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A Study on Hopping Based Control Channel Establishment for Dynamic Spectrum Access

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Abstract

This dissertation provides a study on hopping based control channel establishment (CCE) for dynamic spectrum access (DSA). DSA technique was proposed to improve spectrum efficiency, where unlicensed secondary users (SUs) can utilize licensed spectrum without interfering licensed primary users (PUs) opportunistically. A pair of SUs wishing to communicate with each other needs to exchange control information using control links firstly in DSA networks. The procedure of CCE is referred to as a rendezvous process, plays a critical role in configuring a DSA network. CCE in a DSA network is a challenging problem. To cope with the problems of control channel saturation and channel blocking by PUs, channel hopping (CH) based rendezvous algorithms are commonly used for CCE in DSA networks. In CH based rendezvous algorithms, each SU generates its own CH sequence (CHS) according to the CH algorithms, and then accesses available channels according to the generated CHS sequentially. Control channels between SUs can be established on the channels that they access simultaneously.

The main contributions of this dissertation are summarized as follows. Firstly, a heterogeneous radios based rendezvous (HRR) algorithm is proposed to guarantee rendezvous within upper bounded time for the SUs in heterogeneous DSA networks. Then, a modified enhanced HRR (MEHRR) algorithm is proposed to achieve full rendezvous diversity for avoiding blocking PUs for a long time while increasing the successful probability of CCE. Finally, the performance in terms of rendezvous channel quality, channel loading, and optimal radio allocation manner is evaluated for the proposed algorithms.

Chapter 1 introduces the concept of DSA and the importance of the CCE for DSA firstly. Then, the advantages of the CH based CCE compared with other techniques and methods are described. Moreover, the scope and contributions of this

dissertation are summarized while presenting the disadvantages of the conventional CH based algorithms.

Chapter 2 reviews some representative CH rendezvous algorithms firstly. Then, the pros and cons of the conventional CH based algorithms as well as the motivation of our proposed algorithms are presented.

Chapter 3 proposes the HRR algorithm. The HRR algorithm consists of the multi-radio based rendezvous (MRR) algorithm and the single radio based rendezvous (SRR) algorithm. The MRR algorithm and the SRR algorithm are utilized to generate CHSs for the SUs with multiple radios and the SUs with single radio, respectively. Theoretical analysis and simulation results verify that CCE can be guaranteed among the SUs in heterogeneous DSA networks within upper bounded time using the HRR algorithm.

Chapter 4 proposes the MEHRR algorithm to achieve full rendezvous diversity for the SUs in heterogeneous DSA networks. Theoretical analysis and simulation results verify that CCE with full rendezvous diversity can be guaranteed among the SUs in heterogeneous DSA networks within upper bounded time using the MEHRR algorithm.

Chapter 5 evaluates the performance in terms of the rendezvous channel quality, the channel loading, and the optimal radio allocation manner for the proposed HRR algorithm and the MEHRR algorithm.

Finally, Chapter 6 concludes this dissertation while discussing the future work.

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Chapter 1

Introduction

This dissertation is concerned with two main topics. The first one is to tackle control channel establishment (CCE) for heterogeneous dynamic spectrum access (DSA) networks. The second one is to achieve full diversity based on the first topic, i.e., achieving CCE on all commonly available channels for any pair of unlicensed secondary users (SUs) in heterogeneous DSA networks.

In this chapter, background about DSA is firstly introduced. Then, the knowledge related to CCE for heterogeneous DSA networks including fundamentals, techniques and methods, challenges, and metrics is presented. Finally, the scope and contributions of the dissertation are shown.

1.1 Background

Radio Spectrum is not only a key enabler of technological innovations in wireless communications, but it also plays an important role as an economic growth engine [1]. It is predictable that mobile data traffic will grow up to 1000-fold by 2020 due to the increase of broadband services and the burst traffic of point to point transmission [2]. This explosive growth in mobile traffic imposes a huge challenge to future wireless networks. Along with the rapid development of smart communities, the requirement for spectrum resources grows rapidly [3–5]. Currently, the usage of spectrum resources and regulation of radio emissions are coordinated by national regulatory bodies like the federal communications commission (FCC). Most of the spectrum in the sub 6 GHz frequency has been allocated to licensed holders, also known as primary users (PUs), on a long-term basis for large geographical regions [6, 7]. However, various experimental tests and measurements reveal the fact that a large portion of the assigned spectrum is used sporadically and geographical variations in the utilization of assigned spectrum ranges from 15% to 85% with a high variance in time [8]. Meanwhile, the unlicensed spectrum which is free to use for wireless devices, such as the industrial, scientific, and medical (ISM) band is overcrowding with the increasing demands for wireless services [9]. Thus, the static allocation has led to artificial shortage of spectrum in the sub 6 GHz band. The low utilization efficiency of scarce spectrum resource under static spectrum allocation has gained accelerating focus in the past decades [10, 11]. To increase the underlying spectrum utilization for mobile communication, it is necessary to search for new techniques [12].

To solve this issue, DSA technique was introduced to improve the spectrum efficiency [13–15]. With the DSA technique, unlicensed secondary users (SUs) can access vacant licensed spectrum in either temporal, frequency, or space domain without interfering licensed primary users (PUs) opportunistically [16–19]. Figure 1.1 illustrates the operation of DSA [20], which will be adopted throughout this

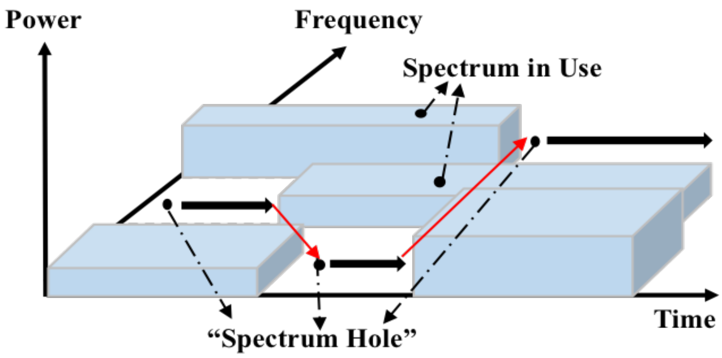


Figure 1.1: Operation of DSA.

dissertation. To support DSA, the FCC held an auction on licenses of advanced wireless services (AWS)-3 bands, including 1695-1710 MHz, 1755-1780 MHz, and 2155-2180 MHz bands [21], process on enabling shared access to TV white spaces [22]. Besides, ongoing progress in 3.5 GHz and 5 GHz proceedings [23, 24] show promise in advancing this vision of increased spectrum sharing in multiple bands, including between commercial and federal government users.

The architecture of DSA networks is shown in Figure 1.2, which consists of primary networks and secondary networks. The secondary network can be further classified as infrastructure-based DSA network (i.e., the network in red solid circle in Figure 1.2) and DSA network without infrastructure (i.e., the network in red dotted circle in Figure 1.2) according to the network architecture [25]. In the infrastructure-based DSA networks, a infrastructure (e.g., secondary based station) can make decisions on how to avoid interfering with primary networks. On the contrary, SUs need to decide their actions by themselves. Because the available channels for SUs are time varying, the widespread access strategy in DSA is sense-then-transmit [26]. The SUs firstly sense the licensed spectrum, then they can access the idle licensed spectrum that is not occupied by PUs. Spectrum sensing is used by the SU to find free available spectrum holes in order to avoid interfering with PUs [27]. In order to enable dynamic and opportunistic utilization of spectrum, SUs have to local each other in varied multiple available channels environments [28].

1.2 Control Channel Establishment for DSA

1.2.1 Fundamentals

In wireless communications, control channels as central channels are essential [29]. Control channel can be used for a wide variety of services, from neighbor discovery, channel access negotiation, propagation of network topology, and routing information updates [30–32]. Multiple control channels are employed for sending control

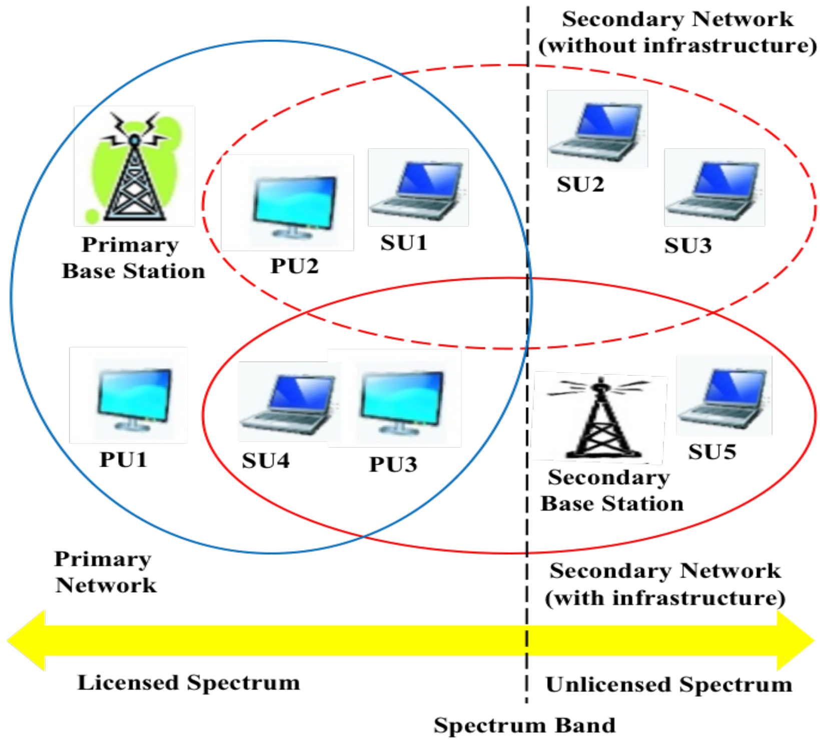


Figure 1.2: Architecture of DSA networks.

information to achieve different functionalities in many networks, such as GSM cellular communication system [33]. In GSM cellular communication, the broadcast channels carry the network/cell identity, the structure of the current control channels and synchronization information. Meanwhile, the common control channels are used for channel assignment and paging notification [34]. In general, When one user wants to transmit data to the other user, it firstly transmits a request-to-send (RTS) packet on the control channel. Upon receiving the RTS, the other user responds with a clear-to-send (CTS) packet on the control channel to confirm the data channel between them [35].

Same as conventional networks, control channel establishment in DSA networks also encounters a fundamental issue, which refers to how a sender and its intended receiver meet with each other on common available channels [36]. Prior to data transmission, SUs firstly need to learn about the presences of their target SUs, and establish control links with them. A pair of SUs wishing to communicate with each other needs to exchange control information using the control links to establish communication links. The procedure of CCE is referred to as a rendezvous process, which plays a critical role in configuring a DSA network [37–39]. Compared with traditional networks, control channel establishment (CCE) is much more challenging in DSA networks due to the varying available channels.

1.2.2 Techniques and Methods

Existing solutions for the rendezvous problem can be classified into centralized manner [40–43] and distributed manner [44–48]. Under the centralized manner, a centralized controller (e.g., Base Station (BS) in IEEE 802.22 Wireless Regional Area Networks (WRAN)) is necessary for accomplishing rendezvous [50]. A dedicated control channel is employed for exchanging information in this system. Most early works on this system to facilitate the rendezvous process owing to the fact that it is simple to implement. However, the dedicated control channel is not scalable, flexible, or robust [51]. The dedicated control channel may face problem of controlling channel saturation when the bottleneck of system becomes closely tied to the its capacity. This problem may lead to the result that no more users are allowed to achieve rendezvous in large scale networks. Moreover, it is vulnerable to jamming attacks [52]. Besides, a global available dedicated control channel may not exist while may be uncertain, because the available channel set of an SU depends on its location relative to PUs and PU activity [53].

Under the distributed manner, rendezvous problem can be solved without any centralized controller, which is more preferable. The distributed manner can be further classified into single global control channel schemes [44, 45], a group control channel schemes [46, 47] and blind rendezvous schemes [48, 49]. Single global control channel schemes incur overhead and may act as a single point of failure while a group control channel schemes have overhead in finding and identifying the control channels [54]. If no control channel is available, the SUs need to figure out a way to find each other blindly, which is referred to as the blind rendezvous problem [55]. Blind rendezvous algorithms are applied for the rendezvous problem in distributed DSA networks where there is no centralized controller, which is more flexible and scalable [56–58]. In blind rendezvous, a representative technique is channel hopping (CH), i.e., each SU hops among its available channels according to its CH sequence (CHS) generated by the CH based algorithm to attempt to rendezvous with its target SUs [59, 60]. SUs can exchange their control information to establish data transmission channels after they access commonly available channels [61, 62].

An example of blind rendezvous process is shown in Fig. 1.3. In the example, the available channel set for SU_A is $\{c_1, c_2, c_3\}$ while that for SU_B is $\{c_2, c_3, c_4, c_5, c_6\}$. The commonly available channel set between SU_A and SU_B is $\{c_2, c_3\}$. SU_B starts CH process four time slots later than SU_A. From Fig. 1.3, we can see that both of SU_A and SU_B access the same channel c_2, i.e., SU_A and SU_B rendezvous on channel c_2 at the seventh time slot of SU_B. Then, the control channel between them can be established on channel c_2. Due to the varying available channels for SUs, it is

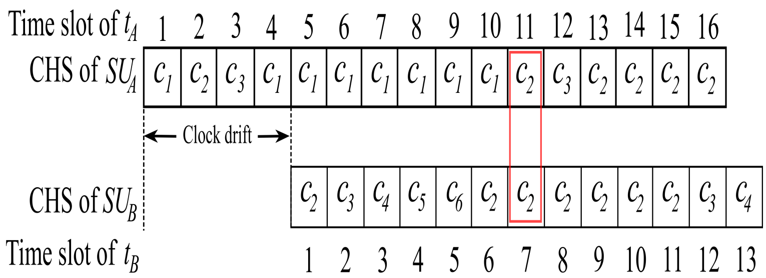


Figure 1.3: An example of blind rendezvous.

necessary to design CHS for SUs that can make them achieve rendezvous quickly. The blind rendezvous techniques will be reviewed in Chapter 2 in detail.

1.2.3 Challenges

In the subsection, we list several of the most challenging aspects of blind rendezvous based CCE for DSA networks. In distributed DSA networks, SUs have no consensus about the channels that their target SUs access before rendezvous, which imposes great challenges [63]. Besides, there also exist some other challenges for designing a CH-based rendezvous algorithm, these include, but not restricted to the following challenges:

(i) Asynchronous local clock. It is necessary to support the asynchronous scenario in distributed DSA networks due to the difficulty and unrealistic to achieve clock synchronization between spatially dispersed SUs [64].

(ii) Heterogeneity. SUs in heterogeneous DSA networks may have different spectrum sensing capabilities, different ranges of observable channels and different numbers of radios [65–67].

(iii) Symmetric roles. Symmetric-role algorithms that do not need pre-assigned role (sender or receiver) are more applicable in practice. Because the prior knowledge of roles is unrealistic, and it is impossible to design different rules for different SUs according to their roles [68].

(iv) Anonymous information. Unique IDentifications (IDs) of SUs are utilized to generate CH sequences for the ID-based CH algorithms [69]. Because IEEE 802.22 uses a 48-bit universal MAC address to identify SUs, the IDs of SUs are usually generated by exploiting these MAC addresses in the existing ID-based CH algorithms [70, 71]. The unique ID can be expressed as a binary string with equal length terms as ID string [72]. In general, the Time To Rendezvous (TTR) for the ID-based CH algorithms is a multiplier of the length of ID string [73]. The TTR for the non-ID based CH algorithms is not related to the length of ID string. In general, the non-ID based algorithms have shorter TTR compared with the ID-based CH algorithms. Thus, the non-ID based CH algorithms are more favorable.

It is necessary to design CHSs for SUs in DSA networks that can be utilized under the above scenarios while achieving rendezvous quickly.

1.2.4 Metrics

Among the extensive research literatures on CH algorithms, four performance metrics, namely Expected TTR (ETTR), Maximum TTR (MTTR), rendezvous diversity, and channel loading are usually of the top concerns. We list their detailed information as follows.

- ETTR: the ETTR is the average (expected) latency before the first successfully rendezvous [74].
- Maximum time to rendezvous (MTTR): The maximum time for a pair of SUs rendezvous with each other under different clock drifts. It is necessary to make SUs achieve rendezvous quickly due to the time-varying available channels [75].
- Rendezvous diversity: the minimum number of channels on which a pair of SUs can rendezvous. By maximizing rendezvous diversity, the probability of rendezvous on commonly available channels can be increased while reducing the impact of blocking PU for a long time. If two SUs can rendezvous on all commonly available channels between them, we say that they can achieve full rendezvous diversity [77–79]. [76].
- Channel loading: the maximum proportion of SUs which can rendezvous on the same channel at the same time slot. Minimizing the channel loading can reduce channel congestion [80].

In addition to the metrics mentioned above, rendezvous channel quality is also considered in the dissertation. Rendezvous on channels with better quality can increase the successful probability of CCE after rendezvous. As described above, it is necessary to design CHSs that can achieve low ETTR, MTTR and channel loading, high rendezvous diversity and rendezvous channel quality.

1.3 Scope and Contributions of the Dissertation

1.3.1 Motivation of the Dissertation

To shorten the rendezvous process under the challenges mentioned in Chapter 1.2.3, multi-radio technique is utilized when designing CH algorithms in several latest researches [81–84,89]. In the multi-radio scenario, one SU can access multiple channels simultaneously. Meanwhile, as the multi-radio wireless devices become realistic and popular, the cost of that is dropping sharply as well. Hence, the TTR can be reduced by a large amount by multiple radios while the additional cost is low. However, the existing multi-radio CH algorithms present several disadvantages, which are listed as follows: (1) Rendezvous cannot be guaranteed within finite time and hence the MTTR is infinity for the random algorithm in [82, 83]. (2) Different SUs are implicitly assumed to be equipped with the same number of radios for the Adaptive Rendezvous (AR) algorithm in [81] and the parallel sequence algorithm in [82, 83], which is unpractical for heterogeneous DSA networks. (3) The number of radios for each SU is implicitly assumed to be more than one for the Role-based Parallel Sequence (RPS) algorithm in [43, 44] and the Adjustable Multi-Radio Rendezvous (AMRR) algorithm in [84]. Rendezvous can not be guaranteed when at least one SU is equipped with one radio for a pair of SUs. (4) Different radios of one SU may access the same channel at the same time for the AMRR algorithm in [84], the Multiple-radios Sunflower-Sets-based pairwise rendezvous (MSS) algorithm in [89], the independent sequence algorithm, the parallel sequence algorithm and the RPS algorithm in [82,83], which is a waste of radio resources. (5). The MTTR can not be shortened for the SUs with multiple radios compared with the SUs with one radio for the independent sequence algorithm in [82, 83].

To solve the problems mentioned above in conventional algorithms, we firstly propose a heterogeneous radios based rendezvous (HRR) algorithm. The HRR algorithm can achieve rendezvous in heterogeneous DSA networks while different radios of one SU can be guaranteed to access different channels simultaneously. To achieve full rendezvous diversity, we present a modified enhanced HRR (MEHRR) algorithm.

1.3.2 Summary of the Dissertation

This dissertation consists of six chapters as shown in Fig. 1.4. In Chapter 1, the background of CCE for DSA is introduced. In Chapter 2, the state-of-the-art hopping based CCE algorithms for DSA are reviewed. In Chapter 3, the HRR algorithm is proposed. In Chapter 4, the MEHRR algorithm is proposed. In Chapter 5, the performance in terms of the channel loading, the channel quality, and the optimal radio allocation is evaluated for the proposed algorithms. Finally, the dissertation is concluded and the future work is discussed in Chapter 6.

1.3.3 Scope of the Dissertation

As described in Chapter 1.2.2, the CCE methods for DSA networks can be classified into centralized manner and distributed manner. The distributed manner can be further classified into a global control channel schemes, a group control channel

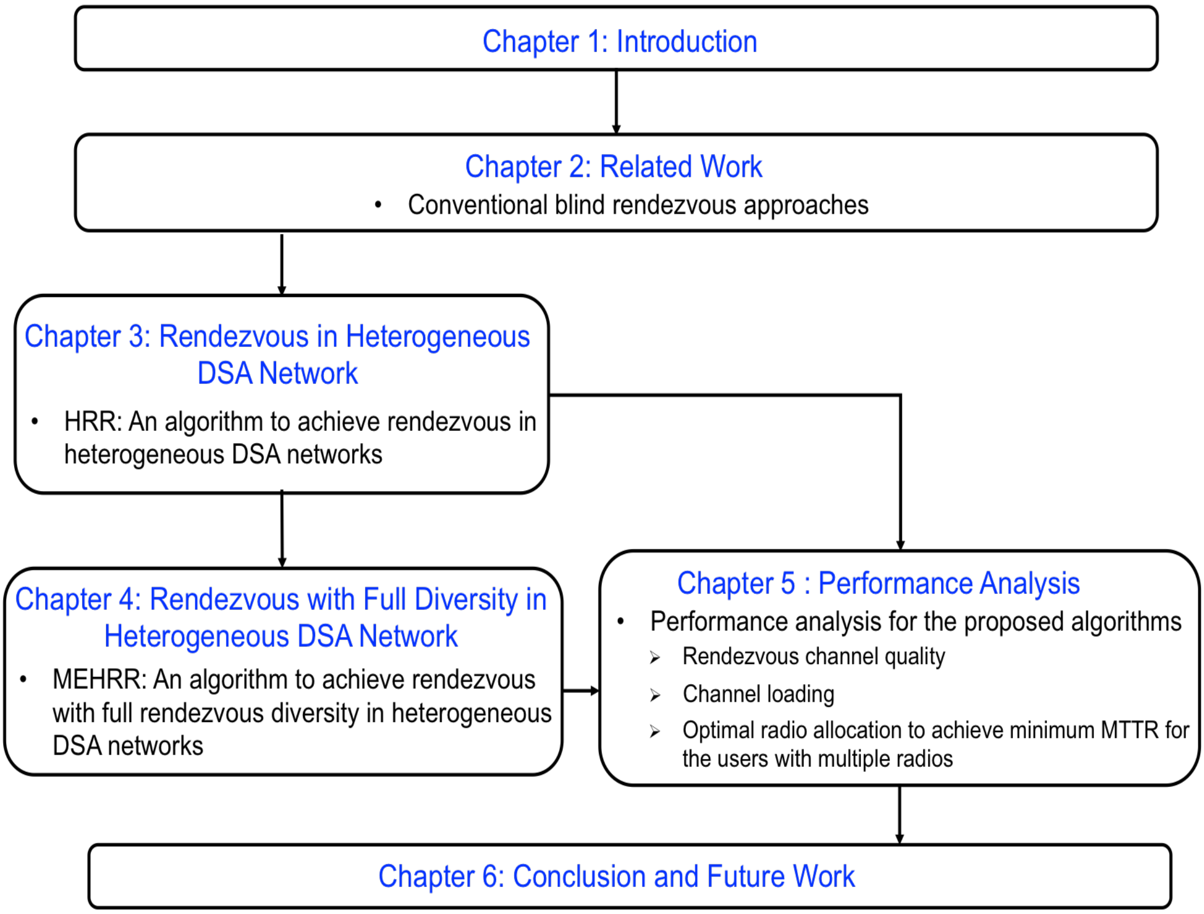


Figure 1.4: Configuration of this dissertation.

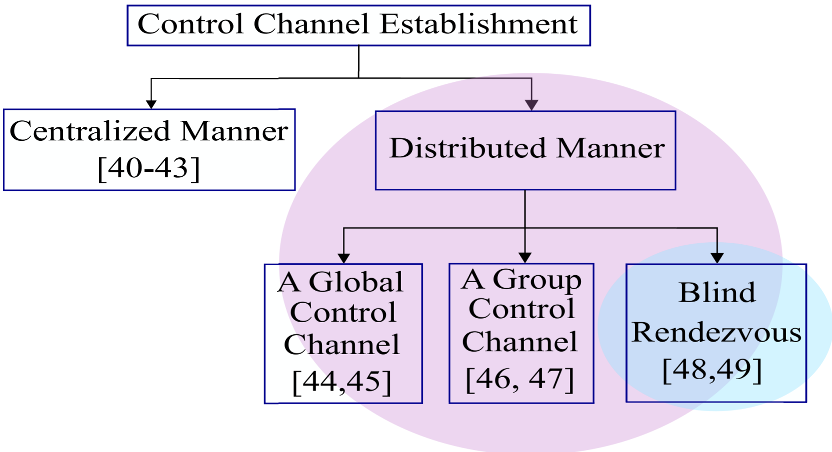


Figure 1.5: The classification of CCE methods for DSA networks.

schemes, and blind rendezvous schemes. Blind rendezvous schemes are more preferable for CCE in DSA networks due to its flexible and scalable. In this dissertation, we focus on the design of blind rendezvous algorithms. The classification of the CCE methods for DSA networks is shown in Fig. 1.5.

In Fig. 1.6, we show the position of our proposed algorithms to perform blind rendezvous for dynamic spectrum access networks in the literature. A wide variety of blind rendezvous techniques have been proposed for CCE in DSA networks. These techniques can be classified into single radio-based CH schemes, multiple radios-based CH schemes, and heterogeneous radios-based CH schemes.

There are some techniques that are utilized in single radio based CH schemes, e.g., random scheme, ID string-based schemes, sunflower-sets based scheme, quorum-based schemes and jump-stay based schemes. With the rapid development of hardware, multi-radio based CH schemes that can attempt rendezvous on multiple channels simultaneously are more preferable, because it can reduce the TTR to a great extent while the hardware cost is low. There are several multi-radio based CH algorithms, e.g., single radio based parallel schemes and role-based schemes. However, these multi-radio based CH algorithms cannot be well utilized in heterogeneous DSA networks. The reason is that SUs have to equip with same number of radios or at least two radios are necessary for each SUs in multi-radio based CH schemes. Heterogeneous radios based CH can be utilized in the DSA networks where SUs can be equipped with any number of radios. Single radio based independent scheme is an representative heterogeneous radios based CH scheme where single radio based CH scheme is utilized to generate CHS for each radio independent. Although single radio based independent schemes can be utilized in heterogeneous DSA networks, the MTTR of the existing algorithms is large. Hence, we propose radio based selectable schemes, i.e., HRR algorithm and MEHRR algorithm to achieve rendezvous for the SUs in heterogeneous DSA networks while shortening TTR as much as possible. The details of the blind rendezvous techniques in related work will be detailed presented in Chapter 2 while the novel CH schemes will be presented in Chapter 3 to Chapter 5.

In Fig. 1.7, we show some of main related metrics to the blind rendezvous schemes for DSA networks. These metrics have been elaborately discussed in Chapter 1.2.4. We highlight the ones that considered in our work, and which we deal with in the remainder of this dissertation. In Chapter 3, the ETTR and the MTTR of the HRR algorithm are considered. The MTTR and rendezvous diversity of the MEHRR algorithm are analyzed in Chapter 4. In Chapter 5 carries out the performance analysis for the proposed HRR algorithm and the MEHRR algorithm in terms of channel loading, rendezvous channel quality, and optimal radio allocation to achieve minimum MTTR for the SUs with multiple radios.

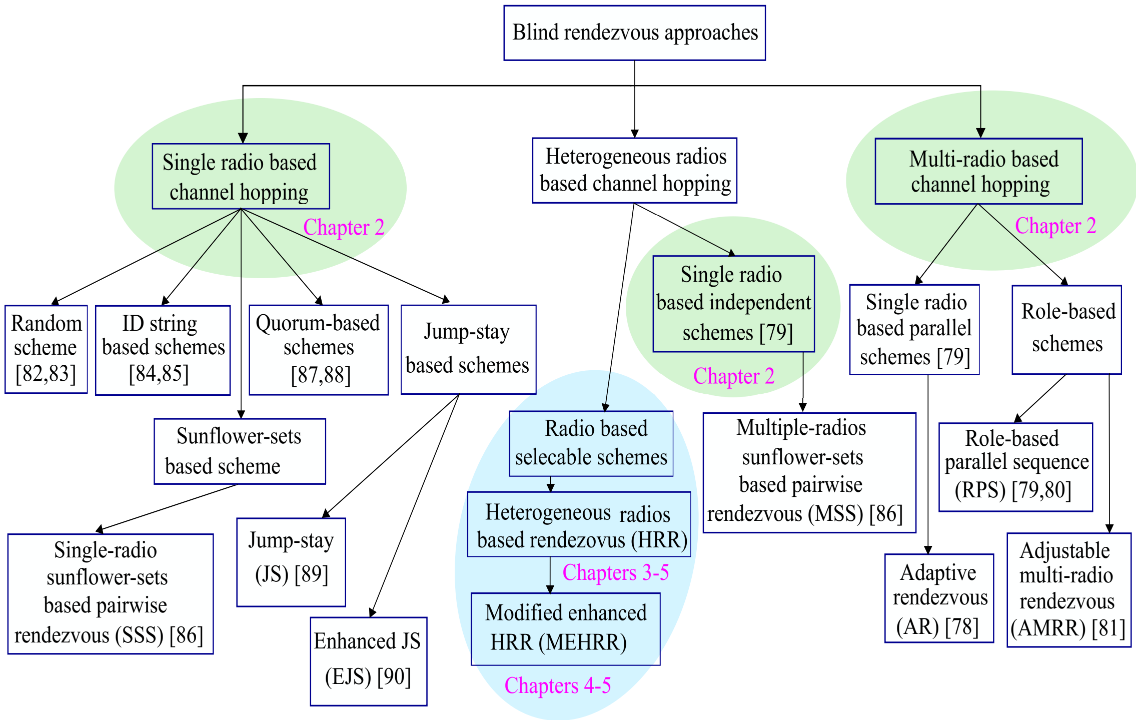


Figure 1.6: Blind rendezvous techniques in the literature.

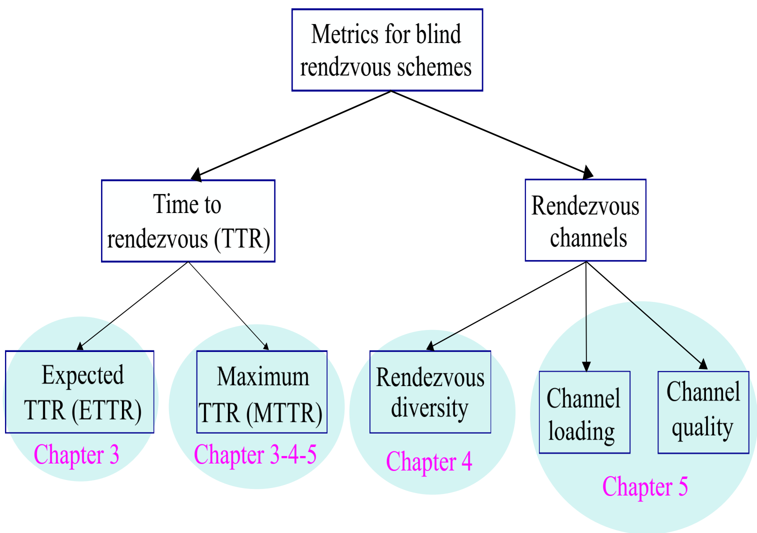


Figure 1.7: Metrics for blind rendezvous schemes.

1.3.4 Contributions of the Dissertation

To address the disadvantages of the conventional CH algorithms mentioned in Section 1.3.1, a new CH algorithm termed as HRR algorithm is firstly developed in this dissertation. Both symmetric model and asymmetric model are considered. In symmetric model, SUs have the same available channel sets. Symmetric model is suitable for the SUs who are located in a relatively small area compared with their distance to PUs, in which scenario, the available channels for different SUs are influenced by the same PUs. In asymmetric model, different SUs have different available channel sets. Asymmetric model is applicable when the geographical locations of SUs are far apart from each other, in which scenario, the available channels for different SUs may be influenced by different PUs. Both symmetric model and asymmetric model have their applicable situation in practice. Besides, SUs can achieve rendezvous by using the HRR algorithm regardless of the number of radios. Moreover, it can be guaranteed that the radios of SUs access different channels at the same time by the HRR algorithm.

To achieve full rendezvous diversity for the SUs in heterogeneous DSA networks, a fast blind CH algorithm termed as MEHRR algorithm is presented. It is proved that the SUs in heterogeneous DSA networks can establish control channels with full rendezvous diversity using the MEHRR algorithm by theoretical analysis. Moreover, minimum channel loading also can be achieved by the MEHRR algorithm. The main contributions of this dissertation can be summarized as follows.

