Ph.D. Dissertation

Enhanced Adaptive Rendezvous with Interface Selection in Cognitive Radio Networks

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Abstract

Cognitive radio (CR) technology enables the opportunistic use of a portion of the licensed spectrum by CR user, while ensuring low interference to the primary user (PU) activity in a licensed band. In multi-channel wireless networks, it is compulsory to set up a control channel and exchange initial information before communication. Blind rendezvous is the fundamental challenge in cognitive radio networks (CRNs) for unknown CR users to find each other on a specific channel and establish a communication link with a selected radio interface. Rendezvous problem involves a collection of users or nodes, each of which would like to discover and communicate with the other in the collection who are within its transmission range. Two users are said to be rendezvous if they sense the presence of each other and able to communicate with an available radio interface. Blindness refers to a set of constraints on any algorithm that is to guarantee rendezvous in a typical wireless networks.

- Users has no information about each other and has no means of coordination,
- Users are not time synchronized, so different agents may be deployed with their clocks offset from one another by some amount,
- Users do not have a common channel set. This means user capable of cognitive sensing decides it's own channel list to attempt rendezvous.

Modern communication devices are equipped with multiple radio interfaces and rendezvous can take advantage of this by using all available interfaces to rendezvous. But finally it has to select a radio interface to start data communication due to the typical characteristics of device. However, users can select a radio interface deterministically based on different applications running on the user or required data rate to support applications. In this approach, the decision depends completely to the end users and user is responsible to exploit the best available characteristics of different radio interface with an object of increased satisfaction. The natural interpretation of satisfaction is to obtain QoS for the lowest price.

Problem of this nature takes different forms in various wireless settings. This dissertation describes two blind rendezvous schemes to rendezvous and is followed by a radio interface selection mechanism to finalize communication. We have designed a rendezvous MAC protocol, V-MAC that is able to work with our proposed rendezvous schemes. We prove that the proposed algorithm provides guaranteed rendezvous and defined time-to-rendezvous (TTR) for comparison. Later we analyze radio interface selection as a non-cooperative game and proposed heuristic algorithm to choose the best-suited radio interface between rendezvoused users for the sake to communication. We have defined utility and cost function to achieve the best output. Finally, through analysis, along with simulation we show that it is possible to achieve rendezvous with a lower TTR and rendezvoused nodes can achieve higher throughput by selecting radio interface efficiently.

Keywords: Cognitiver radio, rendezvous, time-to-rendezvous, radio interface selection, game theory, Nash equilibrium.

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Chapter 1

Introduction

In general, traditional wireless communication system has fixed transmission parameters. In other words, their transmission frequency is fixed and the same in every location and instant of time determined by regulatory policies. However, recent advances in wireless communications and integrated circuit technology have increased the demand of radio spectrum exponentially. The outcome of several investigations have shown that the lack of resources is not an issue, but the spectrum is underutilized in many cases. On the contrary, the unlicensed spectrum ISM 2.4 GHz and 5 GHz band have become overcrowded in the interest of WLAN, Bluetooth, cordless phone, microwave ovens and other devices. In order to accumulate all the interests and quality of service (QoS), new technology needs to be developed which can utilize the under used spectrum resources in a dynamic way [1].

A report from Federal Communication Commission (FCC) shows that, up to 85% of the spectrum is underutilized due to static spectrum allocation policy [2]. Significant part of spectrum resources are used only for some time periods in an ON-OFF manner and with large geographical variation. Apparently, in order to increase the wireless spectrum utilization Cognitive Radio (CR) offers opportunistic spectrum sharing (OSS) where unlicensed bands are used by unlicensed users, also called secondary users (SUs), are allowed to operate in licensed frequency bands without the permission of the licensed users, also called primary users (PUs), provided that they do not introduce harmful interference to the PUs. CRs are currently getting due consideration as an alternative to recent wireless devices in many areas such as smart grid [3], public safety [4], cellular networks [5]-[7] and wireless medical networks [8]. CR enables SUs to sense different channels and attempt rendezvous on a vacant one to discover other SUs. From hereon we will use the term SU or user interchangeably.

1.1 Rendezvous

In a cognitive radio networks a SU is typically in transmission range of one or more neighbor SUs, but communication between the SUs will not occur until they detect and identify each other. In Fig 1.1, an example of rendezvous is presented where three users have discovered each other on channel one and two respectively. Upon rendezvous, two users can exchange information to synchronize for future communication, share data, and perform cooperative tasks. Before rendezvous is achieved, all the users can do is blindly probe with available radio or radios to announce its presence to the surrounding users. Typically, it is in the interest of the network for users to rendezvous with neighbors as early as possible after deployment, but this must often be weighed against other concerns, such as robustness or the need to avoid collision during probe request/response.

1.2 Radio interface Selection

Radio interface selection allows users to select an available radio interface for communication. In literature interface selection is often used to select different network, such as selection among Bluetooth, Wi-Fi, and LTE-A/3G. Because users such as smart-phones are usually equipped with multiple radio interfaces.

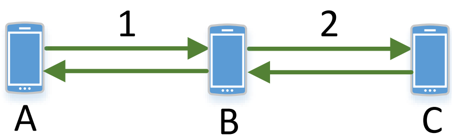


Figure 1.1: An example of rendezvous.

To transfer data these physical interfaces consume a distinct but considerable amount of energy. Moreover, these users operate on limited battery power. In a wireless environment with infrastructure interface selection is crucial and it can impact in a cognitive radio networks with no infrastructure.

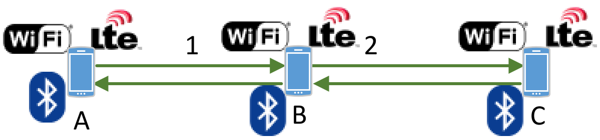


Figure 1.2: Radio interface selection to establish a link.

Radio interface selection can be performed immediately after rendezvous. In a multi-interface scenario a user can rendezvous with a single radio interface. As multi-homing is not considered in this work, user can only connect with one user at any given time. When a users has rendezvoused, i.e., the user has found another user users has to efficiently and automatically select the radio interface that provides the best performance. An example in Fig 1.2 depicts a very general scenario for the problem of interface selection. In order to increase the lifetime of users and their applications it is crucial to to select an interface conveniently. Considering the link quality an adaptive radio interface selection can produce cost effective communication for rendezvoused pairs effectively.

1.3 Challenges

There are some challenges regarding rendezvous problem. We will address them as follows.

1.3.1 Asynchrony

There is no common notion of time among the users in the network. Different users have different clocks, although speeds of the clocks are the same. Therefore, users may "wake up" at different times, which may include a time offset between their schedules. Our goal is to design protocols such that no matter what the offset is, any two users are guaranteed to rendezvous. We also want to minimize the time-to-rendezvous (TTR) from the time they both "wake up" until they rendezvous. For multi-interface, multi-channel problem we consider both synchronous and asynchronous scenarios.

1.3.2 Anonymity

There are no identities for the users; therefore they have to be treated equally. For multi-channel rendezvous problem, an user's hopping schedule only depends on the available subset of channels. For the energy constrained, single channel rendezvous problem, an agent's waking schedule only depends on its duty cycle. In other words, users may not rely on distinct identities for creation of their schedule.

1.3.3 Asymmetry

Different agents may have distinct parameters. For the multi-channel rendezvous problem, we consider two settings: in the symmetric case all the users have the same set of channels, and in the asymmetric case, each user can have different channel set, i.e., number of channels can be different for any two users.

1.3.4 Heterogeneity

Users with a channel list where channels are marked identically and can have homogeneous appearance in the list. We have considered a heterogeneous approach in the set of channels. So each user can sense different channels and rearrange the list considering the sensing results, i.e., noise of channels.

1.3.5 Interference

Each rendezvoused pair communicate with each other using a single channel. Neighbor rendezvoused pair can cause interference if they are rendezvoused on the same channel. This causes severe degradation of throughput among pairs in the same vicinity. Radio interface selection increases the possibility of reducing interference, because interfaces have different transmission energy and range.

1.3.6 Energy Cost

Taking a long time to rendezvous increases the consumption of energy. For robustness we have considered multiple interfaces and they attempt to rendezvous simultaneously. Finally, selecting the proper interface to enable communication link between two users can reduce transmission energy, while guarantees the required data-rate of the user.

1.4 The Contribution of Dissertation

The thesis provides the following main contributions. A rendezvous scheme namely EAR to overcome the channel asymmetry, heterogeneity and asynchrony challenges are proposed. A new MAC model for rendezvous, V-MAC, to reduce the failure of rendezvous due to collision. To confirm the communication link among rendezvoused pairs, an interface selection game is participated.

1.4.1 EAR: Enhanced Adaptive Rendezvous

Rendezvous is the fundamental requirement for users in CRNs to initiate communication. For the multi-interface, multi-channel rendezvous problem, enhanced adaptive rendezvous (EAR) is proposed. In a dynamic radio environment CR nodes observes a different set of channels at distinct time and location. EAR considers this dynamic characteristic of channels and models a ranking based channel list to support channel hopping (CH) scheme for both symmetric and asymmetric channel state scenario. Due to the collision prone nature of the wireless channels, it is better to achieve rendezvous on the best quality channel rather than any available channel. In EAR, with a strict partition scheme it guarantees that the best channel in the list is visited more times to attempt rendezvous. It is assumed that, rendezvous may occur on the most visited channels with a higher probability. This thesis claims guaranteed rendezvous for symmetric and asymmetric model.

1.4.2 V-MAC: Rendezvous MAC Protocol

Initially in EAR, probe request and response messages are considered to ensure the presence of a pair of users. EAR guarantees rendezvous, however it is a mathematical concept. Hence, EAR can not control the collision issues during rendezvous. Therefore, a MAC protocol is desired to overcome the prior concerns of wireless environment. In this thesis a new rendezvous MAC (V-MAC) is modeled based on probe request and response management frame. The proposed rendezvous schemes work perfectly with V-MAC. We modeled our MAC to increase the opportunity of rendezvous by resolving collision and make sure that V-MAC fits to any other CH scheme. To minimize the channel access delay due to PUs or collision because of multi-user probe request/response, the V-MAC modifies the CSMA/CA protocol. No extra fields are added to control additive overhead of the management packets. This new MAC takes the advantage of probe response overhear and reduces probe request packets to bring balance in multiple probe request format.

1.4.3 Radio Interface Selection

When two users successfully rendezvous (discover), the remaining work is to establish a link between them to start data communication. Users are equipped with multiple radio interfaces and any of these can be a medium of communication. For that purpose, the radio interface selection problem is modeled in non-cooperative multi-channel networks with multiple collision domains under device-to-device (D2D) networks. D2D networks is considered for this section as an extension of CRNs where SUs are directly communicating in a single hop manner. To model the network with multiple collision domains, interference model is introduced into the network. Analysis of the cost function and utility function is presented to design a scheme for interference selection. Later, an investigation is conducted for the possible stable state, namely Nash Equilibrium (NE) that the system could achieve. After discussing different decision parameters for radio interface selection, three heuristic algorithms are proposed to adaptively select radio interface for communication purpose between two rendezvous users.

Subsequently, a typical cognitive radio network scenario is adopted for the theoretical analysis, and different parameters are discussed. Thereafter, considering those parameters, the performances of different rendezvous schemes are compared. Extensive simulation is presented focusing on which rendezvous scheme is robust with a lower TTR. With this rendezvous performance we look forward to the execution of our interface selection scheme. Our evolution targets to achieve better utility, energy efficiency and cost with proposed schemes compared to forced radio interface selection.

1.5 Dissertation Roadmap

This thesis follows the structure shown in Fig: 1.3 below, that consists six chapters.

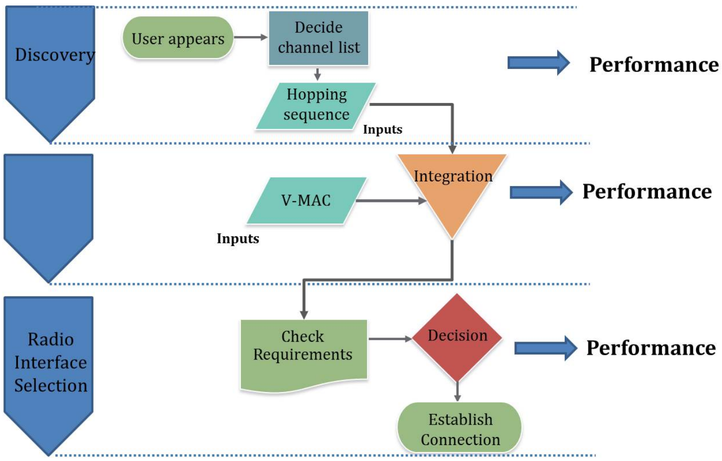


Figure 1.3: Roadmap of the thesis.

The remainder of this dissertation is organized as follows. Chapter 2, discusses the most general concepts of rendezvous, passes through some previous rendezvous schemes along with their limits and trade-offs. It also contains several interface selection schemes in this chapter, and systems where it is used mostly. A new rendezvous scheme namely, enhanced adaptive rendezvous (EAR) is presented in Chapter 3 based on mathematical concepts and the performance is evaluated. Chapter 4 addresses the issues and challenges of EAR in a wireless network model. Upon revisiting CSMA/CA, a rendezvous MAC protocol called V-MAC is modeled that overcomes several issues of rendezvous. Next, a game theoretic model is presented for radio interface selection in Chapter 5. This shows the significance of interface selection to activate data communication upon rendezvous. Finally, Chapter 6 summaries the major findings and concludes the thesis.

Chapter 2

Related Works

In a cognitive network environment, a SU is typically within transmission range of one or more SUs. However, communication between the SUs cannot occur until they identify each other and mutually select a radio interface to attempt communication. Once this happens, two SUs can exchange information to synchronize for future data communication, share data, and perform other cooperative tasks (which are beyond the scope of this document). Before the rendezvous is achieved, all the SUs can blindly probe with its radio interfaces to make its presence known and listen for probes from other SUs. Typically, it is in the interest of the network for nodes to rendezvous with all neighbors as early as possible after deployment, and select an radio interface to start communication.

2.1 Rendezvous in Cognitive Radio

A CRN is usually composed of three types of node; PU, SU, and PU base station. Fig: depicts a simple network model of such kind. Among three types of nodes only the SUs are equipped with cognitive functionality. A SU, i.e., a CR node opportunistically uses the licensed spectrum bands in the presence of PUs. Except sensing the spectrum hole, the SU is required to detect the presence of a PU instantly to avoid interference with PU transmission. Therefore, SUs perform spectrum sensing to establish communication and identify the vacant channels. This assumption changes the problem of classical rendezvous, as different users can have distinct channel set. Moreover, the available channel set for a SU depends on the neighbor PUs activity. In traditional multi-channel environments, there is a common channel available for all nodes in the network to exchange and disseminate the control messages. However, rendezvous channel in CRNs differ significantly. Typical rendezvous models, similar channel information is considered for all the nodes. Based on that, nodes select a global (common for all) or static (common between pairs) control channel . In contrast, CRNs aim to exploit asymmetric channel information in the heterogeneous wireless networks.

2.1.1 Rendezvous: Literature Survey

Rendezvous is a process, where two users find each other on a certain channel and establishes a communication link [9]. There are two main different rendezvous strategies as shown in Fig. 2.1

As is the case in the majority of multi-channel wireless communication networks, setting up a control channel and exchanging initial information, called rendezvous, are the first step for the SUs of CRN to begin communication with each other [10]. There are two approaches to rendezvous in CRNs: one is to use a common control channel (CCC) and the other is blind rendezvous. CCC-based rendezvous schemes assume that a universal channel known a prior for all SUs [11]-[13]. Although using a CCC simplifies the rendezvous process [12]-[14] it has several drawbacks:

- under heavy load a CCC becomes congested,
- PUs' activity and dynamic change of the available spectrum might cause the CCC to become infeasible in the maintenance of all users,
- CCC is vulnerable and a single point of failure for mission critical networks.

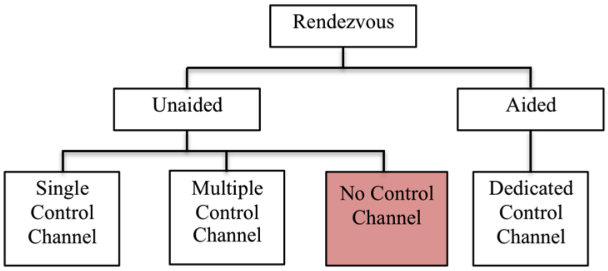


Figure 2.1: Categories of rendezvous.

In light of such limitations, blind rendezvous techniques for decentralized systems are much more challenging. Each user should have the ability to opportunistically identify vacant portions of the spectrum (i.e., idle channels) and be able to hop between channels. To establish communication links, first two SUs in CRNs should identify the existence of each other by any rendezvous procedure. However, the implementation of blind rendezvous technique is nontrivial, because an SU has no information about the presence of other SUs before rendezvousing, and available channels vary from user to user dynamically. Therefore, only channel hopping (CH) based rendezvous protocols are considered for this thesis.

CH Sequence

A representational approach to achieve blind rendezvous is to use the channel hopping (CH)[11]-[15] technique. CH has limited constraints and is highly adaptive to various conditions. A hopping sequence generator (HSG) targets to hop on the same channel as soon as possible. Nodes visit the available channels in a random order [23] with the interest to establish a communication link. The time is considered to be slotted and during each slot CR node will individually select one of the channels with equal priority. TTR is total number of slots until the first rendezvous occurs for independent Bernoulli trials. The authors in [19] proposed a new scheme called adaptive multiple rendezvous control channel (AMRCC), in which the CH sequences are built in an adaptive manner such that the channels that cause lower interference with other devices occur with higher probabilities. However, the results in [19] are essentially random, and the AMRCC cannot guarantee rendezvous in a finite time.

There are several efficient mechanisms that are based on number theory. Permutation based hopping sequence generator (HSG) mechanism for guaranteed rendezvous is proposed in [16]. In this approach, each user follows a predetermined hopping pattern to construct a hopping patter using the available channels in the list. The method shows that the expected TTR is bounded by the quadratic function of the number of available channels. Therefore, expected TTR increases simultaneously with the number of channels. A sequential channel hopping protocol with similar concept is presented in [17]. Unfortunately, it creates additional delay to rendezvous due to PU appearance in the control slot. A simplest form of hopping sequence namely, slotted seeded channel hopping (SSCH) for 802.11 networks is proposed in [18]. SSCH exploits channel diversity, but the requirement of tight time synchronization is a huge drawback for this approach.

