To provide rendezvous in fast-varying CRAHNs, two nested cyclic-quorum based CH schemes that are robust to fast PU dynamics are proposed. The proposed schemes (refereed as NCQ-CH and MNCQ-CH) are augmented with online adaptation capabilities to further enhance their robustness to PU dynamics. The online adaptation is achieved through suitable channel ranking and quorum selection mechanisms that are efficient in estimating the fast PU dynamics. Extensive simulations are conducted to demonstrate the superior performance of the proposed schemes under fast PU dynamics, in terms of the TTR and PU detection accuracy, as compared with existing rendezvous schemes in the literature.

- **Combined Sector and Channel Hopping Schemes for efficient rendezvous in Directional-antenna CRAHNs**
  Firstly, two blind coprimality-based sector hopping (SH) schemes are proposed to establish sector rendezvous in DIR-CRAHNs; one is an asymmetric-role approach, called PES-SH, and the other is a symmetric-role approach, called IPES-SH. The proposed SH schemes are then combined with an efficient ranked CH scheme, called RQS-CH, in order to provide simultaneous sector and channel rendezvous between SUs in DIR-CRAHNs. To prove the guaranteed rendezvous of the proposed schemes, theoretical analysis for the upper-bounds of their rendezvous delay metrics have been conducted. Furthermore, extensive simulation comparisons with other related directional antenna rendezvous schemes are conducted to illustrate the significant out-performance of the developed schemes.

1.7 Organization of the Thesis

The thesis outline is presented in Figure 1.4. Each chapter in this thesis discusses the problems of establishing rendezvous in a different CRAHN type and presents the proposed schemes to solve these problems. The remainder of thesis is organized as follows:-

Chapter 2 elaborates the CR technology and its functionalities as well as the architectures of the CRNs. It also presents a comprehensive review of the previous rendezvous schemes in the literature.

Chapter 3 presents the blind rendezvous schemes that are proposed for establishing rendezvous in the single-radio slow-varying CRAHNs. This chapter contains two main sections. The first section presents a new asymmetric-role blind CH rendezvous scheme that is proposed to provide rendezvous when SUs have pre-assigned different roles prior to the rendezvous process. Meanwhile, the second section presents

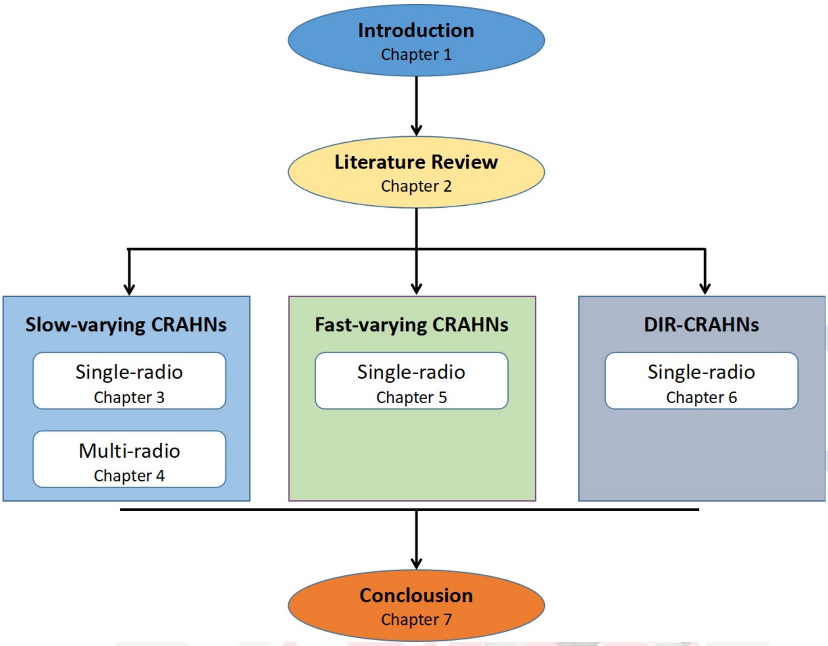


Figure 1.4: Outline of the thesis.

the symmetric-role blind CH rendezvous scheme which does not require the pre-assignment of the sender/receiver role.

Chapter 4 presents the grid-quorums-based rendezvous scheme that is developed to provide rendezvous in multi-radio slow-varying CAHRNs.

Chapter 5 presents the two adaptive CH-based rendezvous schemes that are proposed for establishing rendezvous in fast-varying CRAHNs. This chapter contains two main sections. The first section presents the nested designs of the two robust CH schemes while the second section presents the adaptive channel ranking and quorum selection mechanisms.

Chapter 6 presents the combined sector and channel hopping schemes that are proposed for providing efficient blind rendezvous in DIR-CRAHNs. This chapter contains three main sections. The first two sections present the design and analysis for the asymmetric-role as well as the symmetric-role SH schemes that are proposed to provide sector rendezvous between SUs. Meanwhile, the third section presents the design and analysis for the overall solutions which combine the SH schemes with an efficient ranked CH scheme in order to establish successful sector and channel rendezvous simultaneously.

Finally, chapter 7 concludes the thesis and provide directions for future research.

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BIODATA OF STUDENT

The student received the B.Sc. degree in Computer Engineering from Jordan University of science and technology (JUST) in 2006, and the M.Sc. degree in Computer Science from University Putra Malaysia (UPM), Malaysia, in 2011. Currently, he has been working toward the PhD degree in the Department of Computer and Communication Systems, Faculty of Engineering, University Putra Malaysia (UPM) since Feb 2013. Before joining UPM, he worked for two years as a lecturer at Faculty of Computer Science and Information Technology at Thamar University, Yemen. His research interests include rendezvous schemes and MAC protocols in cognitive radio networks.

LIST OF PUBLICATIONS

Journals Papers

A. Al-Mqdashi, A. Sali, M. J. AbdelRahman, N. K. Noordin, S. J. Hashim, and R. Nordin. Efficient rendezvous schemes for fastvarying cognitive radio ad hoc networks. *Transactions on Emerging Telecommunications Technologies*, 28 (12) August 2017, DOI: 10.1002/ett.3217, (IF:1.61).

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Conferences Papers

A. Al-Mqdashi, A. Sali, N. K. Noordin, S. J. Hashim, R. Nordin, and M. J. Abdel-Rahman. An efficient quorum-based rendezvous scheme for multi- radio cognitive radio networks. *Proceedings of the IEEE 3rd International Symposium on Telecommunication Technologies (ISTT)*. November 2016, Kuala Lumpur, MALAYSIA, pp: 59-64, (Best paper award).