- An available channel distribution (ACD) algorithm is presented, by which available channels are evenly divided among different radios of one SU before generating CHSs. Since each radio only access the available channels allocated to it, the proposed ACD algorithm can guarantee that different radios of one SU access different channels at the same time when the SU is equipped with multiple radios.

- To guarantee rendezvous in heterogeneous DSA networks, the HRR algorithm is proposed, which consists of a designed single radio based rendezvous (SRR) algorithm and a designed multiple radios based rendezvous (MRR) algorithm. The HRR algorithm is a radio based selectable CH algorithm. When the SUs are equipped with one radio, their CHSs are generated by the SRR algorithm while the MRR algorithm is utilized to generate CHSs for the SUs with multiple radios.

- The MTTR for the HRR algorithm is theoretically derived under the symmetric model as well as the asymmetric model. Besides, the HRR algorithm is evaluated by extensive simulation. Both theoretically analysis and simulation results demonstrate that the HRR can guarantee rendezvous for the SUs in heterogeneous DSA networks.

- To achieve full rendezvous diversity, the MEHRR algorithm including the modified enhanced SRR (MESRR) algorithm and the enhanced MRR (EMRR) scheme is proposed. The MESRR algortihm and the EMRR alrorithm are designed to generate CHSs for the SUs with a single radio and multiple radios, respectively. SUs can achieve rendezvous within upper bounded time by the MEHRR algorithm regardless of the number of radios. Besides, full rendezvous diversity and minimum channel loading can be achieved by the MEHRR algorithm.

- The MTTR with full rendezvous diversity for the MEHRR algorithm is derived by theoretical analysis. Moreover, the channel loading of the CHSs generated by the MEHRR algorithm is also derived by theoretical analysis, which shows that the MEHRR algorithm can achieve minimum channel loading.

- The performance in terms of rendezvous channel quality for the HRR algorithm is evaluated, which shows that the frequent of rendezvousing on the channels with higher qualities can be increased by the HRR algorithm.

- The optimal allocation of multiple radios that can achieve minimum MTTR with full rendezvous diversity for the SUs using the MEHRR algorithm is analyzed.

The remainder of this dissertation is organized as follows:

In Chapter 2, the related works related to hopping based CCE for DSA are shown. the single-radio-based CH algorithms are firstly presented. Because MTTR can be shortened for the SUs with multiple radios, the CH algorithms based on multiple radios are then emphatically reviewed.

In Chapter 3, the HRR algorithm is proposed. Rendezvous between SUs in heterogeneous DSA networks can be guaranteed by using the HRR algorithm. The HRR algorithm consists of the MRR algorithm and the SRR algorithm. The MRR algorithm is utilized to generate CHSs for the SUs with multiple radios while the SRR algorithm is utilized to generate CHSs for the SUs with single radio. For guaranteeing that the radios of one SU can access different available channels, the ACD algorithm is also presented. Furthermore, it is proved that rendezvous among SUs in heterogeneous DSA networks can be guaranteed by theoretical analysis. Moreover, simulation results also verify that the proposed HRR algorithm can be well utilized to guarantee rendezvous among SUs in heterogeneous DSA networks.

In Chapter 4, the MEHRR algorithm is proposed. The MEHRR algorithm consists of the MESRR algorithm and the EMRR algorithm. Rendezvous with full diversity can be achieved within upper bounded time for the SUs in heterogeneous DSA networks. Theoretical analysis and simulation results verify that the MEHRR algorithm can be utilized to establish control channels with full rendezvous diversity for the SUs in heterogeneous DSA networks

In Chapter 5, the channel quality, channel loading, and optimal radio allocation for the proposed CH based CCE algorithms are emphatically analyzed and verified.

Finally, in Chapter 6, this dissertation is concluded while the future work is discussed.

An outline of the main contents in Chapters 2, 3, 4, and 5 are presented in Tables 1.1, 1.2, 1.3, and 1.4 respectively.

Table 1.1: Outline of Chapter 2.

<table>
<tr><td>Background</td><td>CH as one representative blind rendezvous technique is applied for the CCE problems in distributed DSA networks where there is no centralized controller, which is more flexible and scalable.</td></tr>
<tr><td>Main Contents</td><td>Review conventional CH algorithms.</td></tr>
<tr><td>Conventional Approaches</td><td>1. Single radio based CH algorithms (the CH algorithms that are utilized for the DSA networks where SUs are equipped with one radio) [85–93]:
Random algorithm [85, 86]
ID-string based algorithms [87, 88]
Sunflower-sets based algorithm [89]
Quorum-based algorithms [90, 91]
Jump-stay based algorithms [92, 93]
2. Multi-radio based CH algorithms (the CH algorithms that are utilized for the DSA networks where SUs are equipped with multiple radios) [81–84]:
Single radio based parallel algorithms [81, 82]
Role-based algorithms [82–84]
3. Heterogeneous radios based CH algorithms (the CH algorithms that are utilized for the DSA networks where SUs are equipped with either single radio or multiple radios) [82, 89] :
Single radio based independent algorithms [89]</td></tr>
<tr><td>Contributions</td><td>Review the basic principles of each kind of CH algorithms.
Comparison of each kind of CH algorithms in terms of pros and cons.
Point out the motivation of the algorithms proposed in this article (HRR and MEHRR).</td></tr>
</table>

Table 1.2: Outline of Chapter 3.

Background	• Multi-radio based CH algorithms can shorten TTR to a great extent while the additional cost is low. • In heterogeneous DSA networks, the SUs may be equipped with either one radio or multiple radios. • It is necessary to design CH algorithms that can achieve low TTR due to the varying available channels.
Objective	• Design CH algorithm that can be applied in heterogeneous DSA networks while shortening TTR as much as possible.
Conventional Approaches	1. Multi-radio based CH algorithms [81–84]: • Single radio based parallel algorithms [81, 82] • Role-based algorithms [82–84] 2. Heterogeneous radios based CH algorithms [82, 89] : • Single radio based independent algorithms [89]
Limitation of Conventional Approaches	1. Multi-radio based CH algorithms: • Can not guarantee rendezvous for SUs in heterogeneous DSA networks. • Different radios of one SU may access the same channel at the same time. 2. Heterogeneous radios based CH algorithms: • Rendezvous can not be guaranteed, or the MTTR is large.
Proposed Solution	• HRR algorithm - Design CH algorithm includes two independent CHS generation methods that can be selected by SUs according to their numbers of radios. - Allocate channels to each radio before generating CHSs.
Summary of result	• Rendezvous can be guaranteed while the MTTR can be shortened for the SUs in heterogeneous DSA.

Table 1.3: Outline of Chapter 4.

Background	• Rendezvous diversity: the minimum number of channels on which a pair of SUs can rendezvous. • Full rendezvous diversity: SUs can rendezvous on all commonly available channels between them. • By achieving full rendezvous diversity, the impact of blocking PU for a long time can be reduced while the successful probability of control channel establishment after rendezvous can be increased.
Objective	• Design CH algorithm that can achieve full rendezvous diversity for the SUs in heterogeneous DSA networks.
Conventional Approaches	• HRR algorithm [Chapter 3]
Limitation of Conventional Approaches	• HRR algorithm - Can not achieve full rendezvous diversity for the SUs in heterogeneous DSA networks.
Proposed Solution	• MEHRR algorithm - By designing CHS generation method that can guaranteeing SUs rendezvous on different available channels during different CHS period.
Summary of result	• Full rendezvous diversity can be achieved for the SUs in heterogeneous DSA.

Table 1.4: Outline of Chapter 5.

Background	• Rendezvous on channels with better quality can increase the successful probability of CCE after rendezvous. • Channel loading: the maximum proportion of SUs which can rendezvous on the same channel at the same time. Minimizing the channel loading can reduce channel congestion. • It is necessary to design CH algorithm that can achieves low TTR.
Objective	• Performance evaluation for the proposed algorithms in terms of channel quality, channel loading, and optimal radio allocation to achieve minimum MTTR.
Related Approaches	• HRR algorithm [Chapter 3] • MEHRR algorithm [Chapter 4]
Contributions	• Performance evaluation for the HRR algorithm in terms of channel quality by simulation. • Channel loading evaluation for the MEHRR algorithm by theoretical analysis. • Optimal radio allocation for the MEHRR algorithm by theoretical analysis and simulation.
Summary of result	• Rendezvous channel quality can be increased by the HRR algorithm. • Minimum channel loading can be achieved by the MEHRR algorithm. • Derived the optimal radio allocation manner for the MEHRR algorithm.

Chapter 2

Related Work

In this Chapter, we firstly review some representative CH rendezvous algorithms according to their categories. As described in Chapter 1.3.3, existing CH algorithms fall into three categories according to the number of radios for SUs, which are single radio based CH algorithms, multi-radio based CH algorithms, and heterogeneous radios based CH algorithms. Then, we compare the representative CH rendezvous algorithms in terms of their advantages and disadvantages.

2.1 Review of the Representative CH Rendezvous Algorithms

2.1.1 Single Radio Based CH Algorithms

Most of the previous work has been focusing on the single-radio-based CH algorithm in which each SU is only equipped with one radio and can only access one channel at the same time slot [85–96]. In this subsection, we review several kinds of representative single-radio-based CH algorithms, which are random algorithm, JS based algorithms, Quorum-based algorithms, and ID string based algorithms, and sunflower-sets based algorithm.

- Random algorithm [85, 86]

  The main idea of the random algorithm is that SU randomly selects an available channel in each time slot to attempt rendezvous with its target SUs on that channel. Although the random algorithm is easier to be implemented, the upper bound of MTTR is infinite for this algorithm. That is, rendezvous can not be guaranteed by the random algorithm.

- ID string based algorithms [87, 88]

  Onymous algorithms rely on distinct IDs of SUs to achieve rendezvous. However, SUs in distributed environments are anonymous in most cases, and they do not possess an explicit ID. Moreover, SUs are easy to be attacked by adversaries once their IDs are exposed. Thus, anonymous algorithm without any individual identities are favorable.

- Sunflower-sets based algorithm [89]

  The SSS algorithm is an representative sunflower-sets based algorithm. It generates CHSs based on sunflower lemma.

- Quorum-based algorithms [90, 91]

  Quorum-based algorithms generate CHSs using quorum systems.

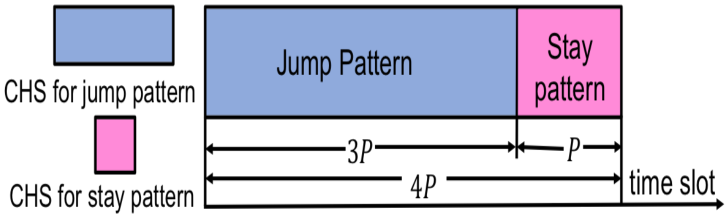


Figure 2.1: Structure of the CHSs generated by the EJS algorithm.

- Jump-stay based algorithms [92–94]

  The basic idea of the jump-stay based algorithms is that CHSs are generated in rounds while each round consists of jump pattern and stay pattern. During the jump pattern, SU keeps jumping to different channels while SU stays at one specific available channel during the stay pattern. The EJS algorithm [93] is a typical jump-stay based algorithm. Same as the jump-stay based algorithms, the EJS algorithm generates CHS in rounds. Each round lasts for $4P$ time slots for the EJS algorithm, where P is the prime number greater than the number of licensed channels. The jump pattern of the EJS algorithm lasts for $3P$ time slots while the stay pattern of the EJS algorithm lasts for P time slots. The channel index for the jump pattern is generated by $j = ((i + t \times r - 1) \bmod P) + 1$, where i is the initial starting-index, r is the step length, t is the time slot. i an integer in $[1, P]$. It is randomly selected from $[1, P]$ at the beginning of the rendezvous process while switching every round. r is randomly selected from $[1, P]$, and keep constant during the rendezvous process. SUs alway stay at the channel whose index equals to r during the rendezvous process. The structure of CHS generated by the EJS algorithm in one round is shown in Fig. 2.1.

2.1.2 Multi-Radio Based CH Algorithms

Multi-radio-based CH algorithm can sharply shorten TTR compared with single-radio-based CH algorithm [82]. In multi-radio-based CH algorithm, multiple radios can attempt to rendezvous simultaneously. Besides, the extra cost is low owe to the rapid development of hardware. Hence, multi-radio-based CH algorithms are more preferable to achieve rendezvous for SUs in DSA networks. Multiple radios are only utilized in a few existing literatures. The existing multi-radio-based algorithms can be classified into single-radio-based parallel algorithm and role-based algorithms. Then, we review these two categories of multi-radio-based CH algorithms respectively.

- Single-radio-based parallel algorithms [82]

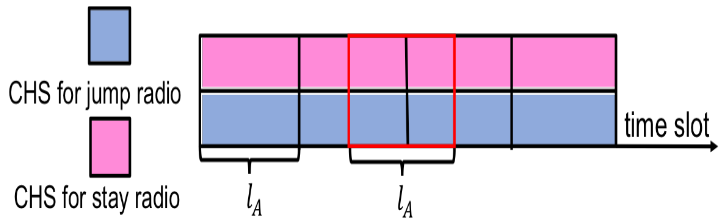


Figure 2.2: Structure of the CHSs generated by the role-based algorithms.

Single-radio-based parallel algorithms are a kind of the simplest way to implement the single-radio-based CH algorithms for the setting with multiple radios. The main idea of the single-radio-based parallel algorithms is that CHSs are generated by the existing single-radio-based algorithm on all radios in parallel. However, SUs need to be equipped with same number of radios for the single-radio-based parallel algorithms. Hence, single-radio-based parallel algorithms is not applicable in heterogeneous DSA networks.

- AR algorithm

  In the AR algorithm [81], the available channels are firstly allocated to each radio. Then, each radio generates its CHS based on the allocated available channel set independently. Although the AR algorithm can be utilized for the SUs with any number of radios, SUs have to be equipped with same number of radios for guaranteeing rendezvous. As we described in last Chapter, SUs may be equipped with different numbers of radios, the AR algorithm is not applicable for heterogeneous DSA networks.

• Role-based algorithms [82–84]

  The basic idea of the role-based algorithms is that the radios are partitioned into two groups, which are jump radios and stay radios. The CHSs are generated in round. Stay radio stays at the same channel during one period while changing stay channel per period. Jump radio keeps jumping on different channels. Hence, rendezvous can be guaranteed between the stay radios of one SU and the jump radios of the other SU. The structure of the CHSs generated by the role-based algorithms in one round period is shown in Figure. 2.2, where l_A is the length of one period for the CHSs generated by the role-based algorithms. There are two representative role-based algorithms in literature, which are the RPS algorithm [82,83] and the adjustable AMRR algorithm [84]. Then, we present these two algorithms in detail.

- RPS algorithm

  In the RPS algorithm, radios are divided into two groups, one dedicated radio and some general radios. The dedicated radio stays at one specific channel for

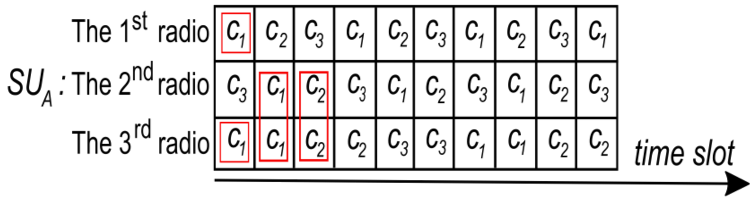


Figure 2.3: CHSs generated by the role-based algorithm.

a while, while the general radios keep on switching to access different available channels in the round-robin manner. If the generated channel is unavailable for SUs, it will be replaced by randomly selecting an available channel. The CHSs are generated based on global licensed channel set in the RPS algorithm. The length of one period for the CHSs generated by the RPS algorithm $l_A = \lceil \frac{P}{k_A} \rceil$, where k_A is the number of jump radios for SU_A. Although the RPS algorithm supposes that the number of radios for SUs can be equal to 1, the upper bounds of MTTR will be infinity when the number of radios for SUs is equal to 1. Besides, different radios of one SU may access the same channel at the same time slot (e.g., both the first radio and the third radio access the same channel c_1 at the first time slot in Fig. 2.3), which is a waste of radio resources.

- AMRR algorithm

In the AMRR algorithm, radios of one SU are divided into two groups, which are stay radios and jump radios. Jump radios parallelly access the available channels while stay radios stay at one specific channel for a while and then switch to stay at another channel during next duration. The different between the RPS algorithm and the AMRR algorithm is the number of stay radios. In the RPS algorithm, there is only one stay radio. In the AMRR algorithm, a group of stay radios can exist. Besides, the CHSs are generated only based on the available channels in AMRR algorithm instead of global licensed channel in AMRR algorithm. The length of one period for the CHSs generated by the AMRR algorithm $l_A = \lceil \frac{C_A}{k_A} \rceil$, where C_A is the number of available channels for SU_A. Fig. 2.4 shows the rendezvous guarantee for role-based CH algorithms. As shown in Figure 2.4, rendezvous can be achieved between the stay radios of the SU with larger CHS period and the jump radios of the other SU for both of the RPS algorithm and the AMRR algorithm. The reasons can be summarized as follow. Assume that the CHS period of SU_A is larger than that of SU_B, i.e., $l_A > l_B$. During the overlapping l_A time slots, each stay radio of SU_A stays at the same channel. Besides, all available channels can be visited once during any continuous l_B time slot by the jump radios of SU_B. Hence, SU_A and SU_B can rendezvous on the channels that visited by the stay radios of

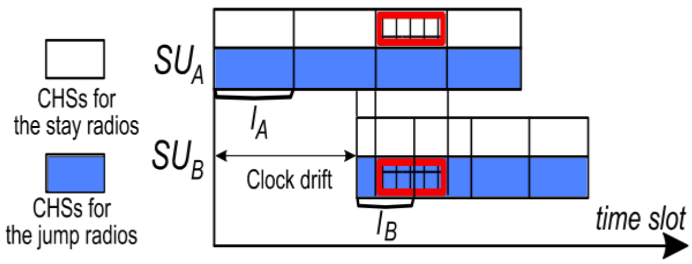


Figure 2.4: Rendezvous guarantee

SU_A. Compared with the RPS algorithm, the AMRR algorithm can further reduce the TTR. However, the AMRR algorithm has the same disadvantages as those of the RPS algorithm. That is, at least two radios are necessary while different radios of one SU may access the same time simultaneously.

As description above, the existing multi-radio-based CH algorithms can shorten the TTR compared with single radio based CH algorithms. However, they cannot be well utilized in heterogeneous DSA networks. The comparison of the multi-radio based CH algorithms is shown in Table 2.1.

2.1.3 Heterogeneous Radios Based CH Algorithms

Heterogeneous radios based CH algorithms can be applied for CCE in heterogeneous DSA networks [82, 89]. As far as we know, there is only one kind of heterogeneous radio based CH algorithm, which is single radio-based independent algorithm [82]. In single radio-based independent algorithm, an existing single radio-based algorithm is utilized to generate CH sequence for each radio.

Multiple-radios sunflower-sets based pairwise rendezvous (MSS) algorithm is one of the single-radio-based parallel algorithms, which is based on the SSS algorithm [89]. Mathematical construction of sunflower sets is exploited to develop the SSS rendezvous algorithm. The SSS algorithm is used to generate periodic CHSs for the first radio while the MSS algorithm cyclically rotates the sequence of the previous radio for the remaining radios. For instance, the CHS for the second radio of SU_A is generated by cyclically rotating the CHS of its previous radio (i.e., the first radio) by $2P_A$ time slots, where P_A is the smallest prime number not smaller than the number of local available channels for SU_A. However, P_A needs to be not smaller than 3 in the MSS algorithm, which is inapplicable to the condition when the number of the available channels for SU_A is equal to 1. Besides, different radios of one SU may access the same channel at the same time. Moreover, the TTR is large compared with multi-radio-based CH algorithms. In summary, although the single radio-based CH algorithm can achieve rendezvous for the SUs in heterogeneous DSA networks,

Table 2.1: Comparison of the multi-radio based CH algorithms.

Alogrithms	• Single radio based parallel algorithms: * AR algorithm • Role-based algorithms: * RPS algorithm * AMRR algorithm
Pros and Cons of the algorithms	• Single radio based parallel algorithm: * AR algorithm - Pros: Can be applied for the SUs with one radio. - Cons: Not applicable for heterogenous DSA networks (SUs have to equipped with same number of radios). • Role-based algorithms: * RPS algorithm * AMRR algorithm - Pros: Can be applied for the scenario where SUs have different numbers of radio. Can achieve shorter MTTR. - Cons: At least two radios (one stay radio and one jump radio) are necessary.

the TTR is large. Hence, we propose the HRR algorithm to shorten the TTR for SUs in heterogeneous DSA networks.

2.2 Comparison of the CH Algorithms

In this section, we compare the conventional schemes (single radio based CH schemes, multi-radio based CH schemes, and existing heterogeneous radios based CH scheme) in terms of MTTR, full rendezvous diversity, and their applicable network scenarios. As shown in Fig. 2.5 and the presentation in last section, single radio based CH schemes is utilized for the DSA networks where SUs are equipped with one radio. SUs with single radio based CH schemes can only attempt rendezvous on one channel at the same time slot. Hence, the MTTR for the single radio based CH schemes is large while it cannot be utilized in heterogeneous DSA networks where SUs may with multiple radios. Some of single radio based CH schemes can achieve full rendezvous diversity. Multi-radio based CH schemes can attempt rendezvous on multiple channels at the same time slot using different radios, which can reduce MTTR to a great extend compared with single radio based CH schemes. However, at least two radios are necessary or the number of radios for SUs have to be same for the multi-radio based CH schemes. Hence, the multi-radio based CH schemes cannot be utilized in heterogeneous DSA networks. Some of the multi-radio based CH schemes can achieve full rendezvous diversity. Heterogeneous radios based CH schemes can be utilized in heterogeneous DSA network while can achieve full rendezvous diversity. However, the MTTR is much larger than the multi-radio based CH schemes. To design CH algorithms that can achieve low MTTR in heterogeneous DSA networks, we propose the HRR algorithm in Chapter 3. By designing CH algorithm including two independent CHS generation methods that can be selected by SUs according to their numbers of radios, the HRR can be utilized in heterogeneous DSA networks while the MTTR can be reduced to a great extend compared with the existing heterogeneous radios based CH schemes. However, the HRR cannot achieve full rendezvous diversity in some scenarios. Hence, we propose the MEHRR algorithm in Chapter 4 to achieve full rendezvous for the SUs by designing CHS generation method in heterogeneous DSA networks. The details of the HRR algorithm and the MEHRR algorithm will be presented in Chapter 3 and Chapter 5, respectively.

Schemes	MTTR	Heterogeneous DSA networks	Full rendezvous diversity
Single radio-based CH schemes	Large	×	✓
Multi-radio-based CH schemes	Small	×	✓
Existing heterogeneous radios based CH schemes	Large	✓	✓
Our proposed HRR scheme	Small	✓	×
Our proposed MEHRR scheme	Small	✓	✓

Figure 2.5: Comparison of the CH algorithms.

Chapter 3

Rendezvous in Heterogeneous DSA Network

In this Chapter, we propose a HRR algorithm to achieve rendezvous in heterogeneous DSA networks with shorter MTTR for the SUs with multiple radios.

3.1 Motivation

As described Chapter 2, the multi-radio based conventional algorithms can shorten the MTTR to a great extend compared with the single radio based CH algorithms and existing heterogeneous radios based CH algorithms, we design the HRR algorithm based on the multi-radio based CH algorithms. The multi-radio based conventional algorithms including single-radio based parallel algorithms and role-based algorithms. In the single-radio based parallel algorithms, the number of radios for SUs have to be same. In the role-based algorithms, at least two radios are needed. Hence, the multi-radio-based conventional algorithms cannot be directly utilized in heterogeneous DSA networks. Hence, we aim to design a CH algorithm that can achieve rendezvous in heterogeneous DSA networks with shorter MTTR for the SUs with multiple radios. The summary of the conventional CH algorithms is shown in Fig. 3.1.

3.2 Objective and Basic Idea

3.2.1 Objective

The objective of this Chapter is to design a CH algorithm that

1. Can guarantee rendezvous for the SUs with any number of radios.
2. Can shorten the TTR when SUs are equipped with multiple radios.
3. Guarantee different radios of one SUs access different channels simultaneously.

3.2.2 Basic Idea

- The basic idea to achieve the objectives 1 and 2.

  We present the HRR algorithm, which is a radio based selectable algorithm. The HRR algorithm includes two methods (SRR and MRR) to generate CHSs for the SUs with one radio and multiple radios, respectively.

- The basic idea to achieve objective 3 is summarized as follow.

  Firstly, available channels are allocated to each radio before generating CHSs. The channel allocation procedure can guarantee that there is no identical available channels for any two radios of one user. Then, CHS is generated for each radio only use the available channels allocated to them.

<table>
<tr><td rowspan="2">Multi-radio based conventional algorithms</td><td>Single radio based parallel algorithms</td><td>• The number of radios for SUs needs to be same</td><td rowspan="2">Advantage:
Can shorten the MTTR to a great extend compared with the single radio based algorithms</td></tr>
<tr><td>Role-based algorithms</td><td>• At least two radios are needed
• The number of radios for SUs needs to be same</td></tr>
<tr><td colspan="2">Existing heterogeneous radios based CH algorithm</td><td colspan="2">• The MTTR is much larger than multi-radio based conventional algorithms</td></tr>
</table>

Figure 3.1: Summary of the conventional CH algorithms.

3.3 Overview of the HRR Algorithm

In this section, we give an overview of the HRR algorithm.

3.3.1 Flowchart of the HRR Algorithm

The algorithm that we proposed is the HRR algorithm in this Chapter. The ACD algorithm, the SRR algorithm, and the MRR algorithm are invoked by the HRR algorithm. To make the algorithms easy to understand, we add a flowchart to present the HRR algorithm as Fig. 3.2. In the HRR algorithm, SU generates CHSs based on the number of its radios. If the SU is equipped with one radio, the CHS is generated by the SRR algorithm. If the SU is equipped with multiple radios, the available channels are firstly allocated to each radio using the ACD algorithm. Then, generating CHS for each radio based on its allocated available channels using the MRR algorithm. After generating CHS, SUs can access channels according to the generated CHS to attempt rendezvous.

3.3.2 Achievement of Objective

In this subsection, we present the basic idea of achieving the objectives by the HRR algorithm.

- Objectives 2 and 3.

  To achieve objectives 2 and 3, we design CH algorithm based on role-based CH algorithms. The reason that we design CH algorithm based on role-based CH algorithms is that it can be utilized for the SUs with different numbers of radios while the TTR can be sharply shortened compared with single radio based channel hopping algorithm. As reviewed in Chapter 2, the basic idea of role-based CH algorithms is that the radios are partitioned into two groups, which are stay radios and jump radios. All available channels are visited once

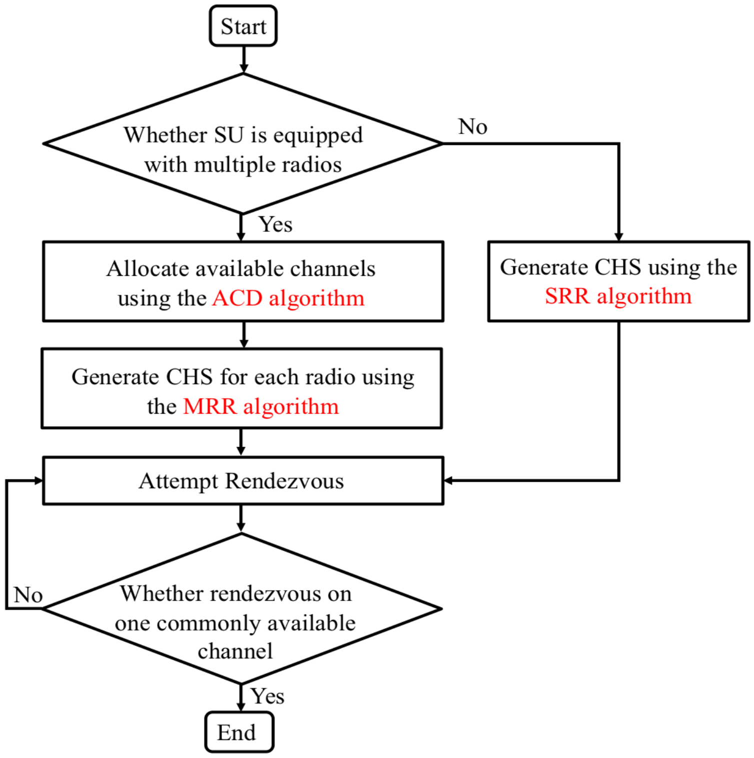


Figure 3.2: Flowchart of the HRR algorithm.

during any continuous l_i time slots, where l_i is the period length of the CHSs generated by the role-based CH algorithms. Rendezvous can be achieved for the SUs with multiple radios by the role-based CH algorithms. However, different radios of one SU may access the same channel at the same time slot, which is a waste of radio resource. Hence, to solve this disadvantage, in our proposed HRR algorithm, we firstly allocate the channels to each radio. The allocation process is summarized as follow. Firstly, allocate one channel to each stay radio to access. Then, the available channels except the channels that have been allocated to the stay radios are divided to each jump radio before generating CHSs. By this allocation manner, there is no identical allocated available channel for any two radios of one SU after allocating channels to each radio. Then, the CHS for each radio is generated only using the available channels allocated to them. Hence, different radio may not access the same channel simultaneously in our proposed HRR algorithm. To make it easy to understand, we show an example in Fig. 3.3. As shown in Fig. 3.3, the available channel set is $1, 2, 3, 4, 5, 6, 7, 8, 9$. There are two stay radios and three jump radios for the SU. Channel 1 and channel 2 are firstly allocated to the first stay radio and the second stay radio, respectively. Then the left available channels $3, 4, 5, 6, 7, 8, 9$ are allocated to the jump radios, respectively. The allocated channel set to the first jump radio is $3, 6, 9$. The allocated channel set to the second jump radio is $4, 7$. The allocated channel to the third jump

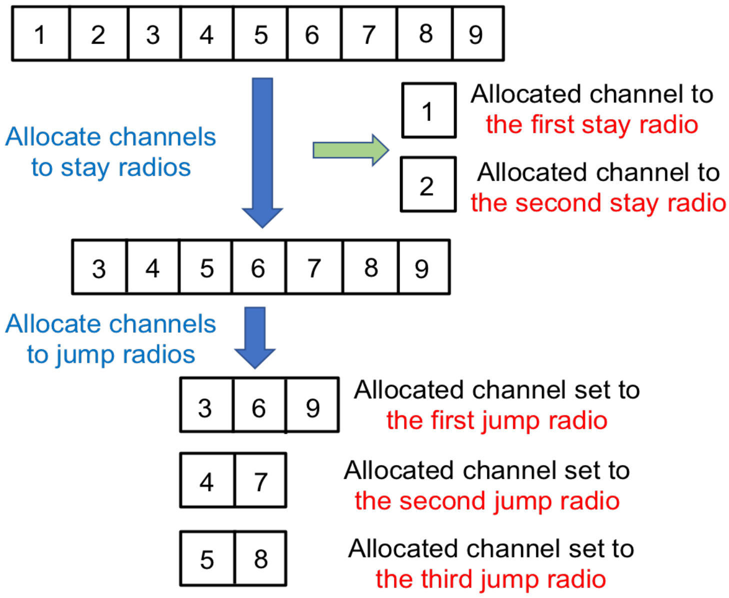


Figure 3.3: An example of channel allocation.

radio is $5, 8$. Then, each radio generates channels based on the allocated channel. Hence, different radios of one SU must access different channels at the same time.

- Objective 1.

Because at least two radios are necessary for the conventional role-based CH algorithms, e.g., RPS algorithm and AMRR algorithm, these algorithms cannot be utilized for SUs with one radio. To achieve objectives 1, i.e., design CH algorithm that can be utilized and can guarantee rendezvous no matter how many radios of the SUs have, we design HRR (radio based selectable) algorithm including two methods (SRR and MRR) to generate CHSs for the SUs with one radio and multiple radios, respectively. As shown in Fig. 3.4, because rendezvous cannot be guaranteed using the conventional single radio-based CH scheme and conventional multi-radio-based CH scheme directly, we design the HRR algorithm including the SRR algorithm and the MRR algorithm by ourselves.