Another efficient rendezvous protocol is modular clock algorithm (MC) [23] and its modified version, MMC [23]. MC is for symmetric channel list and MMC is for asymmetric channel list respectively. Both MC and MMC works with prime number based on the of available channel list. Considering the prime number and channel list size, users generate CH sequence predefined by a modulo operation. But unfortunately, MC does not guarantee rendezvous if two users have the same hop rates. Generated orthogonal sequence (GOS) is another CH technique proposed in [13]. GOS generates a sequence based on random permutation. GOS assumes all the users have same channel set, i.e., only works in symmetric model. Therefore, the channels might not be utilized efficiently because of an imbalance of traffic in different channels.

M-QCH and L-QCH are proposed in [15] to guarantee rendezvous. Both are quorum based HSG mechanisms but only works in synchronous systems. Further, A-QCH [15] is proposed for asynchronous systems. However, A-QCH is useful for a system consists of two channels, which limits its function. It also requires a network wide synchronization to guarantee the rendezvous within a cycle period. Quorum is widely used as a solution for the mutual exclusion problem and the replica control problem [22] in distributed system. Systematic quorum-based approaches are proposed to design CH protocols for control channel establishment in‘[15][24]. They do not support multicast rendezvous, where all the nodes in a multicast group are required to rendezvous in the same time slot. Furthermore, these protocols are intended for a homogeneous spectrum environment. Again, to solve the rendezvous problem without synchronization authors in proposed a grid based quorum formation. However, this can not guarantee rendezvous on each available channel between users.

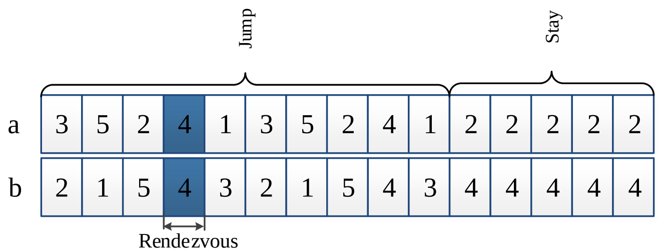


Figure 2.2: Interface selection to establish a link.

Yang et al. proposed two significant algorithms, namely deterministic rendezvous sequence (DRSEQ) [20] and channel rendezvous sequence [21], which provide guaranteed rendezvous for the symmetric and asymmetric model, respectively. Given the number of channels M, a DRSEQ exactly consists of $(2M+1)$ indices, which can be expressed as $1, 2, \ldots, e, M, M - \ldots, 1$, where a denotes a NULL item. In CRSEQ, the sequence is constructed based on triangle numbers and modulo operations. In terms of maximum TTR (MTTR), CRSEQ is quite good under asymmetric model but it does not perform well under symmetric model. The authors in [26] proposed three multicast rendezvous algorithms. They used Chinese reminder theorem (CRT) and uniform k-arbiter quorum systems to design their algorithms. These mechanisms improve the rendezvous process by selecting the top channel to rendezvous. However, none of these mechanisms contemplated channel lists of different size.

Jump-and-Stay (JS) [27] is a rendezvous mechanism that partially adapts the GOS algorithm. Similar to GOS, JS also selects a prime number and a rate that generates a CH sequence. This sequence is used for the 'jump' duration, and the user stays on the same channel during the 'stay' duration. The length of the stay duration is exactly half of the total length of the jump duration. Suppose that two users 'a' and 'b' have a common channel list, $C = 1, 2, 3, 4$. User 'a' selects a random start point 3 and a hopping step (i.e., rate) 2. User 'b' selects a random start point 2 and a hopping step 4. The jump-and-stay pattern using these parameters is presented in Fig. 2.2. Notice that the first ten slots correspond to the jump pattern, whereas the remaining five slots correspond to the stay pattern. Each time the number 5 appears, it is replaced by the initial channel 3 for user 'a' and by 2 for user 'b'.

In this JS algorithm, the guarantee for multiple channels and multiple users to rendezvous has been proven. However, a performance with channel lists of different sizes for different users has not been considered. Instead of preassigning two jump and one stay pattern, an alternative hop-and-wait pattern depend on node ID was proposed in [28]. The basic concept is based on the least significant

Table 2.1: Sequence based rendezvous schemes.

Algorithms	2-user		Multi-user multi-hop	
	Symmetric	Asymmetric	Symmetric	Asymmetric
JS	$3P$	$3MP(P-G)+3P$	$3PD$	$(3MP(P-G)+3P)D$
GOS	$M(M+1)$	$\times$	$\times$	$\times$
MC	$2P$	unknown	$\times$	$\times$
MMC	unknown	unknown	$\times$	$\times$
DRSEQ	$2M+1$	$\times$	$\times$	$\times$
CRSEQ	$\geq (P-1)(3P-1)$	$P(3P-1)$	$\times$	$\times$

bit (LSB) of node's ID. Node waits for length P if LSB is 0. Further node hops for length $2P$, otherwise node hops for $3P$ if LSB is 1. But in this approach the node ID is the main factor to determine the length of CH sequence. In a realistic network this will create big overhead if the number of nodes is large, as node ID will increase proportionally.

In the literature, other blind rendezvous systems can also be found; however, such systems are not based on the CH techniques. For example, the author of [29] proposed to select a leader in the distributed network. The leader will be responsible to discover its neighbor users. In [30], to discover the neighbors special signals such as cyclostationary signatures are employed. Another CH sequence is proposed in [31], where pre-assigned roles are designated as a sender and receiver.

2.2 Radio Interface Selection

Devices these days are equipped with multiple radio interfaces, such as, LTE/3G, Wi-Fi, Bluetooth, WiMAX, etc. These radio interfaces have distinct characteristics considering energy consumption, service area, data transfer rate and other factors [32]-[34]. Most of the wireless devices are limited with battery power. Therefore, for these battery operated devices it is important to achieve energy efficient communication [35].

There are many works in literature to enhance energy efficiency. We can take the advantage of multiple radio interfaces equipped with devices these days and select the most energy efficient one [36][37]. Hence, radio interface selection is an important issue in modern wireless communications. Network selection is defined as a mapping of mobile terminals or applications to one of the available operators whereas, radio interface selection can be done without altering the network. The actual decision for network selection may take place on both sides of the wireless channel; on the user terminal side or on the network operator side. To differentiate between the two, the term interface selection is used for terminal based (user-based) network selection, and resource distribution for operator based networks selection. The decision process at different level is depicted in Fig. 2.3.

In this thesis we have concentrated on user-based radio interface selection. The next subsection we will discuss some related works of this class.

2.2.1 User-Based Network Selection (Interface Selection)

The decision mechanism on the user gets information on relevant factors as inputs, including user preference, application specific requirements, network conditions, price offers, etc. Upon receiving the information, the decision entity employs various decision making techniques resulting in an interface selection. Typically the UE selects a single radio interface for connectivity of the device, which is used by all user applications. However, with increased multitasking capabilities of mobile terminals,interface selection can be done on a per-application basis; i.e. the interface selection decision associates each application running on the UE separately to a suitable access technology.

To reduce power consumption CollSpots is proposed in [38]. It determines the use of Wi-Fi and cellular networks based on bandwidth requirement and

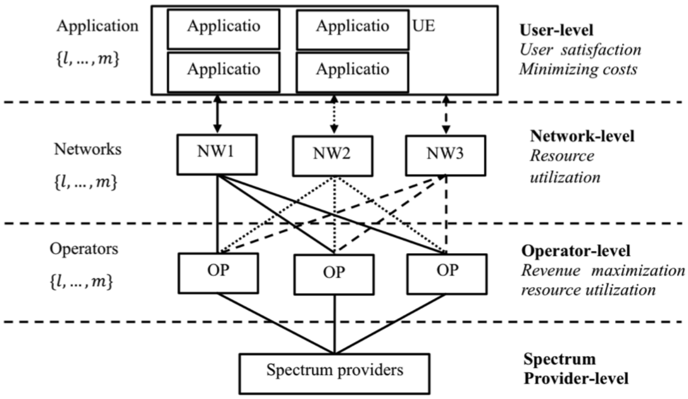


Figure 2.3: A hierarchical diagram of different stakeholders and their objectives.

thus reduces energy consumption. A link selection algorithm between Wi-Fi and EDGE is proposed in [39]. For the purpose of data transfer this approach selects radio interface based on network stability. Based on various available estimation algorithms, they formulates wireless interface selection problem as a decision problem.

Another energy efficient approach is SALSA (Stable and Adaptive Link Selection Algorithm), which considers 3G/EDGE and Wi-Fi interfaces for data transfer [40][41]. This work also mentions about the energy cost for transmitting a given amount of data considering the availability and achievable data transfer rate of these networks. SALSA is an on-line algorithm that adopts Lyapunov optimization framework. It automatically adapts channel information based on the available local information. The real implementation of this algorithm reflects the energy-delay trade-off during efficient data transfer. WINA introduces an auxiliary receiver to active the suitable wireless interface on the user device [42]. But, the decision depends on a special signal received by that auxiliary receiver. During idle times, all the interfaces are in "standby" state.

In heterogeneous wireless networks, an important task for users is to select the best network for various communications at any given time anywhere. This topic has been widely studied by using various mathematical theories. Multiple attribute decision making (MADM) [43] refers to making preference devision over the available alternatives that are characterized by multiple attributes. Most MADM algorithms that have been studied for network selection problem are compensatory algorithms, including simple additive weighting (SAW), multiplicative exponential weighting (MEW), gray relational analysis (GRA), technique for order preference by similarity to an ideal solution (TOPSIS), etc. There are also mathematic theories considering fuzzy logic [44], game theory [45], combinational optimization [46] and Markov chain [47] [48] for network selection. "Best" wireless access network to connect can be selected dynamically and automatically considering these approaches.

2.3 Summary

In this section, the fundamental of CR were presented together with rendezvous issue. Classification of rendezvous problem is discussed. The concept of rendezvous in CRN was presented and briefly explained. The major rendezvous protocols from literature were identified and discussed. Later we discuss about the radio interface selection from different perspective. Though network selection is well studied, the network conditions were totally different than CRNs. In such infrastructure-less or self-organized network, where users are absolutely isolated, radio interface selection becomes more complicated.

Chapter 3

Enhanced Adaptive Rendezvous

In this chapter, a CH based *enhanced adaptive rendezvous (EAR)* is discussed in detail. EAR functions for the following environments: (1) when the channel condition is heterogeneous, i.e., some channels are preferred because of low noise, those channels are visited more frequently, (2) when the channel list is asymmetric, i.e., the number of channels is different for any two users, (3) it works for multiple radio interfaces because of (2), and (4) the algorithm is extended for multi-user rendezvous as a consequence of (3). This chapter holds the detail working principle of EAR and the performance analysis in different conditions.

To achieve rendezvous EAR considers heterogeneous channel conditions; however, in the literature, existing rendezvous algorithms do not have a preference to a specific channel. The fundamental idea is that channels in an interface are sorted in descending sequence (i.e., best to worst) based on sensed channel conditions (e.g., quantity of measured noise) and the user jumps to superior channels more frequently. Thus, it is possible to stay on the best channel for a longer duration, which gives a higher probability to rendezvous on the best channel.

In multi-interface environments, once a user has rendezvoused using a specific interface, it is not necessary to rendezvous on other interfaces. Therefore, using multiple radio interfaces, it is easier to establish connectivity among users in the network with a reduced time-to-rendezvous (TTR). To enable such a scenario, channel list is divided among the interfaces and a channel is non-overlapped between two interfaces. This channel division creates asymmetric channel sets for each interface. This is the first work that addresses the rendezvous issue for heterogeneous channel conditions, asymmetric channel lists, and multiple radio interfaces (hereafter, expressed as simply multiple interfaces).

Under the heterogeneous channel condition, EAR is investigated for two cases: symmetric channel list and asymmetric channel list. For a single-interface network, every user is expected to see the same channel list; for a multi-interface network, each interface hops to a different set of channels. Therefore, multi-interface networks are covered by the second case. Both cases are proven to guarantee rendezvous under EAR, which is also evaluated through extensive simulation. Moreover, the results demonstrate that the scheme functions for a network with multiple users and multiple interfaces. In contrary, the legacy JS algorithm has been proven for the single-interface rendezvous scenario with homogeneous channels and same channel list size. Presented simulation results confirm that EAR significantly reduces the expected TTR compared to the simple extension of the JS algorithm to a multi-interface and single-interface case.

3.1 Adaptive Rendezvous with Symmetric Channel List

3.1.1 System Model and Assumptions

In this section, an enhanced adaptive rendezvous (EAR) method is proposed for users who have the same channel list with different channel qualities to jump, i.e., heterogeneous symmetric channels. This symmetric condition (i.e., the same channel list) does not pertain to environments where users have multiple interfaces, which will be addressed in the next section. Throughout this paper, we consider a self-organizing network that consists of N ($N \geq 2$) users (or SUs in a CRN) who are randomly distributed in a geographical area. The available spectrum is divided into M ($M \geq 1$) non-overlapping orthogonal channels, which are indexed uniquely as $1, 2, 3, \ldots, M$. The entire set of available channels is denoted by $C = \{c_1, c_2, \ldots, c_M\}$, where c_i denotes channel i. Each channel is defined by its central frequency and bandwidth. Without loss of generality, we assume that every channel has equal bandwidth, and that the central frequency has equal spacing of the bandwidth from the next adjacent channel, similar to TV channels or IEEE 802.11 channels [49].

As considered in the majority of the work on CH algorithms, a time slotted model is adapted for this system. In each time slot, a user at each interface listens to a channel to determine if any neighboring user sends a rendezvous request over that channel. If the user fails to identify other users, the user attempts to search others in another channel at the next time slot. There is no co-ordination among users in this process and the process to rendezvous is independent for every user. To ensure the presence of a pair of users, probe request and response messages can be considered as in the Wi-Fi Direct standard [50]. The interface of a user, after sending a beacon, waits for the corresponding probe response from another user who wishes to rendezvous. For simplicity, users are assumed to rendezvous within a slot providing they stay on the same channel and exchange probe messages. We do not consider the implementation details, because our main goal is to simplify the rendezvous problem and design a hopping sequence for an improved TTR. Further issues are found in [51].

As in other works, the performance of the proposed algorithm is evaluated using TTR, i.e., the number of time slots elapsed before a rendezvous occurs. For a two-user scenario, the TTR is measured from the time slot when the second user begins, assuming that the first user started in time slot 0. Therefore, a

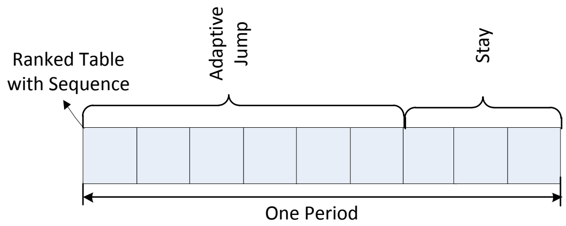


Figure 3.1: Adaptive jump and stay for a user.

lower value of TTR indicates a robust CH sequence to achieve rendezvous.

3.1.2 Frame Structure of Adaptive Rendezvous

In the proposed scheme, a channel sequence is generated where the jump pattern is adaptive and the stay pattern is calculated separately. During the jump duration, each user jumps to given channels sequentially based on the observed channel ranking. The best channel from the list appears more frequently in the jump pattern, whereas other channels in the list appear less frequently. During the stay duration, as in the JS algorithm, each user stays at a specific channel; however, jumps to another channel in the next duration. The slot structure of the proposed algorithm is depicted in Fig. 3.1.

In all previous works, it can be seen that channels in the list have homogeneous channel conditions. However, in the real world, these channels can have different conditions; simply, the quantity of measured noise for each channel can be different. Therefore, in this work a list of channels are sorted in descending order by channel quality, which is generally represented as the measured noise. Once one cycle of the jump-and-stay duration has elapsed without rendezvous, each user can measure the quantity of noise for each channel and then sort the channels in the list in descending order for the following durations.

The proposed adaptive jump-and-stay pattern is applied to the individual

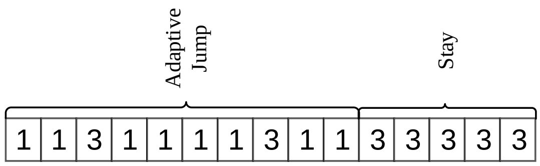


Figure 3.2: Incorrect jump pattern for random r.

user in a network. For each user, as in the JS algorithm, the initial channel, denoted by n, is selected randomly in $[1, M]$ where n indicates the starting channel position in the ranking list of that interface. The step size denoted by r is also a non-zero random number for hopping and P is the smallest prime number greater than M. That is, an interface starts with n, and it jumps channels with step size r. For a channel list $\{1, 2, 3, 4\}$, if we select any value, for example $n = 1$ and $r = 2$, as illustrated in Fig. 3.2, only two channels from the list are visited for the jump pattern, which is a possible error in the original jump-and-stay. To correct this problem, i.e., ensure that all the channels are visited, *Josephus recursive* structure is adopted to set r_j for the proposed adaptive jump pattern, which is given by Eqs. (5.2) and (3.2).

$$jose(M, r, i) = jose(M, r, i-1) + (r-1)\%(M-(i+1)); \tag{3.1}$$

$$jose(M, r, 1) = n. \tag{3.2}$$

Fig. 3.3 depicts an example of the steps using Josephus recursion from Eqs. (3.1) and (3.2), where $M = 4$, $n = 1$, $r = 2$ and $2 \leq i \leq M$. For the same channel list it generates a sequence of $\{1, 3, 2, 4\}$. The fact that Josephus recursion ensures that all the channels are visited in the jump pattern is formally proved by the following lemma.

Lemma 3.1.1. *For any channel number M, step length $r \in [1, M]$ from Eq. (5.2) and Eq. (3.2) ensures that all M channels are visited.*

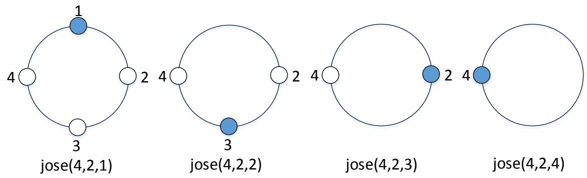


Figure 3.3: Example of Josephus recursive.

Proof. This is proved by induction. Eq. (3.2) selects the first channel from the list by definition. Therefore, in the first round that channel will be selected and removed from the list. In Fig. 3.3 it is observed that in the first round channel 1 is removed after using $n = 1$. Suppose that we know the value for $jose(M, r, i-1) = k$. Hence, if we start counting from channel 1, the $(i-1)$th channel in the list is k. Now consider $jose(M, r, i)$. Because $jose(M, r, 1) = n$, the first step is removed and for the second step we begin counting at number r. Therefore the problem is to determine the $(i-1)$th channel which is removed (after removing n_j), when we start counting at number k. However, this is $(r + k)mod(M)$ and we obtain Eq. (3.1). □

In adaptive jump and stay, the jump pattern is $2P$ slots and stay pattern is P slots. Under the condition of $P > M$, it is guaranteed that in the jump pattern all the channels will appear at least once during P for any value $r \in [1, M]$. These P slots will be distributed among M channels. With Josephus recursion we

Table 3.1: Generated sequences for the number of jumps to the ordered channels.

Channel Rank	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
M_j=4	2	1	1	1								
M_j=8	3	2	1	1	1	1	1	1				
M_j=12	2	1	1	1	1	1	1	1	1	1	1	1

already proved that every channel would appear. With slot distribution, it will be guaranteed that each channel holds at least one slot. After completion of P slots the same sequence will appear for the next P slots. Thus it will complete the $2P$ jump pattern. For this ranking list, we must generate a sequence c_i $(i = 1, \cdots, M)$ that calculates the number of slots for each i^{th} channel in the list. To assign such different slot numbers to each channel, we can simply use any sequence that satisfies:

$$\sum_{i=1}^{M} c_i = P, \tag{3.3}$$

where $c_1 \geq c_2 \geq c_3 \geq \cdots \geq c_M$ and $c_1 - 1 \geq c_i$. Table 3.1 lists the sequences generated for the ordered channels.

To generate such a sequence where the best channel appears more frequently than the other channels, we refer to a recursion formula [52] that enables us to distribute P slots among the different M channels. First, we find the possible partitions using the following equation:

$$T(P, M) = T(P-1, M-1) + T(P-M, M), \tag{3.4}$$

where $T(P, P) = 1$ or $T(P, 1) = 1$ and $T(P, 1) = T(P, M) = 0$ if $M > P$. If we have channel number $M = 4$ and $P = 5$, we can determine the possible partition using Eq. (3.4),

$$\begin{aligned} T(5,4) &= T(5-1, 4-1) + T(5-4, 4) \\ &= T(4,3) + T(1,4) \\ &= T(3,2) + T(4-3,3) + T(1,4) \\ &= T(2,1) + T(1,2) + T(1,3) + T(1,4) \\ &= T(1,0) + T(1,1) + T(1,3) + T(1,4) \\ &= 0 + 1 + 0 + 0 = 1. \end{aligned} \tag{3.5}$$

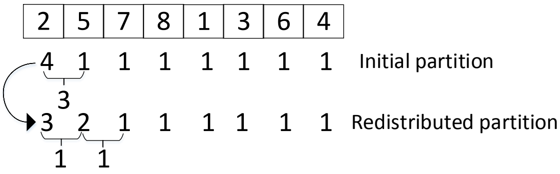


Figure 3.4: Strict partition of slots.

This states that there is only one solution that can distribute five slots among four channels. But there may be multiple solutions for other values of M and P, where generating the optimal distribution of slots is still an open issue.

Inspired by this recursion formula, we devise a simple partition algorithm that generates a sequence $c_i \quad (i = 1, \cdots, M)$ for fixed size M. It starts with a partition,

$$P - M + 1 \tag{3.6}$$

this is assigned to c_1 while the other c_i's $(i = 2, \cdots, M)$ is 1. If $c_1 - c_2$ is greater than 1, c_1 decreases by one and c_2 increases by one. Whenever a previous pair exchanges a slot, the next pairs will also be compared under the same condition. The comparison will be executed for $M - 1$ pairs.

The algorithm terminates if there is no value i such that $c_i < c_1 - 1$; in this case the slot number for each channel in the list is $\lceil \frac{P}{M} \rceil$ or $\lfloor \frac{P}{M} \rfloor$. In the example stated earlier, channel 1 is in the first position as the best channel and therefore, it assumes two slots, the highest number; the reminder of the channels appear in one slot.

Fig. 3.4 presents the process for the strict partition for $M = 8$, when $P = 11$. The initial partition where the best channel 2 appears for four slots, is obtained with Eq. (3.6). This compares the distribution with the next channel in the list, which is 5. The difference is three and as long as the difference is greater than one (> 1), one slot will be shared with the next channel. Similarly, channel 5 compares its partition number with the next channel 7 and as the difference is not greater than one, the distribution remains the same. Thus, we obtain a redistributed partition. The comparison continues between each channel and its immediate next channel. Finally, we achieve a distribution where adjacent channels have a difference less than or equal to one (≤ 1) and the process ends.

3.1.3 Rendezvous Guaranteeing

Each user interface generates initial channel n and step length r independently, considering their individual channel list, as illustrated in Fig. 3.5. The given list size is $M = 4$ for both users, a and b; however, the rankings for their channels are different. Note that each user may have a different time to start the rendezvous. Depending on the starting time, three cases may occur in the rendezvous process. In case one, user a is in jump period and user b in stay period. As we have proven in Lemma 3.1.1, with any step length r an interface will visit every channel in his list within P. If the overlap is not less than P, user a will visit all the channels including the channel that user b is holding in the stay period. Thus, a rendezvous is guaranteed. In the second case, user a and b are both in a jump period with identical r. In this case, a rendezvous is guaranteed in the stay period as both the users will stay on the same channel. In the final case, if an overlap is in any jump period and the users have different r's, according to the number theory, we can prove Lemma 3.1.2 that confirms that a rendezvous is guaranteed if the overlapping portion is not less than P.

Lemma 3.1.2. *For $\delta \leq P$, where r_x and r_y are two different step lengths, there must be an integer $k \in [0, M]$ such that $k(r_x - r_y)\%M = \delta$, to guarantee a rendezvous.*

Proof. δ denotes the time slot difference between two users. $r_x \in [0, M]$ and $r_y \in [0, M]$. Without loss of generality, assume $r_y > r_x$. This means that $(r_y - r_x)$

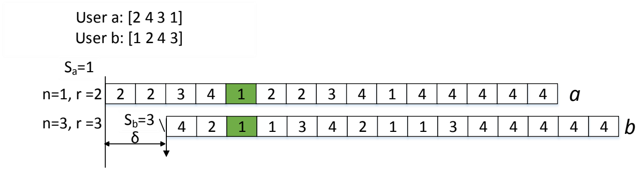


Figure 3.5: Rendezvous for two-user case.

is relatively prime to P as P itself is prime. Thus, there exists an integer k, where $k(r_y - r_x)\%P = \delta$. We claim that both users hop on a common channel during the jump stage if and only if this equality is true. □

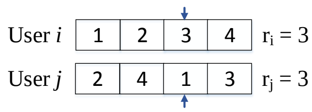


Figure 3.6: Heterogeneous channel list with same r.

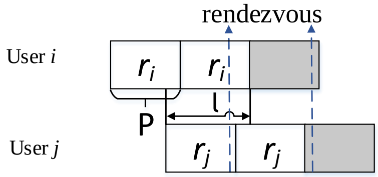
Two users may have completely different channel ranking lists; consequently, the same n and r will not always select the same channel from the list. In Fig. 3.6, we can observe that user i has a different ranking list compared to user j. Although they have the same r_i and r_j, for the stay pattern they will select two different channels 3 and 1.

Lemmas 3.1.1 and 3.1.2 yield the following theorem.

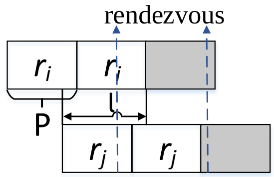
Theorem 3.1.3. *For the proposed adaptive jump and stay, a rendezvous is guaranteed for any two users, if P remains the same for the two users and there exists k that satisfies Lemma. 3.1.2.*

3.1.4 Analysis of TTR Performance

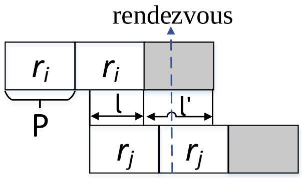
For the proposed adaptive jump and stay, we now analyze the maximum TTR performance. The maximum TTR is calculated based on six cases as depicted in Fig. 3.7.



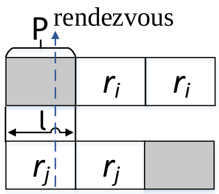
(a) $l \geq P$,$r_i \neq r_j$,$TTR \leq P$



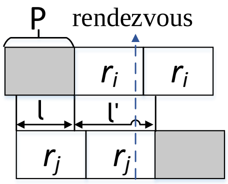
(b) $l \geq P$,$r_i = r_j$,$TTR \leq 2P + 1$



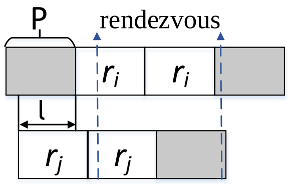
(c) $l \leq P$,$l' = P$,$TTR \leq 2P$



(d) $l = P$,$TTR \leq P$



(e) $l < P$,$r_i \neq r_j$,$l' > P$,$TTR \leq 2P$



(f) $l < P$,$r_i = r_j$,$TTR \leq 3P$

Figure 3.7: Six cases to rendezvous in the proposed framework

Theorem 3.1.4. *For symmetric channel lists, any two users achieve rendezvous within at most* $3P$ *time slots, where* P *is the smallest prime number greater than* M*.*

Proof. We assume that user j begins to rendezvous only slightly after user i. From this characteristics, patterns between these two users may vary differently. When user i is in jump pattern, user j is in either a jump or stay duration. Thus, we discuss the following six cases.

(a) In Fig. 3.7a, users i and j are in jump duration and the overlapped part l is greater than P. According to Lemma 3.1.2, a rendezvous should occur during the first overlap of P slots. With asymmetric channel list, different step lengths r_i and r_j can select the same channel from the list. In such a case a rendezvous will appear after $2P$ of the overlapped stay duration. Thus, a rendezvous is achieved within $3P$.

(b) In Fig. 3.7b, both users have the same step length r. If the same step lengths r_i and r_j are selected, a rendezvous will appear in $2P + 1$; otherwise it will appear during the first overlap of P slots because of $l > P$ and Lemma 3.1.2.

(c) In Fig. 3.7c, we observe $l' = P$, which implies that user j's jump duration will overlap with user i's stay duration of P slots. According to Lemma 3.1.1, user j will visit all the channels in his list while user i will stay on channel r_i. Thus a rendezvous is achieved during $2P$.

(d) In Fig. 3.7d, $l = P$. According to Lemma 3.1.1, user j will visit all the channels in his list whereas user i will stay on channel r_i. In this case, a rendezvous is achieved during P.

(e) In Fig. 3.7e, the overlap l' for both users is more than P time slots. Considering Lemma 3.1.2, a rendezvous will appear within the first overlap of the P slots. In this case, the overlapped portion appears after the first P and a rendezvous is achieved during $2P$.

(f) Finally, in Fig. 3.7f, $l' > P$. According to Lemma 3.1.2, a rendezvous will appear during $2P$. For $r_i = r_j$, if the same channel is selected from the channel list, a rendezvous will appear during $3P$.

From the six cases, the maximum TTR is proved to be 3P. □

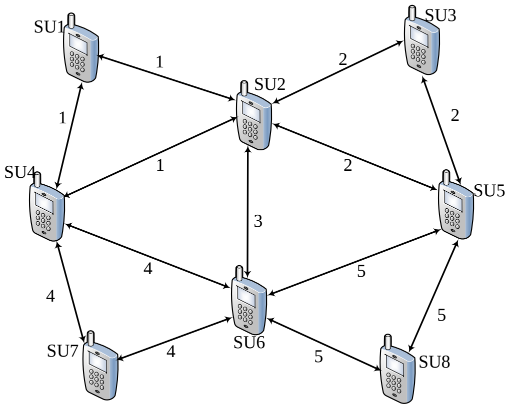


Figure 3.8: Network model for multi-interface rendezvous.

3.2 Adaptive Rendezvous with Asymmetric Channel List

3.2.1 System Model and Assumptions

We now extend the proposed adaptive jump and stay to the rendezvous of multi-interfaced users with asymmetric channels. For simplicity, lets assume each user is provided with three cognitive radio interfaces, $I = 3$, and all these three interfaces have only one channel set C. It is worth noting that asymmetric channels with a single interface are feasible with $I = 1$. The set of interfaces for user n is denoted as $n_j = \{n_1, n_2, n_3\}$. Let $C_i \subseteq C$ denote the set of available channels for user i, $i = 1, 2, \ldots, N$. These channels are first divided approximately equally among the three interfaces; it is also ensured that none of the interfaces shares the same channel. From the viewpoint of the rendezvous, assigning a certain channel to multiple interfaces of a user at one time is not required. The channel in use could be accessed from other interfaces for other purposes; however, we do not consider such a case. Let B denote the number of common channels between the channel lists of two users, where $B \geq 1$ to assure rendezvous.

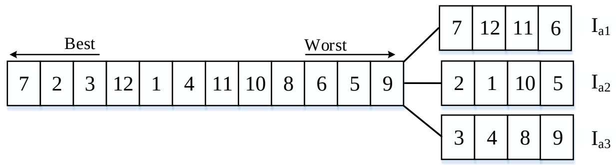


Figure 3.9: Distribution of sorted channels to multiple interfaces.

For a given multiuser CRN that consists of k ($k \geq 2$) users. The conventional rendezvous indicates that all the users must rendezvous on the same channel; however, we are only required to ensure that all the users on the network are connected with one another using more than one channel, because multiple interfaces are available. Fig. 3.8 illustrates a simple example of our network model. When there is a single interface, the rendezvous process continues to execute until all the users are rendezvoused on the same channel. Conversely, when there are multiple interfaces, the rendezvous process continues to execute until all the users are rendezvoused on any channel, thereby significantly enhancing the possibility of network rendezvous. In Fig. 3.8, a single user can communicate on three different channels to three different users in the network.

3.2.2 Frame Structure for Multiple Interfaces

The given channels are distributed into multiple interfaces, such that each interface uses a subset of the channel list to attempt to rendezvous with other users. A simple example of channel division to multiple interfaces is depicted in Fig. 3.9, where 12 sorted channels ($M = 12$) in descending order by channel quality are distributed to three interfaces ($I = 3$) of user a. The channels are evenly distributed to each interface such that the quality of rendezvoused channels is not jeopardized to a specific channel. Then, each interface maintains an individual channel list of four ($= M/I$) channels. We denote the number of channels for interface j by M_j.

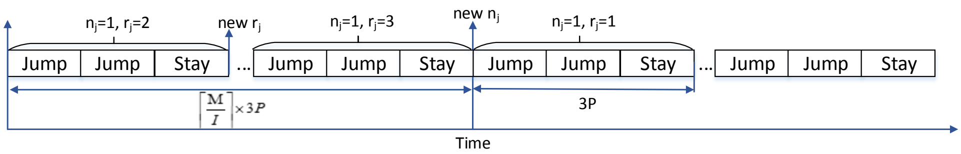


Figure 3.10: CH sequence for one common channel.

When the total number of channels is not a multiple of I, the number of channels for each interface may be different, which is the case of channel lists of different size. The proposed adaptive rendezvous algorithm, described previously, is applied to each interface. At the end of $2P$ jump cycle, the user chooses to stay on a channel with index r for P cycle.

When the jump-pattern ends, the user switches to the stay pattern immediately and stays on the channel with index r. Examples of the adaptive jump and stay are presented in Fig. 3.11. Multiple interfaces of a user are geographically at the same location; thus, it is clear that the interfaces will observe the same quality for each channel. After one cycle of observation for each channel, the observed channels may be re-sorted and re-distributed to each interface for a specific period. The provision of the channels among the interfaces of the same user must assure the use of all the channels. When an interface pauses to send

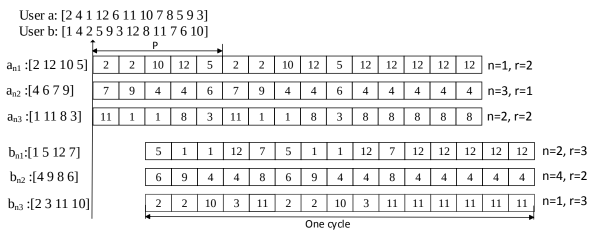


Figure 3.11: Example of the adaptive jump and stay pattern.

a rendezvous request after rendezvousing, the remainder of the jumped channels on the rendezvoused interface must be moved to other non-rendezvoused interfaces that continue to search for a neighbor user to rendezvous. To guarantee a rendezvous in the asymmetric scenario, the number of common channels between any two users should be at least one, i.e., $G \geq 1$. If there are no available channels common between them, the rendezvous cannot be achieved. Two users i and j can rendezvous if and only if $N_i \cap N_j \neq 0$.

For multiple interfaces, the proposed adaptive rendezvous algorithm continues to function; however, a rendezvous may not be realized within $3P$ duration, because the channel list for each interface is asymmetric. To design a framework that guarantees a rendezvous, we repeat the jump-and-stay pattern with random r_j; however, the same r_j never appears more than once within a given duration, $\lceil \frac{M}{I} \rceil \times 3P$. In this case, we know $M_j = \lceil \frac{M}{I} \rceil$ is the number of channels in that interface and I is the number of interfaces. If r_j changes every $3P$ slots and none of the interfaces have the same r_j, it is clear that the user will generate all the possible different channels within $\lceil \frac{M}{I} \rceil \times 3P$. Fig. 3.10 depicts the CH sequence that is generated.