To well present that the reasons that rendezvous cannot be guaranteed using the conventional single radio-based CH scheme and conventional multi-radio-based CH scheme, we shown an example in Fig. 3.5, where the EJS scheme is utilized as the conventional single radio-based CH scheme while the AMRR scheme is utilized as the conventional multi-radio CH scheme. Firstly, rendezvous cannot be achieved between stay pattern of the EJS scheme and the AMRR scheme, because SU always stay at the same channel for the EJS scheme during stay pattern. In asymmetric scenario, the available channels

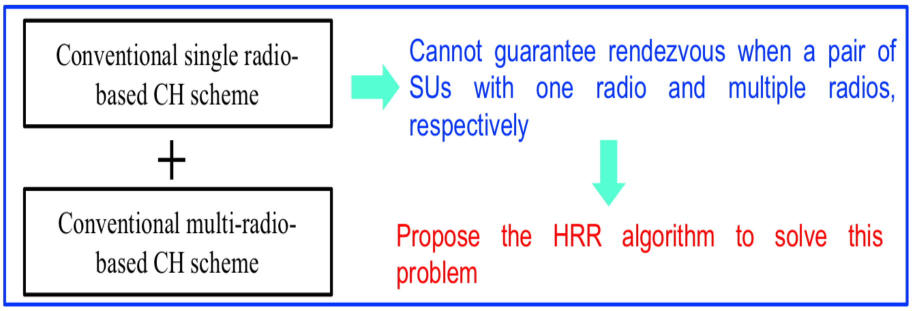


Figure 3.4: Motivation of CH algorithm design.

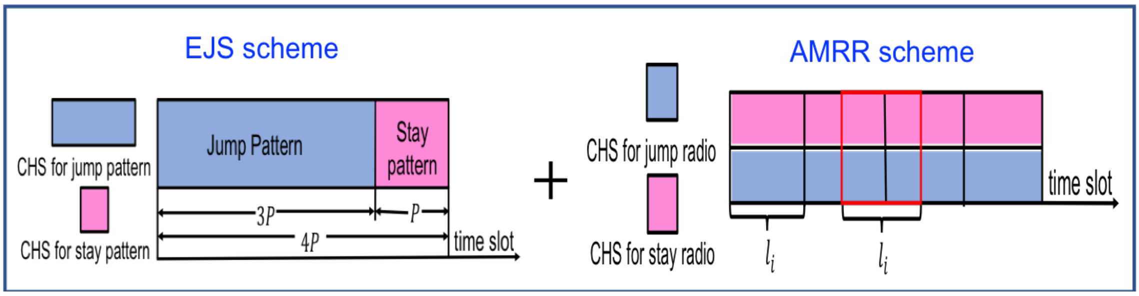


Figure 3.5: An example of conventional CH schemes combination.

may different for SUs. If the channel that one SU stays at is not available for the other SU, rendezvous will not happen between the EJS scheme and the AMRR scheme. Besides, rendezvous cannot be achieved between jump pattern of the EJS scheme and the AMRR scheme. The reasons are list as follow. All available channels are visited once during P for the EJS scheme while stay radios stay at the same channel during l_i for the AMRR scheme. Because $l_i < P$, during the overlapping, the SU with one radio may not access the channel that the stay radios of the SU with multiple radios stay at.

Hence, to achieve objective 1, we present the SRR algorithm based the EJS algorithm and the MRR algorithm based on the AMRR algorithm.

Fig. 3.6 shows the structure comparison of the CHS generated by the EJS algorithm and our proposed SRR algorithm in one period. The main idea of the SRR algorithm is to add one second stay pattern to guarantee rendezvous between the SUs with one radio and multiple radios, respectively. In the second stay pattern, SU stays at the same channel during one period while changing stay channels for different periods. To further reduce the TTR as much as possible while guaranteeing rendezvous, the length of the jump pattern is reduced to $2P$ from $3P$.

Fig. 3.7 shows the structure comparison of the CHS generated by the AMRR algorithm and our proposed MRR algorithm in one period. The length of one period for the CHS generated by the AMRR algorithm change to w_A form l_A after dividing channels to each radio, where $l_A = \lceil \frac{C_A}{k_A} \rceil$, $w_A = \lceil \frac{C_A-(m_A-k_A)}{k_A} \rceil$. C_A is the number of available channels while k_A is that of jump radios. However, we cannot guarantee

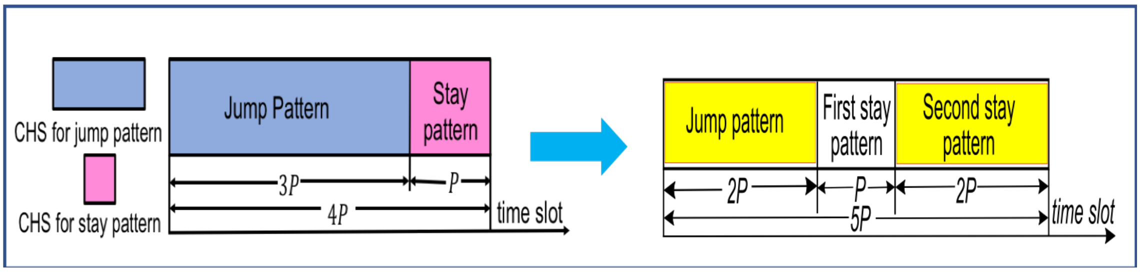


Figure 3.6: The structure comparison for the EJS algorithm and the SRR algorithm.

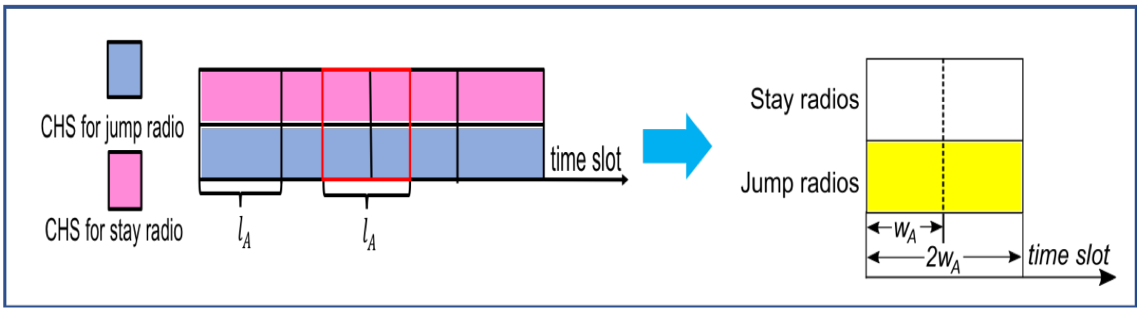


Figure 3.7: The structure comparison for the AMRR algorithm and the MRR algorithm.

that every channel can be visited once during w_A. Hence, rendezvous cannot be guaranteed when both of SUs with multiple radios. To solve this problem, we extend the length of one period from w_A to $2w_A$.

Then, we present the HRR algorithm in detail. The rest of this chapter is organized as follows. Chapter 3.4 describes the system model and formulates the problem that we aim to solve in this chapter. Chapter 3.5 presents the HRR algorithm in detail. Chapter 3. 6 analyzes the proposed HRR algorithm in terms of MTTR by theoretical analysis. Chapter 3.7 evaluates the proposed HRR algorithm in terms of ETTR and MTTR under different scenarios by simulation.

3.4 System Model and Problem Formulation

In this section, the system model and the formulation of the CH based rendezvous problem are presented.

3.4.1 System Model

A DSA network with N non-overlapping licensed channels denoted as $\mathcal{N} = \{c_1, c_2, \cdots c_i, \cdots, c_N\}$ is considered, where c_i is the i^{th} licensed channel in DSA network. P is the smallest prime number greater than N. The available channel set of SU_A is referred to as $\mathcal{C}_A$. The number of available channels for SU_A is C_A. These available channels are indicated as $\mathcal{C_A} = \{C_A(1),\ C_A(2), \cdots, C_A(i), \cdots, C_A(C_A)\}$, where $C_A(i)$ represents the i^{th} available licensed channel for SU_A. Without loss of generality, we consider the rendezvous between a pair of SUs, such as SU_A and SU_B. Besides, We assume that there exists at least one commonly available channel between SU_A and SU_B, i.e., $\mathcal{C_A} \cap \mathcal{C_B} \neq \emptyset$. The rendezvous between a pair of SUs can be extended to multiple pairs of SUs. Typically, the TTR is usually in the order of tens of milliseconds, which is very small compared with the PU dynamic [51]. Therefore, the status of channels (available or unavailable) is assumed to be static during the rendezvous process. The network time is divided into time slots. The length of each time slot is equal to $2t_e$. t_e is the sufficient time for SUs to successfully complete the processes of beaconing, handshaking, and establishing a link if they access the same available channel at the same time slot. In general, $t_e = 10$ms according to the IEEE 802.22 [71]. The local clock of SU_A is t_A. The clock drift between SU_A and SU_B is denoted as δ_{AB}.

SU_A is equipped with M_A ($M_A \geq 1$) radios while SU_B is equipped with M_B ($M_B \geq 1$) radios. Note that M_A may be not equal to M_B in heterogeneous DSA networks. SU_A can access M_A channels at each time slot to attempt rendezvous with other SUs. When $M_A > 1$, the radios of SU_A are generally divided into jump radios and stay radios. Assume that the number of jump radios for SU_A is equal to J_A. Hence, the number of stay radios for SU_A will be $Y_A = M_A - J_A$. The available channel sets for the stay radios and the jump radios of SU_A is denoted as $\mathcal{C}_A^S$ and $\mathcal{C}_A^J$, respectively. Note that $\mathcal{C}_A^J = \mathcal{C}_A \backslash \mathcal{C}_A^S$. For guaranteeing that the radios of one SU access different channels at the same time slot, the available channels for the jump radios of SU are first allocated to each jump radio before generating CHSs. The set consisting of the available channel sets for the jump radios of SU_A is denoted as $\mathcal{C}_A^{J*}$. The available channel set for the j^{th} radio of SU_A is $\mathcal{C}_A^{J*}(j)$. The length of half period of the CHS generated by the MRR algorithm for SU_A is w_A, where $w_A = \left\lceil \frac{C_A - Y_A}{J_A} \right\rceil$. In order to explicitly present the proposed algorithm, we define $C[i]$ and C as the i^{th} channel and the number of channels in the channel set $\mathcal{C}$, respectively.

3.4.2 Problem Formulation

The CH rendezvous problem is how to devise a fully distributed CH algorithm whereby each SU autonomously generates its CHS such that the SU can achieve small ETTR and bounded MTTR, in spite of random clock drift between them.

The CHS for SU_A can be denoted as $\mathcal{S}_A = \left\{\mathcal{S}_A^1, \mathcal{S}_A^2, \cdots, \mathcal{S}_A^{x_A}, \cdots, \mathcal{S}_A^{M_A}\right\}$, where $S_A^{x_A}$ is the CHS for the x^{th} radio of SU_A. The $S_A^{x_A}$ during T time slots can be denoted as $\{S_A^{x_A}(1), S_A^{x_A}(2), \cdots, S_A^{x_A}(t_A), \cdots, S_A^{x_A}(T)\}$, where $S_A^{x_A}(t_A)$ is the channel that the x^{th} radio of SU_A accesses at its t^{txh} local time slot. The channel set consisting of

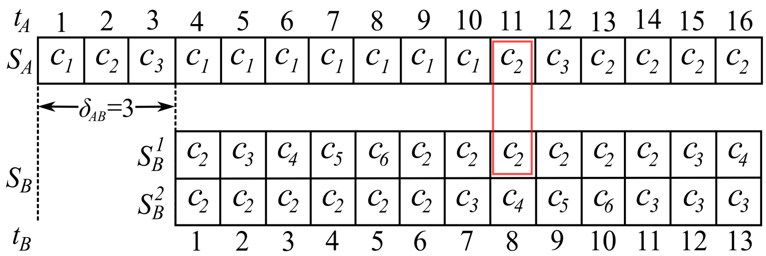


Figure 3.8: An example of CH rendezvous.

the channels that SU_A accesses at its t^{th} local time slot is denoted as $\mathcal{S}_A(t_A)$, which can be expressed as:

$$\mathcal{S}_A(t_A) = \left\{S_A^1(t_A), S_A^2(t_A), \cdots, S_A^{x_A}(t_A), \cdots, S_A^{M_A}(t_A)\right\}.$$

The CH rendezvous problem for multiple radios scenario is different with that for single radio scenario. In the multiple radios scenario, rendezvous can be achieved when any radio of one SU and any radio of its target SU access the same channel simultaneously. Hence, a new formulation for the multi-radio-based CH rendezvous problem needs to be presented, which can be formulated as:

If $\forall \delta_{AB}, \forall \mathcal{C}_A, \mathcal{C}_B, \exists c \in \mathcal{C}_A \cap \mathcal{C}_B, x_A, x_B,\ s.t.\ S_A^{x_A}(t_A) = S_B^{x_B}(t_A + \delta_{AB}) = C$, and C is available for SU_A and SU_B at time slot t_A, then the rendezvous is achieved. Note that δ_{AB} is the clock drift between SU_A and SU_B.

Let $\Gamma(A, B, \delta_{AB})$ denote the TTR between SU_A and SU_B given that the local clock of SU_A is δ_{AB} time slots behind that of SU_B. The TTR is indexed in accordance with the local clock left behind. This idea is natural because the zeroth slot of the clock left behind denotes when both of SUs start CH [72].

Fig. 3.8 illustrates an example of CH rendezvous process, where $\mathcal{C}_A = \{c_1, c_2, c_3\}$, $\mathcal{C}_B = \{c_2, c_3, c_4, c_5, c_6\}$, SU_B starts CH process behind SU_A for $\delta_{AB} = 3$ time slots, $M_A = 1$, and $M_B = 2$. In this case, the TTR is indexed in accordance with the local clock of SU_B. From Fig. 3.8, we can see that SU_A and SU_B rendezvous with each other on channel c_2 at the 8^{th} time slot of SU_B. Hence, the $\Gamma(A, B, \delta_{AB}) = t_B = 8$ while the rendezvous channel is c_2.

In this chapter, we analyze and evaluate the performance of the HRR algorithm in terms of ETTR and MTTR. The ETTR can be expressed as

$$ETTR(A, B) = E[\min \Gamma(A, B, \delta_{AB})],$$

where $E[\cdot]$ denotes the expection operation. The MTTR can be expressed as

$$MTTR(A, B) = \max_{\forall \delta_{AB}} \min \Gamma(A, B, \delta_{AB}).$$

Some important notations being used in this Chapter are listed in Table 3.1.

Table 3.1: Notations.

Variables	Definitions
$\mathcal{N}$	The licensed channel set
N	The number of licensed channels
c_i	The i^{th} licensed channel
P	The smallest prime number greater than $\|N\|$
$\mathcal{C}_A$	The available channel set of SU_A
C_A	The number of available channels for SU_A
$C_A(i)$	The i^{th} available licensed channel for SU_A
G_{AB}	The number of commonly available channels between SU_A and SU_B
t_A	The local clock of SU_A
δ_{AB}	The clock drift between SU_A and SU_B
M_A	The number of radios for SU_A
J_A	The number of jump radios for SU_A
Y_A	The number of stay radios for SU_A
$\mathcal{C}_A^S$	The available channel set for the stay radios of SU_A
$\mathcal{C}_A^J$	The available channel set for the jump radios of SU_A, $\mathcal{C}_A^J = \mathcal{C}_A \backslash \mathcal{C}_A^S$
C_A^J	The number of available channels for the jump radios of SU_A
$\mathcal{C}_A^{J*}$	The set consisting of the available channel sets for the jump radios of SU_A
$\mathcal{C}_A^*(j)$	The available channel set for the j^{th} radio of SU_A
$w_A = \left\lceil \frac{C_A - Y_A}{J_A} \right\rceil$	The length of half period of the CHS generated by the MRR algorithm for SU_A; The length of one inner period for the CHS generated by the EMRR algorithm.
$\mathcal{S}_A$	The CHS for SU_A
$\mathcal{S}_A^{x_A}$	The CHSs for the x^{th} radio of SU_A
$S_A^{x_A}(t_A)$	The channel that the x^{th} radio of SU_A accesses at its t^{th} local time slot
$\mathcal{S}_A(t_A)$	The channel set consisting of the channels that SU_A accesses at its t^{th} local time slot
$\Gamma(A, B, \delta_{AB})$	The TTR between SU_A and SU_B
$\Gamma(G_{AB}, A, B, \delta_{AB})$	The TTR with full rendezvous diversity between SU_A and SU_B

3.5 Heterogeneous Radios Based Rendezvous Algorithm

In this subchapter, we first present the ACD algorithm, by which the available channels are divided among different jump radios of one SU. Then, we propose the MRR algorithm for the SUs who are equipped with multiple radios to generate their CHSs. The ACD algorithm is invoked by the MRR algorithm for guaranteeing that radios of one SU access different channels at the same time slot. Next, we introduce the SRR algorithm. The SRR algorithm is utilized to generate CHSs for the SUs who are equipped with one radio. Finally, we present the HRR algorithm. The HRR algorithm consists of the MRR algorithm and the SRR algorithm. SUs can generate their CHSs using the HRR algorithm regardless of the number of radios. The MRR algorithm is invoked by the HRR algorithm when the SU is equipped with multiple radios while the SRR algorithm is invoked when the SU is equipped with one radio. The HRR algorithm can guarantee rendezvous between any pair of SUs in heterogeneous DSA networks.

3.5.1 ACD Algorithm

For guaranteeing that the radios of one SU access different channels at the same time slot, we propose the ACD algorithm to divide the available channels among the jump radios for each SU. After dividing, each jump radio of one SU possesses an individual available channel set. The intersection of any two individual available channel sets for two different jump radios is empty. Besides, the jump radios only access the channels in their individual available channel sets. Hence, the ACD algorithm can guarantee that the jump radios of one SU access different channels at the same time slot. The ACD algorithm is formally presented in Algorithm 1. Note that C_A^J denotes the number of channels allocated to the jump radios of SU_A in the ACD algorithm. Besides, from the first radio to the $(Y_A)^{th}$ radio are stay radios while from the $(Y_A+1)^{th}$ radio to the $(M_A)^{th}$ radio are jump radios for SU_A.

An example for the ACD algorithm is depicted in Fig. 3.9, where 15 sorted available channels ($C_A^J = 15$) for the jump radios of SU_A are evenly divided among its four jump radios ($J_A = 4$). The available channels are sorted in descending order according to the channel quality in the HRR algorithm before carrying out the ACD algorithm. The channel quality can be measured by noise and/or interference. The reason for sorting available channels is to increase the probability of rendezvousing on the channels whose qualities are better. $M_A = 5$, and $w_A = 4$. The jump radios of SU_A start from its 2^{nd} radio to 5^{th} radio. After allocation, each jump radio of

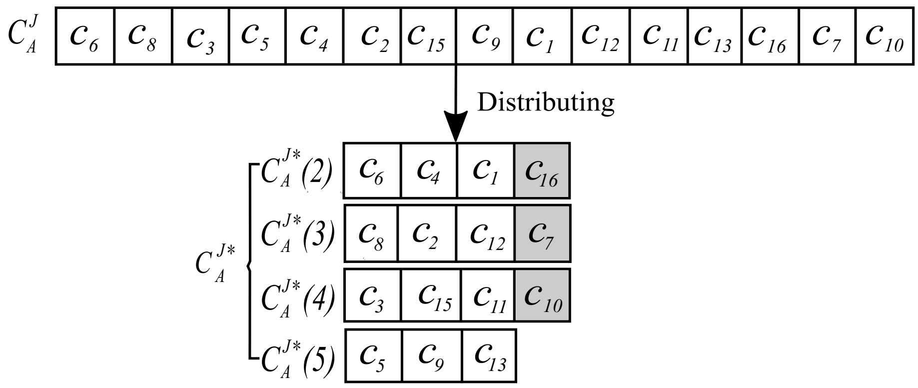


Figure 3.9: An example for the ACD algorithm.

SU_A possesses an individual available channel set. For instance, the 1^{st} jump radio of SU_A possesses an individual available channel set $\mathcal{C}_A^{J*}(2)$.

Algorithm 1 ACD Algorithm

Input: $\mathcal{C}_A^J,\ w_A,\ M_A,\ J_A,\ Y_A \ \backslash\backslash for\ SU_A$

Output: $\mathcal{C}_A^{J*}$

$\mathcal{C}_A^{J*} = \emptyset$

for $j = Y_A + 1$ to M_A **do**

  for $q = 0$ to $w_A - 1$ **do**

    if $qJ_A + j - Y_A \leq C_A^J$ **then**

      $\mathcal{C}_A^{J*}(j) = \mathcal{C}_A^{J*}(j) \cup \mathcal{C}_A^J(qJ_A + j - Y_A)$

    end if

  end for

end for

3.5.2 MRR Algorithm

The MRR algorithm is proposed to generate CHSs for SUs who are equipped with more than one radio. For guaranteeing rendezvous between the SUs in spite of the clock drift, the radios of one SU generally consist of stay radios and jump radios. Each stay radio stays at one specific available channel during one period, and changes the stay channel every period. Each jump radio sequentially accesses the available channels in its individual available channel set generated by invoking the ACD algorithm at different time slots. All available channels except the channels that the stay radios stay at are visited at least once by the jump radios of SU_A during any continuous w_A time slots within one period. Hence, rendezvous must be achieved on the stay channel that the stay radio of the SU with a longer CHS period stays at regardless of the clock drift. The situation where the number of available channels is smaller than that of radios for one SU is also considered in the MRR

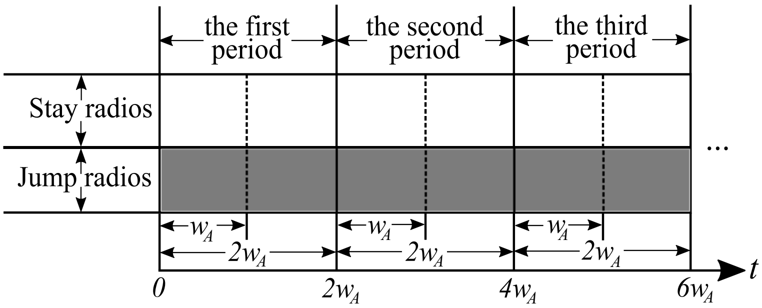
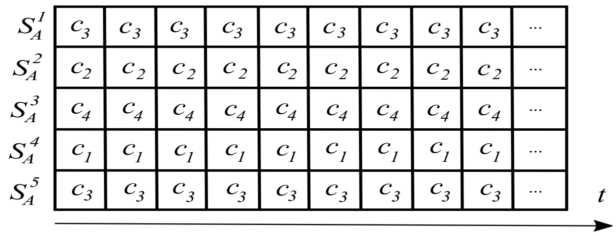
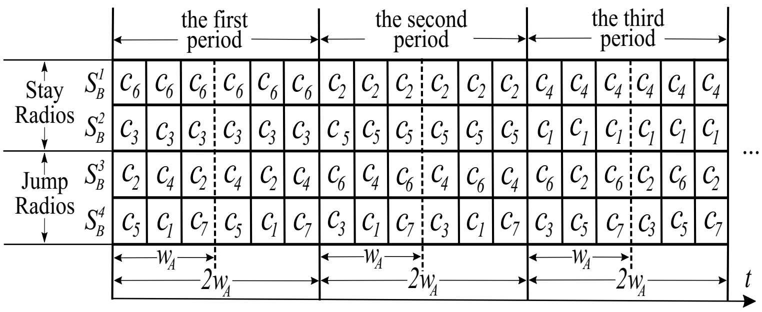


Figure 3.10: Structure of the CHSs generated by the MRR algorithm.



(a) $M_A > C_A$



(b) $M_B < C_B$

Figure 3.11: CHSs generated by the MRR algorithm.

algorithm. In such situation, all radios are stay radios, and each radio stays at the same channel all the time. Hence, rendezvous must be achieved on any commonly available channel for a pair of SUs in such situation.

The length of one period for the CHSs generated by the MRR algorithm is equal to $2w_A$, where $w_A = \left\lceil \frac{C_A - Y_A}{J_A} \right\rceil$. The structure of the CHSs generated by the MRR algorithm is shown in Fig. 3.10 while the pseudo code for the MRR algorithm is presented in Algorithm 2.

Two simple examples of the CHSs generated by the MRR algorithm are depicted in Fig. 3.11. In Fig. 3.11(a), $\mathcal{C}_A = \{c_3, c_2, c_4, c_1\}$ after being sorted in descending order according to the channel quality, M_A=5. Since $M_A > C_A = 4$, all radios of SU_A are stay radios and then the CHSs for the radios of SU_A are generated by lines 21∼24 in Algorithm 2. For instance, the first radio of SU_A stays at channel c_3 derived by $\mathcal{C}_A(h) = \mathcal{C}_A((1-1) \bmod 4 + 1) = \mathcal{C}_A(1) = c_3$ while the second radio of SU_A stays at channel c_2 derived by $\mathcal{C}_A(h) = \mathcal{C}_A((2-1) \bmod 4 + 1) = \mathcal{C}_A(2) = c_2$. In Fig. 3.11(b), $\mathcal{C}_B = \{c_6, c_3, c_2, c_5, c_4, c_1, c_7\}$ after being sorted in descending order according

Algorithm 2 MRR Algorithm

Input: $\mathcal{C}_A,\ M_A,\ J_A,\ Y_A,\ t_A \ \backslash\backslash for\ SU_A$

Output: $\mathcal{S}_A\left(t_A\right)$

$\mathcal{S}_A\left(t_A\right) = \emptyset$; $\mathcal{C}_A^S = \emptyset$;
if $C_A > M_A$ **then**
  $w_A = \left\lceil \frac{C_A - Y_A}{k_A} \right\rceil$;
  for $i = 1$ to Y_A **do**
    $h = \left(\left(\left(\left\lfloor \frac{(t_A-1)}{2w_A} \right\rfloor Y_A + i - 1\right) \bmod C_A\right) + 1\right)$
    $S_A^i\left(t_A\right) = C_A\left[h\right]$
    $\mathcal{C}_A^S = \mathcal{C}_A^S \cup C_A\left[h\right]$
  end for
  if $\left(t_A - 1\right) \bmod 2w_A = 0$ **then**
    $\mathcal{C}_A^J = \mathcal{C}_A \backslash \mathcal{C}_A^S$
    Invoke ACD Algorithm to divide the available channels among J_A jump radios
  end if
  for $i = Y_A + 1$ to M_A **do**
    $h = \left(t_A - 1\right) \bmod C_A^{J*}(i) + 1$
    $S_A^i\left(t_A\right) = \mathcal{C}_A^{J*}\left(i\right)\left(h\right)$
  end for
  for $x = 1$ to M_A **do**
    $\mathcal{S}_A\left(t_A\right) = \mathcal{S}_A\left(t_A\right) \cup S_A^x\left(t_A\right)$
  end for
else
  for $q = 1$ to M_A **do**
    $h = \left(\left(q - 1\right) \bmod C_A\right) + 1$
    $S_A^q\left(t_A\right) = \mathcal{C}_A\left(h\right);\ \mathcal{S}_A\left(t_A\right) = \mathcal{S}_A\left(t_A\right) \cup S_A^q\left(t_A\right);$
  end for
end if

to the channel quality. M_B=4 while J_B=2. Since $M_B < C_B = 7$, the CHS is generated by lines 2∼19 in Algorithm 2. Fist, the length of half period for the CHS of SU_B is calculated by $w_B = \left\lceil \frac{C_B - Y_B}{J_B} \right\rceil = \left\lceil \frac{7-(4-2)}{2} \right\rceil = 3$. In the first period (i.e., form the 1^{th} time slot to the 6^{th} time slot), the index of the channel that the first stay radio of SU_B stays at is calculated by line 5, i.e., $h = \left(\left(\left(\left\lfloor \frac{(t_B-1)}{2w_B} \right\rfloor Y_B + i - 1\right) \bmod C_B\right) + 1\right) = \left(\left(\left(\left\lfloor \frac{(1-1)}{6} \right\rfloor (4-2) + 1 - 1\right) \bmod 7\right) + 1\right) = 1$. Hence, the first stay radio of SU_B stays at channel $C_B[h] = C_B[1] = c_6$ during the first period. The second stay radio of SU_B gets its stay channel c_3 during the first period as the same way as the first radio. Therefore, the available channel set for the stay radios of SU_B during the first period is $\mathcal{C}_B^S = \{c_6, c_3\}$ while the available channel set for the jump radios of SU_A during the first period is $\mathcal{C}_B^J = \mathcal{C}_B \backslash \mathcal{C}_B^S = \{c_2, c_5, c_4, c_1, c_7\}$. Then, the ACD algorithm is invoked to divide $\mathcal{C}_B^J$ among the 2 jump radios of SU_B. After dividing, each jump radio of SU_B possesses its individual available channel set for the first period, which are $\mathcal{C}_B^{J*}(3) = \{c_2, c_4, c_7\}$ and $\mathcal{C}_B^{J*}(4) = \{c_5, c_1\}$, respectively. After that, the channels that the jump radios access are generated by lines 14 and 15 based on $\mathcal{C}_B^{J*}(3)$ and $\mathcal{C}_B^{J*}(4)$. For instance, the first jump radio gets its access channel c_2 at the 1^{st} time slot by $h = (1-1) \bmod |2| + 1 = 1$, and $\mathcal{C}_B^{J*}(3)(h) = c_2$.

From Fig. 3.11, we can see that the MRR algorithm can guarantee that different radios of one SU access different channels at the same time slot when the number of radios is not larger than that of the available channels for the SU.

3.5.3 SRR Algorithm

The SRR algorithm is proposed to generate CHSs for the SUs who are equipped with only one radio. For guaranteeing rendezvous between the SUs in heterogeneous DSA networks regardless of the clock drift as soon as possible, the length of one period for the CHSs generated by the SRR algorithm lasts for $5P$ time slots in our setting. Three patterns exist during one period, which are jump pattern, first stay pattern and second stay pattern. The jump pattern lasts for $2P$ time slots while the first stay pattern lasts for P time slots, and the second stay pattern lasts for $2P$ time slots during one period. The structure of the CHSs generated by the SRR algorithm is shown in Fig. 3.12. During the jump pattern, SU_A incessantly switches to access different available channels according to the step length s_A and the initial channel index i_A. The value of the s_A is generated by the HRR algorithm while the value of i_A is calculated from the initial channel index i_{A0} generated by the HRR algorithm. In the HRR algorithm, s_A is randomly selected from the subscripts of channels in $\mathcal{C}_A$ while i_{A0} is randomly selected from $[1, C_A]$. It is worth mentioning that the unavailable channels generated for the jump pattern are replaced by the available channels in the sorted available channel set sequentially in the SRR algorithm. The main

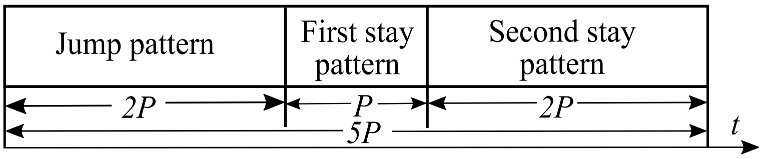


Figure 3.12: Structure of the CHSs generated by the SRR algorithm.