For this framework, we can prove a guarantee of rendezvous provided $G \geq 1$. Let us assume user j initiates the rendezvous procedure immediately after user i. According to Lemma 3.1.2 when user i and j have different step lengths r they will rendezvous if the overlap is more than P between them. However, with $G = 1$, this is not possible. The only situation to rendezvous is when one of the users is in its own stay pattern. Assume, user i has three interfaces and each of them has four channels in their list. Without loss of generality, let us assume interfaces of the same users will not generate the same step length r_j. The step length will change every $3P$ time slots and will maintain a sequence, where it will have a different step length from the previous $3P$. Therefore, within $\lceil \frac{M}{I} \rceil \times 3P$, users will have all the possibilities of four different channels. In the stay pattern of every $3P$ there will be a different channel.

Theorem 3.2.1. *When the proposed adaptive jump-and-stay algorithm is used and all the r_j's appear once during $\lceil \frac{M}{I} \rceil \times 3P$ for any asymmetric channel list with $G \geq 1$, rendezvous is guaranteed and the maximum TTR is $\frac{3P \times M}{G \times I}$.*

Proof. Within $\lceil \frac{M}{I} \rceil \times 3P$, the common available channel will also appear in the stay pattern. That is, the common channel will stay for P time slots. According to Lemma 3.1.1, the users will visit all the channels within P. Recalling Fig. 3.7c and Fig. 3.7d, a rendezvous will be realized when the common channel is in the stay duration and the other user is in the jump duration. Considering Fig. 3.7b and Fig. 3.7f, if two users generate the same sequence of r, a rendezvous will occur either when both users are in jump duration or both are in stay duration. Because there are G common channels available to the users, the maximum TTR will be $\frac{3P \times M}{G \times I}$. $\square$

3.2.3 Multi-User Multi-interface Rendezvous

The two-user scenario is easily extended to a multi-user scenario. The purpose of the complete rendezvous is that all the users in the network that use any interface must be connected with at least a certain user in the network as shown in Fig. 3.8.

Corollary 3.2.2. *For asymmetric channel lists of multiple users, the maximum TTR is $\frac{3PML}{G \times I(L-D)}$, where $L = \frac{N(N-1)}{2}$ and D are the number of missing links ($L > D$).*

Proof. Suppose, N users in the network have maximum $L = \frac{N(N-1)}{2}$ links if they are in range of each other. In such a network we have $(L - D)$ links. In a multiple user scenario, we cannot predict a fixed common channel number, as it varies among users. Every pair of users will rendezvous at most $\frac{3PM}{G \times I}$, as stated earlier. Then, the total TTR for all the $(L - D)$links is $\frac{3PML}{G \times I(L-D)}$. $\square$

As previously stated, without a single common channel between any two channel lists, a rendezvous is never achieved. When $L = D$, the maximum TTR is infinity as there is no possible links in the network.

3.2.4 Further Issues

Channel Allocation

In our proposed rendezvous algorithm, users rendezvous on better channels. However, this may cause high interference to those channels; in other words, "rendezvous diversity" is sacrificed. The philosophy behind our work to rendezvous on the best channel is to force more users in vicinity to rendezvous on the same channel, thus improving reliability of networking. If the users are encouraged to rendezvous with channel diversity, the TTR will increase and the rendezvous probability will decrease because the number of interfaces at each user is limited. Hence, the rendezvous diversity is not helpful for quick rendezvous.

To resolve a possible interference problem from our algorithm, it is possible to adopt rendezvous first, and then re-allocate channels, although the channel re-allocation is not handled in this paper because it is beyond the scope. Once two users rendezvoused for the first time, they can exchange information between them, which will allow them to switch the channel later. This way, the rendezvous diversity can be considered without sacrificing the TTR performance.

Spectrum Sensing

To measure the channel quality, spectrum sensing should be performed for each slot or separately as in IEEE 802.22 [53]. For spectrum sensing, energy detection is the simplest method and can be implemented without separate sensing period. It is because users are ready to receive other users' probe request at each slot while measuring the channel quality on the channel as in IEEE 802.11. This is why channels can be sorted after one initial round, when available channels are basically known. In this paper we suppose such a simple technique but it remains further implementation issues to include spectrum sensing for high accuracy and to obtain an available channel list.

3.3 Performance Analysis

To justify our work, we conduct extensive simulation using a MATLAB Monte Carlo simulator. For performance evaluation, the proposed algorithm is compared to the JS algorithm for symmetric and asymmetric scenarios. Because the case of the different list size has not been considered in the literature, our proposed algorithm is compared to JS only for same list size. For our simulation environment, we consider an area of 2000m $\times$2000m, where users are randomly distributed (not for two users). We assume users have no mobility and they are able to rendezvous each other if and only if they are within 200m. A distance matrix is utilized to follow the rendezvous among users in different positions. The performance is measured in term of TTR that is counted as the number of time slots required to achieve a rendezvous.

To observe the performance of proposed EAR, three specifications are varied: size of the channel set (M), the number of users (N) and the number of common channels (G). For each set of parameter values, average TTR and maximum TTR are computed after 1000 independent runs. Given that the condition of a channel tends to be correlated between any two users in the vicinity, we generate a noise level for each channel such that the noise in a particular user's channel is determined by path loss and some deviation assuming that a distant user could transmits on the same channel. The deviation follows a lognormal distribution with 6dB variance like shadowing. Eventually, users detect the noise between -120dBm and -95dBm and the channels are similarly sorted. For each iteration, we assume that the order of channel list does not change.

We consider cases with a single interface and three interfaces where the cases with AR are represented by AR-S (single interface) and AR-M (multiple interfaces), respectively. These are compared with JS-S and JS-M. As the original JS was not designed for multiple interfaces, we devise JS-M simply by dividing the available channels among the three interfaces for a fair comparison. The available channels are almost evenly distributed among the interfaces as mentioned earlier. The starting time of a user is randomly selected from the initial $2P$ time.

3.3.1 Two-user rendezvous

Symmetric model

This is the scenario where users in the network have the same number of channels to visit, i.e., symmetric model. Fig. 3.12 compares JS and AR in the symmetric model and indicates that AR achieves a reduced TTR compared to JS in both cases, single interface and multiple interfaces. One reason is found from the fact that JS randomly selects an available channel to replace the unavailable channel on the generated channel sequence. It is seen that use of multiple interfaces significantly improves the maximum and average TTR. In Fig. 3.12, we also present the theoretical upper bound as given in Theorems 3.1.4 and 3.2.1. The TTR for both JS-M and AR-M is significantly less than JS-S and AR-S, respectively, owing to the advantage of using multiple interfaces.

Asymmetric model

In this scenario, users have different channel lists with different common channels between them, i.e., asymmetric model. To simulate this scenario, we assign a randomly selected channel list to each user and maintain a ratio of 50% common channels between them; i.e., if both users have a list of 12 channels, they have six common channels between them, $G = 6$. Users already have a channel list

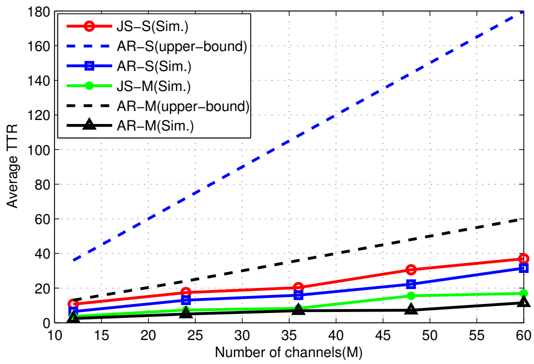


Figure 3.12: TTR of two-user rendezvous for a symmetric channel list.

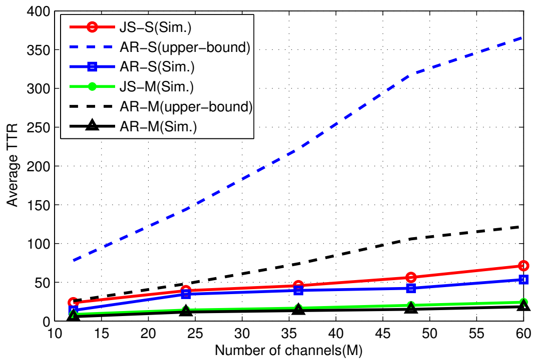


Figure 3.13: TTR of two-user rendezvous for a asymmetric channel list.

and rearrange the ranking after sensing the noise level for the channel list. In Fig. 3.13, AR outperforms JS in both cases, although the channel list is different for each user in AR whereas JS provides the same ranking list for all users.

Another finding is that increasing the number of interfaces can reduce the overall energy for rendezvous. For instance, when the number of interfaces increases from one to three, the average time spent for rendezvous reduces up to 60%. Following the practice of Wi-Fi Direct [66], we assume for rendezvous it is necessary to send a handshake packet of size 100 bytes (e.g., containing information such as user IDs) and the data rate of the wireless channel is 5Mbps, which yields the duration of each frame, $(100 \times 8)/(5 \times 10^6) = 0.16$ms. Active

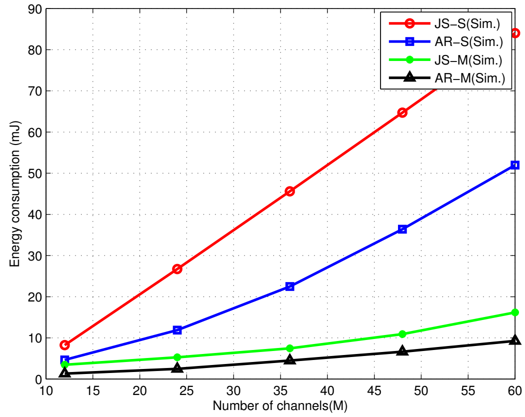


Figure 3.14: Consumed energy for two-user case.

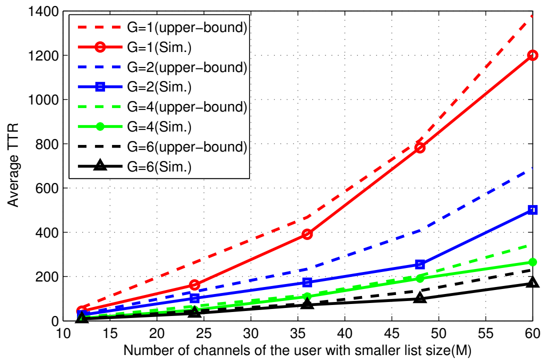


Figure 3.15: TTR of two-user rendezvous for an asymmetric channel list.

scanning that involves probe request and response [54] is adopted in our evolution. Then, the time necessary to rendezvous is calculated by $2 \times (0.16)$ms. Thus, the duration of each time slot is 0.32ms (i.e., the overlap of two time slots is no less than 0.16ms). Assume that the energy consumed for probe request and response, E_{probe} and E_{resp}, is 60mW and 4.5mW, respectively [55]. Then the energy consumption is calculated by $TTR \times I \times (E_{probe} + E_{resp})$. Fig. 3.14 shows the consumed energy when each user is equipped with a single interface and multiple interfaces (here, three interfaces). The proposed AR-M scheme

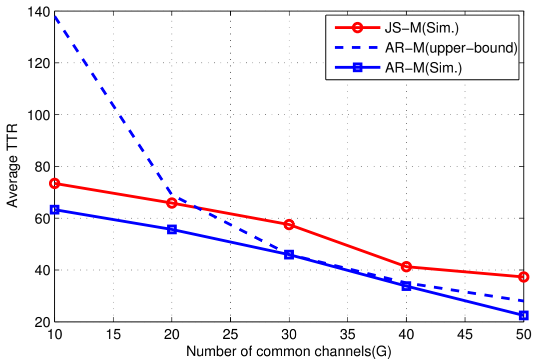


Figure 3.16: TTR vs. G for two-user case.

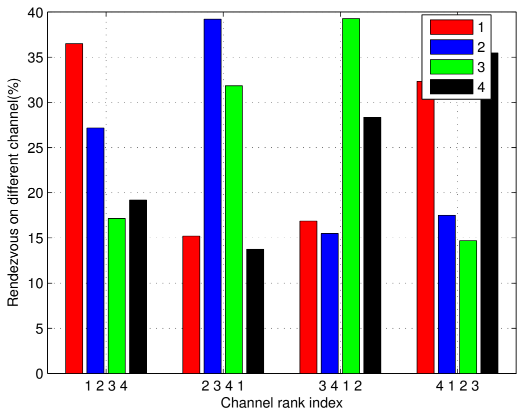


Figure 3.17: Rendezvous ratio on each channel for two-user case.

outperforms JS-M by 5mJ for any number of channels.

For different channel list sizes, it is difficult to compare the performance of the proposed algorithm with any other because none of the previous works in literature considered a channel list of different sizes among users. In this network model, the ratio of the number of channels for two users is maintained at $4:5$; i.e., for the highest difference, user a has a list of size 60 and user b has a list of size 75. Both users have the same P, although they have different list sizes. As shown in Fig. 3.15, with the increase of G, the average TTR decreases; thus, the TTR is least when $G = 6$, even with the increase of the channels. This indicates that increase in the number of common channels between two users improves TTR.

Further, we assign different channel sets to two users for $M = 60$ while varying G, the number of common channels between the two users. In Fig. 3.16 the TTRs of both JS and AR reduce simultaneously with the increase of G. Our result demonstrates that, with 50 common channels, the TTR is less than three times compared to ten common channels.

To demonstrate how AR makes users rendezvous on better channels, we obtained the ratio of rendezvouses on each channel for several channel rank indices: [1 2 3 4], [2 3 4 1], [3 4 1 2] and [4 1 2 3] as depicted in Fig. 3.17. In all the cases, rendezvouses occur more on higher-ranked channels in the list. For example, when the best channel is 1 in channel set [1 2 3 4], rendezvouses occur on channel 1 with 37%. In the case of [4 1 2 3], rendezvouses occur on the best channel 4 with 36%. Thus, AR is shown to provide preference to better channels for rendezvous.

3.3.2 Multi-user rendezvous

Symmetric model

To evaluate the performance of AR, this work is extended for the multi-user case and compared with multi-user JS.

we extended our work for the multi-user case and compared this with multi-user JS. For the symmetric model, we consider 65 users in the network; each of them has the same list of channels with different rankings. As shown in Fig. 3.18, the TTR of multiple interfaces for both JS and AR outperforms the single interface. With 60 channels, the TTR of both JS-M and AR-M became half of that of JS-S and AR-S. AR-M achieves a less average TTR compared to JS-M.

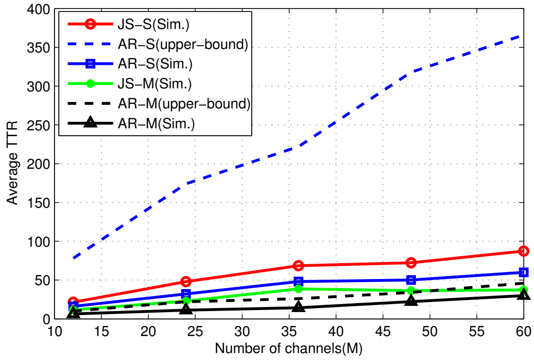


Figure 3.18: TTR of multi-user rendezvous for a symmetric channel list.

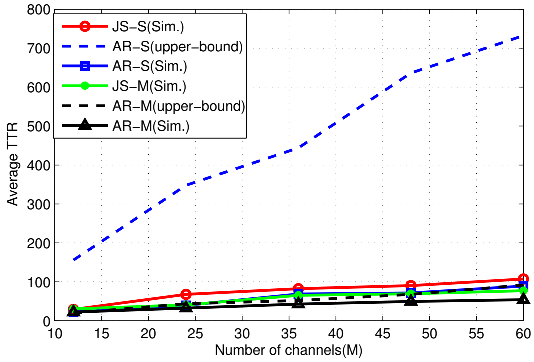


Figure 3.19: TTR of multi-user rendezvous for an asymmetric channel list.

Asymmetric model

Under the asymmetric model, each user selects a random channel set provided that G is restrained as a random number, and $G >> 1$. Therefore, the number of common channels, G, between the different pairs of users can be different. In Fig. 3.19, AR demonstrates a lower TTR compared to JS in both interface cases. As multiple interfaces escalates the probability of rendezvous occurrence, we experienced improved performance.

Furthermore, total consumed energy for rendezvous with multiple users in the network is calculated by using the same parameters of the symmetric model.

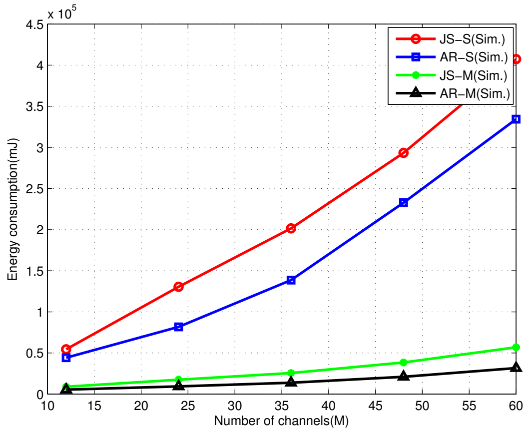


Figure 3.20: Consumed energy for multi-user case.

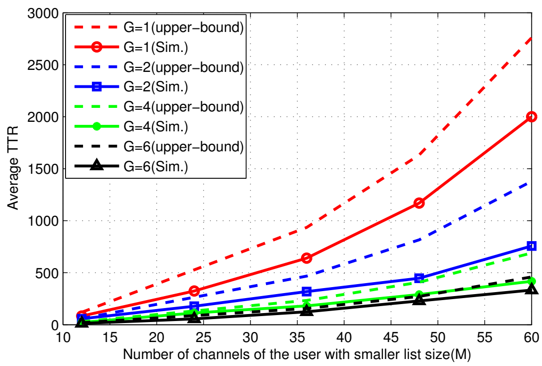


Figure 3.21: TTR vs. different list size for multi-user case.

We observe that, with three interfaces, the energy consumption is three times less than the a single interface as depicted in Fig. 3.20.

For the different list sizes, we assigned a random channel set to each user provided that G is maintained at the same number. The ratio of the number of channels for a pair of users is maintained at $4 : 5$. Fig. 3.21 depicts the performance of multi-user and multi-interface rendezvous for different common channels G. Similar to the performance of the two-user case as depicted in Fig. 3.15, the average TTR for multiple users decreases as G increases. Similarly, the TTR increases concurrently with the increase of channels with a fixed G. We can observe that TTR decreases approximately 85% with $G = 6$, compared to $G = 1$.