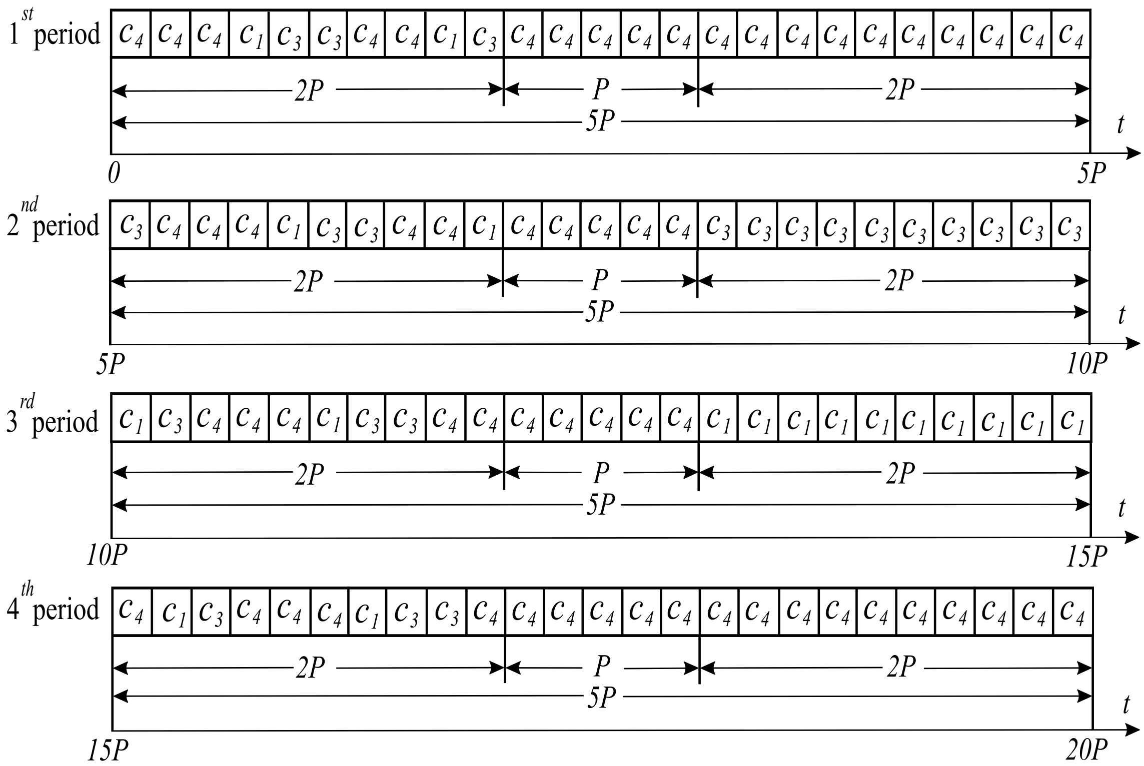


Figure 3.13: CHS generated by the SRR algorithm.

intention of the method mentioned above is to increase the frequency of accessing the channels whose channel qualities are better. During the first stay pattern, SU_A always stays at the channel c_{s_A}. During the second stay pattern, SU_A stays at one specific available channel during one period and then changes to stay at another specific channel during next period. Rendezvous between SUs in heterogeneous DSA networks can be guaranteed by the SRR algorithm and the MRR algorithm. The detailed proofs for guaranteeing rendezvous will be presented later. The steps of the SRR algorithm are presented in Algorithm 3.

An example of the CHS generated by the SRR algorithm is depicted in Fig. 3.13, where $s_A = 4$, $i_{A0} = 2$, $\mathcal{N} = \{c_4, c_2, c_3, c_1\}$, and $\mathcal{C}_A = \{c_4, c_3, c_1\}$ after being sorted in descending order according to the channel quality. When $t = 1$, the channel index $j = 2$ is derived by line 4. Because $\mathcal{N}(2) = c_2 \notin \mathcal{C}_A$, c_2 is replaced by lines 17∼19, where $k = k + 1 = 1$ and $S_A(1) = \mathcal{C}_A(1) = c_4$. When $t = 2$, the channel index $j = 5$ is also derived by line 4. Because $j = 5 > N = 4$, j is replaced by lines 14∼16. $j = (j - 1) \bmod N + 1 = 1$ after replacing. Because $\mathcal{N}(1) = c_4 \in \mathcal{C}_A$,

Algorithm 3 SRR Algorithm

Input: $\mathcal{N}, P, \mathcal{C}_A, t_A, i_{A0}, s_A \ \backslash\backslash for\ SU_A$

Output: $\mathcal{S}_A(t_A)$

$t^* = (t_A - 1) \bmod 5P;$

$n = \lfloor (t_A - 1)/5P \rfloor ;\ i_A = (i_{A0} + n) \bmod P;$

if $t^* < 2P$ **then**

    $j = ((i_A + t^* \cdot s_A - 1) \bmod P) + 1$

else if $2P \le t^* < 3P$ **then**

    $S_A(t_A) = c_{s_A}$

else

    $j = (n \bmod C_A) + 1;\ S_A(t_A) = \mathcal{C}_A(j);$

end if

if $t^* = 0$ **then**

    $k = 0$

end if

if $t^* < 2P$ **then**

    if $j > N$ **then**

        $j = (j - 1) \bmod N + 1$

    end if

    if $\mathcal{N}(j) \notin C_A$ **then**

        $k = k + 1$

        $S_A(t_A) = \mathcal{C}_A((k - 1) \bmod C_A + 1)$

    else

        $S_A(t_A) = \mathcal{N}(j)$

    end if

end if

$S_A(2) = \mathcal{N}(1) = c_4$. Other channels during the jump pattern are also generated by this way. When $t = 11$, the CHS of SU_A enters its first stay pattern. The stay channel during the first stay pattern is generated by line 6. Because $s_A = 4$, $S_A(11) = c_{s_A} = c_4$. When $t = 16$, the CHS of SU_A enters its second stay pattern. The stay channel is generated by line 8, i.e. $S_A(16) = \mathcal{C}_A(1) = c_4$. After $5P$ time slots, the CHS of SU_A enters its second period. At the beginning of the second period, the initial channel index is changed to 3 derived by $i_A = i_{A0} + n = 2 + 1 = 3$ while the counter k is reset to zero.

3.5.4 HRR Algorithm

The HRR algorithm consists of the MRR algorithm and the SRR algorithm. The HRR algorithm is utilized to generate CHSs for all SUs in heterogeneous DSA networks. Rendezvous between SUs can be guaranteed by the HRR algorithm. In the HRR algorithm, SU keeps attempting rendezvous on the channel generated by invoking the SRR algorithm or the MRR algorithm until achieving rendezvous with its target SUs. The SRR algorithm is invoked to generate CHSs for the SUs with one radio while the MRR algorithm is invoked to generate CHSs for the SUs with multiple radios. The details of the HRR algorithm are shown in Algorithm 4.

Algorithm 4 HRR Algorithm

Input: $t_A, M_A, J_A, Y_A, \mathcal{C}_A, \mathcal{N}$ \\\\$for\ SU_A$

t_A=1
P = the smallest prime number greater than N
s_A = the step length randomly selected from the subscripts of channels in $\mathcal{C}_A$
i_{A0} = the initial channel index randomly selected form $[1, C_A]$
Sort $\mathcal{C}_A$ and $\mathcal{N}$ in descending order according to channel quality
while not rendezvous **do**
    if $M_A = 1$ **then**
        Invoke SRR algorithm to generate CHS
    end if
    if $M_A > 1$ **then**
        Invoke MRR algorithm to generate CHS
    end if
    Attempt rendezvous on $S_A(t_A)$
    $t_A = t_A + 1$
end while

An example of rendezvous by using the HRR algorithm is shown in Fig. 3.14, where $\mathcal{N} = \{c_1, c_2, c_3, c_4\}$, $\mathcal{C}_A = \{c_1, c_2\}$, $\mathcal{C}_B = \{c_1, c_2, c_3, c_4\}$, $\mathcal{C}_C = \{c_2, c_3, c_4\}$, $M_A = 1$, $M_B = 3$, $J_B = 2$, $M_C = 4$, s_A=2, and $i_{A0} = 2$. After sorting the channels in descending order according to their qualities, $\mathcal{N} = \{c_3, c_2, c_4, c_1\}$, $\mathcal{C}_A = \{c_2, c_1\}$, $\mathcal{C}_B = \{c_3, c_2, c_4, c_1\}$, and $\mathcal{C}_C = \{c_3, c_2, c_4\}$. $\delta_{AB} = 3$, $\delta_{BC} = 3$, and $\delta_{AC} = 6$. From

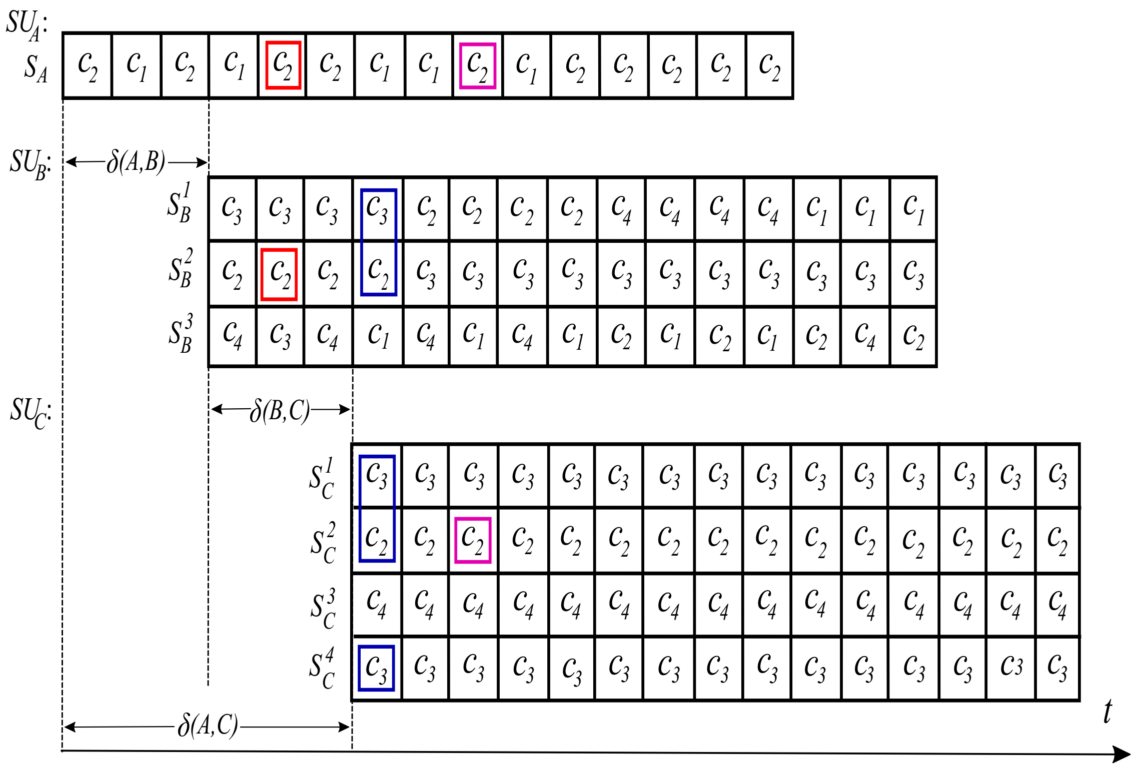


Figure 3.14: An example of rendezvous by using the HRR algorithm.

Fig. 3.14, we can see that SU_B can achieve rendezvous with SU_A at its third local time slot on channel c_2, while SU_C can achieve rendezvous with SU_B at its first local time slot on channels c_3 and c_4. Besides, SU_C can achieve rendezvous with SU_A at its third local time slot on channel c_2. Hence, $\Gamma(A, B, \delta_{AB}) = 3$, $\Gamma(B, C, \delta_{BC}) = 1$, and $\Gamma(A, C, \delta_{AC}) = 3$.

3.6 Performance Analysis

The proposed HRR algorithm is applicable for realistic DSA networks with the following characteristics: asynchronous local clock, heterogeneity, symmetric roles and anonymous information. For the characteristics of symmetric roles and anonymous information, because pre-assigned roles and IDs are not required when generating CHSs by the HRR algorithm. Hence, the HRR algorithm is applicable for the DSA networks with the characteristics of symmetric roles and anonymous information. Specifically, for proving that the HRR algorithm is also applicable for the DSA networks with the characteristic of asynchronous local clock and heterogeneity, we derive the upper bounds of MTTR for the HRR algorithm under both symmetric model and asymmetric model in the following scenarios.

- Both of two SUs are equipped with only one radio ($M_A = M_B = 1$).

- One SU is equipped with one radio while the other SU is equipped with multiple radios ($M_A > 1, M_B = 1$ or $M_A = 1, M_B > 1$).
- Both of two SUs are equipped with multiple radios ($M_A > 1, M_B > 1$).

To formally derive the upper bounds of MTTR for the HRR algorithm, we first give the following Lemmas.

Lemma 1. *Given the number of global licensed channels N, prime number P, step length $s_A \in (0, P)$, arbitrary initial channel index i_{A0}, all N channels are visited in any consecutive P time slots during the jump pattern of the CHS generated by the SRR algorithm.*

Proof. According to the SRR algorithm, we denote the CHS during any consecutive P time slots of the jump pattern as $\mathcal{S} = \{((i_A - 1) \bmod P) + 1,\ ((i_A + s_A - 1) \bmod P) + 1, \cdots, ((i_A + (P-1)s_A - 1) \bmod P) + 1\}$. Suppose that $((i_A + js_A - 1) \bmod P) + 1$ and $((i_A + ks_A - 1) \bmod P) + 1$ are identical, which implies that $((j-k) * s_A) \bmod P = 0$. Since P is a prime number and $s_A \in (0, P)$, P and s_A are co-prime. Hence, we must have $(j-k) \bmod P = 0$, which leads to $j = k$ due to $j - k < P$. Because j and k represent two different time slots, which contradicts that $j = k$. Hence, any two number in S must be different. i.e., Lemma 1 is proved. □

Lemma 2. *Given the number of channels C_A^J and the length of half period w_A, all C_A^J channels are visited by the jump radio of SU_A in any consecutive w_A time slots during one period of the CHS generated by the MRR algorithm.*

Proof. According to the MRR algorithm, we denote the CHS during any consecutive w_A time slots of one period for the j^{th} radio of SU_A by $\mathcal{S}_A^j = \{(t_A - 1) \bmod C_A^{J*}(j) + 1,\ ((t_A + 1) - 1) \bmod C_A^{J*}(j) + 1, \cdots, (t_A + (w_A - 1) - 1) \bmod C_A^{J*}(j) + 1\}$, where $Y_A + 1 \leq j \leq M_A$. Suppose that $(((t_A + i) - 1) \bmod C_A^{J*}(j) + 1)$ and $(((t_A + k) - 1) \bmod C_A^{J*}(j) + 1)$ are identical, which implies that $(i - k) \bmod C_A^{J*}(j) = 0$. According to the MRR algorithm, $C_A^{J*}(j) = w_A$ or $C_A^{J*}(j) = w_A - 1$. When $C_A^{J*}(j) = w_A$, since $i - k \leq w_A - 1$, $(i-k) \bmod C_A^{J*}(j) = 0$ leads to $i = k$. Since i and k represent different time slots, which contradicts that $i = k$. Hence, any consecutive w_A channels in $\mathcal{S}_A^j$ must be different when $C_A^{J*}(j) = w_A$. When $C_A^{J*}(j) = w_A - 1$ and $i - k \leq w_A - 2$, $(i-k) \bmod C_A^{J*}(j) = 0$ leads to $i = k$, which means any consecutive $w_A - 1$ channels in $\mathcal{S}_A^j$ must be different. Thus, Lemma 2 is proved. □

Lemma 3. *Given a prime number P, if s_A and s_B are two different numbers in $(0, P)$, then for any initial channel index $i_A \in [0, P)$ and $i_B \in [0, P)$, there must exist an integer $k \in [0, P)$ such that $(i_A + ks_A - 1) \bmod P = (i_B + ks_B - 1) \bmod P$.*

Proof. The proof is given in [97]. □

Lemma 3 implies that rendezvous between two SUs can be guaranteed by the SRR algorithm when the CHSs of the two SUs are in their jump patterns with different step lengths and the overlap between their jump patterns is not less than P time slots.

Based on the Lemma 1, Lemma 2 and Lemma 3, we derive the upper bounds of MTTR for the proposed HRR algorithm, which are presented in the following Theorems.

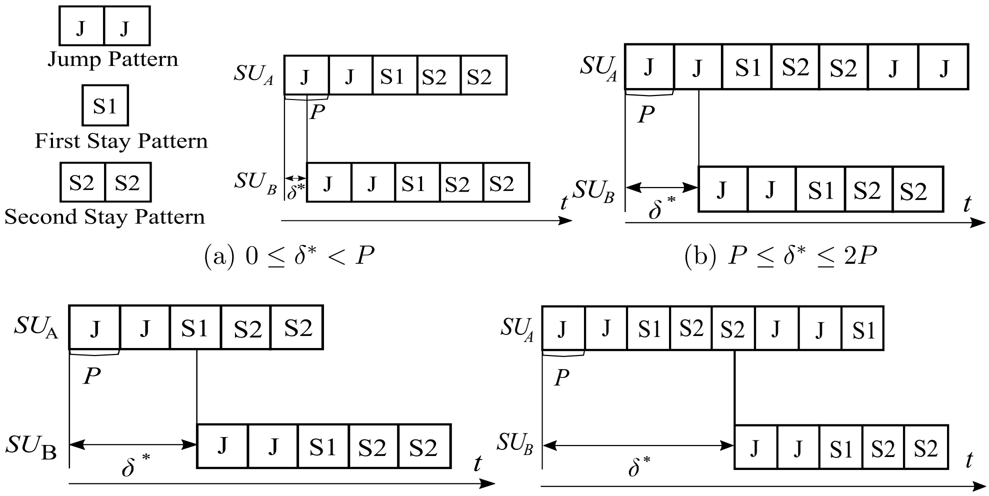
Theorem 1. *The MTTR of the HRR algorithm is upper bounded by* $3P$ *time slots under the symmetric model when* $M_A = M_B = 1$.

When $M_A = M_B = 1$, both of SU_A and SU_B generate their CHSs by the SRR algorithm. The rendezvous between SUs can be divided into four scenarios according to the clock drift δ_{AB} between them and their step lengths. The four rendezvous scenarios are: rendezvous between the jump patterns, rendezvous between the first stay patterns, rendezvous between the first stay pattern and the jump pattern, and rendezvous between the jump pattern and the second stay pattern. According to Lemma 3, rendezvous will be achieved between the jump patterns when the overlap between the jump patterns of two SUs is not less than P time slots and the step lengths of the two SUs are different. Owing to the fact that SU always stays at the same channel whose channel index is equal to its step length. Hence, rendezvous must be achieved between the stay patterns of two SUs when they have the same step length and at least one time slot overlap between their stay patterns. Besides, when the overlap between the jump pattern of one SU and the first stay pattern or the second stay pattern of the other SUs is not less than P, the rendezvous will be achieved between the jump pattern and the first stay pattern, or between the jump pattern and the second stay pattern. The reason is that all available channels are visited at least once for one SU while the other SU always stays at the same channel during these P time slots. Hence, rendezvous must be achieved on the stay channel that one of the SUs always stays at. Then, we give the specific proof as follows.

Proof. When $M_A = M_B = 1$, the CHSs of SU_A and SU_B are generated by the SRR algorithm. Without loss of generality, we assume that SU_B starts rendezvous process later than SU_A for δ_{AB} ($\delta + AB \geq 0$) time slots. Let $\delta^* = \delta_{AB} \bmod 5P$. The theoretical analysis also can be used for the case that SU_A starts rendezvous process later than SU_B.

Case1: $s_A = s_B = s$

Subcase 1.1: $0 \leq \delta^* < P$. As shown in Fig. 3.15(a), an overlap must exist between SU_A's and SU_B's first stay pattern. Since both SU_A and SU_B stay at the channel c_s during their first stay patterns, rendezvous must be achieved on channel c_s. Thus, we have $TTR \leq 2P + 1$.



(a) $0 \leq \delta^* < P$ (b) $P \leq \delta^* \leq 2P$

(c) $2P < \delta^* \leq 4P$ (d) $4P < \delta^* < 5P$

Figure 3.15: Guaranteed rendezvous when $M_A = M_B$=1.

Subcase 1.2: $P \leq \delta^* \leq 2P$. As shown in Fig. 3.15(b), there must exist P time slots overlap between SU_A's first stay pattern and SU_B's jump pattern. During these overlapping P time slots, SU_A stays at channel c_s while SU_B visits all $|N|$ channels according to Lemma 1. Thus, rendezvous must be achieved in one of these P time slots on channel c_s, we have $TTR \leq 2P$.

Subcase 1.3: $2P < \delta^* \leq 4P$. As shown in Fig. 3.15(c), there must exist P time slots overlap between SU_A's second stay pattern and SU_B's jump pattern. During these overlapping P time slots, SU_A stays at one specific channel while SU_B visits all N channels. Thus, rendezvous must be achieved in one of these P time slots on the channel that SU_A stays at, we have $TTR \leq 2P$.

Subcase 1.4: $4P < \delta^* < 5P$. As shown in Fig. 3.15(d), an overlap must exist between SU_A's and SU_B's first stay pattern. Since both SU_A and SU_B stay at the same channel c_s during their first patterns, rendezvous must be achieved on channel c_s. Thus, we have $TTR \leq 3P$.

Case2: $s_A \neq s_B$

Subcase 1.1: $0 \leq \delta^* < P$. As shown in Fig. 3.15(a), there must exist P time slots overlap between SU_A's and SU_B's jump patterns. Since the step lengths of SU_A and SU_B are different in this Subcase, a rendezvous must happen in one of these overlapping P time slots according to Lemma 3. Thus, we have $TTR \leq P$.

Subcase 1.2: $P \leq \delta^* \leq 2P$. As shown in Fig. 3.15(b), there must exist P time slots overlap between SU_A's first stay pattern and SU_B's jump pattern. Hence, rendezvous must happen on channel c_{s_A}, we have $TTR \leq 2P$.

Subcase 1.3: $2P < \delta^* \leq 4P$. As shown in Fig. 3.15(c), there must exist P time slots overlap between SU_A's second stay pattern and SU_B's jump pattern.

Rendezvous must happen in one of these P time slots on the channel that SU_A stays at, we have $TTR \leq 2P$.

Subcase 1.4: $4P < \delta^* < 5P$. As shown in Fig. 3.15(d), an overlap must exist between SU_A's and SU_B's jump patterns. Using the similar method described as Subcase 1.1, we have $TTR \leq 2P$.

To sum up, the MTTR of the HRR algorithm can be upper bounded by $3P$ time slots under the symmetric model when $M_A = M_B = 1$. □

Theorem 2. *The MTTR of the HRR algorithm is upper bounded by* $(N - G_{AB} + 1)5P$ *time slots under the asymmetric model when* $M_A = M_B = 1$*, where* G_{AB} *is the number of commonly available channels between* SU_A *and* SU_B*.*

The main idea of achieving rendezvous in this scenario is similar to that for Theorem 1. The difference between them is that the potential rendezvous channel may not be available for both of SUs simultaneously in this scenario owing to the heterogeneous available channels. Hence, several periods of CHSs for two SUs may cost before rendezvous on the same commonly available channel. The specific proof is shown as follows.

Proof. Case 1: $s_A = s_B = s$

Subcase 1.1: $0 \leq \delta^* < P$. As shown in Fig. 3.15(a), an overlap must exist between SU_A's and SU_B's first stay patterns. Thus, we have $TTR \leq 2P + 1$.

Subcase 1.2: $P \leq \delta^* \leq 2P$. As shown in Fig. 3.15(b), there must exist P time slots overlap between SU_A's first stay pattern and SU_B's jump pattern. Rendezvous must be achieved on channel c_s, we have $TTR \leq 2P$.

Subcase 1.3: $2P < \delta^* \leq 4P$. As shown in Fig. 3.15(c), there must exist P time slots overlap between SU_A's second stay pattern and SU_B's jump pattern. Since SU_A stays at one specific channel while SU_B visits all N channels during these overlapping P time slots, the potential rendezvous on the channel that SU_A stays at must happen in one of these overlapping P time slots. However, the potential rendezvous channel may not be available for SU_B under the asymmetric model. Since the channel that SU_A stays at changes every period, the potential rendezvous must happen on different channels for different periods. Since the number of commonly available channels between SU_A and SU_B is G while each period lasts for $5P$ time slots. Thus, the TTR will not exceed $(N - G_{AB})5P + 2P$ time slots.

Subcase 1.4: $4P < \delta^* < 5P$. As shown in Fig. 3.15(d), an overlap must exist between SU_A's and SU_B's first stay patterns. We have $TTR \leq 3P$.

Case 2: $s_A \neq s_B$

Subcase 1.1: $0 \leq \delta^* < P$. As shown in Fig. 3.15(a), there must exist P time slots overlap between SU_A's and SU_B's jump patterns. A potential rendezvous must happen in one of these overlapping P time slots. However, the potential rendezvous channel may not be available for SU_A and SU_B simultaneously. According to the SRR algorithm, the initial channel index changes every period while the step length does not change for the SU. Hence, the potential rendezvous must happen on different channels during different periods. Thus, the TTR will not exceed $(N - G_{AB})5P + P$ time slots.

Subcase 1.2: $P \leq \delta^* \leq 2P$. As shown in Fig. 3.15(b), there must exist P time slots overlap between SU_A's jump pattern and SU_B's second stay pattern. Using the similar method described as before, we have $TTR \leq (N - G_{AB} + 1)5P$.

Subcase 1.3: $2P < \delta^* \leq 4P$. As shown in Fig. 3.15(c), there must exist P time slots overlap between SU_A's second stay pattern and SU_B's jump pattern. Using the similar method described as before, we have $TTR \leq (N - G_{AB})5P + 2P$.

Subcase 1.4: $4P < \delta^* < 5P$. As shown in Fig. 3.15(d), there must exist P time slots overlap between SU_A's and SU_B's jump patterns. Using the similar method described as Subcase 1.1, we have $TTR \leq (N - G_{AB})5P + 2P$.

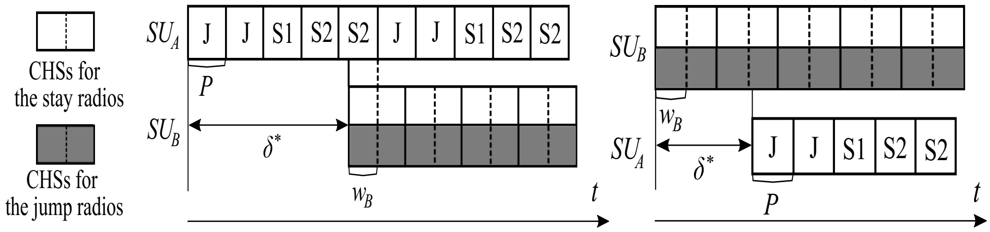
To sum up, the MTTR of the HRR algorithm can be upper bounded by $(N - G_{AB} + 1)5P$ time slots under the asymmetric model when $M_A = M_B = 1$. □

Theorem 3. *Two SUs (SU_A and SU_B) performing the HRR algorithm achieve rendezvous in at most $5P + w_i$ time slots under the symmetric model when $M_A = 1, M_B > 1$ or $M_A > 1, M_B = 1$, where $i = B$ or A.*

In this scenario, two SUs generate their CHSs by using the SRR algorithm and the MRR algorithm, respectively. The rendezvous must be achieved between the second stay pattern of the CHS for the SU with one radio and the other SU with multiple radios. Because the SU with one radio always stays at the same channel during its second stay pattern within one period while all available channels are visited at least once during any continuous w_i time slots within one period by the radios of the SU with multiple radios. Moreover, the overlap between the second stay pattern for the SU with one radio and one period of the CHS for the SU with multiple radios is not smaller than w_i. The specific proof is given as follows.

Proof. Without loss of generality, we assume that $m_A = 1$ and $m_B > 1$, the theoretical analysis also can be used for the case that $M_A > 1$ and $M_B = 1$. It can be easily seen that $w_B < P$ according to the HRR algorithm.

Case 1: SU_B starts hopping later than SU_A for δ^* time slots. As shown in Fig. 3.16(a), there must exist a w_B time slots overlap between SU_A's second stay pattern and SU_B's one period. SU_A stays at one specific channel while SU_B visits all C_B channels during these overlapping w_B time slots according to the MRR algorithm and Lemma 2. Hence, rendezvous must be achieved in one of these w_B time slots on the channel that SU_A stays at, we have $TTR < 5P + w_B$.



(a) $t_A = t_B + \delta^*$ (b) $t_B = t_A + \delta^*$

Figure 3.16: Guaranteed rendezvous when $M_A = 1$ and $M_B > 1$.

Case 2: SU_A starts hopping later than SU_B for δ^* time slots, as shown in Fig. 3.16(b), using similar method described as Case 1, we have $TTR < 5P$.

To sum up, the MTTR of the HRR algorithm can be upper bounded by $5P + w_i$ time slots under the symmetric model when $M_A = 1, M_B > 1$ or $M_A > 1, M_B = 1$, where $i = B$ or A. □

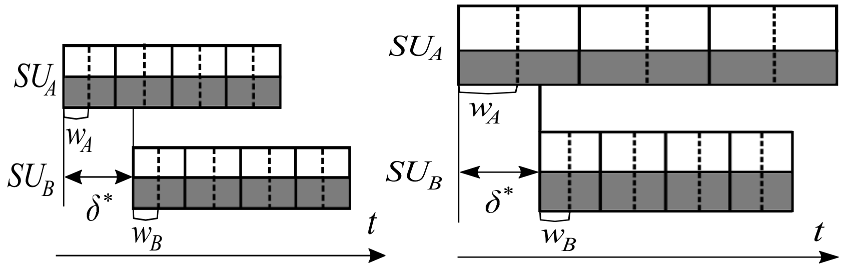
Theorem 4. *Two SUs (SU_A and SU_B) performing the HRR algorithm achieve rendezvous in at most $(N - G + 1)5P$ time slots under the asymmetric model when $M_A = 1, M_B > 1$ or $M_A > 1, M_B = 1$.*

The main idea of achieving rendezvous in this scenario is similar to that for Theorem 3. The difference between them is that the potential rendezvous channel may not be available for both of the SUs simultaneously in this scenario. Owing to the fact that the stay channel is changed every period for the second stay pattern of the CHSs generated by the SRR algorithm. Rendezvous must be achieved when the SU with one radio stays at one commonly available channels during its second stay pattern. The specific proof is shown as follows.

Proof. Case 1: SU_B starts hopping later than SU_A for δ^* time slots. As shown in Fig. 3.16(a), there must exist w_B time slots overlap between SU_A's second stay pattern and SU_B's one period. The potential rendezvous must happen in one of these w_B time slots on the channel that SU_A stays at. Since the potential rendezvous channel may not be available for SU_B while the channel that SU_A stays at during its second stay pattern changes every period, the potential rendezvous must happen on different channels for different periods. Thus, we have $TTR < (N - G_{AB} + 1)5P$.

Case 2: SU_A starts hopping later than SU_B for δ^* time slots. As shown in Fig. 3.16(b), using the similar method described as Case 1, we have $TTR < (N - G_{AB} + 1)5P$.

To sum up, the MTTR of the HRR algorithm can be upper bounded by $(N - G_{AB} + 1)5P$ time slots under the asymmetric model when $M_A = 1, M_B > 1$ or $M_A > 1, M_B = 1$. □



(a) $w_A = w_B$ (b) $w_A \neq w_B$

Figure 3.17: Guaranteed rendezvous when $M_A > 1$ and $M_B > 1$.

Theorem 5. *Two SUs (SU_A and SU_B) performing the HRR rendezvous algorithm achieve rendezvous in at most $2min(w_i)$ time slots under the symmetric model when $m_A > 1$ and $m_B > 1$, where $i = A, B$.*

In this scenario, both of two SUs generate their CHSs by the MRR algorithm. Rendezvous must be achieved between the stay radios of the SU with a larger CHS period and the radios of the other SU. The reason is that all available channels are visited at least once in any continuous w_i time slots during one period by the radios of the SU with a smaller CHS period. Meanwhile, the stay radios of the SU with a larger CHS period always stay at the same channels during one period. Moreover, the overlap between the CHSs of one period for the SUs is long enough for achieving rendezvous. The specific proof is shown as follows.

Proof. Case 1: $w_A = w_B$, as shown in Fig. 3.17(a). Without loss of generality, we assume that SU_B starts CH process later than SU_A, the theoretical analysis can also be used for the case that SU_B starts hopping earlier than SU_A. In this Case, there must exist w_B time slots overlap within one period of the CHSs for SU_A and SU_B. Since the stay radios of SU_A and SU_B stay at specific channels while the radios of SU_A and SU_B visit all available channels during each period, rendezvous must be achieved in one of these w_B time slots between SU_A's stay radios and SU_B's radios, and between SU_B's stay radios and SU_A's radios. Thus, we have $TTR < 2w_B$.

Case 2: $w_A \neq w_B$. Without loss of generality, we assume that $w_A > w_B$. As shown in Fig. 3.17(b), there must exist w_B time slots overlap within one period of CHSs for SU_A and SU_B. Thus, rendezvous must be achieved in one of these w_B time slots between SU_A's stay radios and SU_B's radios, we have $TTR < 2w_B$.