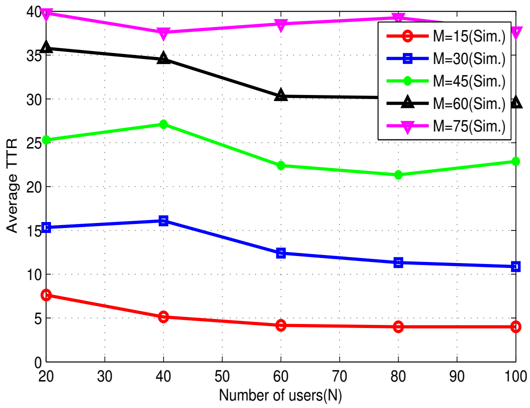


Figure 3.22: TTR of AR-M as a function of the number of users and M for an asymmetric channel list and multiple users.

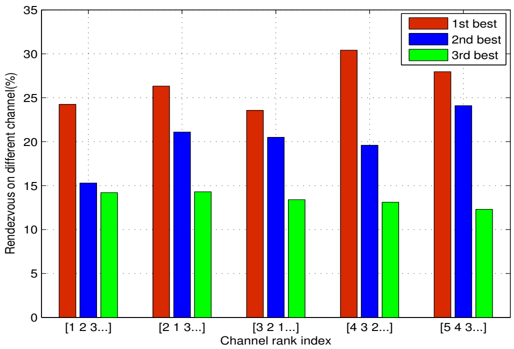


Figure 3.23: Rendezvous ratio on each channel for multi-user case.

Fig. 3.22 presents the TTR of AR-M for an asymmetric channel list as a function of the number of users and M. From these results, it is demonstrated that for a fixed number of channels the TTR does not vary significantly in terms of the number of users, which indicates the scalability with respect to the network size.

We also demonstrate the number of rendezvouses based of channel quality for multiple users. For this we consider the case of 8 users and 12 channels. Fig. 3.23 depicts the rendezvous ratio on each channel when the channel numbers are indexed in the descending order in terms of channel quality. Those results show that rendezvouses appear on the best channel with the highest probability. JS does not have a preference for the rendezvoused channel; however, AR requires users to rendezvous on channels with better conditions.

3.4 Summary

The goal of this research is to devise efficient means to achieve rendezvous for cognitive radio networks under a wide range of possible system, policy and environmental conditions. In this work, we have studied a dynamic channel hopping algorithm for blind rendezvous with the objective of TTR reduction. We have proposed to extend the JS algorithm to multi-interface scenarios that yield different channel lists. Moreover, this algorithm adopts adaptive jumping based on channel ranking to consider different channel qualities. We theoretically derive the maximum TTR and conduct extensive simulation to evaluate the performance. We observe the following properties:

- Multiple interfaces can significantly speed up a rendezvous. The performance is much significant for asymmetric channel list and when the number of users is big. When the number of common channels between two users is small, multiple interfaces play an important role to achieve much smaller TTRs.

- Multiple interfaces are also beneficial from the viewpoint of energy consumption. With multiple interfaces, TTR is remarkably low which debases the consumed energy.

- We can achieve a rendezvous on a that is in better condition. The proposed scheme achieves a rendezvous on the best channel most of the time.

As future work, there are further challenges from the perspectives of rendezvous diversity and secure rendezvous. Especially when the number of radio interfaces is large, it is possible to distribute the rendezvoused channels among users for interference reduction. Also, the proposed algorithm can be enhanced to protect normal users from malicious users. It is a challenging issue to handle these features without sacrificing the TTR.

Chapter 4

Rendezvous MAC(V-MAC)

In the previous chapter EAR was discussed and evaluated under different network conditions. The evaluation showed a significant performance gain compared to the existing CH sequence. But, proposed EAR is particularly a mathematical concept of channel hopping to guarantee rendezvous. However, in a wireless environment EAR can not perform well due to the unstable nature of channels. Previously, it was assumed that if two users are on the same channel at the same time slot rendezvous is successful. However, this is not true in reality because it is not guaranteed that the messages exchanged between two users are delivered reliably, due to noise, interference or collision which are inherent problems in wireless communications.

There are a few references in literature that design medium access control (MAC) protocols for rendezvous; e.g., in [10], it is suggested that for the purpose of rendezvous users exchange request-to-send (RTS) and clear-to-send (CTS) that are used to reserve a channel before sending data in the IEEE 802.11 protocol. However, RTS/CTS is efficient when the destination MAC address is known. For the purpose of rendezvous when peers are unknown yet, a better option is to employ probe messages that are designed for active scanning in IEEE 802.11 protocol. Thus it is essential to have MAC to incorporate with

HS algorithms. In this chapter, a new rendezvous MAC protocol, *V-MAC*, using probe request and probe response is developed. However, there is a possibility of unreliable delivery of such messages; i.e, a rendezvous is not achieved although two users visit the same channel simultaneously. Especially, when there are many users to rendezvous, collisions between probe messages or any other interference may occur. To deal with such cases, we adopt the collision resolution procedure of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) in the IEEE 802.11 MAC protocol that increases the back-off window size per failure. That is, if a probe request with an initial random back-off number fails, the probe request is sent again with an increased random back-off number. This procedure also holds for responding with probe responses.

Furthermore, such a MAC protocol enables us to design multiple rendezvous opportunities even in a slot while users visit a certain channel. If the slot size is short, they may transmit the probe message only once. However, considering the channel switching overhead between consecutive slots, several rendezvous opportunities are possible; i.e., probe requests and responses are sent multiple times within a slot until they are successful. This V-MAC incorporates with the proposed hopping sequence and holds the integrity of rendezvous.

The contributions of this chapter are summarized as follows.

1. We design a new rendezvous protocol, V-MAC, based on probe request and response that is integrated with any channel hopping sequence as well as V-HS. To resolve reliable transmission issues such as collision, we tailor part of the IEEE 802.11 MAC protocol appropriately with the rendezvous scheme.

2. We introduce multiple rendezvous opportunities in a slot against failure of a rendezvous. V-MAC handles rendezvous failure and its resolution in a slot while a user is visiting the same channel.

The chapter is organized as following order. In section 4.1, system model is presented for the new MAC protocol design. Different issues regarding rendezvous considering wireless environment are outlined in section 4.2. In section, 4.3, the V-MAC protocol is discussed thoroughly. The evaluation of proposed protocol is presented in section 4.4. Finally, the chapter is summarized in section 4.5.

4.1 System Model and Parameters

Lets consider a CRN where SUs are distributed randomly in a single collision domain. There are N orthogonal licensed channels, labeled as $1, 2, \ldots, N$ and indices are well known to all SUs. PUs communicate on those channel with higher priority as a part of the primary networks in a synchronous slotted manner. Each channel is defined by its central frequency and bandwidth. Without loss of generality we assume that every channel has a equal bandwidth and the central frequency has a equal spacing of the bandwidth from the next adjacent channel like most wireless systems such as IEEE 802.11 [49]. A single half duplex transceiver is considered for each SU, and this transceiver can work only on a channel at a time but each SU can visit all N channels. Both PU and SU activities are assumed to follow the ON-OFF Markov model; however, this assumption is just to understand how those factors affect rendezvous. Whenever a PU wants to transmit data, a channel is randomly chosen by the system and carry out data transmission in slot-by-slot manner. In this way, a channel can also be assigned to multiple PUs simultaneously. So, a channel can be unavailable at anytime. Therefore, the obtained channels may become invalid during rendezvous process due to time-varying channel availability.

In an asynchronous network setup, SUs have to achieve rendezvous without any time synchronization. Therefore, the overlapping duration between two slots of any two users have to be long enough to complete the message exchange for successful rendezvous. Lets assume that the clock offset for SUs are a random integer, multiple of mini-slots [56]. This Chapter proceeds by considering a simple and efficient reliable active scanning (RAS) scheme that performs loss detection of probe request and fast retransmit or hop on the next channel. However, successful transmission of the probe request is unpredictable due to some collision probability and the lack of acknowledgment. In this active scanning, an SU broadcasts a probe request and expects to receive a probe response from any neighbor SU.

4.1.1 Channel Access

Channel availability is flexible during the channel hopping and SUs have to detect whether the channel is free from incumbent or any other SUs. e integrate 802.11-based CSMA/CA MAC with a channel hopping scheme. According to the CSMA/CA method, a station having a packet to transmit must initially 'listen' to the channel if another station is transmitting. If no transmission takes place for some interval such as distributed interface space (DIFS), which is equal to the minimum duration of inactivity for considering the medium to be free, the transmission may proceed. If the medium is busy, the station has to wait until the end of the current transmission.

The unit time at which each SU visits each channel is defined as a slot and a slot consists of mini-slots. Our hopping sequence in section 3.1.2 works in the unit of slots and our MAC protocol in section 4.3 works in the unit of mini-slots within a slot. In other words, TTR of the hopping sequence is counted as the number of slots and TTR of the MAC protocol is further counted as the number of mini-slots. For example, probe request and response messages in our proposed MAC protocol are sent on a selected mini-slot within the visited slot. Our hopping sequence works for asynchronous slots, which means the starting time of a slot may be different for users.

4.2 Performance Issues in Rendezvous

Before having a connection, a SU must find another SU to achieve rendezvous. In wireless world, stations must identify a compatible network to join. The process of identifying existing networks in the area is called scanning. In literature, scanning can be of two types: active and passive. In active scanning the mobile node sends request frames to all 802.11 channels and waits for the responses from the probed. In passive scanning, the mobile node spends a fixed amount of time (usually 100ms) on every 802.11 channel, listening to the beacon. In this section we discuss about different performance issues in active scanning implementation from CRNs perspective.

In CRNs, SU transmits a probe request and waits for the probe response on each time slot. This time slot is the scanning time, in milliseconds, and ensures that an empty channel/collision does not completely block the scan. Upon successful transmission of both packets, rendezvous is guaranteed. However, in CRNs, probe response can be lost if probe request is lost in error prone wireless channel or there is a collision between probe request/response packets. In such scenario, rendezvous cannot be achieved though both SUs are on the same channel at the same time slot. Therefore, a general setting of probe request and response has to be investigated. In this section we discuss about different performance issues in current probe request/response implementation from CRNs perspective.

4.2.1 Handshake Collision

In active scanning SUs play an assertive role and on each time slot probe request frames are used to solicit responses from other SUs with a given name. Probe Request/Response/Ack is a three way handshake mechanism by which distributed co-ordinated function (DCF) 802.11 is adopted to discover neighbor

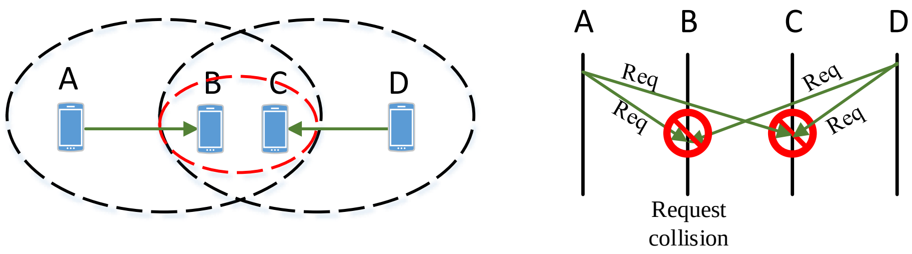


Figure 4.1: Probe request collision at the receiver end.

access points (APs). Unlike 802.11, any SU who receives probe request tries to send probe response. It is worth noting that other SUs can overhear this probe response packet. Probe request is broadcast message and can be received by any user in range. Problems arise when probe request and response packets are not correctly received or collide at the receiver or sender SU respectively. In 802.11, AP generates response packets, but still collision can occur. In reality number of users are much higher than AP, so collision is obvious in such network, known as (i) request collision, (ii) response collision and (iii) request/response collision.

In Fig. 4.1 probe request collision is illustrated, where two SUs A and D hop on the same channel and simultaneously transmits probe request during the one rendezvous slot. Lets assume that they are not in the sensing range of each other and the probe request collides as both nodes B and D are in the transmission range of A and C. Again this collision can occur if they are in sensing range as well due to time asynchronous behavior. In this scenario rendezvous can not be achieved though both SUs are in the same channel at the same time.

The probe request and response collision are depicted in Fig. 4.2, where the probe response from user C collides with the probe request from user A. Even sense before probe request/response can not prevent this collision as both SUs (A and D) are each others transmission range. Hence, rendezvous between A-B and C-D can not be achieved even though they appear in the same channel at

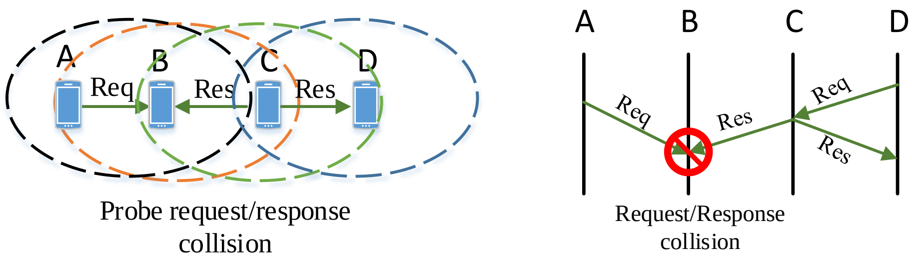


Figure 4.2: Probe request/response collision scenario.

the same time.

Similar to probe request collision, probe responses can collide at the receiver end. As users are trying to rendezvous with neighbor users, probe request packets are usually broad-casted. Hence all the neighbors can listen to it. All successful receiver will respond with probe response packets.

4.2.2 False Blocking

A SU can not rendezvous on a hopped channel if it senses the presence of a PU on that channel. Let us consider a scenario where a SU D wants to rendezvous on channel with user C. Assume C is in transmission range of a PU B, and B transmits RTS packet to the access point (AP). As a neighbor node C can overhear that RTS and updates its network allocation vector (NAV) for a certain time in which the channel will be busy. This mechanism is known as virtual carrier sensing (VCS) and it efficiently reserves a channel for the ongoing transmission. However, there is a possibility that CTS packet is not transmitted or not successfully received by the PU B due to unsuccessful RTS packet, a channel error or different packet collisions. In all cases C and D can not rendezvous and the channel remains blocked. This scenario is illustrated in Fig. 4.3.

It is evident that in a wireless scenario, a mathematical model of rendezvous

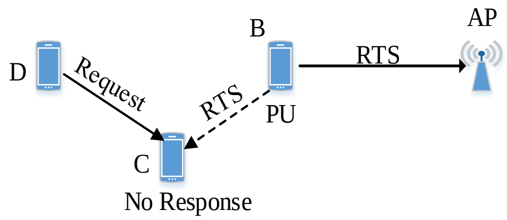


Figure 4.3: RTS false blocking.

channel hopping sequence can not guarantee successful rendezvous. For example, a SU can not confirm either his probe request collided or there is no other SU on that channel for the time being. It is obvious that, if both the users are on different channels they will not achieve rendezvous. However, handshake collision and false blocking can cause rendezvous failure even though both users are on that same channel at the same time.

4.3 Design of the Rendezvous MAC Protocol

Although V-HS is proved to show better TTR, a rendezvous in reality will be achieved by some message exchange between two users. We now describe our proposed rendezvous MAC protocol, V-MAC, that can be integrated with V-HS as well as any other channel hopping scheme.

4.3.1 Description of the Protocol

Rendezvous Attempt using Probe Request and Response

Two SUs achieve a rendezvous with each other by exchanging some messages. As stated earlier, we propose to use probe request and probe response packets for such a purpose which is similarly used for scanning in the IEEE 802.11 systems. We define a rendezvous attempt (RA) as the duration to exchange a

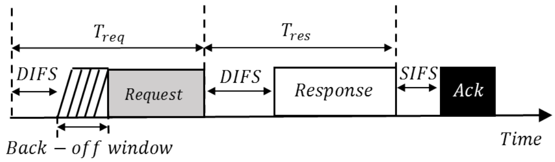


Figure 4.4: Basic structure of exchanging a probe request and response.

probe request and response. Fig. 4.4 depicts the basic structure of a RA where a pair of probe request and response is exchanged.

However, those probe messages are exposed to collision or interference from PUs or other SUs. Especially, when there are too many SUs trying to send probe messages for rendezvousing, collisions are inevitable. Collisions during rendezvous can be classified into types: (i) between probe requests (from SUs) and data packets (from PUs) and (ii) collisions between probe requests and responses. CSMA/CA can resolve the first type of collision by checking busy medium condition. However, the collision between probe requests and responses are unavoidable in a protective way due to the property of blind rendezvous. We design a protocol that considers such collision possibility and retransmissions.

Collision Resolution using CSMA/CA

To resolve the collision possibility, V-MAC is integrated with the CSMA/CA mechanism of the IEEE 802.11 protocol that supports random access and collision resolution with a back-off window. When an SU hops to a channel and if the channel is sensed idle for DIFS, the SU will select a value randomly between $[0, CW_{min}-1]$ to set its back-off counter. During back-off counting down process, the back-off counter is decremented by one and when it is 0, the SU broadcasts a probe request. Upon receiving a probe request, the receiver SU follows the same process to reply with a probe response. Finally, the transmitter SU sends an ACK for the sake of confirmation after receiving a probe response because

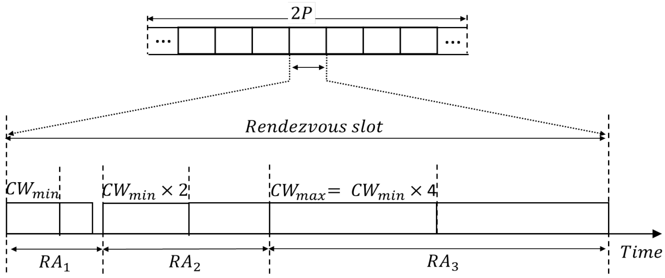


Figure 4.5: Multiple rendezvous opportunities in a slot in the case of three RAs.

there is a collision possibility of probe responses from multiple SUs or any PU. Here, T_{req} and T_{res} represent the consumed time to send a probe request and to receive a probe response, respectively. Notice that setting a right CW_{min} is not trivial; because if CW_{min} is too big, channel access delay will increase [57], and if CW_{min} is too small, the collision probability will increase.[1]

Multiple Rendezvous Opportunities in a Slot

Once a probe request or response fails due to collision or any other reason, the SUs may retry a rendezvous attempt as long as the remaining mini-slots in the slot are sufficient for the second RA. In most existing rendezvous work, multiple rendezvous opportunities are not considered in a slot. Because of multiple RAs, chances for rendezvous failure due to collision reduces and also rendezvous opportunity increases. Fig. 4.5 shows an example of three RAs. Let RA_{max} be the maximum number of retransmissions in a slot.[2] Let $T_{req,i}$ and $T_{res,i}$ represent the time to send a probe request and response at i-th RA, RA_i, then they are expressed by [58]

$T_{req,i} = DIFS + rand(0, CW_i - 1),$

[1]For equivalence with the IEEE 802.11 systems where $CW_{min} = 15$, CW_{min} in our system model can be smaller, since the randomness increases over several channels as well as over the contention window. In simulation we will study the effect of CW_{min} on the performance.