To sum up, the MTTR of the HRR algorithm can be upper bounded by $2\min(w_i)$ time slots under the symmetric model when $M_A > 1$ and $M_B > 1$, where $i = A, B$. □

Theorem 6. *When $M_A > 1$ and $M_B > 1$, two SUs (SU_A and SU_B) performing the HRR algorithm achieve rendezvous in at most $min\left(2\left\lfloor \frac{C_i - G_{AB}}{Y_i} \right\rfloor w_i\right) + 2w_B$ time* *slots when $w_A = w_B$ and at most $\left(2\left\lfloor\frac{C_A-G_{AB}}{Y_A}\right\rfloor w_A\right)+2w_B$ time slots when $w_A > w_B$ under the asymmetric model, where $i = A, B$.*

The reason for achieving rendezvous in this scenario is similar to that for Theorem 5. The difference between them is that the potential rendezvous channel may not be available for the two SUs simultaneously under the asymmetric model. Owing to the fact that the stay channels that the stay radios of the SU stay at are changed every period. The rendezvous must be achieved when any stay radio of the SU with a larger CHS period stays at one commonly available channel. The specific proof is shown as follows.

Proof. Case 1: $w_A = w_B$. As shown in Fig. 3.17(a), there must exist w_B time slots overlap within one period of the CHSs for SU_A and SU_B. The potential rendezvous must happen in one of these w_B time slots. Since the potential rendezvous channel may not be available for SU_A and SU_B simultaneously, while the stay channels for the stay radios of SU_A and SU_B are changed every period. The potential rendezvous channels must be different for different periods. Thus, we have $TTR < min\left(2\left\lfloor\frac{C_i-G_{AB}}{Y_i}\right\rfloor w_i\right)+2w_B,\ i = A, B$.

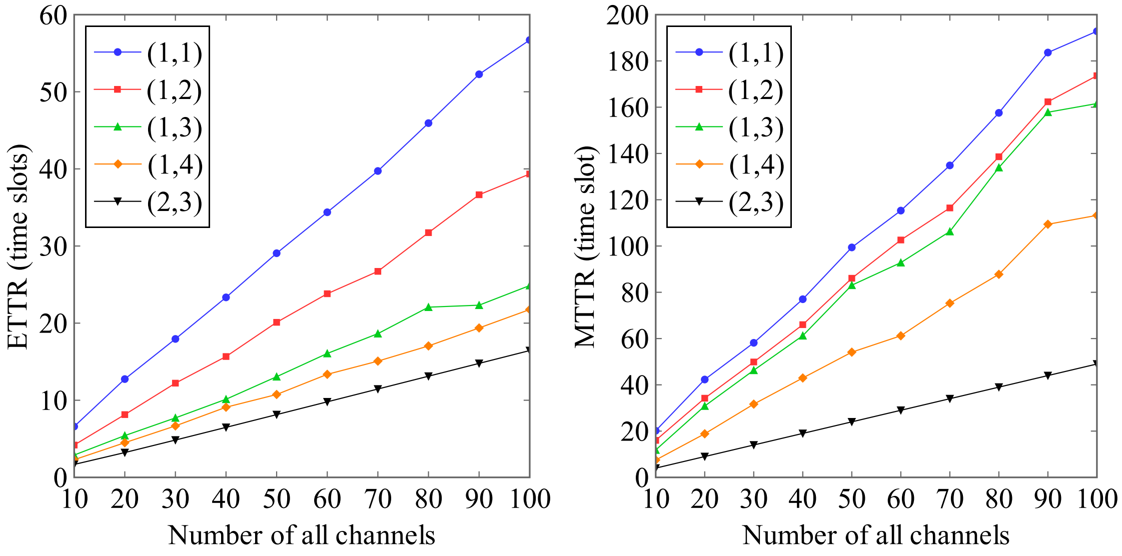
Case 2: $w_A \neq w_B$. As shown in Fig. 3.17(b), there must exist w_B time slots overlap within one period of CHSs for SU_A and SU_B. The potential rendezvous must happen between SU_A's stay radios and SU_B's radios. Using the similar method described as Case 1, we have $TTR < \left(2\left\lfloor\frac{C_A-G_{AB}}{Y_A}\right\rfloor w_A\right)+2w_B$.

□

From the above analysis, we can see that the HRR algorithm can guarantee rendezvous between SUs in spite of the clock drift and the number of radios under the asymmetric model. Hence, the HRR algorithm is also applicable for DSA networks with the characteristics of asynchronous local clock and heterogeneity. In summary, the HRR algorithm is applicable for realistic DSA networks with the characteristics of asynchronous local clock, heterogeneity, symmetric roles and anonymous information.

3.7 Performance Evaluation

We conduct extensive simulations using MATLAB to evaluate the proposed HRR algorithm. First, we evaluate the performance of the HRR algorithm under different numbers of radios. Then, we evaluate the performance of the HRR algorithm under different parameter settings. Moreover, we compare the performance of the HRR algorithm to several representative multi-radio-based CH rendezvous algorithms.



(a) ETTR VS. N

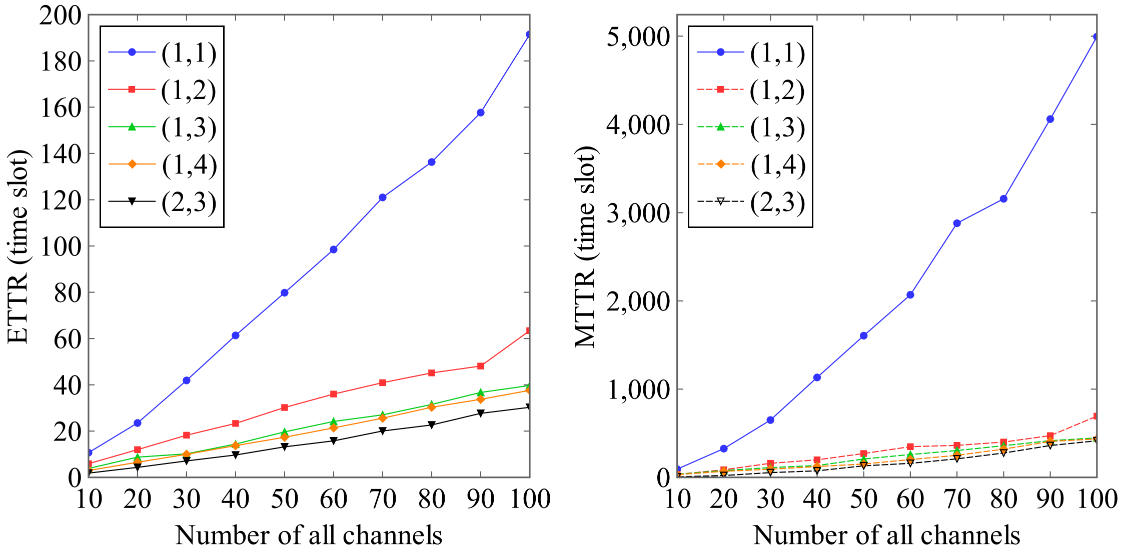
(b) MTTR VS. N

Figure 3.18: Comparison of different numbers of radios under the symmetric model.

3.7.1 Performance under Different Numbers of Radios

In this subsection, we evaluate the ETTR and the MTTR of the HRR algorithm under the scenarios with different numbers of radios. The performance is evaluated under both the symmetric model and the asymmetric model. We use the notation (M_A, M_B) to denote the case that SU_A and SU_B are equipped with M_A and M_B radios, respectively. The values of J_A and J_B are set to be equal to $\lceil \frac{M_A}{2} \rceil$ and $\lceil \frac{M_B}{2} \rceil$, respectively. The number of the global channels N is varied from 10 to 100. All global channels are available to SUs under the symmetric model while different parts of global channels are available to different SUs under the asymmetric model. The numbers of available channels for SUs are set to be $0.8N$ while the number of commonly available channels between two SUs is set to be $0.6N$ under the asymmetric model.

Fig. 3.18 and Fig. 3.19 show the comparison of the ETTR and the MTTR among five combinations of (M_A, M_B) which are $(1,1)$, $(1,2)$, $(1,3)$, $(1,4)$, $(2,3)$ under the symmetric model and the asymmetric model, respectively. We can see that SU_A and SU_B can achieve rendezvous with each other within the MTTR derived in Chapter 3.6, which verifies the correctness of the theoretical analysis. For instance, when $N = 100$, i.e. $P = 101$, the upper bound of MTTR for (1,1) under the symmetric model derived by Theorem 1 is $3P$, which equals 303 time slots. While the MTTR under this situation obtained by simulation is about 190 time slots, which is less than 303 time slots.

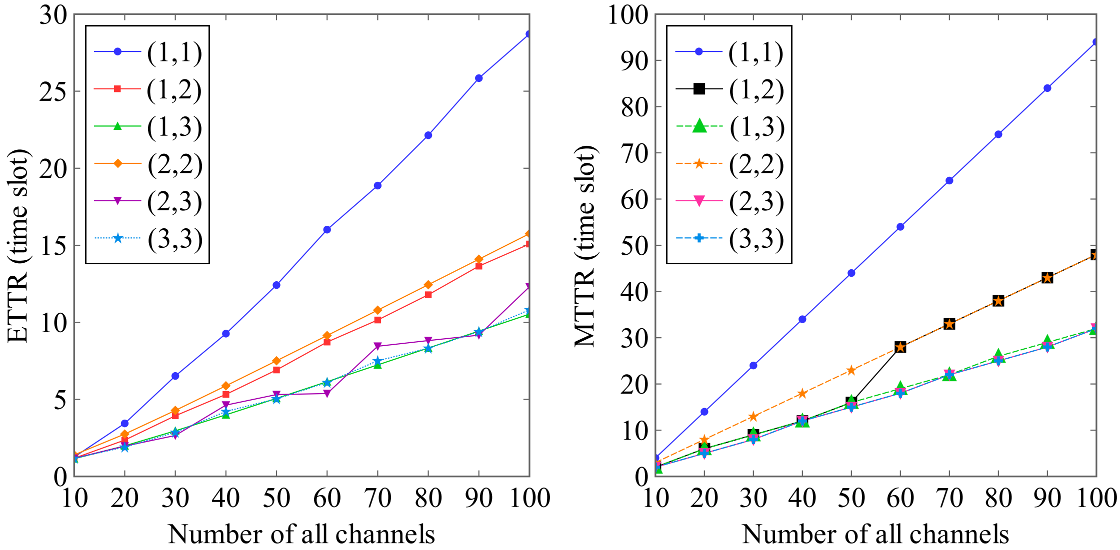


(a) ETTR VS. N (b) MTTR VS. N

Figure 3.19: Comparison of different numbers of radios under the asymmetric model.

Besides, the ETTR and the MTTR increase with the increase of the total number of channels for SU_A and SU_B under both the symmetric model and the asymmetric model. The reason is that the ETTR and the MTTR are related to the length of one period for the CHSs. When the numbers of all channels and available channels increase, the length of one period for the CHSs increases, which directly leads to the rise of the ETTR and the MTTR.

Moreover, when the total number of channels for SU_A and SU_B is fixed, the ETTR and the MTTR between them when both of them are equipped with multiple radios are shorter than that when one of them is equipped with one radio under both symmetric model and asymmetric model. The reason is listed as follows. First, we consider the scenario where a pair of SUs is equipped with a single radio and multiple radios, respectively. In this case, the rendezvous may be achieved between the stay patterns for the SU with a single radio and the jump radios for the SU with multiple radios. Meanwhile, the rendezvous also can be achieved between the jump patterns for the SU with a single radio and the stay radios of the SU with multiple radios, simultaneously. Compared with the scenario where both SUs are equipped with a single radio, SUs have more chance to achieve rendezvous during each period in this scenario. Then, we consider the scenario where both SUs are equipped with multiple radios. In this scenario, the stay radios of one SU may rendezvous with the radios of the other SU. Meanwhile, the stay radios of the other may also rendezvous with the radios of that SU. With the increase in the number of radios, the rendezvous chance can be increased during each period.



(a) ETTR VS. N

(b) MTTR VS. N

Figure 3.20: Comparison of different allocations of radios under the symmetric model.

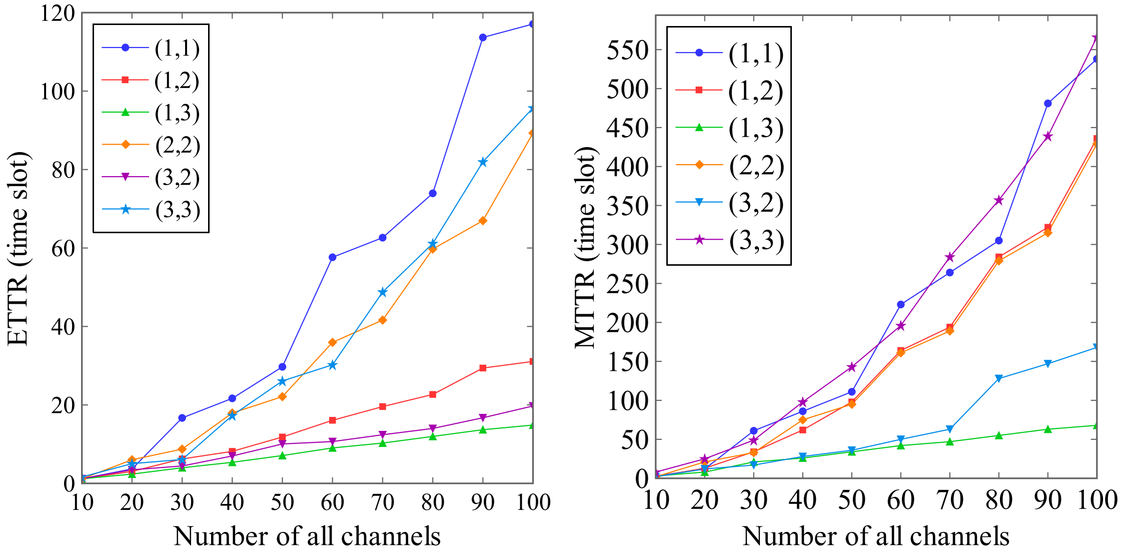
3.7.2 Performance under Different Parameter Settings

In this subsection, we evaluate the performance of the proposed HRR algorithm under different parameter settings, including the allocation of radios, the number of commonly available channels, and the number of available channels.

- Comparison of different allocations of radios

  The performance of the HRR algorithm influenced by different allocations of radios is evaluated. The total numbers of radios for SU_A and SU_B are fixed to 4. We use the notation (J_A, J_B) to denote the numbers of jump radios for SU_A and SU_B, which also can be used to denote the different allocations of radios. Six kinds of allocations exist when the total numbers of radios for SU_A and SU_B are equal to 4, including (1,1), (1,2), (1,3), (2,2), (2,3), and (3,3). The global channels, available channels, and commonly available channels are set as same as before.

  Fig. 3.20 and Fig. 3.21 show the comparison of the ETTR and the MTTR among the six kinds of allocations under the symmetric model and the asymmetric model, respectively. From Fig. 3.20, we can see that the ETTR and the MTTR are shorter when one of SUs is equipped with three jump radios under the symmetric model. The reason is that the MTTR decrease with the increase of the number of jump radios for the SU with smaller CHS period when the numbers of its radios and available channels are fixed under the symmetric model, which can be easily seen from Theorem 5. Hence, it is better to set



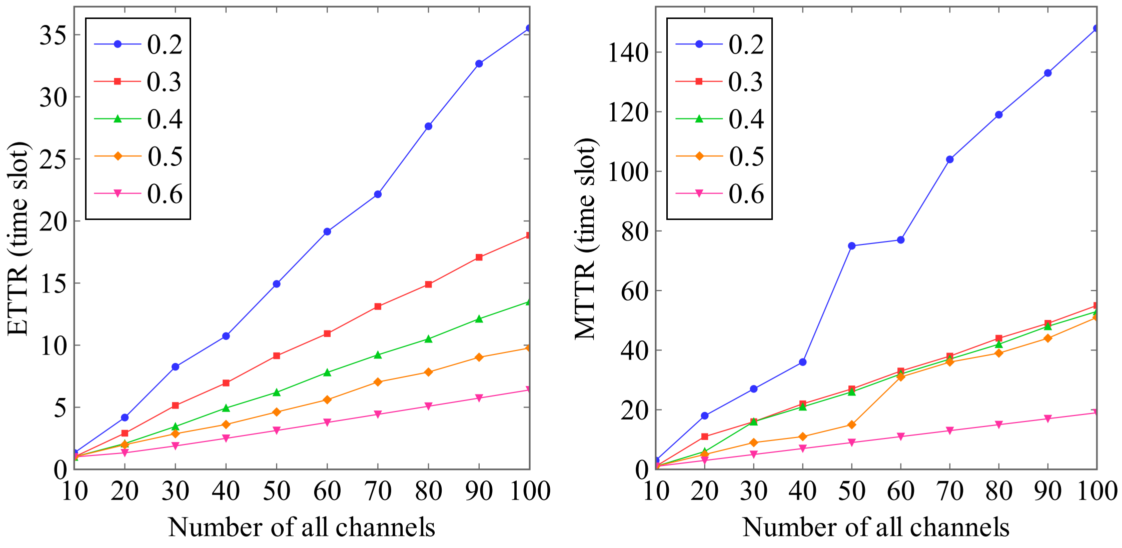
(a) ETTR VS. N (b) MTTR VS. N

Figure 3.21: Comparison of different allocations of radios under the asymmetric model.

$(M_i - 1)$ jump radios for SU_i to obtain minimum TTR under the symmetric model. From Fig. 3.21, we can see that the allocation (1,3) can achieve the smallest ETTR and MTTR under the asymmetric model. The optimal radio allocation is the allocation that can minimize the MTTR derived by Theorem 6. We will theoretically analyze how to allocate radios to achieve minimum MTTR in Chapter 5. From Fig. 3.20 and Fig. 3.21, we can also see that the ETTRs or MTTRs of several radio allocation manners are not increase smoothly with the increase of the number of all channels. The reason of that can be summarized as follows. Rendezvous may also achieves between the jump radios of one SU and the radios of the other SU. Besides, the channel access order may be changed with the number of all channels under different radio allocation manner. The regularity of rendezvousing between the jump radios of one SU and the radios of the other SU, as well as the relationship between the channel access order and radio allocation manner is out of the scope of this dissertation, which will be researched in detail in our future work.

- Comparison of different numbers of commonly available channels

  The performance of the HRR algorithm influenced by different numbers of commonly available channels is evaluated. The total numbers of radios for SU_A and SU_B are set to be 4. The numbers of jump radios for SU_A and SU_B are set to be 1 and 3, respectively. The numbers of available channels for SU_A and SU_B are set to be $0.6|N|$, while that of commonly available channels



(a) ETTR VS. N

(b) MTTR VS. N

Figure 3.22: Comparison of different numbers of commonly available channels.

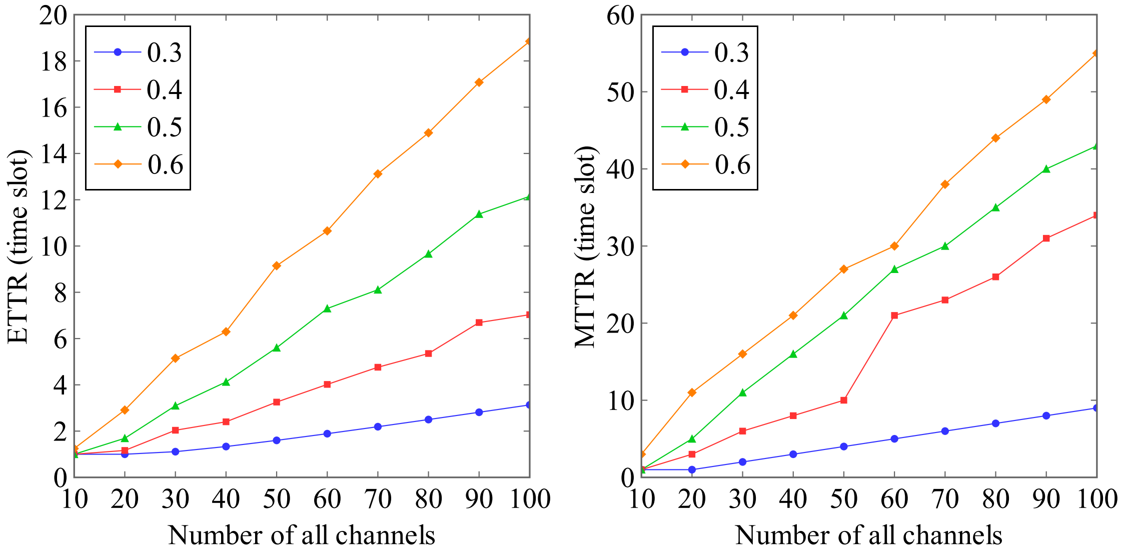
between SU_A and SU_B is varied from $0.2N$ to $0.6N$. The global channels are set as same as before.

Fig. 3.22 shows the comparison of different numbers of commonly available channels between SU_A and SU_B. From Fig. 3.22, we can see that the ETTR and the MTTR decrease with the increase of the number of commonly available channels. When the number of commonly available channels between SU_A and SU_B is same as that of their available channels, i.e., under the symmetric model, the rendezvous between SU_A and SU_B can be achieved with the shortest ETTR and MTTR. The reason is that the commonly available channels may occur earlier with its number increases when executing the rendezvous process.

- Comparison of different numbers of available channels

The performance of the HRR algorithm influenced by the different numbers of available channels is evaluated. The total numbers of radios for two SU_A and SU_B are set to be 4 while that of jump radios for SU_A and SU_B are set to 1 and 3, respectively. The global channels N varies from 10 to 100. The number of commonly available channels between SU_A and SU_B is fixed to $0.3N$. The numbers of available channels for SU_A and SU_B are varied from $0.3N$ to $0.6N$.

Fig. 3.23 shows the comparison of different numbers of available channels. From Fig. 3.23, we can see that the ETTR and the MTTR decrease with the decrease of the number of available channels. When the numbers of available channels for SU_A and SU_B are equal to $0.3N$, i.e., under the symmetric model.



(a) ETTR VS. N (b) MTTR VS. N

Figure 3.23: Comparison of different numbers of available channels.

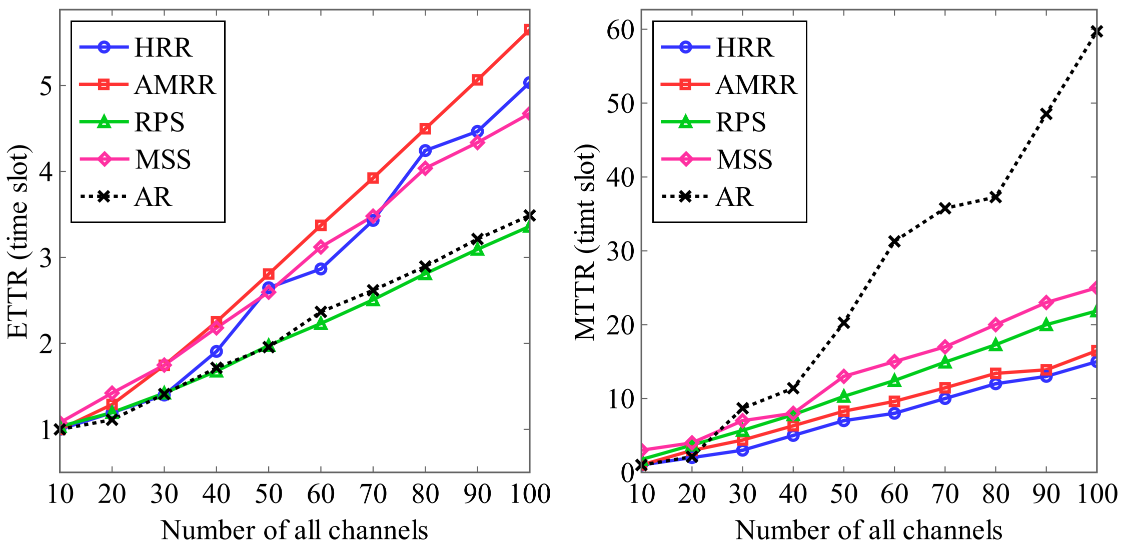
The rendezvous between SU_A and SU_B can achieved with the shortest ETTR and MTTR. The reason is that the length of one period for the CHSs generated by the MRR algorithm decrease with the decrease of the number of available channels when the numbers of total radios and that of the jump radios are fixed. Hence, the ETTR and MTTR decrease with the decrease of the number of available channels. Besides, we can see that the upper bound of MTTR for SUs under the symmetric model is less than that under the asymmetric model in any case form Theorem 5 and Theorem 6.

3.7.3 Comparison of Different CH Algorithms

In this subsection, we compare the ETTR and the MTTR of the proposed HRR algorithm to several multi-radio-based representative CH rendezvous algorithms, including the AR algorithm, the RPS algorithm, the AMRR algorithm and the MSS algorithm under the symmetric model and the asymmetric model, respectively.

- Under the symmetric model

  The performance of the proposed HRR algorithm and several multi-radio-based CH rendezvous algorithms is compared under the symmetric model. The numbers of radios for SU_A and SU_B are set to be 4. The numbers of available channels for two SUs are set to be $0.5N$. The number of commonly available channels between SU_A and SU_B is set to be $0.5N$. The number of global channels varies from 10 to 100.



(a) ETTR VS. N

(b) MTTR VS. N

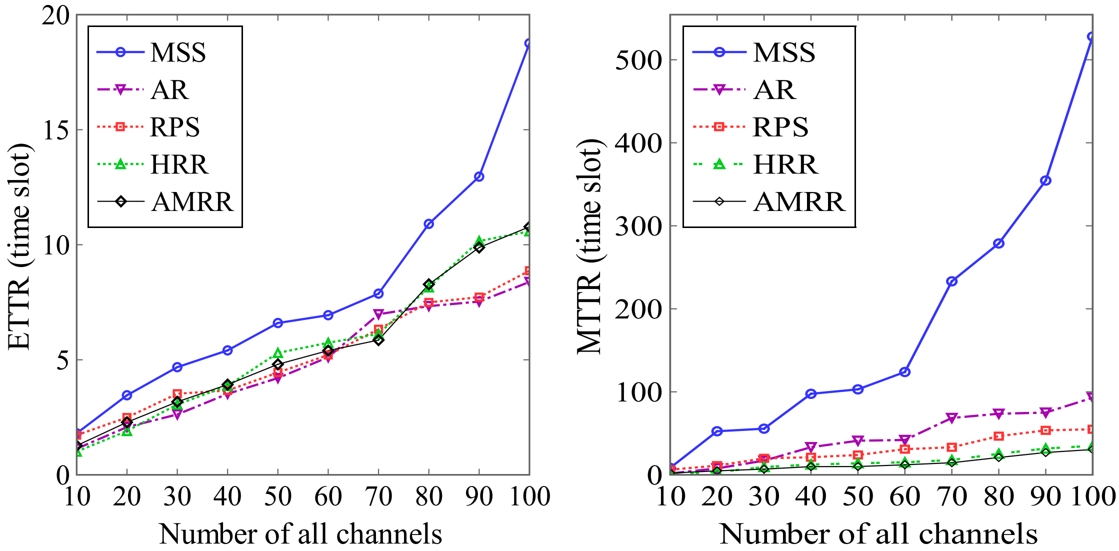
Figure 3.24: Comparison of different algorithms under the symmetric model.

Fig. 3.24 shows the comparison of different algorithms under the symmetric model. From Fig. 3.24, we can see that the MTTR of the HRR algorithm outperforms all of the compared CH algorithms while its ETTR is close to that of other CH algorithms. Besides, although the ETTR of the AR algorithm, the RPS algorithm and the MSS algorithm outperforms the HRR algorithm under some situations, the gap between them is very small. Moreover, there exist several drawbacks in the compared CH algorithms, which are presented as follows. The numbers of radios for different SUs are assumed to be same by the AR algorithm while that for each SU cannot be equal to 1 for the RPS algorithm and the AMRR algorithm.

- Under the asymmetric model

  The performance of the proposed HRR algorithm and several representative multi-radio-based CH rendezvous algorithms is compared under the asymmetric model. The numbers of radios for SU_A and SU_B are set to be 4. The numbers of available channels for SU_A and SU_B are set to be $0.5N$. The number of commonly available channels between SU_A and SU_B is set to $0.2N$. The number of global channels varies form 10 to 100.

  Fig. 3.25 shows the comparison of different algorithms under the asymmetric model measured by the average values of 10 times simulations. From Fig. 3.25, we can see that the MTTR of the proposed HRR algorithm is smaller than that of the MSS algorithm, the AR algorithm, and the RPS algorithm. Besides, when the number of the licensed channels is small, the MTTR of the



(a) ETTR VS. N

(b) MTTR VS. N

Figure 3.25: Comparison of different algorithms under the asymmetric model.

HRR algorithm is also shorter than the AMRR algorithm. When the number of the licensed channels is larger, the MTTR of the HRR algorithm is longer than that of the AMRR algorithm. However, the difference between them is tiny. Moreover, we can see that the ETTR of the proposed HRR algorithm is smaller than that of the MSS algorithm. Besides, when the number of licensed channels is smaller, the ETTR of the proposed HRR algorithm is also lower than the RPS algorithm, the AMRR algorithm, and the AR algorithm. When the number of licensed channel is larger, even though the ETTR of the proposed HRR algorithm is longer than that of the other algorithms, the difference between them is small.

In summary, although the ETTR of the AR algorithm, the AMRR algorithm, and the RPS algorithm outperform the HRR algorithm under several scenarios for the asymmetric model, the difference between them is very tiny. Besides, although the MTTR of the HRR algorithm is larger than that of the AMRR algorithm under several scenarios for the asymmetric model, the difference between them is very small. In addition, the AR algorithm assumed that the numbers of radios for different SUs are same, while the RPS algorithm and the ARMM algorithm are not applicable for the situation where one of SUs is equipped with one radio. Moreover, although the ETTR of the MSS algorithm is close to that of the HRR algorithm under the symmetric model, the MTTR of the MSS algorithm is much larger than that of the HRR algorithm under both symmetric model and asymmetric model, while the ETTR of the MSS algorithm is larger than that of the HRR algorithm under the asymmetric model. Thus, the proposed HRR algorithm is more applicable for the heterogeneous DSA networks than any other compared representative multi-radio-based CH rendezvous algorithms.

Chapter 4

Rendezvous with Full Diversity in Heterogeneous DSA Network

In this chapter, to achieve fully rendezvous diversity while further shortening the TTR, we propose the MEHRR algorithm. The system model utilized in this chapter is same as that of the Chapter 3.

4.1 Motivation

As shown in Fig. 4.1, full rendezvous diversity cannot be achieved when a pair of SUs is equipped with one radio and $0 < \delta^* \leq P$. Because SU always stay at the same channel during the first stay pattern in our designed HRR algorithm. Hence, if two SUs stay at the same channel during their first stay pattern. They will always rendezvous on the same channel. To achieve full rendezvous diversity for the SUs in heterogeneous DSA networks, we propose the MEHRR algorithm consisting of the EMRR algorithm and the MESRR algorithm. The MESRR algorithm changes the generation way of access channel index and the structure of the CHSs generated by the SRR algorithm in the HRR algorithm. To further shorten MTTR, the EMRR algorithm changes the structure of the CHSs generated by the MRR algorithm in the HRR algorithm.

4.2 Objective and Basic Idea

4.2.1 Objective

The objective of this chapter is to design a CH algorithm that

1. Can further shorten MTTR compared with the HRR algorithm when the SUs are equipped with multiple radios.

2. Can achieve full rendezvous diversity while shortening the MTTR as much as possible for the SUs with one radio.

4.2.2 Basic Idea

- The basic idea to achieve the objective 1.

  We design the EMRR algorithm to generate CHSs for the SUs with multiple radios. Compared with the MRR algorithm, the length of period for the CHSs generated by the EMRR algorithm is shortened from $2w_A$ to w_A.

- The basic idea to achieve the objective 2.