[2]In IEEE 802.11, the maximum retransmissions is 7 by default and it is 4 for RTS/CTS [58]. Fig. 4.5 presents an example of three retransmissions; i.e., $RA_{max} = 3$. This number is also a design parameter that fits within the length of a slot.

$T_{res,i} = DIFS + slotTime \times CW_i$,

where CW_i is the contention window size at RA_i and simply $CW_i = 2^{i-1} \times CW_{min}$ and $CW_1 = CW_{min}$ following the practice of the IEEE 802.11. These parameters are reset whenever a new slot starts, because SUs switch to another channel per slot and thus the channel status changes every slot.

When an SU does not receive any response during $T_{res,i}$, CW_i is doubled and the probe request is retransmitted. Simultaneously, the time $T_{res,i}$ for receiving probe response is also doubled. Both $T_{req,i}$ and $T_{res,i}$ are generated with a doubled contention window, because it is impossible to determine whether the probe request failed or the probe response failed. This procedure is depicted in Fig. 4.5. If an SU cannot succeed in any rendezvous by transmitting the probe request RA_{max} times, rendezvous fails in that slot; therefore, rendezvous may not be achieved in the MAC layer, although rendezvous is declared from the jumping sequence.

Fig. 4.6 depicts the collision of probe requests between SU A and SU B. According to legacy channel hopping schemes, in such a condition, SUs fail to rendezvous and hop to the next channel, which is a waste of rendezvous opportunity. In contrast, in our scheme, SUs attempt for the second time (i.e., in the next RA) with an increased back-off window as long as the remaining mini-slots in the slot are sufficient for the second RA. In Fig. 4.6 it is observed that probe responses from SU A and C also collide. Accordingly, users attempt for the third time with an increased back-off window. Finally, SU B rendezvouses with SU A and C.

Adjusted VCS

Network allocation vector (NAV) is used in CSMA/CA to differ the data transmission of other users. SUs in a CRN can overhear this RTS packet and defers the transmission as it presumes that a PU is active on that channel. However,

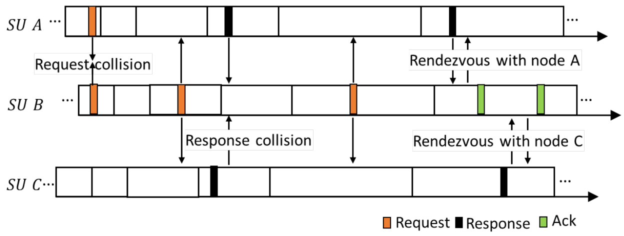


Figure 4.6: An example of collision resolution of probe messages.

similar to PUs, SUs in CRNs can suffer from false blocking due to RTS NAV. The problem of false blocking is explained in 4.2.2. To solve the problem of false blocking VCS is adjusted which is called adjusted virtual carrier sensing (AVCS). The revised process is illustrated in Fig. 4.7.

If a PU sends RTS and a SU, C is in range of the PU it will immediately update its NAV as recommended in legacy VCS. Even though it receives a probe request successfully, C will not respond to it. If AP does not reply to the RTS due to packet RTS loss/collision, the SU C will still hold the transmission. In the AVCS mechanism upon RTS overhear the NAV value will $T_{AVCS} = 2SIFS+CTS$. After T_{AVCS} period C will perform sensing to update the channel status. If C does not overhear any data packet it will try to rendezvous on the channel with the minimum contention window. On the other hand, C update the NAV when overhears the data packet. When this NAV value is greater than the slot duration, i.e., the transmission time of PU is greater than the rendezvous slot size, C will immediately hop to the next channel to attempt rendezvous.

Probe Response Overhear

Multiple probe requests will create the opportunity of rendezvous but with every request neighbor users will response which will also create the rendezvous opportunity vulnerable due to response collisions. So a SU can take the advantage of probe response overhear and skip the next probe request attempt without

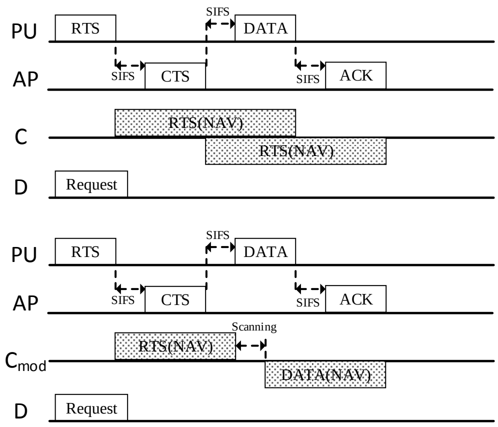


Figure 4.7: Example of adjusted virtual carrier sensing.

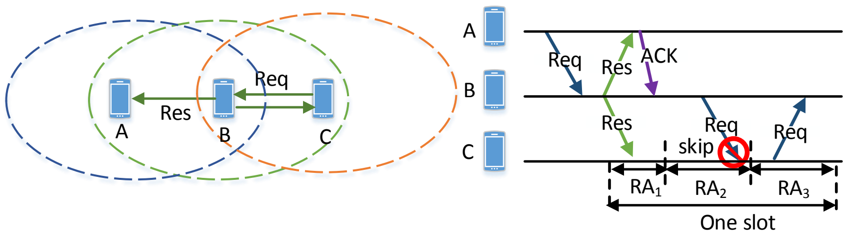


Figure 4.8: Advantage of probe response overhear.

degrading the rendezvous performance. Fig. 4.8 explain detail of the procedure to assure rendezvous chance does not reduce though probe request is skipped.

It is considered that SU A sends a probe request and successfully received by SU B. When B sends a response packet to A to accomplish rendezvous neighbor C can overhear the probe response and confirms that there is someone on that channel. In this request/response model if a response is successfully overhear by other neighbors they skip the next RA. In this case when C receives a probe response but not against C's probe request, C skips next probe request attempt RA_2. But B considers itself responsible as successfully rendezvoused pair and with the minimum CW_{min} will create probe request for other users who skipped their probe request. In Fig. 4.8 user B sends probe request after rendezvous but C fails to receive it due to collision or channel error. B will send a probe request for the next RA, in this is case RA_3. The SU A and B will successfully rendezvous and can mutually decide to rendezvous more users on the same channel. They can also cooperatively manage their contention window to generate probe request in different times.

Another simple but effective property of this scheme is, CW management based on success/failure rendezvous. This CW doubles after each unsuccessful probe request on that rendezvoused channel. Similarly, this CW will decrease to half when a successful rendezvous is achieved.

4.3.2 Expected TTR in MAC Layer

From the designed rendezvous MAC protocol, we can obtain the expected TTR in unit of mini-slots from the perspective of MAC layer. For simplicity of our analysis, we consider collisions of probe messages only. A channel becomes unavailable if it is occupied during or before a rendezvous. The IEEE 802.11 systems are considered slotted (equivalently mini-slotted in our system) and the counting-down process of all the SUs are homogeneous [59]. Therefore, the transmission probability τ of an SU can be obtained using the following Bianchi model [59]:

$$\tau = \frac{2(1-P_c)}{(1-2P_c)(W+1)+WP_c(1-(2P_c)^m)}, \tag{4.1}$$

where P_c means the probability of collision and depends on the number of users attempting to transmit on the same channel. Here, P_c can be written as $P_c = 1-(1-\tau)^M$, where M is the number of other users. So, the probability of successful probe request can be calculated as $P^{\circ}_{req} = 1 - P_c$. Similarly the probability of successful probe response can be calculated as $P^{\circ}_{res} = 1 - P_c$ for M other nodes who are trying to respond upon successful receive of the probe request.

Let $P_{req}(k)$ and $P_{res}(k)$ denote the probability of successful probe request and response, respectively, at k-th RA in a slot. Then, $P_{req}(k)$ is given under the condition that either a failure of previous probe request or a failure of previous probe response at every RA for $1, \cdots, k-1$. Also, $P_{res}(k)$ is given under the condition that the probe request at k-th RA is successful. Therefore, for $k \geq 2$, they are expressed as

$$P_{req}(k){=}P^{\circ}_{req}\prod_{m=1}^{k-1}\big(1{-}P_{req}(m){+}P_{req}(m)(1{-}P_{res}(m))\big), \tag{4.2}$$

$$P_{res}(k) = P^{\circ}_{res} \times P_{req}(k). \tag{4.3}$$

Note that $P_{req}(1) = P^{\circ}_{req}$ and $P_{res}(1) = P^{\circ}_{res}$.

The expected TTR under a condition that rendezvous occurs at j-th slot with probability $P_{R,j}$ is calculated as follows:

$$\begin{aligned}\mathbf{E}[TTR_{MAC} \mid P_{R,j}] = &\sum_{l=1}^{j-1} T_{slot} + \sum_{k=1}^{RA_{max}} P_{req}(k)P_{res}(k) \\ &\cdot\Big\{ \sum_{m=1}^{k} T_{req,m} + \sum_{n=1}^{k} T_{res,n} + SIFS + ACK \Big\},\end{aligned} \tag{4.4}$$

where T_{slot} is the length of a slot and $\sum_{l=1}^{j-1} T_{slot} \equiv 0$ for $j = 1$.

By using eq. (4.2), the probability that rendezvous fails at j-th slot, $P_{F,j}$, is calculated as

$$P_{F,j} = 1 - P_{R,j} = 1 - P_{req}(\psi) + P_{req}(\psi)(1 - P_{res}(\psi)), \tag{4.5}$$

where $\psi = RA_{max}$.

Finally, we obtain $\mathbf{E}[TTR_{MAC}]$ as follows:

$$\mathbf{E}[TTR_{MAC}] = \sum_{j=1}^{\infty} \mathbf{E}[TTR_{MAC} \mid P_{R,j}] \times P_{R,j}, \tag{4.6}$$

which can also be expressed in terms of eqs. (4.4) and (4.5).

4.4 Performance Evolution

We have conduct an extensive simulation to evaluate our work using MATLAB. The topology of a single-hop CRN is designed by randomly distributing PUs and SUs in an area of 100m × 100m. The transmission range of an SU is set to 250m, smaller compared to that of a PU. Each PU randomly chooses a channel if he has any packet to deliver. PU activity follows a Poisson distribution and the receiver is also randomly chosen. The probability of channel availability is set to 50% by adjusting the ON-OFF channel availability model throughout our simulation. Each result is averaged by 100 runs of simulation with identical parameters. Mobility is not considered for this work. The performance is measured in terms of TTR in unit of slots for the hopping sequence and in unit of milliseconds for the MAC protocol.

Table 4.1: Prtocol parameters of MAC and PHY layer

Number of PUs	40
Number of SUS	60
Simulation area	100 m × 100 m
Data rate	1 Mbps
DIFS	50 μs
SIFS	10 μs
Probe request	40 bytes
Probe response	63 bytes
ACK	14 bytes
slottime	20 μs

Due to the performance achievement of JS over other rendezvous frameworks in literature, we choose JS [27] and EAR [60] for comparison with our work, each

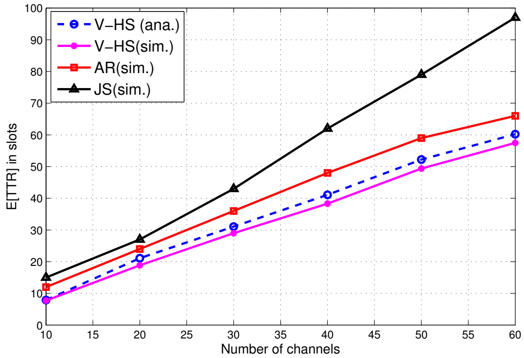


Figure 4.9: Comparison of **E**[TTR] for symmetric model.

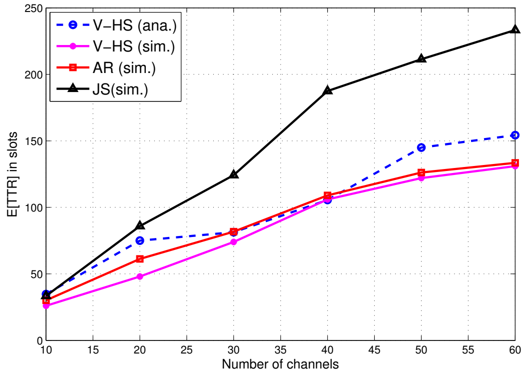


Figure 4.10: Comparison of **E**[TTR] for asymmetric model.

for symmetric and asymmetric models. We also compare with V-HS[3], which is a hopping based rendezvous scheme. V-HS takes the advantage of odd and even time slot to achieve rendezvous. Though JS and EAR handle a hopping pattern without MAC, we imposes our MAC on them by setting general parameters to evaluate the performance. The parameters used for our simulation are listed in Table 4.1.

Fig. 4.9 and Fig. 4.10 illustrate the TTR of our scheme without MAC, where V-HS is compared with JS and EAR for symmetric and asymmetric models, respectively, as a function of the number of channels. In Fig. 4.10, G is considered

[3]Details of V-HS can be found in Appendix A

to be 60%, i.e., users have 60% of channels common between them. These results indicate that V-HS achieves reduced TTR compared to JS and EAR for both symmetric and asymmetric models. In case of JS and EAR, a user stays for a long time in the stay period which is P in every $3P$, which increases the expected TTR, whereas V-HS takes advantage of odd and even slot structure, thus reducing the overall TTR as proved in our theoretical analysis. The simulation results also justify the theoretical $\mathbf{E}$[TTR]. In both figures $\mathbf{E}$[TTR] increases with the number of channels, because users have to hop on more channels.

Table 4.2: Cases for simulation in Fig. 4.13.

	CW_{min}	CW_{max}	RA
case:1	2	16	4
case:2	4	32	4
case:3	8	32	3
case:4	10	20	2

In the next comparison V-MAC is integrated with V-HS, JS and enhanced adaptive rendezvous (AR) for both symmetric and asymmetric models. To see the effect of multiple rendezvous opportunities in V-MAC separately, we assume no retransmission in each slot; i.e., if a collision occurs on probe request or response, the user will hop for the next channel without retransmitting it. Also, the CW is fixed. Fig. 4.11 shows significant performance improvement from the integration of V-MAC and V-HS, especially when the number of channels is high. The increment in the number of channels causes SU more distributed among channels. In both symmetric and asymmetric models, the TTR of $CW = 8$ is better than that of $CW = 4$. With a higher CW the probability of collision will reduce; i.e., rendezvouses fail less. In Fig. 4.12 proposed MAC is compared with a random MAC model which has a higher CW size. However, upon collision no retransmission will occur. Though the CW size is double compare to V-MAC, proposed MAC shows better $\mathbf{E}$[TTR]. The reason is, in a random MAC collision

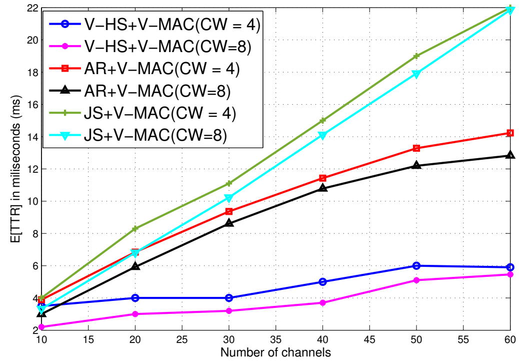


Figure 4.11: **E**[TTR] of V-MAC compared to V-HS, AR and JS for symmetric model.

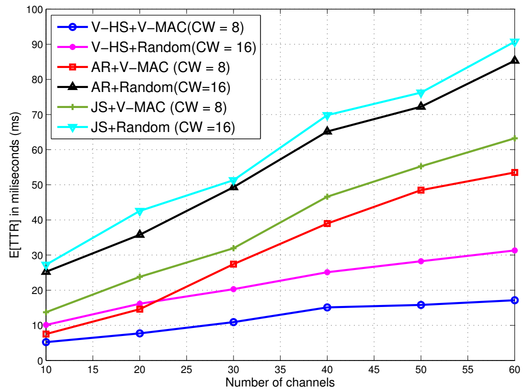


Figure 4.12: **E**[TTR] of V-MAC compared to V-HS, AR and JS for asymmetric model.

has no solution rather than hop again to find users on another channel whereas V-MAC takes multiple attempts on that same channel to reduce the effect of collisions. Both figures verify that collision has a strong impact on the TTR performance.

In Fig. 4.13 the TTR of V-MAC is obtained for various combinations of CW_{min}, CW_{max} and RA_{max} that are shown in Table 4.2, where the number of channels is fixed to 20 ($N = 20$). Here, V-MAC adopts multiple rendezvous opportunities in a slot and adaptive window size. Another simple case with $RA = 1$

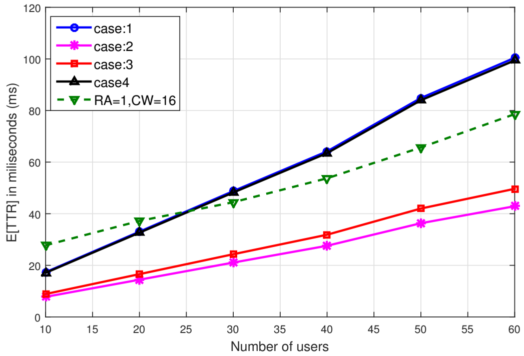


Figure 4.13: $\mathbf{E}$[TTR] with AR for various CW parameters.

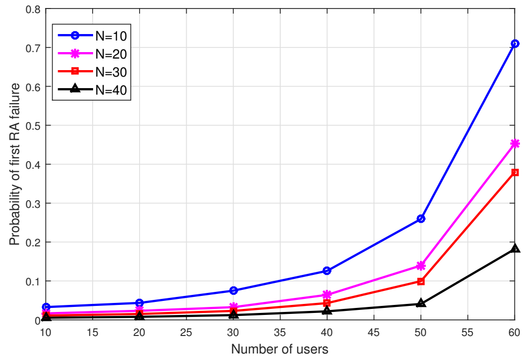


Figure 4.14: Probability of failure in first RA when $CW = 8$.

and $CW = 16$ (here CW is always fixed) is also compared to understand the effect of RA and CW. We can see that the TTR of cases 1 and 4 is much better compared to the simple case. When the number of users is small, the performance does not degrade much for low CW_{min}. When the number of users increases, especially exceeding 25, the TTR increases and it is even worse than the simple case, because most users set small initial CW, thereby always ending with a collision. Though case 4 has a higher CW_{max}, it has only two RA opportunities during a slot. For these reasons, case 2 and case 3 show better performance and outperform the simple case in any case. From this we can claim that V-MAC works well for well chosen parameters as in case 2 and case 3.

4.5 Summary

In this chapter, we propose a novel V-MAV for CH sequences, that addresses practical communication issues and guarantees rendezvous for asynchronous and asymmetric channel models. We address different collision issues during rendezvous considering a real wireless scenario. Our fundamental idea is that during rendezvous in one time slot we can initiate multiple probe request attempt to guarantee successful rendezvous. In addition, another rendezvous CH scheme namely V-HS is also compared and studied. Also, the rendezvous opportunity increases owing to our design of multiple rendezvous attempts in a slot. Simulation results confirm that our proposed scheme enhances TTR performance from the perspective of channel hopping sequence as well as the MAC protocol. $\mathbf{E}[\mathrm{TTR}]$ is 60% less when the channel number is maximum in an asymmetric model. Which indicates the performance improvement of CH sequence due to collision resolution.

Chapter 5

Radio Interface Selection

The focus of this chapter is to investigate *radio interface selection*, where end users can choose their radio interface among different available radio interfaces to establish a communication link effectively. Upon rendezvous two users in a pair can select a suitable radio interface autonomously to enable a communication path.

The selection of the radio interface among different rendezvoused pairs is modeled as a non-cooperative game where a pair of users selfishly select a radio interface to minimize their communication cost. Study of the existence of Nash equilibrium in the game is realized and concludes that, in spite of the non-cooperative behavior of such devices it is possible to achieve a balanced strategy. D2D communication is the most applicable network model for such rendezvoused based radio interface selection game. Hence, a game model for the perspective of D2D communication is designed.

Previously wireless communication was possessed by a single operator/technology, but nowadays availability of multiple access networks allows smart-phone users to favor among available opportunities. Those end users are often equipped with multiple radio interfaces (i.e., 3G/LTE, Bluetooth, and Wi-Fi), which complements their cellular communication capabilities. A recent market research report estimates that about 70% across all mobile phones are equipped with Bluetooth, while 80% of smart-phones are enabled with Wi-Fi[61]. The proliferation of smart-phones and bandwidth intensive wireless applications imposes stringent performance constraints on the next-generation of wireless networks [62]. In this respect, device-to-device (D2D) communications [63] are seen as one of the promising approaches for boosting the capacity of wireless systems and meeting the surge in demand [64].

Leading telecommunication companies are performing experimental studies using early stage prototypes, being motivated with higher performance gain of D2D. Even 3GPP, one of the standardization bodies has considered D2D communications (so called LTE direct) as public safety feature in the next release of LTE-A [65][66]. Several academic publications, industries, and standardization bodies justify D2D communications as an important feature of next generation networks. Nevertheless, there are still a lot of challenges to be addressed in different fields.

On the network side, signaling architecture is required to support resource allocation; on the user's side, effective techniques are required to discover and classify connectivity opportunity based on quality parameters (throughput, delay, interference level, etc.) to achieve the best connectivity. From the perspective of D2D, access opportunities are more abundant as found in LTE Direct [65][66], Wi-Fi Direct [67], and Bluetooth [68].

The main focus is thus how to ensure the best D2D connectivity among multiple opportunities, since multiple radio interfaces are available in a device to enabled D2D communications. We define this problem as *radio interface selection* (hereafter, simply expressed as interface selection). However, none of those D2D radio technologies can guarantee minimum interference, cost effective throughput, and QoS. These multiple radio interfaces consume different amounts of energy during communication and therefore spawn distinct interference to

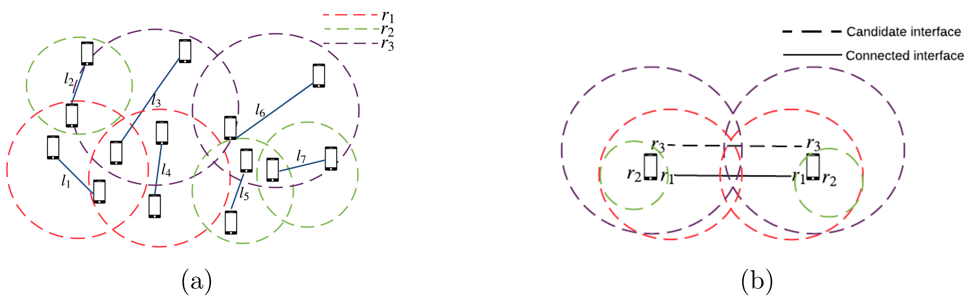


Figure 5.1: (a) A network with multi-interfaced D2D links; (b) Interface selection.

neighbor users. As a consequence, interface selection is also an issue that needs to be resolved.

5.1 System Model and Game Formulation

5.1.1 Network Model

To model, lets consider many D2D links that are randomly distributed in a geographical area. Each link l_j is modeled as an undirected link between two rendezvoused nodes. Available links are presented as a set $\mathbb{L} = \{l_1, l_2, \ldots, l_j, \ldots\}$. Since links are undirected, two D2D pairs can select the same channels for communication from the available M_r channels. Each node has multiple radio interface/transceivers to use and they are denoted as $\mathbb{R} \in \{1, 2, 3, \ldots, r, \ldots\}$. We assume that wireless transceivers have different transmission power and interfering users are within transmission range of each other. Assume that, two rendezvoused nodes select one of their radio interfaces on the same channel to communicate. Another necessary condition to maximize the throughput is there can be at most one radio interface activate on each channel [69][70]. Fig. 5.1a depicts the general network model where the range of an interface r differs based on the selected interface. Fig. 5.1b shows an example of interface selection where r_1 is selected although the other two interfaces r_2 and r_3 are also available to establish a link between the two nodes.

5.1.2 Interference Model

In D2D networks, D2D pairs can have same channel for communication in the same vicinity. Due to the decentralize model of the networks, D2D pairs will rendezvous on any channel, thus the transmission on a D2D link will interfere with the other D2D links and visa versa. In literature, there are several works for the channel allocation problem for non-cooperative networks [69][70]. But the common assumption is that any transmission will interfere with others if they are on the same channel within interference range. However, the transmit power at a receiver from source reduces exponentially with proportion to increased distance. Therefore, if two D2D pairs are on that same channel but they are distant, the transmission of one pair will not interfere the other from succeeding. Several model have been proposed considering multiple collision domain for networks, for example, the primary interference model [71], the protocol interference model [72] and the physical interference model [72].

In this chapter, D2D networks with multiple collision domain is modeled based on protocol interference model. This is the most common model used for channel allocation problems [73][74] in literature. According to protocol interference model, transmission range and interference range are equally large. Any node $i \in l_j$ will interfere with node $i' \in l'_j$ if i is within i''s interference range. Every l_j forms an interference range that combines the interference range of both users in that link. l_j will interfere with pair l'_j if and only if i and i' in those pairs have one communication channel common between them.

5.1.3 Game Theory Concept in a Nutshell

Game theory is a discipline aimed at modeling scenarios where individual decision makers have to choose specific actions that have mutual or possible conflicting consequences. In order to study the strategic interaction of the node pairs, this work relies on the concept of Nash equilibrium. To analyze the interface selection game lets revisit some basic concepts of game theory. For completeness, some general definitions are included below [75],

A game consists of a set $\mathcal{P} = P_1, P_2, \ldots, P_n$ of players. Each player $P_i \in \mathcal{P}$[1] has a non-empty strategy set $\mathbb{S}$. Let s_i denote the strategy selected by P_i. A strategy profile s consists of all player's strategies, i.e., $s = (s_1, s_2, \ldots, s_n)$. Let s_{-i} denote the strategy profile excluding s_i. As a notational convention, we then have (s_i, s_{-i}). The utility (or payoff) function $u_i(s)$ of P_i measures P_i's valuation on strategy profile s.

Definition 1. *(Nash Equilibrium (NE)) Let* $(\mathbb{S}, \mathbb{U})$ *be a game with player set* $\mathcal{P}$*, where* s_i *is the strategy for player* i*,* $\mathbb{S} = (s_1, s_2, \ldots, s_{|\mathcal{P}|})$ *is the set of strategy profiles and* $\mathbb{U} = (u_1(s), u_2(s), \ldots, u_{|\mathcal{P}|}(s))$ *is the utility function for* $s \in \mathbb{S}$*. The strategy profile* $s^* = \{s_1^*, s_2^*, \ldots, s_{|\mathcal{P}|}^*\}$ *is a Nash equilibrium (NE) if for every player* $i \in \mathcal{P}$*, we have*

$$u_i(s_i^*, s_{-i}^*) \geq (u_i(s_i, s_{-i}^*) \tag{5.1}$$

for all strategies.

In any game NEs are known as the stable states*, because none of the players have incentive to leave the strategy. Normally, when a system converges to a NE, it permanently stays there. Similarly, NEs should guarantee good properties such as energy efficiency.*

Definition 2. *(Pareto Optimality) Let* $(\mathbb{S}, \mathbb{U})$ *be a game with the player set* $\mathcal{P}$*, where* s_i *is the strategy set for player* i*,* $\mathbb{S} = (s_1, s_2, \ldots, s_{|\mathcal{P}|})$ *is the set of strategy profiles and* $\mathbb{U} = (u_1(s), u_2(s), \ldots, u_{|\mathcal{P}|}(s))$ *is the utility function for* $s \in \mathbb{S}$*. A strategy profile* s^{po} *is Pareto-optimal if for every strategy profile* s *such that there exists player* $i \in \mathcal{P}$*,*

$u_i(s^{po}) < u_i(s)$*,*

there must exist another player $j' \in \mathcal{P}$*,*

$u_j(s^{po}) < u_{j'}(s)$*.*

Intuitively, no player can get more payoff without hurting another player if it is in a Pareto-optimal state. In a system there can be Pareto-optimal states which are not NE and visa versa. According to the definition, the best case is to guarantee that all NEs are Pareto-optimal.

[1] In this work, a player indiates a pair of nodes (D2D pair).

5.1.4 Proposed Game Theoretic Model

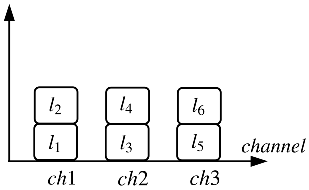
We formulate the interface selection problem in a non-cooperative game simply with two interfaces and multiple channels. In this game each pair of nodes (or each link) are considered as a player and their action is the selection of a certain radio interface between the available ones. Hereafter, the terms, link and pair are used interchangeably. A pair is determined by the user's position and available channel between them.

For data communication one node can select any radio interface considering the distance between nodes, energy consumption, and required data rate. In this model each interface has a compatible target area of coverage. We have depicted the scenario in Fig. 3.8 where many D2D pairs are connected via different interfaces. The interface selection on a channel is defined to be a vector $s_i = \{z_1^1, z_2^1, \ldots, z_M^1, z_1^2, z_2^2, \ldots, z_M^2, \ldots, z_M^r, \ldots\}$, where $z_m^r = 1$ if user i is active on channel $m \in M$ using radio interface $r \in \{1, 2, \ldots, n\}$. The strategy profile s is then an $M\times \mid \mathbb{N} \mid$ matrix defined by all players' strategies, $s = \{s_1, s_2, \ldots, s_{|\mathbb{N}|}\}$. Formally, presented as

$$z_m^r = \begin{cases} 1 & \text{if interface } r \text{ is used on channel } m, \\ 0 & \text{if interface } r \text{ is unused on channel } m. \end{cases}$$

Each D2D pair pays cost C_{l_j} that depends on the interference level perceived by the receiver on link l_j. Cost increases with the increase of the number of users on channel l_j. The effect of D2D pairs are irrespective of their selected interface for communication, i.e., different links on the same channel will interfere with each other. The objective of each pair is to minimize cost and maximize utility at the same time. The strategy of each pair is to decide whether to use its radio interface and which channel to put the radio on.

Fig. 5.2a depicts the active links on different channels, and Fig. 5.2b presents active interfaces on those channels. Here K_{l_j} presents the set of pairs who have



(a)

	$ch1$	$ch2$	$ch3$
l_1	1		
l_2	0		
l_3		0	
l_4		1	
l_5			0
l_6			0

(b)

Figure 5.2: (a) Active link (D2D) profile on different channels; (b) Active interfaces on those links.

an active link l'_j using the same frequency m and interfere with pair i on link l_j. In this chapter, a utility function is derived as a parameter to extent interface selection. More specifically, the utility function U_{l_j} of each pair depends on the energy consumption (cost) of the selected interface and delay on the specific link. In the next section a detail discussion to formulate the utility function is presented.

5.2 Utility Function

We define two different attributes which approximate the actual utility function for provided radio interfaces. A pair must choose the interface wisely such that expected data rate is satisfied. For instance, an interface with higher transmission power will increase the interference for surrounding neighbors whereas a low transmission power with a different interface may fail to satisfy the required data rate. Therefore, the trade-off between users' energy cost and satisfaction on the link has to be resolved in the interface selection game where the utility function for each pair can be formulated based on the following network factors: transmit power, expected capacity, average waiting time before transmission, and cost involved for transferring a file. The following subsections discuss these factors to finally derive the utility function.

5.2.1 Capacity

User's quality of service usually depends on actual throughput in wireless access networks. Since the bandwidth is same for all the connected users, the quality/cost recognized by a pair will strictly depends on the total number of users who are also competing for the same resource.

In general wireless access networks, the quality of service obtained by each user strictly depends on the perceived actual throughput. Since the nominal bandwidth is shared among all connected users, the quality/cost perceived by an accessing pair depends on the number of competing users sharing the very same resource. Overall interference ($\sum_{K_{l_j}} I_{l_j}$) from other pairs reduces the expected capacity. It is thus feasible to introduce capacity to the cost in the form of cost function which depends on the number of interfering users. According to Fig. 3.8, the SINR for D2D pair l_j is given as

$$SINR_{l_j} = \frac{P_i^r \alpha_i^r g_i^r}{\sigma^2 + \sum\limits_{\substack{i \neq i' \\ i,i' \in \mathbb{N}}}^{K_{l_j}} P_{i'}^r \alpha_{i'}^r}, \tag{5.2}$$

where P_i^r and $P_{i'}^r$ are the transmission power of $i \in l_j$ and $i' \in l_{j'}$ D2D pairs, respectively. Here α_i^r is a link gain, σ^2 is the additive white Gaussian noise, and g_i^r is the processing gain of link i on interface r. The capacity of each D2D link is given by

$$\mathbb{E}[C_{l_j}] = W_r \log_2(1 + SINR_{l_j}), \tag{5.3}$$

where W_r is the bandwidth given for radio r.

5.2.2 Waiting Time

We have analyzed a general probabilistic delay model for our approach. Since connections are established in adhoc manner, a variable number of D2D pairs

Table 5.1: LIST OF NOTATIONS

$\mathbb{L}$	Set of undirected links
$\mathbb{N}$	Set of D2D pairs
$\mathbb{R}$	Set of transceivers
s_i	Strategy of user i
M_r	Number of channels for interface r
C_{l_j}	Cost function of link l_j
U_{l_j}	Utility function of link l_j
W_r	Bandwidth of interface r
K_{l_j}	Number of interfering pairs on l_j
P_i^r	Transmit power of user i on interface r
$\mathbb{E}[C_{l_j}]$	Expected capacity of link l_j
L	Normalized load for each pair
$\mathbb{E}[T_{l_j}^{wait}]$	Expected waiting time on l_j
$T_{l_j}^{tx}$	Average transmission time on l_j

may coexist in the same channel/area. Each D2D pair is independent and wishes to communicate using the channel they have established. We suppose each channel is accessible in terms of time slots that are opportunistically used by D2D pairs.

Let L be the normalized load over every D2D pair. For a D2D pair, which is transmitting in a slot, in a particular link, the probability of collision with other D2D pairs is $\frac{L}{M_r}$. A collision does not occur with probability $1 - \frac{L}{M_r}$. Therefore, the probability of a successful transmission on link l_j is given by

$$Prob(l_j) = \big(1 - \frac{L}{M_r}\big)^{K_{l_j}}. \tag{5.4}$$

Each time slot in a link has three states: no transmission attempts, collision and a successful transmission. The wasted slots due to collisions correspond to a sequence of Bernoulli trails with probability of success, $Prob(l_j)$. The number of wasted slots is therefore geometrically distributed, so its mean is $\frac{1-Prob(l_j)}{Prob(l_j)}$.

Since the probability of a successful transmission is obtained as a function of the probability of new transmission attempts, now it is simple to estimate the mean delay that a packet suffers due to possible collision with other D2D pairs. Considering that every D2D pair will transmit in alternative slots, the mean delay including the successful slot is

$$\mathbb{E}[T_{l_j}^{wait}] = 2\Big(\frac{1 - Prob(l_j)}{Prob(l_j)}\Big) + 1. \tag{5.5}$$

In communication, delay also induces energy consumption. Here, lets assume that each user has a minimum energy consumption for each slot before transmission. For mean delay $\mathbb{E}[T^{wait}]$, energy consumption is presented as $E_{l_j}^{wait} = P_{slot} \times \mathbb{E}[T_{l_j}^{wait}]$, where P_{slot} presents energy per slot.