  We design the MESRR algorithm to generate CHSs for the SUs with single radios. Compared with the SRR algorithm, the CHSs generated by the MESRR algorithm consists of two kinds of period, which are inner period and outer

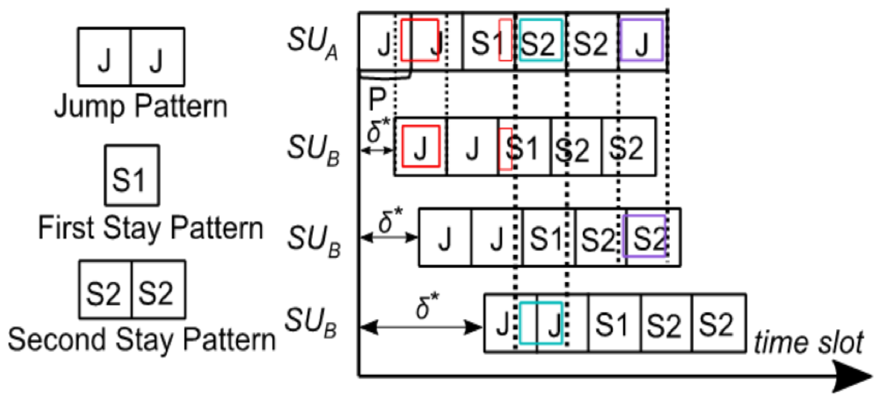


Figure 4.1: Rendezvous for the HRR algorithm

period. The index of the channel that visited by the stay pattern is changed per inner period of the CHSs while the index of the channel that visited by the jump pattern is changed per outer period of the CHSs. Besides, the length of one inner period for the CHSs generated by the SRR algorithm is shortened from $5P$ to $3P$ by deleting the second stay pattern of the CHSs generated by the SRR algorithm.

4.3 Overview of the MEHRR Algorithm

In this section, we give an overview of the MEHRR algorithm.

4.3.1 Flowchart of the MEHRR Algorithm

The algorithm that we proposed is the MEHRR algorithm in this chapter. The ACD algorithm, the MESRR algorithm, and the EMRR algorithm are invoked by the MEHRR algorithm. To make the algorithms easy to understand, we add a flowchart to present the MEHRR algorithm as Fig. 4.2. In the MEHRR algorithm, SU generates CHSs based on the number of its radios. If the SU is equipped with one radio, the CHS is generated by the MESRR algorithm. If the SU is equipped with multiple radios, the available channels are firstly allocated to each radio using the ACD algorithm. Then, generating CHS for each radio based on its allocated available channels using the EMRR algorithm. After generating CHS, SUs can access channels according to the generated CHS to attempt rendezvous.

4.3.2 Achievement of Objective

In this subsection, we present the basic idea of achieving the objectives by the MEHRR algorithm in more detail.

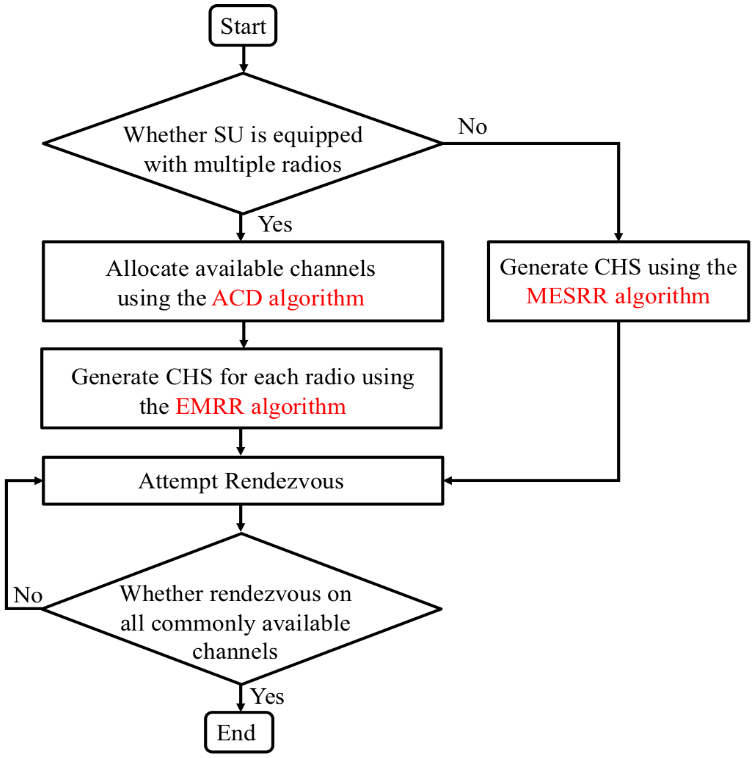


Figure 4.2: Flowchart of the MEHRR algorithm.

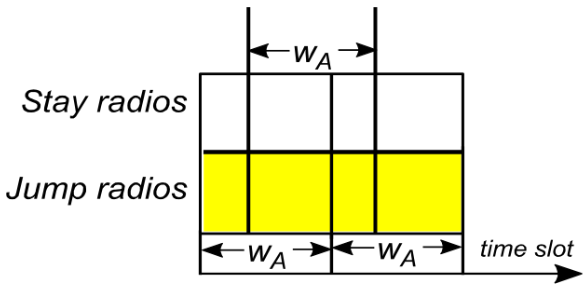


Figure 4.3: The structure of the CHS for the EMRR algorithm

- Objective 1.

  To further shorten the MTTR for the SUs with multiple radios, we firstly modified the MRR algorithm. We reduce the length of the CHS period generated by the MRR from $2w_A$ to w_A in the EMRR algorithm. The basic idea is that we prove that all available channel can be visited once during any continuous w_A as shown in Fig. 4.3.

- Objective 2.

  Then, to further shorten the MTTR while achieve full rendezvous diversity for the SUs with single radio, we propose the MESRR algorithm by improving the SRR algorithm. Fig. 4.4 shows the comparison of the SRR algorithm and the MESRR algorithm. To achieve full rendezvous diversity, we change the index

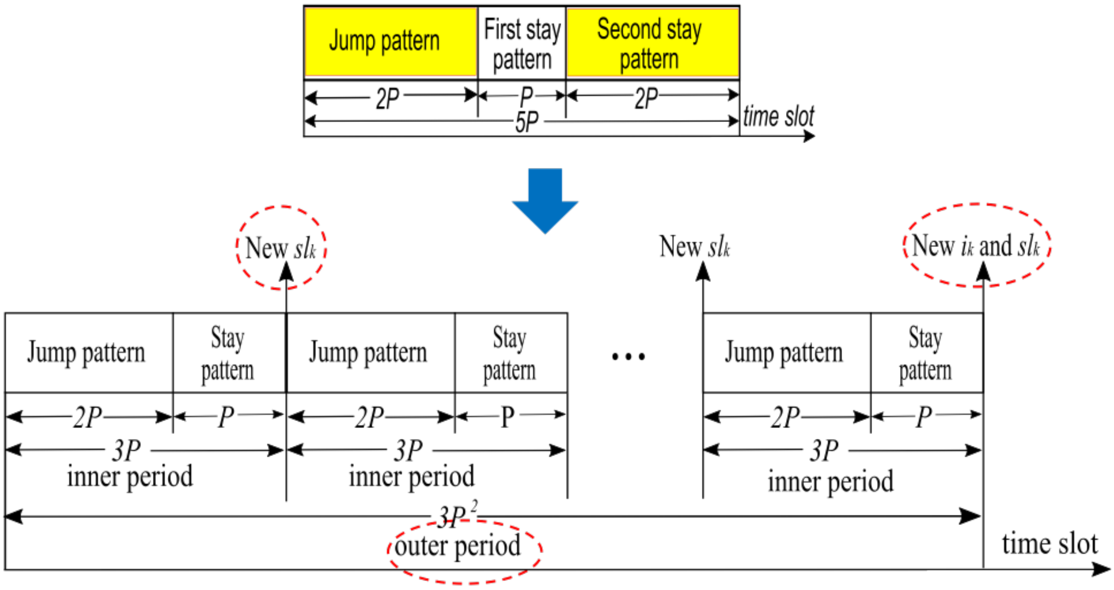


Figure 4.4: Comparison of the SRR algorithm and the MESRR algorithm.

of the channel that visited by the stay pattern pre inner period. Rendezvous can be achieved during stay pattern after changing the stay channel for the first stay pattern pre inner period. Hence, we delete the second stay pattern. Hence, the length of the one period is reduced form $5P$ to $2P$. However, rendezvous cannot be guaranteed when the channels that a pair of SUs visit during the stay pattern are different. To solve this problem, we change the initial index per outer period. Due to this, rendezvous can be guaranteed on different channels between jump patterns for different outer periods when sl_k is different for a pair of SUs.

Then, we present the MEHRR algorithm in detail. The rest of this chapter is organized as follows. Chapter 4.4 formulates the problem that we aim to solve in this chapter. Chapter 4.5 presents the MEHRR algorithm. Chapter 4.6 analyzes the proposed MEHRR algorithm in terms of MTTR with full rendezvous diversity by theoretical analysis. Chapter 4.7 evaluates the proposed MEHRR algorithm in terms of MTTR with full rendezvous diversity under different scenarios by simulation.

4.4 Problem Formulation

Let $\min \Gamma(G_{kl}, k, l, \delta_{kl})$ denote the minimum TTR on all commonly available channels between SU_k and SU_l (i.e., the minimum TTR with full rendezvous diversity) given that the clock of SU_l is δ_{kl} time slots behind that of SU_k. G_{kl} is the commonly

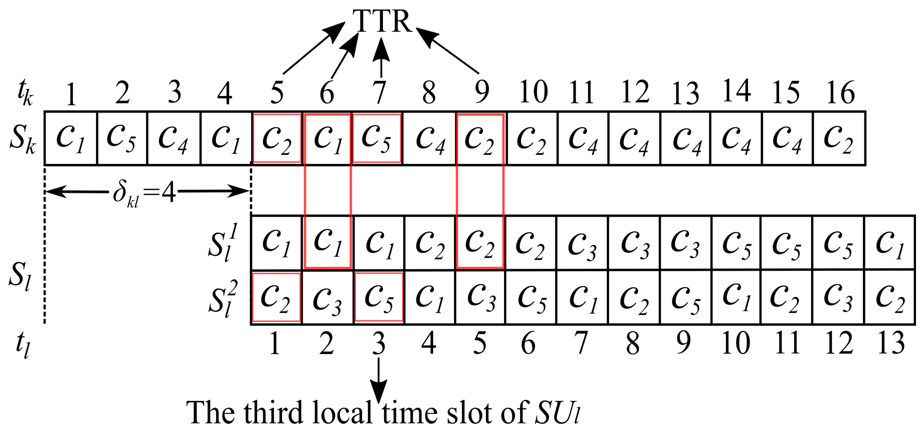


Figure 4.5: An example of rendezvous process.

available channel set between SU_k and SU_l. The MTTR with full rendezvous diversity between SU_k and SU_l is defined as the maximum $\min \Gamma(G_{kl}, k, l, \delta_{kl})$ given arbitrary δ_{kl}, which can be expressed as follows:

$$MTTR(G_{kl}, k, l, \delta_{kl}) = \max_{\forall \delta_{kl}} \min \Gamma(G_{kl}, kl, \delta_{kl}). \tag{4.1}$$

For easily understanding, Fig. 4.5 illustrates an example of the rendezvous process. In the example, the licensed channel set $\mathcal{N} = \{c_1, c_2, c_3, c_4, c_5\}$. The available channel set of SU_k, $\mathcal{C}_k = \{c_1, c_2, c_4, c_5\}$. Meanwhile, the available channel set of SU_l, $\mathcal{C}_l = \{c_1, c_2, c_3, c_5\}$. Hence, the commonly available channels between SU_k and SU_l, $G_{kl} = \{c_1, c_2, c_5\}$. Besides, the numbers of radios for SU_k and SU_l, i.e., M_k and M_l, are 1 and 2, respectively. The radios of SU_l consists of one jump radio and one stay radio. Meanwhile, $\delta_{kl} = 4$. From Fig. 4.5, we can see that SU_k and SU_l can rendezvous on all commonly available channels (i.e., c_1, c_2, and c_5.) once until the third local time of SU_l. In this case, the third local time slot of SU_l is called the minimum TTR on all commonly available channels, i.e., the MTTR with full rendezvous diversity between SU_k and SU_l. Note that the TTR is count from the starting point when both SUs start hopping. Besides, the TTR is defined as the time that a pair of SUs accesses the same channel. For instance, the 5^{th}, the 6^{th}, the 7^{th} and the 9^{th} local time slots of SU_k are the TTRs between SU_k and SU_l in Fig. 4.5.

To solve the optimization problems mentioned above by using combinatorics, a channel hopping pattern determined by the blind rendezvous algorithm is necessary. Hence, our objective is to design a blind rendezvous algorithm that can achieve fast rendezvous with full rendezvous diversity for the SUs in heterogeneous DSA networks.

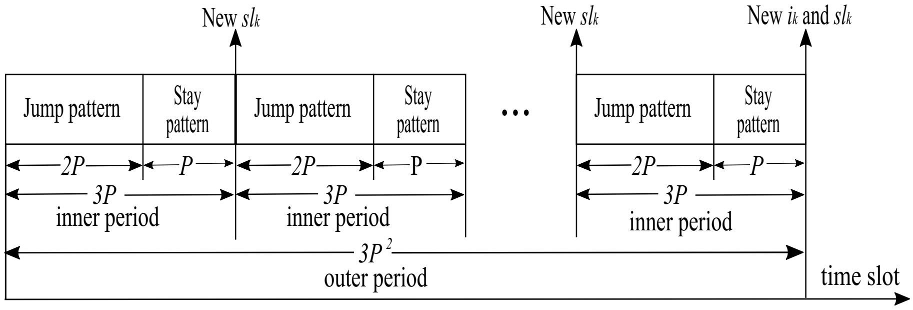


Figure 4.6: The structure of the CHSs generated by the MESRR algorithm.

4.5 Fast Blind Rendezvous Algorithm

In this section, we first present the MESRR algorithm that is proposed to generate CHSs for the SUs with single radio. After that, we introduce the EMRR algorithm that is proposed to generate CHSs for the SUs with multiple radios. Finally, we present the MEHRR algorithm based on the MESRR algorithm and the EMRR algorithm.

4.5.1 MESRR Algorithm

The MESRR algorithm is proposed to construct CHSs for the SUs with only one radio. The CHSs are periodically generated by the MESRR algorithm. Two kinds of periods exist for the CHSs generated by the MESRR algorithm, which are inner period and outer period.

The length of one inner period for the CHSs generated by the MESRR algorithm lasts for $3P$ time slots. Two patterns exist in one inner period, which are jump pattern and stay pattern. The jump pattern and the stay pattern last for $2P$ time slots and P time slots in one inner period, respectively. During the jump pattern, SU incessantly switches among its available channels. SU always stays at the channel whose index equals to the step length during the stay pattern. The step length is generated in the MEHRR algorithm, which will be presented in detail later. The length of one outer period is $3P^2$. One outer period consists of P inner periods. The structure of the CHSs generated by the MESRR algorithm is shown in Fig. 4.6 while the pseudocode of the MESRR algorithm is presented in Algorithm 5.

The input parameters sl_{k0} and i_{k0} in the MESRR algorithm are the initial step length and the initial channel index, respectively. The values of the sl_{k0} and the i_{k0} are generated in the MEHRR algorithm, which will be presented later. In lines 3 and 4 of Algorithm 5, the initial channel index and the step length used at local time slot t_k of SU_k are generated to construct CHS for SU_k. The step length sl_k is changed per inner period while the initial channel index i_k is changed pre outer period. In lines 5∼10, the counters that are used to count the number of generated

Algorithm 5 MESRR algorithm

Input: $\mathcal{N}, P, \mathcal{C}_k, t_k, sl_{k0}, i_{k0}$ \\for SU_k
Output: $\mathcal{S}_k(t_k)$

$t^* = ((t_k - 1) \bmod 3P) + 1$
$t^{**} = ((t_k - 1) \bmod 3P^2) + 1$
$sl_k = ((sl_{k0} + \lfloor \frac{t_k - 1}{3P} \rfloor - 1) \bmod P) + 1$
$i_k = ((i_{k0} + \lfloor \frac{t_k - 1}{3P^2} \rfloor - 1) \bmod P) + 1$
if $t^* = 1$ **then**
    $q = 0$
end if
if $t^{**} = 1$ **then**
    $z = 0$
end if
if $t^* \leq 2P$ **then**
    $j = ((i_k + t^* \cdot sl_k - 1) \bmod P) + 1$
else
    $j = sl_k$
end if
if $j > N$ **then**
    $j = ((j - 1) \bmod N) + 1$
end if
if $c_j \notin \mathcal{C}_k$ **then**
    if $t^* \leq 2P$ **then**
        $q = q + 1$
        $S_k(t_k) = C_k(((q - 1) \bmod C_k) + 1)$
    else
        if $t^* = 2P + 1$ **then**
            $z = z + 1$
        end if
        $S_k(t_k) = C_k(((z - 1) \bmod C_k) + 1)$
    end if
else
    $\mathcal{S}_k(t_k) = c_j$
end if

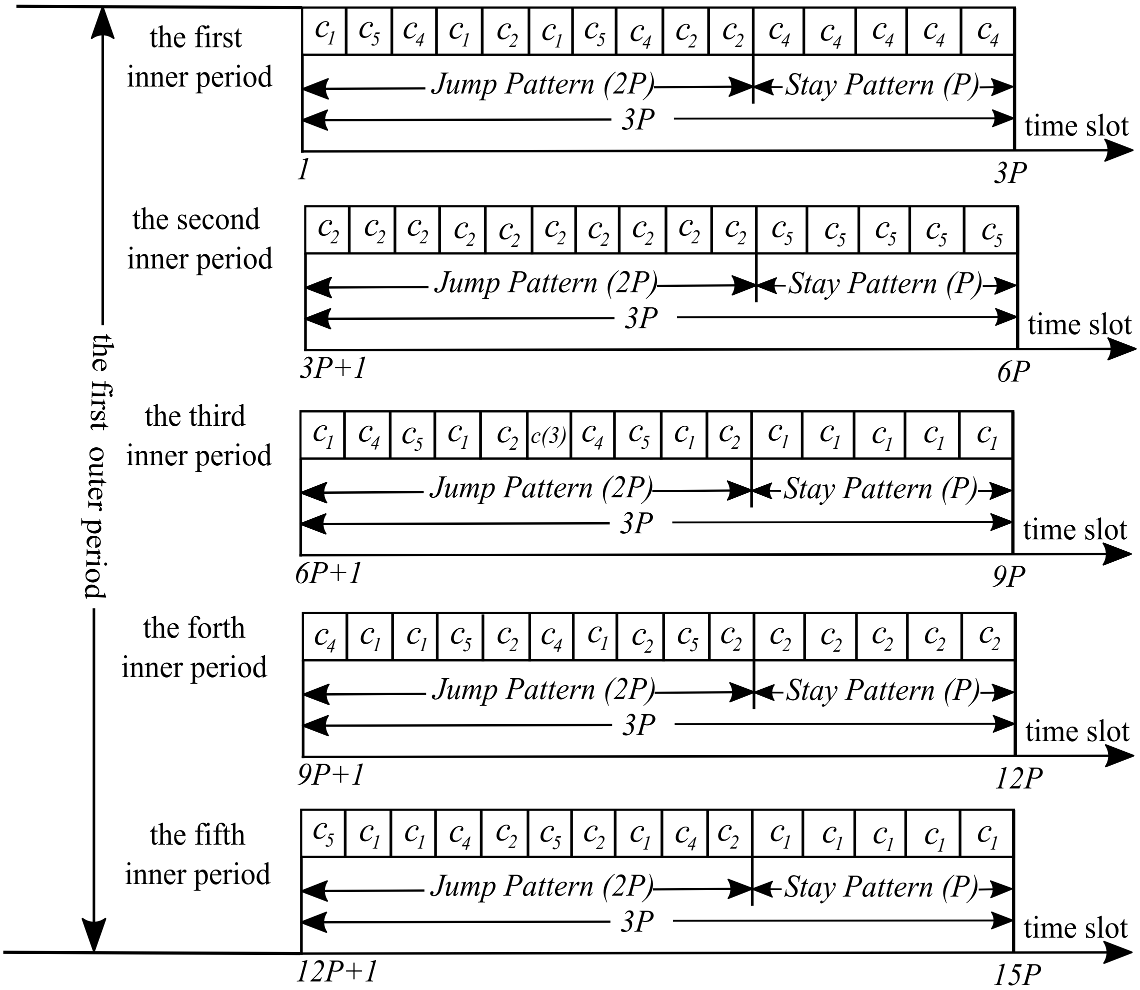


Figure 4.7: An example of the CHS generated by the MESRR algorithm.

unavailable channels is reset. Among them, the counter that is used to count the number of generated unavailable channels for the jump pattern of the CHS is reset to zero at the beginning of each inner period by line 6. Meanwhile, the counter that is used to count the number of generated unavailable channels for the stay pattern of the CHS is reset to zero at the beginning of each outer period by line 9. The purpose of counting the number of generated unavailable channels is to replace the unavailable channels using the channels with high channel qualities, which will be detailedly presented in the MEHRR algorithm. The indexes of the channels that SUs access during the jump patterns and the stay patterns are generated by line 12 and 14, respectively. The channel indexes whose values exceed the number of licensed channels in DSA networks are replaced by line 17. Then, if the licensed channel with the channel index derived above is available for SU_k, the channel becomes the t_k^{th} channel in the CHS of SU_k by line 30. Otherwise, the unavailable channel needs to be replaced by lines 19∼28. The unavailable channels during the jump patterns are replaced by lines 20∼ 23 while the unavailable channels during the stay patterns are replaced by lines 24∼ 28.

To make the MESRR algorithm easier for readers to understand, we show an example of one outer period of the CHS generated by the MESRR algorithm in Fig. 4.7. In the example, the licensed channel set $\mathcal{N} = \{c_1, c_2, c_3, c_4, c_5\}$, the available channel set $\mathcal{C}_k = \{c_1, c_2, c_4, c_5\}$, the initial channel index $i_{k0} = 2$, and the initial step length $sl_{k0} = 4$. Since $P = 5$ in the example, each outer period consists of 5 inner periods. Then, we present the generation process of three typical channels (i.e., the 1^{st} channel, the 4^{th} channel, and the 11^{th} channel) in the CHS. Since t^* for the 1^{st} channel in the CHS derived by line 1 in the MESRR algorithm equals to 1, which is less than $2P = 10$. The index of the 1^{st} channel is generated by line 12, where sl_k can be derived by line 3 in the MESRR algorithm, i.e., $sl_k = (((sl_{k0} + \lfloor \frac{t_k - 1}{3P} \rfloor - 1) \bmod P) + 1) = (((4 + \lfloor \frac{1-1}{3\times 5} \rfloor - 1) \bmod 5) + 1) = 4$; i_k can derived by line 4 in the MESRR algorithm, i.e., $i_k = (((i_{k0} + \lfloor \frac{t_k - 1}{3P^2} \rfloor - 1) \bmod P) + 1) = (((2 + \lfloor \frac{1-1}{3\times 5^2} \rfloor - 1) \bmod 5) + 1) = 2$. Hence, the index for the first channel in the CHS is 1, which is derived by $j = (((i_k + t^* \cdot sl_k - 1) \bmod P) + 1) = (((2 + 1 \times 4 - 1) \bmod 5) + 1) = 1$. Since c_1 is available for SU_k, it becomes the first channel in the CHS of SU_k.

The generation of the index for the 4^{th} channel in the CHS of SU_k is same as that for the 1^{st} channel. After calculating, we can get the channel index for the 4^{th} channel, which equals to 3. Because c_3 is not available for SU_k, it is necessary to replace it according to lines 21 and 22 in the MESRR algorithm. Because q in line 21 is set to zero at the beginning of each inner period while the first three generated channels are available for SU_k. Hence, we can get that $q = q + 1 = 1$ at this moment. Then, the 4^{th} channel in the CHS of SU_k can be derived by line 22, i.e., $S_k(t_k) = C_k(((q - 1) \bmod C_k) + 1) = C_k(((1 - 1) \bmod 4) + 1) = C_k(1) = c_1$. For the generation of the 11^{th} channel in the CHS of SU_k, $t^* = ((11 - 1) \bmod 3\times 15 + 1) = 11 > 2P = 10$. Hence, the channel index is generated by line 14, i.e., $j = sl_k = 4$. Because c_4 is available for SU_k, c_4 becomes the 11^{th} channel in the CHS of SU_k.

4.5.2 EMRR Algorithm

The EMRR algorithm is designed for the SUs with multiple radios. The CHSs of the SUs with multiple radios are generated periodically by the EMRR algorithm. The length of one outer period for the CHS generated by the EMRR algorithm for SU_k is $w_k \cdot \frac{LCM(C_k, Y_k)}{Y_k}$, where $LCM(C_k, Y_k)$ denotes the least common multiple of C_k and Y_k, w_k denotes the length of one inner period for the CHS of SU_k when $m_k > 1$. $w_k = \left\lceil \frac{C_k - Y_k}{J_k} \right\rceil$, where Y_k and J_k denote the numbers of stay radios and jump radios of SU_k, respectively. There are $\frac{LCM(C_k, Y_k)}{Y_k}$ inner periods during one outer period. The orders of the channels in the CHS for different outer periods are same. The structure of the CHSs generated by the EMRR algorithm is shown in Fig. 4.8. The white part denotes the CHS for the stay radios while the gray part denotes the CHS

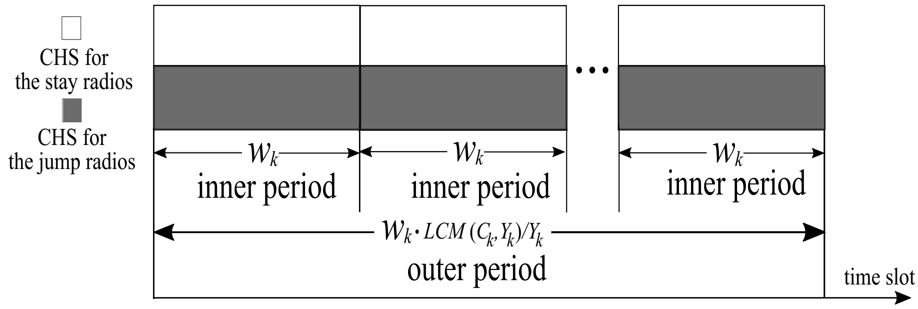


Figure 4.8: The structure of the CHSs generated by the EMRR algorithm.

for the jump radios. Each stay radio stays at the same channel during one inner period while the stay channel for each stay radio is changed per inner period. Each jump radio of the SU incessantly accesses different channels at each time slot. The details of the EMRR algorithm are shown in Algorithm 6.

Algorithm 6 EMRR algorithm

Input: $\mathcal{C}_k,\ M_k,\ J_k,\ Y_k,\ t_k$ \\for $\mathcal{S}U_k$
Output: $\mathcal{S}_k(t_k)$
1: $\mathcal{C}_k^S = \emptyset$
2: $w_k = \left\lceil \frac{C_k - Y_k}{J_k} \right\rceil$
3: **for** $i = 1$ to Y_k **do**
4: $\quad h = \left(\left(\left(\left\lfloor \frac{(t_k-1)}{w_k} \right\rfloor Y_k + i - 1\right) \bmod C_k\right) + 1\right)$
5: $\quad S_k^i(t_k) = C_k(h)$
6: $\quad \mathcal{C}_k^S = \mathcal{C}_k^S \cup C_k(h)$
7: **end for**
8: **if** $(t_k - 1) \bmod w_k = 0$ **then**
9: $\quad \mathcal{C}_k^J = \mathcal{C}_k \backslash \mathcal{C}_k^S$
10: Invoke the ACD algorithm to divide the channels in $\mathcal{C}_k^J$ among J_k jump radios, and obtain $\mathcal{C}_k^{J*}$
11: **end if**
12: **for** $i = Y_k + 1$ to M_k **do**
13: $\quad h = (((t_k - 1) \bmod w_k) \bmod C_{ki}^{J*}) + 1$
14: $\quad S_k^i(t_k) = C_{ki}^{J*}(h)$
15: **end for**
16: **for** $x = 1$ to M_k **do**
17: $\quad \mathcal{S}_k(t_k) = \mathcal{S}_k(t_k) \cup S_k^x(t_k)$
18: **end for**

In line 1, the available channel set for the stay radios is initialized as an empty set. In line 2, the length of one inner period for the CHS of SU_k is calculated. In lines 3∼7, the CHS for the stay radios of SU_k at t_k is generated. In lines 8∼11, the available channel sets for the jump radios of SU_k are constructed by invoking the available channel distribution (ACD) algorithm proposed in [66]. The purpose of invoking the ACD algorithm to allocate channels to the jump radios is that different

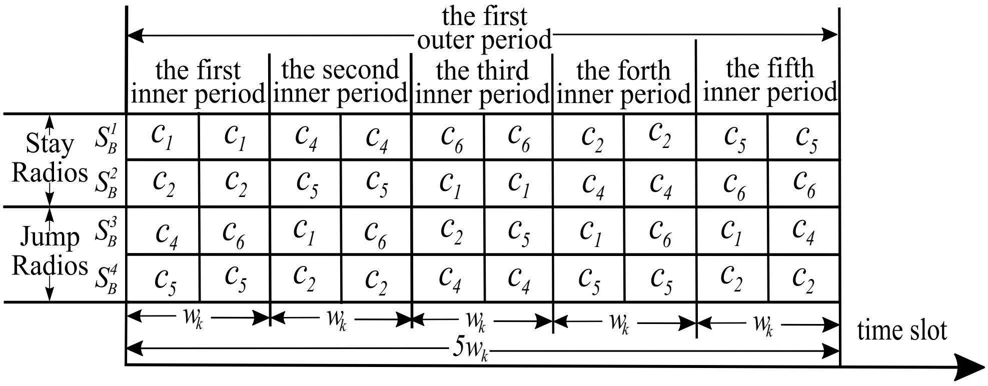


Figure 4.9: An example of the CHS generated by the EMRR algorithm.

radios of SU_k can be guaranteed to access different channels at the same time slot. The main idea of the ACD algorithm is that evenly dividing the channels in $\mathcal{C}_k^J$ to J_k jump radios. The input of the ACD algorithm is $\mathcal{C}_k^J$. The output of the ACD algorithm is $\mathcal{C}_k^{J*}$, where $\mathcal{C}_k^{J*}$ denotes the set consisting of the available channel sets allocated to the jump radios of SU_k. The available channel sets for the jump radios of SU_k are constructed at the beginning of each inner period. In lines 12∼15, the CHS for the jump radios of SU_k at t_k is generated. Let $\mathcal{C}_{ki}^{J*}$ denote the allocated available channel set for the i^{th} radio of SU_k while $C_{ki}^{J*}(h)$ denotes its h^{th} allocated available channel. In lines 16∼18, the CHS for SU_k with multiple radios at t_k is generated.

To make the EMRR algorithm easier for readers to understand, we show an example of one outer period of the CHS generated by the EMRR algorithm in Fig. 4.9. In the example, the licensed channel set $\mathcal{N} = \{c_1, c_2, c_3, c_4, c_5, c_6\}$, the available channel set $\mathcal{C}_k = \{c_1, c_2, c_4, c_5, c_6\}$, the number of radios $M_k = 4$, the number of stay radios $Y_k = 2$, and the number of jump radios $J_k = 2$. Since $w_k = \left\lceil \frac{C_k - Y_k}{J_k} \right\rceil = \left\lceil \frac{5-2}{2} \right\rceil = 2$, the length of each period lasts for two time slots. Besides, since $\frac{LCM(C_k, Y_k)}{Y_k} = \frac{LCM(5,2)}{2} = 5$, there are five inner periods during one outer period. In Fig. 4.9, the first two radios are stay radios while the last two radios are jump radios. We then present the generation of the CHS for the first time slot in detail. The indexes of the channels that are visited by the stay radios of SU_k at the first time slot are generated by line 4 in the EMRR algorithm. For the first stay radio, the channel index is $h = \left(\left(\left(\left\lfloor \frac{(t_k-1)}{w_k} \right\rfloor Y_k + i - 1\right) \bmod C_k\right) + 1\right) = \left(\left(\left(\left\lfloor \frac{(1-1)}{2} \right\rfloor 2 + 1 - 1\right) \bmod 5\right) + 1\right) = 1$. For the second stay radio, the channel index is $h = \left(\left(\left(\left\lfloor \frac{(1-1)}{2} \right\rfloor 2 + 2 - 1\right) \bmod 5\right) + 1\right) = 2$. Hence, the stay radios of SU_k visit channel c_1 and channel c_2 at its first time slot, respectively. Since $(t_k - 1) \bmod w_k = 0$ for the first time slot, the ACD algorithm is invoked to allocate the channels to the jump radios of SU_k by lines 9 and 10. After allocating, the first jump radio and the second jump radio possess their own available channel sets. That is,

$\mathcal{C}_{k1}^{J*} = \{c_4, c_6\}$ and $\mathcal{C}_{k2}^{J*} = \{c_5\}$. Then, the indexes of the channels that are visited by the jump radios of SU_k are generated by line 13 in the EMRR algorithm. For the first jump radio, $h = (((t_k - 1) \bmod w_k) \bmod C_{ki}^{J*}) + 1 = (((1-1) \bmod 2) \bmod 2) + 1 = 1$. For the second jump radio, $h = (((t_k - 1) \bmod w_k) \bmod C_{ki}^{J*}) + 1 = (((1-1) \bmod 2) \bmod 1) + 1 = 1$. Hence the jump radios visit $C_{k1}^{J*}(1)$ and $C_{k2}^{J*}(1)$ (i.e., c_4) and c_5) at the first time slot.

4.5.3 MEHRR Algorithm

Based on the MESRR algorithm and the EMRR algorithm, we present the MEHRR algorithm. In the MEHRR algorithm, SUs select either MESRR algorithm or EMRR algorithm to generate their CHSs according to their numbers of radios. The MESRR algorithm is invoked to generate CHSs for the SUs with one radio while the EMRR algorithm is invoked to generate CHSs for the SUs with multiple radios. SUs continue attempting rendezvous by visiting the channels generated by the MESRR algorithm or the EMRR algorithm until achieving rendezvous with their intended SUs in the MEHRR algorithm. The details of the MEHRR algorithm are shown in Algorithm 7.

Algorithm 7 MEHRR algorithm

Input: $t_k, M_k, Y_k, J_k, \mathcal{C}_k, \mathcal{N}, P$ \\for SU_k

1: t_k=1
2: sl_{k0}, i_{k0} : the step length and the initial channel index randomly selected from $[1, P)$.
3: Sorting $\mathcal{C}_k$ and $\mathcal{N}$ in descending order according to the channel quality
4: **while** not rendezvous **do**
5:   **if** $M_k = 1$ **then**
6:     Invoke the MESRR algorithm to generate CHS, i.e., $\mathcal{S}_k(t_k) = \text{MESRR}(\mathcal{N}, P, \mathcal{C}_k, t_k, sl_{k0}, i_{k0})$
7:   **end if**
8:   **if** $M_k > 1$ **then**
9:     Invoke the EMRR algorithm to generate CHS, i.e., $\mathcal{S}_k(t_k) = \text{EMRR}(\mathcal{C}_k, M_k, J_k, Y_k, t_k)$
10:   **end if**
11:   Attempt rendezvous on $\mathcal{S}_k(t_k)$
12:   $t_k = t_k + 1$
13: **end while**

In lines 1∼2, the local time slot, the initial step length, and the initial channel index are initialized. In line 3, the available channel set of SU_k and the licensed channel set are sorted in descending order according to the channel quality measured by channel noise. The purpose of line 3 is to improve the frequency of rendezvousing on the channels whose qualities are better [98]. SUs rendezvous on the channels with better quality may increase the success probability of establishing control channels after rendezvous [36]. We will discuss about the channel quality in next chapter. In lines 4∼13, SU_k attempts rendezvous until successfully achieving rendezvous. Among them, either the MESRR algorithm or the EMRR algorithm is invoked to generate the CHS for SU_k according to its radio number by line 6 or line 9.

4.6 Performance Analysis

In this subchapter, we theoretically analyze the MTTR with full rendezvous diversity for the MEHRR algorithm under three scenarios: 1) both of the SUs are equipped with one radio; 2) One SU is equipped with one radio while the other SU is equipped with multiple radios; 3) both of the SUs are equipped with multiple radios. The upper bounds on the TTR with full rendezvous diversity under these three scenarios are derived, which show that our proposed MEHRR algorithm can be applied to achieve rendezvous with full rendezvous diversity for the SUs in heterogeneous DSA networks. To well analyze the MTTR with full rendezvous diversity for the proposed MEHRR algorithm, we firstly present one Lemma. Then, the MTTR with full rendezvous diversity are analyzed based on the Lemma under the three different scenarios.

Lemma 4 shows that all available channels of the SU with multiple radios can be visited at least once during any contiguous w time slots (i.e., the length of one inner period of the CHS generated by the EMRR algorithm) by the SU using the EMRR algorithm. Fig. 4.10 shows the structure of two adjacent inner periods of the CHS generated by the EMRR algorithm. For clear deriving Lemma 4, we firstly give some notations. Note that the notations given here are only applicable to present Lemma 4. The length of one inner period for the CHS generated by the EMRR algorithm is denoted as w. We intercept any contiguous w time slots of the CHS in two adjacent inner periods, and enlarge the intercepted part in Fig. 4.10. Let x denote the number of time slots intercepted in the front inner period while $(w-x)$ denotes that intercepted in the behind inner period. Let S and J denote the numbers of stay radios and jump radios for the SU, respectively. $\mathcal{C}$ denotes the available channel set for the SU. $\mathcal{C} = \{c_1, c_2, \cdots, c_C\}$, where C is the number of available channels for the SU. $\mathcal{C}_{fS}$ and $\mathcal{C}_{fJ}$ denote the channel sets consisting of the channels that the stay radios and the jump radios visit during the front x time slots, respectively. $\mathcal{C}_{bS}$ and $\mathcal{C}_{bJ}$ denote the channel sets consisting of the channels that the stay radios and the jump radios visit during the behind $(w-x)$ time slots, respectively. $\mathcal{C}_f$ and $\mathcal{C}_b$ denote the channel sets consisting of the channels that the radios visit during the front x time slots and the behind $(w-x)$ time slots, respectively. Then, we present Lemma 4 as follows.

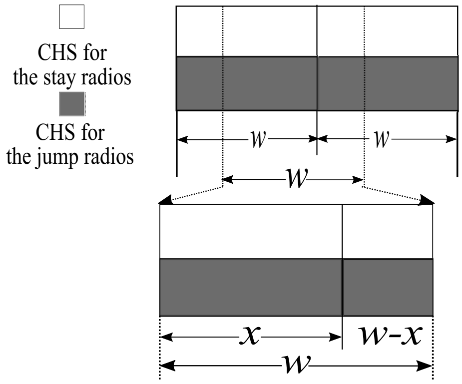


Figure 4.10: The structure of two inner periods of the CHS generated by the EMRR algorithm.

Lemma 4. *All available channels for the SU with multiple radios can be visited at least once during any contiguous w time slots, where w is the length of one inner period for the CHS of the SU generated by the EMRR algorithm.*

Proof. According to the EMRR algorithm, C equals to $(S+J\cdot(w-1)+((C-S-1) \mod J)+1)$. As shown in Fig. 4.10, the number of different channels that the jump radios access during the x time slots equals to $(x \cdot J)$. Among them, there are k^1_{fJ} channels that are from the set $\mathcal{C}^1_{fJ} = \{c_{(C-k^1_{fJ}-S+1)}, \cdots, c_C\}$, where $k^1_{fJ} = ((x-1)\cdot J + ((C-S-1) \mod J)+1)$. The number of different channels that the jump radios access during the first $(w-x)$ time slots of the behind inner period equals to $((w-x)\cdot J)$. The channels are from the set $\mathcal{C}^1_{bJ} = \{c_1, \cdots, c_{((w-x)\cdot J+S)}\}$.

Case 1: $\mathcal{C}_{fS} \subseteq \{c_{(C-k^1_{fJ}-S+1)}, \cdots, c_C\}$.

Because the channels that the jump radios access are different from that the stay radios stay at, we can get that $\{c_{(C-k^1_{fJ}-S+1)}, \cdots, c_C\} \subseteq \mathcal{C}_f$. That is, the channels in $\{c_{(C-k^1_{fJ}-S+1)}, \cdots, c_C\}$ are visited by the radios during the front x time slots. Besides, $\{c_1, \cdots, c_{((w-x)\cdot J)}\} \subseteq \mathcal{C}_b$. Denote $\mathcal{S}_1 = \{c_1, \cdots, c_{((w-x)\cdot J)}, c_{(C-k^1_{fJ}-S+1}), \cdots, c_C\} \subseteq \mathcal{C}_f \cup \mathcal{C}_b$. The number of channels in $\mathcal{S}_1$ is $((w-x)\cdot J + k^1_{fJ} + S) = ((w-1)\cdot J + ((C-S-1) \mod J)+1+S) = C$. Hence, all available channels for the SU with multiple radios can be visited at least once during any contiguous w time slots in this case.

Case 2: There exist channels in $\mathcal{C}_{fS}$ that do not belong to $\{c_{(C-k^1_{fJ}-S+1)}, \cdots, c_C\}$.

Subcase 2.1: $\mathcal{C}_{bS} \subseteq \{c_1, \cdots, c_{((w-x)\cdot J+S)}\}$.

Using the similar method discussed as above, we can get that $\{c_1, \cdots, c_{((w-x)\cdot J+S)}\} \subseteq \mathcal{C}_b$. Besides, $\{c_{(C-k^1_{fJ}+1)}, \cdots, c_C\} \subseteq \mathcal{C}_f$. Denote $S_2 = \{c_1, \cdots, c_{((w-x)\cdot J+S)}, c_{(C-k^1_{fJ}+1)}, \cdots, c_C\} \subseteq \mathcal{C}_f \cup \mathcal{C}_b$. The number of channels in $\mathcal{S}_2$ is $((w-x)\cdot J + S + k^1_{fJ}) = ((w-x)\cdot J + S + ((C-2S-1) \mod J)+1+S) = C$. Hence, all available channels for the SU with multiple radios can be visited at least once during any contiguous w time slots in this case.

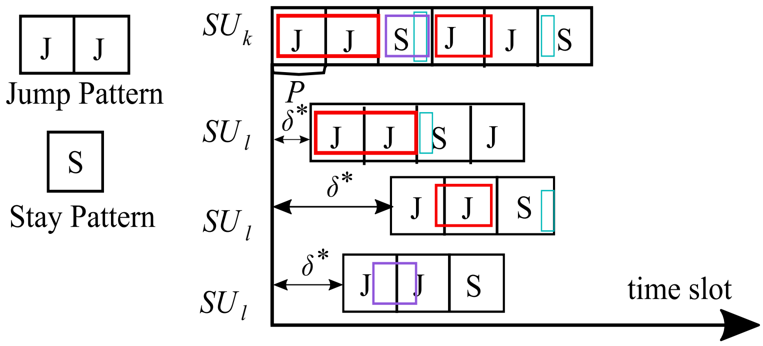


Figure 4.11: Guaranteed rendezvous when both of the SUs are equipped with one radio.

Subcase 2.2: There exist channels in $\mathcal{C}_{bS}$ that do not belong to $\{c_1, \cdots, c_{((w-x)\cdot J+S)}\}$.

Assume that the channel index of the first channel in $\mathcal{C}_{fS}$ is c_{fS}^S. Hence, $\mathcal{C}_{fS} = \{c_{(c_{fS}^S)}, c_{((c_{fS}^S \mod C)+1)}, \cdots, c_{(((c_{fS}^S+S-2) \mod C)+1)}\}$. According to the EMRR algorithm, we can easily see that $\mathcal{C}_{bS} = \{c_{(((c_{fS}^S+S-1) \mod C)+1)}, \cdots, c_{(((c_{fS}^S+2S-2) \mod C)+1)}\}$. If the channel $c_{(((c_{fS}^S+S-2) \mod C)+1)}$ in $\mathcal{C}_{fS}$ belongs to $\{c_1, \cdots, c_{((w-x)\cdot J)}\}$, all channels in $\mathcal{C}_{bS}$ will belong to $\{c_1, \cdots, c_{((w-x)\cdot J+S)}\}$, which is contradictory with the assumption. If the channel $c_{(((c_{fS}^S+S-2) \mod C)+1)}$ in $\mathcal{C}_{fS}$ belongs to $\{c_{(C-k_{fJ}^1+1)}, \cdots, c_C\}$, all channels in $\mathcal{C}_{fS}$ will belong to $\{c_{(C-k_{fJ}^1-S+1)}, \cdots, c_C\}$, which is also contradictory with the assumption. Hence, the channel $c_{(((c_{fS}^S+S-2) \mod C)+1)}$ in $\mathcal{C}_{fS}$ belongs to $\{c_{((w-x)J+1)}, \cdots, c_{(C-k_{fJ}^1)}\}$. In this case, $\{c_1, \cdots, c_{((w-x)\cdot J+S)}, \cdots, c_C\} \subseteq \mathcal{C}_f \cup \mathcal{C}_b$.

To sum up, all available channels for the SU with multiple radios can be visited at least once during any contiguous w time slots, where w is the length of one inner period for the CHS of the SU generated by the EMRR algorithm. □

Based on Lemma 4, we then derive the MTTR with full rendezvous diversity for the MEHRR algorithm under three different scenarios, i.e., 1) both of the SUs are equipped with one radio, 2) one of the SUs is equipped with one radio while the other SU is equipped with multiple radios, 3) both of the SUs are equipped with multiple radios.

Theorem 7. *The TTR of the MEHRR algorithm is upper bounded by* $3P^3$ *time slots with full rendezvous diversity when both of the SUs are equipped with one radio.*

Proof. We assume that SU_l starts the rendezvous process later than SU_k for δ_{kl} time slots. $\delta^* = \delta_{kl} \bmod 3P$. Then, we derive the upper bound on the TTR with full rendezvous diversity according to varying δ^*.

Case 1: $0 \leq \delta^* \leq P$ or $2P < \delta^* < 3P$

As shown in Fig. 4.11, P overlapping time slots must exist between the jump patterns of SU_k and SU_l. Besides, at least one overlapping time slot exists between their stay patterns. We box the overlapping time slots between the jump patterns and that between the stay patterns with red and blue lines in Fig. 4.11, respectively.

When the step lengths of SU_k and SU_l are same for the overlapping jump patterns, they stay at the same channel during their overlapping stay patterns. Hence, the potential rendezvous must occur between their stay patterns. Their step lengths are changed per inner period. Invariably, they are always same during the overlapping time slots in this case. Hence, SUs stay at the same channels during their overlapping stay patterns. Within one outer period, all available channels are visited at least once during the stay patterns of the SUs. Hence, two SUs can rendezvous on all commonly available channels within $3P^2$ time slots in this case.

When the step lengths of SU_k and SU_l are different for the overlapping jump patterns. According to Lemma 4 in [99], we can easily see that a potential rendezvous must occur during the P overlapping time slots between their jump patterns. Owing to the heterogeneity of the available channels for the SUs, the potential rendezvous channel may be not available for both of the SUs. Since the initial channel index is changed per outer period, the rendezvous channels during the overlapping jump patterns between two SUs at different outer periods are different. Any two SUs can rendezvous on all commonly available channels within $3P^3$ time slots, i.e., the MTTR with full rendezvous diversity for the MEHRR algorithm is $3P^3$ time slots in this case. In summary, the TTR of the MEHRR algorithm is upper bounded by $3P^3$ with full rendezvous diversity when $0 \leq \delta^* \leq P$ or $2P < \delta^* < 3P$.

Case 2: $P < \delta^* \leq 2P$

As shown in Fig. 4.11, P overlapping time slots must exist between the jump pattern of one SU and the stay pattern of the other SU in this case. We box the overlapping time slots between jump pattern and stay pattern with purple line in Fig. 4.11. When the step length of the SU for the overlapping jump pattern does not equal to P, all available channels are visited at least once for the SU. Besides, the other SU stays at the same channel during the P overlapping time slots. Hence, a potential rendezvous must occur during the P overlapping time slots. Owing to the heterogeneity of the available channels for SUs, the potential rendezvous channel may not be available for both of SUs simultaneously. Since the step length is changed per inner period, all available channels are visited by the stay patterns during one outer period. Two SUs can rendezvous on all commonly available channels except the channel that the stay pattern stays at when the step length of the corresponding overlapping jump pattern equals to P. For clear description, we denote the stay channel described above as z. When the step length of the overlapping jump pattern equals to P, SU stays at the channel whose index equals to the initial index. Because the initial index is changed per outer period while the step length corresponding to the same inner period in different outer periods is same. Hence, SUs can rendezvous

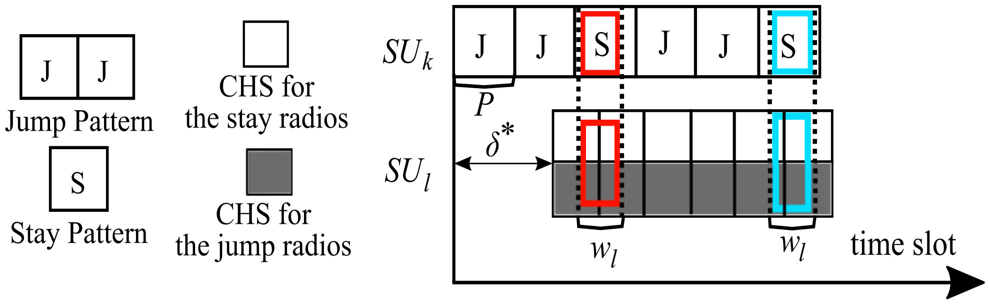


Figure 4.12: Guaranteed rendezvous when one SU with one radio and the other SU with multiple radios.

on z when the initial index of the corresponding overlapping jump pattern equals to the channel index of channel z. Hence, two SUs can achieve full rendezvous diversity within $3P^3$ time slots.

In summary, the TTR of the MEHRR algorithm is upper bounded by $3P^3$ time slots with full diversity when both of the SUs are equipped with one radio. □

Theorem 8. *The TTR of the MEHRR algorithm is upper bounded by $3P^2 + w_l$ time slots with full rendezvous diversity when one SU is equipped with one radio while the other SU is equipped with multiple radios.*

Proof. We assume that SU_k and SU_l are equipped with one radio and multiple radios, respectively. Besides, we assume that SU_l starts rendezvous process later than SU_k. The analysis also can be applied for the case where SU_k starts rendezvous process later than SU_l. Let $\delta^* = \delta \bmod 3P$.

As shown in Fig. 4.12, the potential rendezvous must happen between the stay pattern of SU_k and the radios of SU_l. We box the potential rendezvous with red and blue lines in Fig. 4.12. The reasons for potential rendezvous are listed as follows. First, we can easily see that $w_l < P$ according to the MEHRR algorithm. Hence, the length of the stay pattern in one inner period of the CHS for SU_k must larger than w_l. SU_k stays at the same channel during its stay pattern in one inner period while all available channels are visited once by the radios of SU_l during any contiguous w_l time slots according to Lemma 4. Hence, potential rendezvous must happen during the w_l overlapping time slots between the stay pattern of SU_k and the radios of SU_l.

Because the stay channels that the stay patterns stay at are changed per inner period for SU_k, all channels can be visited by the stay patterns during one outer period of the CHS for SU_k. Hence, SU_k and SU_l can rendezvous on all commonly available channels during one outer period of the CHS for SU_k, i.e., $3P^2$ time slots. If the first overlapping time slots between the stay pattern of SU_k and SU_l is less than w_l, rendezvous can not be guaranteed during the first overlapping time slots. Hence, the TTR of the MEHRR algorithm is upper bounded by $3P^2 + w_l$ time slots

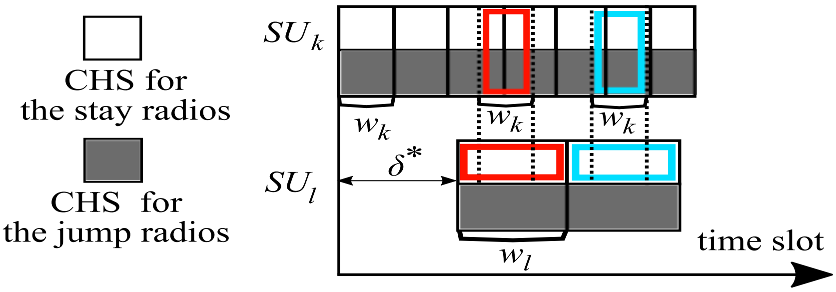


Figure 4.13: Guaranteed rendezvous when both of the SUs are equipped with multiple radios.

with full rendezvous diversity when one SU is equipped with one radio while the other SU is equipped with multiple radios. □

Theorem 9. *When both of the SUs are equipped with multiple radios, the TTR of the MEHRR algorithm is upper bounded by* $w_l \cdot \left\lceil \frac{C_l}{Y_l} \right\rceil + w_k$ *time slots with full rendezvous diversity. Note that* $w_k < w_l$*, or* $w_k = w_l$ *and* $\left\lceil \frac{C_l}{Y_l} \right\rceil \leq \left\lceil \frac{C_k}{Y_k} \right\rceil$.

Proof. As shown in Fig. 4.13, when $w_k < w_l$, the potential rendezvous must happen between the stay radios of SU_l and the radios of SU_k. We box the potential rendezvous with red and blue lines in Fig. 4.13. The reasons for potential rendezvous are listed as follows. First, all available channels are visited once during any contiguous w_k time slots by the radios of SU_k according to Lemma 4. Meanwhile, the stay radios of SU_l stay at same channels during one inner period. Hence, the SUs can rendezvous on the stay channels that SU_l stay at during the w_k overlapping time slots. Because the stay channels for the stay radios of the SU are changed per inner period, two SUs must rendezvous on all commonly available channels after $\left\lceil \frac{C_l}{Y_l} \right\rceil$ inner periods of SU_l. In case of that the first overlapping time slots between the SUs are not enough for them achieving rendezvous. The TTR of the MEHRR algorithm is upper bounded by $w_l \cdot \left\lceil \frac{C_l}{Y_l} \right\rceil + w_k$ time slots with full rendezvous diversity.

When $w_k = w_l$ and $\left\lceil \frac{C_l}{Y_k} \right\rceil \leq \left\lceil \frac{C_k}{Y_k} \right\rceil$, the MTTR of the MEHRR algorithm is also upper bounded by $w_l \cdot \left\lceil \frac{C_l}{Y_l} \right\rceil + w_k$ time slots with full rendezvous diversity. The reason is that all available channels for SU_l will be visited by its stay radios within $w_l \cdot \left\lceil \frac{C_l}{Y_l} \right\rceil$ time slots. Meanwhile, all available channels are visited at least once during any continus w_k time slot for SU_k. Hence, a pair of SUs can rendezvous on all commonly available channels within $w_l \cdot \left\lceil \frac{C_l}{Y_l} \right\rceil + w_k$. □

4.7 Performance Evaluation

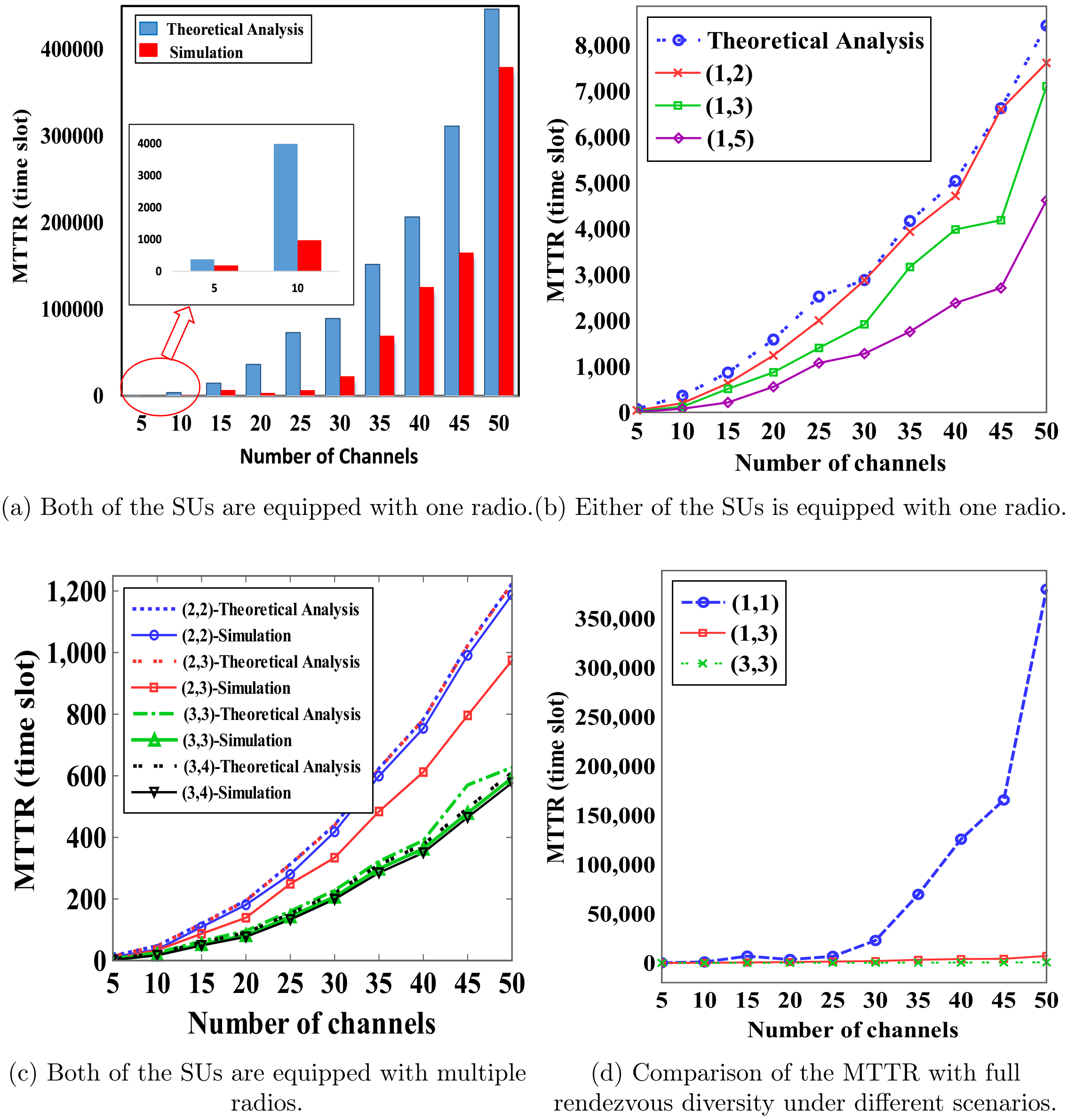
In this subchapter, we evaluate the performance of the proposed MEHRR algorithm by simulation. We firstly assess the MTTR with full rendezvous diversity for the

MEHRR algorithm. Simulation results verify the correctness of the upper bounds on the TTR with full rendezvous diversity for the MEHRR algorithm derived by the theoretical analysis. Then, we compare our proposed MEHRR algorithm with several state-of-the-art CH algorithms in terms of MTTR with full rendezvous diversity.

4.7.1 MTTR with Full Rendezvous Diversity

We evaluate the MTTR with full rendezvous diversity for the proposed MEHRR algorithm under three scenarios, which are 1) both of the SUs are equipped with one radio; 2) One SU is equipped with one radio while the other SU is equipped with multiple radios; 3) both of the SUs are equipped with multiple radios. In the simulation, the number of licensed channels N varies from 5 to 50. The number of the available channels for each SU is set to $0.7N$. The number of commonly available channels between any a pair of SUs is set to $0.5N$.

Fig. 4.14 shows the simulation results of the MTTR with full rendezvous diversity for the MEHRR algorithm. In Fig. 4.14, denote (M_k, M_l) as the numbers of radios for a pair of SUs. Figs. 4.14(a), 4.14(b) and 4.14(c) show the MTTR with full rendezvous diversity derived by theoretical analysis and simulations under the three scenarios, respectively. From Figs. 4.14(a), 4.14(b) and 4.14(c), we can see that the MTTR with full rendezvous diversity evaluated by the simulation is not larger than the upper bounds obtained by the theoretical analysis under the three scenarios, by which the correctness of the upper bounds derived by the theoretical analysis is verified. Besides, from Fig. 4.14(b) and Fig. 4.14(c), we can see that the MTTR increases along with the growth of the number of channels. The reason is that the length of one inner period of the CHS generated by the MEHRR algorithm increases along with the growth of the number of channels, which directly impacts on the MTTR with full rendezvous diversity. Generally, the larger the length of an inner period of the CHS is, the larger of the MTTR with full rendezvous diversity is. Also, the MTTR with full rendezvous diversity decreases along with the increase of the number of radios for any SU of the two SUs. The reason is that the length of a period of the CHS decreases along with the increase in the number of radios. Besides, the probability of rendezvous also increases along with the rise in the number of radios for any SU. Fig. 4.14(d) shows the performance comparison of the MEHRR algorithm under three scenarios. From Fig. 4.14(d), we can easily see that the MTTR with full rendezvous diversity can be drastically shortened when one of the SUs is equipped with multiple radios.



(a) Both of the SUs are equipped with one radio.

(b) Either of the SUs is equipped with one radio.

(c) Both of the SUs are equipped with multiple radios.

(d) Comparison of the MTTR with full rendezvous diversity under different scenarios.

Figure 4.14: Evaluation of the MTTR with full rendezvous diversity for the MEHRR algorithm.

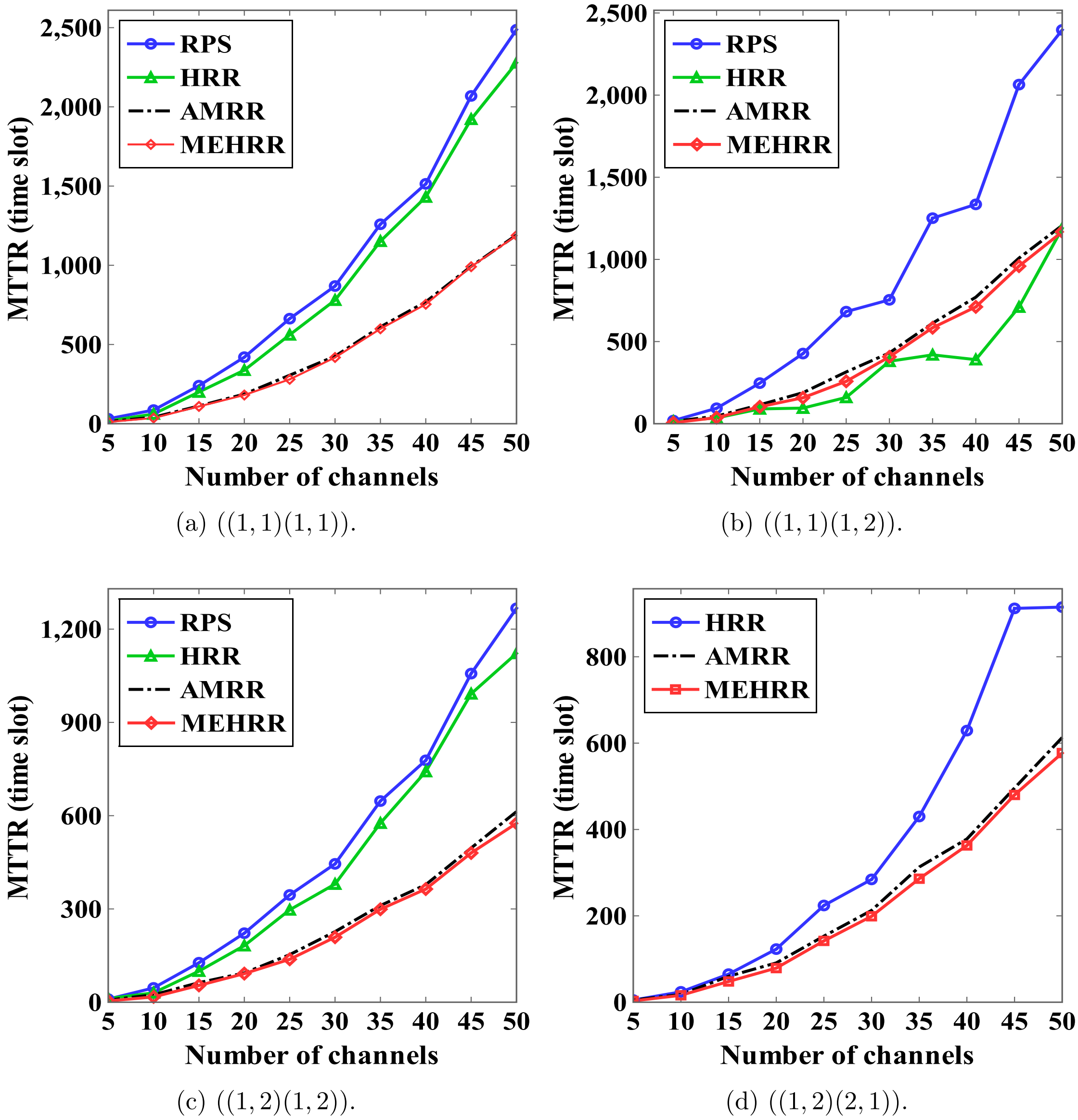
4.7.2 Comparison of Different CH Algorithms

We compare our proposed MEHRR algorithm with several state-of-the-art blind rendezvous algorithms, which are the HRR algorithm, the RPS algorithm and the AMRR algorithm in terms of MTTR with full rendezvous diversity. Denote $((Y_k, J_k), (Y_l, J_l))$ as the radio allocations of SU_k and SU_l. We evaluate the MTTR with full rendezvous diversity for the blind rendezvous algorithms under four different scenarios where the radio allocations are $((1,1),(1,1))$, $((1,1),(1,2))$, $((1,2),(1,2))$, $((1,2),(2,1))$. In the simulation, the number of channels N varies from 5 to 50. The number of available channels is set to be $0.7N$ while that of the commonly available channels between a pair of SUs is set to be $0.5N$.

Fig. 4.15 shows the simulation results under the four scenarios. From Fig. 4.15, we can see that the proposed MEHRR algorithm shortens the MTTR with full rendezvous diversity compared with the RPS algorithm to a great extent under the scenarios where the radio allocations are $((1,1),(1,1))$, $((1,1),(1,2))$, $((1,2),(1,2))$. The reason is that the CHSs of the SUs generated by the MEHRR algorithm are based on its available channel set while those generated by the RPS algorithm are based on all licensed channels. Hence, the period length of the CHSs generated by the RPS algorithm is much larger than that generated by the MEHRR algorithm. Besides, because the number of stay radios of SUs is fixed to 1 in the RPS algorithm, it can not be applied for the scenario where the radio allocation is $((1,2),(2,1))$.

Moreover, the MTTR with full rendezvous diversity of the AMRR algorithm is also much shorter than that of the RPS algorithm. The reason is that the CHSs of SUs generated by the AMRR algorithm are also based on their available channel sets. Compared with the AMRR algorithm, the MTTR with full rendezvous diversity for the MEHRR algorithm is a little bit shorter under the four scenarios. The reason is that the radios may access the same channel at the same time slot for the AMRR algorithm while it can be avoided by the MEHRR algorithm, by which the MTTR with full rendezvous diversity can be further shortened.

The MTTR with full rendezvous diversity of the MEHRR algorithm is shorter than that of the HRR algorithm under the scenarios where the radio allocations are $((1,1),(1,1))$, $((1,2),(1,2))$ and $((1,2),(2,1))$. The reason is that the period length of the CHSs generated by the MEHRR algorithm is shorter than that generated by the HRR algorithm, which can accelerate rendezvous on all commonly available channels for SUs. However, the MTTR of the HRR algorithm under several different numbers of channels is smaller than that of the MEHRR algorithm when the radio allocation is $((1,1),(1,2))$. The reason is that two SUs may rendezvous on more than one potential channel during one period between their radios for the HRR algorithm under this scenario.



(a) $((1,1)(1,1))$.

(b) $((1,1)(1,2))$.

(c) $((1,2)(1,2))$.

(d) $((1,2)(2,1))$.

Figure 4.15: Comparison of blind rendezvous algorithms.

In summary, the proposed MEHRR algorithm can get shorter MTTR with full rendezvous diversity compared with the other blind rendezvous algorithms under most scenarios. Moreover, the MEHRR algorithm is more stable under different radio allocation scenarios compared with the HRR algorithm.

Chapter 5

Performance Analysis: Channel Quality, Channel Loading, and Optimal Radio Allocation

In this chapter, the performance in terms of the rendezvous channel quality, the channel loading, and the optimal radio allocation manner of the proposed algorithms are analyzed. We firstly analyze the rendezvous channel quality for the proposed HRR algorithm. Then, we analyze the channel loading and the optimal radio allocation manner for the proposed MEHRR algorithm.

5.1 Motivation

As described in Chapter 1.2.4, four performance metrics, namely ETTR, MTTR, rendezvous diversity, and channel loading are usually of the top concerns among the extensive research literatures on CH algorithms. Besides, rendezvous channel quality is also a considerable metric for the CH algorithms. In previous chapters, we mainly analyzed the ETTR, the MTTR, and the rendezvous diversity for the proposed algorithms. The ETTR and the MTTR are analyzed for the proposed HRR algorithm in Chapter 3 while the MTTR and the rendezvous diversity are analyzed for the proposed MEHRR algorithm in Chapter 4. In addition to the ETTR, the MTTR, and the rendezvous diversity, there are some other important metrics for the CH algorithms that are not considered, such as channel loading, rendezvous channel quality, and so on. In this chapter, we further analyze our proposed algorithms in terms of those important metrics.

Channel loading is defined as the maximum proportion of SUs which can rendezvous on the same channel at the same time. Minimizing channel loading can reduce channel congestion. In this chapter, we analyze the channel loading for the MEHRR algorithm. In addition, the MTTR is related to the allocation of stay radios and jump radios for the MEHRR algorithm.

In addition, rendezvous on channels with better quality can increase the successful probability of CCE after rendezvous. To achieve rendezvous on channels with better quality, the licensed channels and the available channels of the SUs are sorted in descending order according to the channel quality in our designed HRR algorithm and MEHRR algorithm. Besides, generated unavailable channels are replaced by the available channels in the sorted available channel set sequentially for the SRR algorithm and the MESRR algorithm in the HRR algorithm and the MEHRR algorithm, respectively. To verify that SUs can rendezvous on the channels with higher channel qualities more frequent by using our proposed algorithms, we evaluate the HRR algorithm in terms of rendezvous channel quality by simulation in this chapter.

Moreover, since the MTTR is related to the allocation manner of radios for SUs in the MEHRR algorithm, we analyze the optimal radio allocation for the MEHRR algorithm in this chapter to achieve MTTR as small as possible.

5.2 Objective

The objective of this chapter is to evaluate several performances of the proposed algorithms that are not well analyzed in the previous chapters, which are summarized as follows.

- Performance evaluation for the HRR algorithm in terms of channel quality by simulation.
- Channel loading evaluation for the MEHRR algorithm by theoretical analysis.
- Optimal radio allocation for the MEHRR algorithm by theoretical analysis and simulation.

5.3 Summary of Results

The results obtained in this chapter can be summarized as follows.

- Rendezvous channel quality can be increased by the HRR algorithm.
- Minimum channel loading can be achieved by the MEHRR algorithm.
- The optimal radio allocation manner for the MEHRR algorithm is derived.

The rest of this chapter is organized as follows. Chapter 5.4 evaluates the rendezvous channel quality for the HRR algorithm. Chapter 5.5 analyzes the channel loading for the MEHRR algorithm by theoretical analysis. Chapter 5.6 derives the optimal radio allocation for the MEHRR algorithm by theoretical analysis and simulation.

5.4 Rendezvous Channel Quality for the HRR Algorithm

In this section, we evaluate the performance in terms of channel quality for our proposed HRR algorithm. Two places are related to the channel quality in our proposed HRR algorithm. We list them as follows. First, in the HRR algorithm, the licensed channels and the available channels of the SUs are sorted in descending order according to the channel quality. Second, generated unavailable channels are replaced by the available channels in the sorted available channel set sequentially for the SRR algorithm. To verify that SUs can rendezvous on the channels with higher channel qualities more frequent by using our proposed HRR algorithm, we compare the percentages of rendezvousing on different commonly available channels in our simulation.

In the simulation, we set the number of licensed channels as 20, the number of available channels for SUs as 10, and the number of commonly available channels between a pair of SUs as 5. Fig. 5.1 shows the simulation results. The abscissa of Fig. 5.1 is channel rank index, which means the position of the channel in the commonly available channel set between a pair of SUs. For instance, the channel with channel rank index 1 is the first channel in the commonly available channel set between a pair of SUs. We assume that the channel qualities for different SUs are same in our simulations. The vertical axis of Fig. 5.1 is the percentages of rendezvousing on different commonly available channels, which are measured by the average values of 1000 times simulations. In Fig. 5.1, SR-SR-HRR and SR-SR-Random denote that replacing unavailable channels by our proposed HRR algorithm and by randomly selecting available channels for the SUs with single radio, respectively. SR-MR(1,1)-HRR and SR-MR(1,1)-Random denote that replacing unavailable channels by our proposed HRR algorithm and by randomly selecting available channels for the scenario where one of the SUs is equipped with single radio and the other SU is equipped with multiple radios (one stay radio and one jump radio), respectively. MR((1,1)(1,1)) denotes the rendezvous between two SUs with multiple radios (one stay radio and one jump radio) using our proposed HRR algorithm. We only compare the unavailable channel replacement by using the proposed HRR algorithm and randomly replacement method when at least one of a pair of SUs is equipped with one radio. The reason is that the CH sequences generated based on the available channels when SUs are equipped with multiple radios. Hence, we do not need to replace channels when both SUs are equipped with multiple radios.

Form the performance results of the SR-SR-HRR and the SR-MR(1,1)-HRR in Fig. 5.1, we can see that the percentages of rendezvousing on the commonly available channels decrease with the ascending order of the channels in the commonly available channel set between SUs under the scenario where at least one SU is equipped with one radio. Hence, SUs can rendezvous on the channels with higher channel qualities more frequent after sorting the channels according to their channel qualities in this scenario. Besides, form the simulation results of the MR-MR((1,1)(1,1)) in Fig. 5.1, we can see that the percentage of rendezvousing on the first channel in the commonly available channel set between two SUs is higher than those of rendezvousing on the other channels. Moreover, the difference between the percentages of rendezvousing on the channels except the first channel is low. In summary, SUs can rendezvous on the commonly available channels with higher channel qualities more frequent after sorting the channels in descending order according to the channel quality. In addition, we evaluate the performance of replacing unavailable channels by randomly

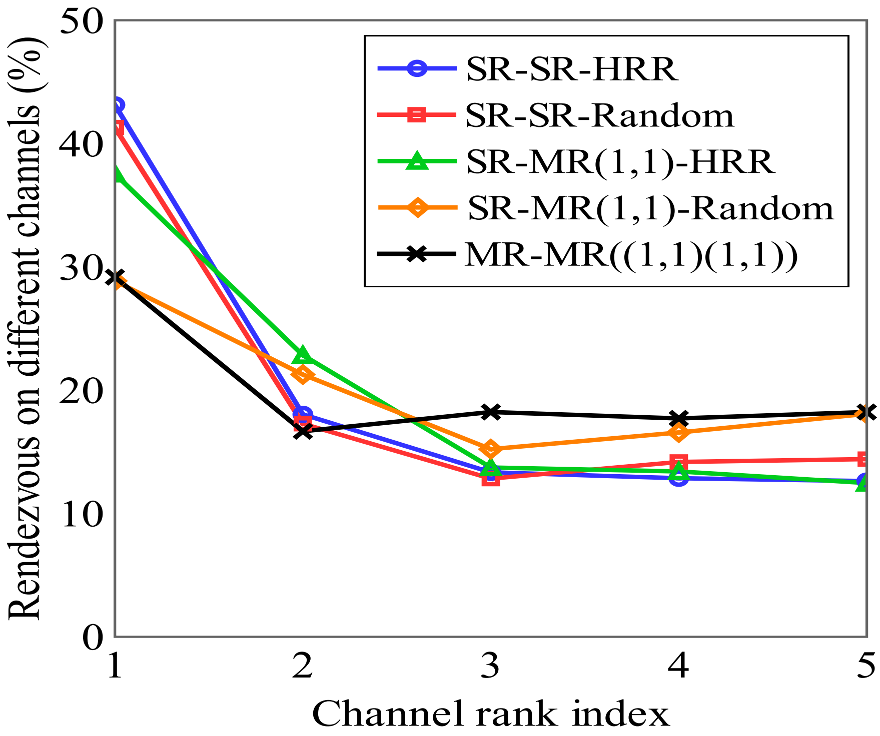


Figure 5.1: Performance evaluation in terms of channel quality.

selecting available channels instead of replacing unavailable channels by the available channels with higher qualities under the scenario where at least one SU is equipped with single radio. From the simulation results, we can see that the percentages of rendezvousing on the front channels in the sorted commonly available channel set for the replacement method in our proposed algorithm are higher than random replacement. Hence, the frequent of rendezvousing on the channels with higher qualities can increase by the HRR algorithm.

5.5 Channel Loading

5.5.1 Definition of Channel Loading

The order of the channels that the SU accesses at each time slot changes under different clock drift scenarios. For the CHS with period length L_P, L_P different CHSs can be generated under different clock drift scenarios. The period length here means the length of the basic CHS. The CHS are generated by repeating the basic CHS. For instance, the basic CHS is $\{c_1, c_3, c_5\}$. Then, the CHS is $\{c_1, c_3, c_5, c_1, c_3, c_5, c_1, c_3, c_5 ...\}$. Denote the channel c_i appears Q_i times during L_P. Then, according to the definition of the channel loading, it can be formulated as:

$$CL = \max_{\forall c_i \in N} \frac{Q_i}{L_P}. \tag{5.1}$$

5.5.2 Channel Loading for the MEHRR Algorithm

Channel loading can be measured as the maximum proportion of the different CHSs that visit the same channel at the same time slot. A large channel loading may cause channel congestion. To reduce the channel congestion, it is better to minimize the channel loading when designing blind rendezvous algorithms. We prove that the minimum channel loading can be achieved by the CHSs generated by the MESRR algorithm and the EMRR algorithm. The theoretical analysis is shown as follows.

Theorem 10. *The channel loading of the CHSs generated by the MESRR algorithm equals to $1/P$ when all licensed channels are available for the SU, and the number of licensed channels is a prime number.*

Proof. The CHSs of the SUs with one radio are periodically generated by the MESRR algorithm. Besides, the frequency of occurrence for one specific channel during different P outer periods is same when all licensed channels are available for the SU, and the number of licensed channels is a prime number. Hence, we can only consider the CHSs within P outer periods when deriving the channel loading. The length of P outer periods for the CHSs generated by the MESRR algorithm is $3P^3$. Due to the rotation of the CHSs caused by the clock drift, $3P^3$ different CHSs can be generated during P outer periods. When all licensed channels are available for the SU and the number of licensed channels is a prime number, one specific channel c is visited P^2 times during the stay patterns within P outer periods of the CHS. Meanwhile, we can easily see that the channel c is visited $2P^2$ times during the jump patterns within P outer periods of the CHS according to Lemma 1 in [28]. Hence, the channel c is totally visited $3P^2$ times during P outer periods of the CHS generated by the MESRR algorithm. Hence, the maximum proportion of the $3P^3$ different CHSs rendezvous on the same channel at the same time slot is $\frac{3P^2}{3P^3} = \frac{1}{P}$. Hence, we can see that the CHSs generated by the MESRR algorithm can achieve minimum channel loading. That is, each channel is visited by one SU at the same time slot when there are P SUs, which minimize the channel congestion. □

Theorem 11. *The channel loading of the CHSs generated by the EMRR algorithm equals to $\frac{M_k}{|C_k|}$ when $\frac{|C_k|-Y_k}{J_k}$ is an integer.*

Proof. The CHSs of the SUs with multiple radios are periodically generated by the EMRR algorithm. The length of one outer period of the CHS generated by the EMRR algorithm for SU_k is $L = w_k \cdot \frac{LCM(C_k,Y_k)}{Y_k}$. Besides, the frequency of occurrence for one specific channel during different outer period is same for the CHSs generated by the EMRR algorithm. Hence, we can only consider the CHSs within one outer period when deriving the channel loading. Due to the rotation of the CHSs caused by the clock drift, L different CHSs can be generated for one outer period of the CHS generated by the EMRR algorithm. During one outer period of the CHS generated by the EMRR algorithm, the same channel c is visited $w_k \cdot \frac{LCM(C_k,Y_k)}{C_k} + \left(\frac{LCM(C_k,Y_k)}{Y_k} - k\right)$ times by the radios of SU_k, where $k \in \left[\left(\frac{LCM(C_k,Y_k)}{C_k} - \frac{LCM(C_k,Y_k)}{Y_k}\right), \frac{LCM(C_k,Y_k)}{C_k}\right]$. k is related to $\frac{C_k - Y_k}{J_k}$. Hence, the maximum proportion of the L different CHSs rendezvous on the same channel at the same time slot is $\frac{w_k \cdot \frac{LCM(C_k,Y_k)}{C_k} + \left(\frac{LCM(C_k,Y_k)}{Y_k} - k\right)}{L}$. When $w_k = \frac{C_k - Y_k}{J_k}$, i.e., $\frac{C_k - Y_k}{J_k}$ is an integer, $k = \frac{LCM(C_k,Y_k)}{C_k}$. Then, the channel loading function above can be simplified to $\frac{M_k}{C_k}$. Hence, we can see that the EMRR algorithm can achieve minimum channel loading when $\frac{C_k - Y_k}{J_k}$ is an integer for SU_k. □

In summary, it can be guaranteed that the MESRR algorithm and the EMRR algorithm can achieve minimum channel loading by the theoretical analysis above.

5.6 Optimal Radio Allocation

We evaluate the MTTR with full rendezvous diversity under different radio allocation scenarios to see the impact of the radio allocation on the performance of the MEHRR algorithm. By the comparison of the optimal radio allocation derived by the simulation and that calculated by the theoretical analysis, we can see that the simulation results match with the theoretical analysis.

5.6.1 Theoretical Analysis

We analyze the optimal allocation of radios for the SU using the MEHRR algorithm to minimize the MTTR with full rendezvous diversity. From Theorems derived in the last chapter, we can easily see that the MTTR with full rendezvous diversity for the MEHRR algorithm is related to the allocation of the radios only when both of the SUs are equipped with multiple radios. When both of the SUs are equipped with multiple radios, the MTTR with full rendezvous diversity for the MEHRR algorithm is $w_l \cdot \left\lceil \frac{C_l}{Y_l} \right\rceil + w_k$ time slots, where $w_k < w_l$, or $w_k = w_l$ and $\left\lceil \frac{C_l}{Y_k} \right\rceil \leq \left\lceil \frac{C_k}{Y_k} \right\rceil$. Since w_k has little impact on the MTTR with full rendezvous diversity compared with $w_l \cdot \left\lceil \frac{C_l}{Y_l} \right\rceil$, we only consider the impact of the allocation of radios on $w_l \cdot \left\lceil \frac{C_l}{Y_l} \right\rceil$. To get the optimal allocation of the radios for the SU that can minimize the MTTR with full rendezvous diversity, we formulate the objective function as follows.

$$(Y_l, J_l)^* = \underset{(Y_l, J_l)}{\arg\min}\, w_l \cdot \left\lceil \frac{C_l}{Y_l} \right\rceil \quad \text{subject to } Y_l + J_l = M_l. \tag{5.2}$$

Since $w_l = \left\lceil \frac{C_l - Y_l}{J_l} \right\rceil$, Equation (5.2) can be transformed into:

$$(Y_l, J_l)^* = \arg\min_{(Y_l, J_l)} \left\lceil \frac{C_l - Y_l}{J_l} \right\rceil \cdot \left\lceil \frac{C_l}{Y_l} \right\rceil \quad \text{subject to } Y_l + J_l = M_l. \tag{5.3}$$

For clear deriving the optimal allocation of the radios, we denote o as $\left\lceil \frac{C_l - Y_l}{J_l} \right\rceil \cdot \left\lceil \frac{C_l}{Y_l} \right\rceil$, then we derive the derivative of o with respect to Y_l. Since $Y_l + J_l = M_l$, we can get:

$$\frac{do}{dY_l} = \frac{d\left(\left\lceil \frac{C_l - Y_l}{M_l - Y_l} \right\rceil \cdot \left\lceil \frac{C_l}{Y_l} \right\rceil\right)}{dY_l}. \tag{5.4}$$

After simplification, we can get that

$$\frac{do}{dY_l} = \frac{-C_l^2 Y_l^2 + 2C_l^2 Y_l - M_l C_l^2}{\left(M_l Y_l - Y_l^2\right)^2}. \tag{5.5}$$

Denote K as $-C_l^2 Y_l^2 + 2C_l^2 Y_l - M_l C_l^2$. For K, we can get that

$$\begin{cases} K > 0 \\ \text{when } Y_l \in \left(\left(C_l - \sqrt{C_l\left(C_l - M_l\right)}\right), \left(C_l + \sqrt{C_l\left(C_l - M_l\right)}\right)\right) \\ K < 0 \\ \text{when } Y_l < \left(C_l - \sqrt{C_l\left(C_l - M_l\right)}\right) or Y_l > \left(C_l + \sqrt{C_l\left(C_l - M_l\right)}\right). \end{cases} \tag{5.6}$$

Since $\left(M_l Y_l - Y_l^2\right)^2 > 0$, we can get that

$$\begin{cases} \frac{do}{dY_l} > 0 \\ \text{when } Y_l \in \left(\left(C_l - \sqrt{C_l\left(C_l - M_l\right)}\right), \left(C_l + \sqrt{C_l\left(C_l - M_l\right)}\right)\right) \\ \frac{do}{dY_l} < 0 \\ \text{when } Y_l < \left(C_l - \sqrt{C_l\left(C_l - M_l\right)}\right) or Y_l > \left(C_l + \sqrt{C_l\left(C_l - M_l\right)}\right). \end{cases} \tag{5.7}$$

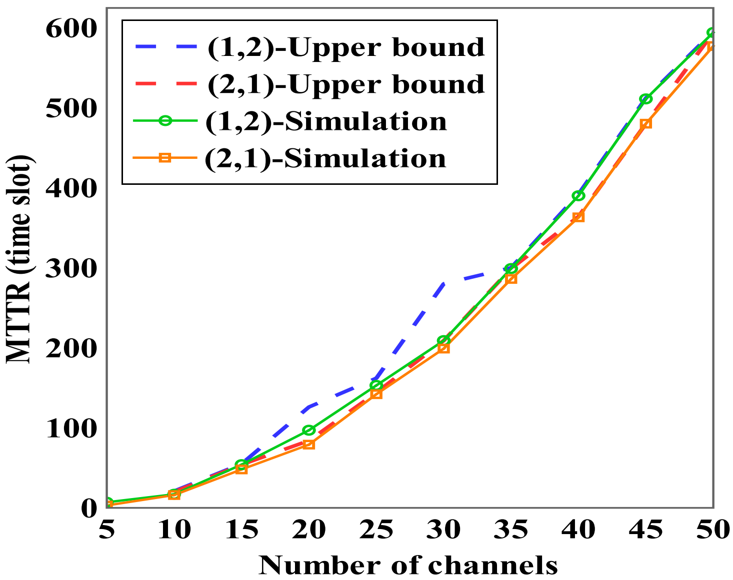
Hence, we can see that o is a monotonically increasing function when $Y_l \in \left(\left(C_l - \sqrt{C_l\left(C_l - M_l\right)}\right), \left(C_l + \sqrt{C_l\left(C_l - M_l\right)}\right)\right)$. Meanwhile, o is a monotonically decreasing function when $Y_l < \left(C_l - \sqrt{C_l\left(C_l - M_l\right)}\right)$ or $Y_l > \left(C_l + \sqrt{C_l\left(C_l - M_l\right)}\right)$. Since $1 < Y_l < C_l$, we can only consider $Y_l \in (1, C_l]$. Within $Y_l \in (1, C_l]$, $\min o$ will be achieved when $Y_l = \left(C_l - \sqrt{C_l\left(C_l - M_l\right)}\right)$. Because Y_l is the number of stay radios of SU_l, Y_l should be an integer. Denote D_1 as $\left(\left(C_l - \sqrt{C_l\left(C_l - M_l\right)}\right) - \lfloor C_l - \sqrt{C_l\left(C_l - M_l\right)} \rfloor\right)$, D_2 as $\left(\lceil C_l - \sqrt{C_l\left(C_l - M_l\right)} \rceil - \left(C_l - \sqrt{C_l\left(C_l - M_l\right)}\right)\right)$. Then, the optimal allocation of the radios can be formulated as follows.

$$\begin{cases} Y_l = \lfloor C_l - \sqrt{C_l\,(C_l - M_l)} \rfloor, \text{when } D_1 < D_2 \\ Y_l = \lceil C_l - \sqrt{C_l\,(C_l - M_l)} \rceil, \text{when } D_1 \geq D_2. \end{cases} \tag{5.8}$$

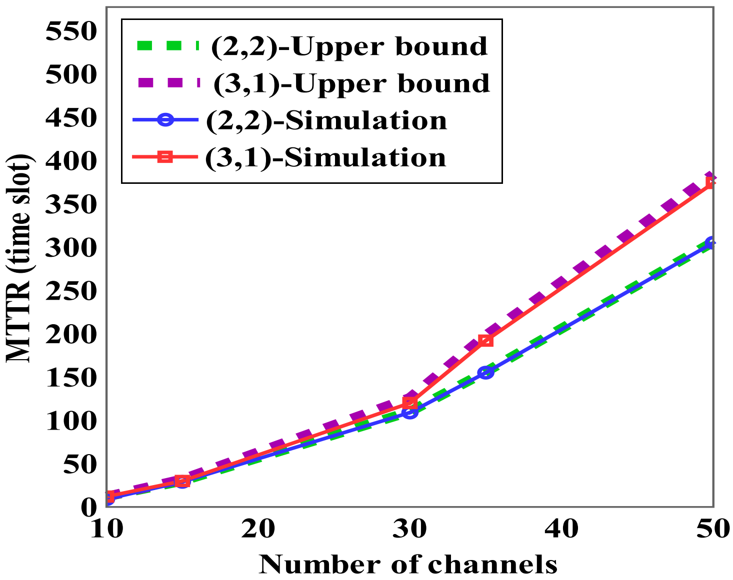
5.6.2 Simulation Results

We evaluate the performance of the MEHRR algorithm under different radio allocation scenarios in terms of MTTR with full rendezvous diversity. We consider two scenarios according to the sum of the number of radios for a pair of SUs (i.e., SU_k and SU_l), which are $M_k + M_l = 6$ and $M_k + M_l = 7$. We consider that both SUs are equipped with three radios for the scenario where $M_k + M_l = 6$. We assume that SU_k is equipped with one stay radio and two jump radios. Fig. 5.2(a) shows the MTTR with full rendezvous diversity derived by Theorem 9 and by simulation under these two scenarios. Denote (Y_l, J_l) as the allocation of the stay radios and jump radios for SU_l. There are two kinds of radio allocation combinations for SU_l in this scenario, i.e., $(1, 2)$ and $(2, 1)$. From Fig. 5.2(a), we can see that the MTTR with full rendezvous diversity is minimum when SU_l is equipped with 2 stay radios both for the upper bounds derived in Theorem 9 and simulation results regardless of the number of channels. Besides, the optimal number of stay radios calculated by equation 5.8 is also equal to 2, which matches with Theorem 9 and simulation results.

We consider that SU_k is equipped with three radios while SU_l is equipped with four radios for the scenario where $M_k + M_l = 7$. Then, we consider the case where $(Y_k, J_k) = (1, 2)$. There are three radio combinations for SU_l under this scenario, i.e., $(1, 3)$, $(2, 2)$, and $(3, 1)$. The MTTR with full rendezvous diversity is related to the radio allocation of SU_l under the combinations $(2, 2)$ and $(3, 1)$. In constrast, the MTTR with full rendezvous diversity is related to the radio allocation of SU_k under the combination $(1, 3)$. Hence, we consider the performance of the MEHRR algorithm under the radio allocation combinations $(2, 2)$ and $(3, 1)$ to see the impact of the radio allocation on the MTTR with full rendezvous diversity. Fig. 5.2(b) shows the MTTR with full rendezvous diversity derived by theoretical analysis and by simulation. From Fig. 5.2(b), we can see that the MTTR with full rendezvous diversity is minimum when SU_l is equipped with 2 stay radios both for the upper bounds derived by Theorem 9 and simulation results regardless of the number of radios. Besides, the optimal number of stay radios derived by equation 5.8 also equals to 2, which matches with Theorem 9 and simulation results.



(a) $M_k + M_l = 6$ and $(Y_k, J_k) = (1, 2)$.



(b) $M_k + M_l = 7$ and $(Y_l, J_l) = (1, 2)$.

Figure 5.2: Evaluation of the allocation of the radios.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

In this dissertation, a heterogeneous radios based CH algorithm termed as HRR algorithm is firstly proposed for the CCE among unlicensed SUs in heterogeneous DSA networks. Theoretical analysis and simulation results show that the SUs in heterogeneous DSA networks can establish control channel with their target SUs within upper bounded time by using the HRR algorithm. Moreover, simulation results showed that the MTTR of the HRR algorithm outperforms the MSS algorithm, the AR algorithm, and the RPS algorithm both under the symmetric model and the asymmetric model. Although the MTTR of the HRR algorithm is larger than that of the AMRR algorithm under several scenarios, the difference between them is very tiny. In addition, the difference between the ETTRs of the HRR algorithm, the RPS algorithm, the AR algorithm, and the AMRR algorithm is very small both under the symmetric model and the asymmetric model. Meanwhile, their ETTRs are smaller than that of the MSS algorithm under the asymmetric model.

Then, a MEHRR algorithm is presented to achieve CCE with full diversity. Theoretically analysis is carried out to prove that the SUs in heterogeneous DSA networks can establish control channels with full rendezvous diversity within upper bounded time by using the MEHRR algorithm. In addition, the performance of the MEHRR algorithm in terms of MTTR with full diversity is compared to several state-of-the-art hopping based CCE algorithms. Simulation results showed the superiority of the MEHRR algorithm. Besides, it is also shown that the proposed HRR algorithm could improve the probability of establishing control channels on the channels with better channel quality. Furthermore, the channel loading and the optimal allocation of radios for the MEHRR algorithm are also theoretically analyzed. Moreover, simulation results verified the derived Theorems.

6.2 Future Work

Although a variety of research topics related to the CCE for SUs in DSA networks has been researched by many scholars, there still exist some other interesting aspects which were barely considered. For instance, dynamically variable available channels, competition among SUs, and maliciously attacker by jammers. The research topics related to CH technique that I may deeply consider in my future work are listed as follows.

- For the proposed MEHRR algorithm, I will try to derive the probability of establishing control channels on the channels that accessed by the jump radios of the multi-radio based SUs. If the probability can be derived, the MTTR with full rendezvous diversity may be further shortened by designing CHSs based on that.

- Variable availability of the licensed channels needs to be considered. The availability of the licensed channels is commonly assumed to be static during the CCE process by most of the existing CH algorithms, which is inapplicable for realistic DSA networks. The availability of the licensed channels may be dynamically varied during the CCE owing to the activities of PUs and the mobility of SUs. Considering this problem, I will try to predict the long-term status of the licensed channels. I plan to design CHSs utilizing the licensed channels that trend to be available for a long-term, by which the successful probability of CCE will be increased while the TTR can be further shortened.

- Competition among SUs. Although the channel loading has been well considered when designing CH algorithms, more than one pair of SUs will access to the same available licensed channel simultaneously when the number of SUs is much more than that of available licensed channels. Hence, the competition among SUs during CCE process still needs to be well considered.

- The design of CH algorithm needs to be robust, by which SUs can avoid attacking from jammers in DSA networks.

- The evaluation of the channel quality. Control channel may be established on the channels with high quality based on the evaluation of the channel quality, which may further increase the successful probability of CCE after a pair of SUs accesses to commonly available channels.

- Deep learning (DL) based CCE. DL has already shown astonishing capabilities in dealing with many real-world scenarios, such as the success of AlphaGo [100, 101]. Researchers in wireless communications cast strong interested in deep learning applications currently [102–104]. By using DL model the complex problems can be simplified, abstract features can be obtained, and a better decision can be achieved [105, 106]. There are many problems in dynamic spectrum access can combine the deep learning, such as resource allocation, channel estimation, spectrum predicted, etc [107–109]. Similarly, CCE also can combine the deep learning. For instance, SUs can firstly predict long-term states (availability, channel quality, etc.) of the licensed channels before generating CHSs based on DL technique. Then, selecting the channels with better long-term states to generate CHSs. By this method, rendezvous channel quality may be improved while interference with PUs may be reduced. Moreover, the TTR may be reduced, because the number of channels utilized to generate CHSs is reduced while the TTR is in proportion to the number of channels that are utilized to generate CHS.

Appendix A

Publication List

A.1 Journals

[1] A. Li, G. Han and T. Ohtsuki, "A fast blind scheme with full rendezvous diversity for heterogeneous cognitive radio networks," *IEEE Trans. Cognitive Commun. Netw.*, vol. 5, no. 3, pp. 805 - 818, Sept. 2019.

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A.2 Full Articles on International Conferences Proceedings

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