5.2.3 Cost Function

To model the cost function lets assume user i needs to transfer data of size L with a selected radio interface on any link l_j. The maximum packet length is denoted as B bytes and the total number of packets for each user is N_p, where $N_p > 0$. The file transmission time for any r interface is inversely proportional to the expected link capacity $\mathbb{E}[C_{l_j}]$ and link capacity is directly proportional to energy consumption P_i^r. Therefore, if the capacity of a link is low i.e., the transmit energy is low the end-to-end delay will be high. The estimated duration for a packet to be successfully delivered can be expressed as $\frac{B}{\mathbb{E}[C_{l_j}]}$. The average delivery time $T_{l_j}^{tx}$ of a user to transfer N_p packets on link l_j can be expressed as

$$T_{l_j}^{tx} = \sum_{l_j \in \mathcal{L}} \frac{N_p B}{\mathbb{E}[C_{l_j}]}. \tag{5.6}$$

Note that interfaces have competitive performance but the energy consumption is different in distinct interfaces [76][77]. Lets assume a user's transmission cost depends on the number of bytes it passes through the selected channel and the transmission time. Therefore, the estimated cost for user i to transmit total N_pB bytes of data with interface r can be expressed as

$$C_{l_j} = P_i^r T_{l_j}^{tx} + E_{l_j}^{wait}. \tag{5.7}$$

5.2.4 Utility Function

In formulating the overall utility expression, each pair always aims to find a strategy that results to cost effective channel capacity. Utility can be calculated considering how much energy the adopted strategy can save for each pair. To model the utility function, it is required to calculate the maximum achievable data rate where $(\sum_{K_{l_j}} I_{l_j}) = 0$. Considering equation (5.7), maximum cost $C_{l_j}^{max}$ is calculated. The utility function after reducing the energy cost for selected interface can be expressed as

$$U_{l_j} = \frac{1}{1 + e^{C_{l_j} - C_{l_j}^{max}}}. \tag{5.8}$$

5.3 Finding Nash Equilibrium

One of the major objectives of this work is to observe the NE of a game, where the existence of NE should first be proven. There are two main types of NE defined in the non-cooperative game [75] the pure strategy NE and the mixed strategy NE. Since the mixed strategies are considered impractical to describe the interface selection problem, the major concern in the network is to obtain the pure strategy NE.

Assumption 1. *A pair i is a neighbor of another pair i' if i is located in the interference range of i'.*

Assumption 2. *Node x and y are D2D pair i, which means they have at least one common channel between them for communication. And that channel can be reused by other pairs i' around it.*

Assumption 1 indicates that $i, i' \in \mathbb{N}$ are pairs of D2D nodes when they are in transmission range of each other. Fig. 3.8 depicts the D2D pairs and their range of transmission. Assumption 2 mentioned above renders that each D2D pair has a communication channel and any other neighbor node pair can transmit on that channel. This transmission can be provided through a multiplexing technique like time division multiplexing access (TDMA). Assuming the interference range of each node is the same, the neighboring relation is symmetric. This means if i is a neighbor of i', i' is also a neighbor of i. This assumption is sensible since the transmission range of radio interfaces may differ. It is noted that both assumptions imply that all pairs will pose the same payoff function, and the payoff function depends on that channel selected by other pairs. Before analyzing the properties of NE in the interface selection game, we first provide a necessary and sufficient condition for strategy profile to become NEs.

Theorem 1. s_i is NE if and only if the following three conditions hold:
(1) $\forall l_j$ if $s_i = 0$, then $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 1$
(2) $\forall l_j$ if $s_i = 1$, then $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 0$
(3) $\forall l_j$, there does not exist player i, s.t. $s_i = 0$, then $\prod_{i' \in \mathbb{N}} s_{i'} = 1$.

Lemma 1. *s_i is NE, then $\forall l_j$, if $s_i = 0$, when $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 1$.*

Proof. We proceed by contradiction. Suppose $\exists i, l_j$ s.t., $s_i = 0$ and $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 0$. We consider another strategy for i, s'_i which equals s_i. Then compare the utilities of player i taking strategies s_i and s'_i where the strategies of player i remain the same.

$$\begin{aligned} U(s'_i, s_{-i}) - U(s_i, s_{-i}) &= \frac{1}{1 + e^{C(s'_i, s_{-i})}} - \frac{1}{1 + e^{C_{max}(s'_i, s_{-i})}} \\ &\quad - \frac{1}{1 + e^{C(s_i, s_{-i})}} + \frac{1}{1 + e^{C_{max}(s_i, s_{-i})}} \\ &= \frac{1}{1 + e^{C(s'_i, s_{-i})}} - \frac{1}{1 + e^{C(s_i, s_{-i})}} > 0 \end{aligned} \tag{5.9}$$

This contradicts with the fact that s_i is a NE. □

Lemma 2. *s_i is NE, then $\forall l_j$, if $s_i = 1$, we have $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 0$.*

Proof. This is also proved by contradiction. As it is methodically similar, the proof is skipped to avoid redundancy. □

Pairs will choose the channel with less interference, which is another straightforward condition to achieve NE. On that channel a user will achieve his required data rate with the selected interface. Formally it is expressed as the following lemma.

Lemma 3. *s_i is NE, then there does not exist i s.t., $\forall l_j$, $s_i = 0$ and $\prod_{i' \in \mathbb{N}} s_{i'} = 1$.*

Proof of Theorem 1.

Proof. We have to just proof that if these three conditions, Lemma 1, Lemma 2 and Lemma 3 hold, s is a NE.

Suppose, a player i can unilaterally change his utility by changing his strategy to s'_i under the three conditions above. The possible ways to do so are explained below.

∗ change s_i from 0 to 1 for some players.

If $s_i = 0$, it claims that $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 1$. In this case, $U(s'_i, s_{-i}) - U(s_i, s_{-i}) \leq 0$. Therefore, i cannot increase his utility if current strategy s_i changes from 0 to 1.

∗ change s_i from 1 to 0 for some players.

If $s_i = 1$, then $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 0$. In this case, utility will reduce if strategy s_i changes to 0.

Hence, there is no other strategy which will improve the utility of user i with other strategies being equal. Therefore, s_i is a NE. □

In this section, different properties of NEs from system wide perspective are studied. If achieved NE is not Pareto optimal, then some pairs lose opportunity to increase their utility without hurting anyone else. Therefore it is important to consider Pareto optimality along with NE in radio interface selection game.

Example 1. *Consider a network with two D2D pairs i, i' and a single channel. Each player has two interfaces. Fig. 5.3 presents an intuitive utility profile.*

		i: B	i: W
i'	B	$(U_i, U_{i'})$	$(U_i + \theta, U_{i'} - \theta')$
	W	$(U_i - \theta, U_{i'} + \theta')$	$(U_i, U_{i'})$

Figure 5.3: A utility profile for two pairs.

Here we present a simple matrix of utility profile between two pairs of a D2D link, based on their interface selection. θ and θ' are simple parameters to present the utility increase or decrease due to the change of strategy. We can define it as $-1 \leq (\theta, \theta') \leq 1$. D2D pair i and i' can choose strategy B or W. Here, B stands for Bluetooth and W stands for Wi-Fi, respectively. From the simple definition of game (B, B) is a NE as given in Lemma 1. Here, (B, B) is also Pareto optimal. If pair i moves the interface to W, it imposes interference on the other pair. In this way pair i can increase his utility but decrease the utility of pair i', which implies that this strategy is Pareto optimal. This specification is legitimate for the other pair i'.

This example shows that Pareto optimality is a property of NE in the non-cooperative interface selection game. Another major observation is that the strategies of other players have high impact on Pareto optimality. If the strategy of neighbors induces low interference, compared to the interference on current channels there can be NEs that are Pareto optimal.

Proposition 1. *If $I_{l_j} \leq I_{l'_j}$, all the NEs are Pareto optimal.*

Proof. If $I_{l_j} \leq I_{l'_j}$, for any NE, suppose it is not Pareto optimal.

First we observe that, a necessary condition for i to increase his utility by changing his strategy from s_i to s'_i.

$\exists l_j$, s.t., $s_i = \emptyset$ and $\exists l'_j$, s.t., $s'_i = 1$ or $s'_i = 0$.

Since there is no empty channel lets assume that

$\exists l'_j$,s.t., $s_i \neq \emptyset$, $s_{i'} = 1$ or $s_{i'} = 0$.

Hence, the pair has no interface on a channel and the strategy is $\emptyset$. Now lets check four cases regarding s_i and $s_{i'}$

Case 1. *$\forall l_j$, $s_i = 0$ and $\forall l'_j$, $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 1$. Now pair i meets the same situation with user j on channel l'_j as give in Lemma 1. This is a contradiction with the condition because utility will not increase.*

Case 2. *$\forall l_j$, $s_i = 1$ and $\forall l'_j$, $\prod_{i' \in \mathbb{N}}(1 - s) = 1$. Here, pair i changes the strategy but it will increase the interference for strategy $s_{i'} = 0$ and thus will reduce the utility.*

Case 3. *$s_i = 0$ and $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 0$, then $\forall s_{i'} = 1$. It contradicts with Theorem 1.*

Case 4. $s_i = 1$ *and* $\prod_{i \in \mathbb{N}}(1 - s_{i'}) = 0$. *This conceives as given in Lemma 2, thus yielding a contradiction for Pareto improvement.*

Therefore, if $I_{l_j} \leq I_{l'_j}$, all the NEs are Pareto optimal. $\square$

Proposition 1 explains that when $I_{l_j} \leq I_{l'_j}$, there are no channels which has lower interference than the current one. In a NE if a pair wants to increase utility by changing its strategy by employing the same interface on another channel l'_j, neighbor pairs on that channel change their strategy or remove their interface. As there is no empty channel, when a pair moves the interface to another channel, some other pairs lose part of their utility due to a new strategy.

5.4 Proposed Algorithm

Section 5.3 demonstrates that the behavior of a selfish D2D pair leads to Nash equilibrium. With the formulated non-cooperative game and identified solution, the next step is to develop an algorithm that can model the interactions between D2D pairs. In this section, three algorithms are proposed, each using a different set of available information, to enable selfish D2D pairs to converge to one of these Nash equilibria from an arbitrary initial configuration. We propose three algorithms as follows.

1. a centralized algorithm using global information (*Social*),

1. a distributed algorithm with global information (*Greedy*), and

1. a distributed algorithm using local information (*Local*).

5.4.1 *Social*

A coordinator iterates over a set of D2D pairs having information about each pair. It selects an interface for each pair which escalates the aggregated utility (lines $6 - 14$ in Algorithm 1). In this central algorithm, a selection for a pairs depends on the selection of other pairs in the networks. Initially, all D2D pairs can be connected to the coordinator with any of the available interface.

The radio interface selection will repeats till there is a scope to maximize the utility. This approach is *social* because it decides with a cooperation with other D2D pairs and considers the overall welfare. This algorithm will always converge, as *social* will never change radio interface if any decision reduces the utility.

Algorithm 1 *Social*

```
Input: ℕ: set of D2D pairs are formed.
I_{l_j}, I'_{l_j}: interference of other pairs on link l_j and l'_j respectively.
Output: s_i, ∀i ∈ ℕ
Initialize: s_i = s_old = ∅, ∀i ∈ ℕ; U_max = U_sum
while s_i ≠ s_old do
    for i ∈ ℕ do
        for r ∈ {1, 2, ..., n} do
            Calculate U_sum|i is in interface r
            if U_sum > U_max then
                U_max = U_sum
                s_i = r
            end if
        end for
    end for
end while
```

5.4.2 *Greedy*

The proposed *greedy* algorithm is quite similar to *social*. But in *greedy* individual utility is important rather than overall utility. Similar to several greedy algorithms this may not converge as well which is a drawback of *greedy* approach. The *greedy* algorithm occurs in a coordinator and a decision is made in the proactive manner. The coordinator will make a decision for each pair iteratively and balances decisions to assure utility, i.e., utility of a D2D pair due to a decision has no impact because of the next decision for another pair. Once a decision is made for all the pairs, the algorithm stops its iteration.

5.4.3 *Local*

We also propose a local heuristic algorithm that operates on individual D2D pairs. Both *social* and *greedy* operate with a coordinator and have information about D2D pairs in the network. In contrast, in this approach each D2D pair has information about other pairs who exist on the same channel m. If a D2D pair changes its strategy, that will be always a different interface on the same channel but not other available channels. The strategy matrix for each D2D pair is much smaller compared to *social*. Therefore the computational overhead to end users is reduced greatly. Each pair will calculate its strategy and terminate upon completion of decisions.

Algorithm 2 *Greedy*

```
Input: ℕ: set of D2D pairs are formed.
I_{l_j}, I'_{l_j}: interference of other pairs on link l_j and l'_j respectively.
Output: s_i, ∀i ∈ ℕ
Initialize: s_i = s_old = ∅, ∀i ∈ ℕ;
while s_i ≠ s_old do
    U_max = U_{l_j}
    for i ∈ ℕ do
        for r ∈ {1, 2, ..., n} do
            Calculate U_{l_j} | i is in mode r
            if U_{l_j} > U_max then
                U_max = U_{l_j}
                s_i = r
            end if
        end for
    end for
end while
```

5.4.4 *Complexity Analysis*

Our proposed heuristic *social* and *greedy* both compute $|\mathbb{L}||\mathbb{R}|(|\mathbb{N}|-1)$ utilities for each strategy and for every D2D pair in a sequential manner, i.e.,

Algorithm 3 *Local*

```
Input: I_{l_j}: interference of other pairs on link l_j.
Output: s_i, ∀i ∈ ℕ
Initialize: s_i = s_old = ∅;
while s_i ≠ s_old do
    for r ∈ {1, 2, ..., n} do
        U_max = U_{l_j}
        Calculate U_{l_j} | i is in mode r
        if U_{l_j} > U_max then
            U_max = U_{l_j}
            s_i = r;
        end if
    end for
end while
```

total $\mid \mathbb{N} \mid\mid \mathbb{L} \mid\mid \mathbb{R} \mid \times(\mid \mathbb{N} \mid -1)$ number of utilities per round of evolution. In this work we have considered evolution cycle to be 1, and the decision converges within one cycle if and only if the D2D pairs and channel number do not change during evolution. Therefore the complexity of *social* and *greedy* is $\mathcal{O}(\mid \mathbb{N} \mid\mid \mathbb{L} \mid\mid \mathbb{R} \mid \times(\mid \mathbb{N} \mid -1))$. In case of *local* approach it targets the utility of individual pairs and the algorithms function on the edge users. As a result the complexity of this approach varies among different pairs. Hence, the complexity for *local* is $\mathcal{O}(\mid \mathbb{R} \mid \times(K_{l_j} - 1))$.

Definition 3. *Efficiency: The efficiency ϕ of a strategy is defined as a proportion between the utility of selected strategy and best case strategy. It can be presented as $\phi(s_i) = \frac{U_{l_j}}{U_{max}}$.*

Definition 4. *Convergence Time: We define the convergence time of* social *and* greedy*, as the time when the efficiency of strategy selection reaches the value of one (i.e., the efficiency of NE, $\phi(s) = 1$).*

The convergence of algorithms depend on the number of users, available interfaces and channels in the network, which is tested through our simulation.

5.5 Performance Evaluation

To verify the performance of the proposed algorithms, MATLAB event-driven simulation is used. We considered devices with Bluetooth and Wi-Fi interfaces where both the interfaces can access the same spectrum band of 2.4GHz; thus some of the channels of the two radio systems are overlapped. We assumed rendezvoused pairs have the ability to mutually select a radio interface between Bluetooth and Wi-Fi to achieve the best utility. Error bars in the results are the 95% confidence intervals. In addition, to compare our algorithms, we evaluated two benchmark schemes, namely, exclusive Wi-Fi and exclusive Bluetooth. In exclusive Wi-Fi all D2D pairs in the network are forced to communicate using Wi-Fi Direct and in exclusive Bluetooth, they are forced to communicate using Bluetooth. Wi-Fi with a higher transmission power provides better data rate whereas it increases interference for the surrounding D2D pairs. On the contrary, Bluetooth has a lower data rate, but due to its small transmission power neighbor D2D pairs can achieve comparatively better data rate. Now the question is: *What is the best choice for a D2D pair?* Our simulation is to reflect a justification for such argument.

Table 5.2: THE PARAMETERS USED IN THE SIMULATION

Parameter	Value
Number of channels (Bluetooth)	40
Number of channels (WiFi)	11
Bandwidth (Bluetooth)	2MHz
Bandwidth (Wi-Fi)	20 MHz
Fading, shadowing	Reyleigh, 6dB
Path loss model	148.1 + $40log10$(d[m])
Noise spectral density	−17dBm/Hz
Antenna gain (Omni-directional)	Device: 0 dBi
Wi-Fi TX power	20 dBm
Bluetooth TX power	10 dBm

5.5.1 Simulation setup

We consider an area of 200m $\times$ 200m and users are uniformly distributed in that area. The SNR of a pair is measured based on the distance and the number of other pairs on the same channel. The default values for the overall simulation are listed in Table 5.2. Note that the maximum utility U_{max} is calculated considering load balancing among all the available channels in the network. Mobility of the D2D pairs are not considered. For each set of parameter values, we perform 1000 independent runs and then compute the average value. Given that the condition of a channel tends to be correlated between any two users in the vicinity, we generate a noise level for each channel such that the noise in a particular user's channel was determined by path loss and some deviation assuming that a distant user could transmit on the same channel.

We compare our proposed algorithms with the benchmarks by varying the number of channels, data rates, and D2D pairs. The performance is obtained from the perspective of utility, energy consumption and efficiency, where the efficiency is defined as the amount of transmitted data per Joule.

5.5.2 Simulation Results

Fig. 5.4 illustrates the impact of the utility when the number of channels varies in the network but the number of D2D pairs is retained at 100. We can observe that the utility of Bluetooth is better than Wi-Fi when the number of channels is small. This is due to interference by high-powered Wi-Fi transmission. The utility of Wi-Fi increases uniformly but still with 40 channels it is only 0.57. On the other hand, with the same number of channels, *social* improves the utility to 0.68, which is almost 19% improvement compared to exclusive Bluetooth and Wi-Fi. With a much smaller number of channels we can observe little improvement only in case of *social* but both *greedy* and *local* present identical utility compared to others. *Greedy* and *local* are outperformed by *social* due to their

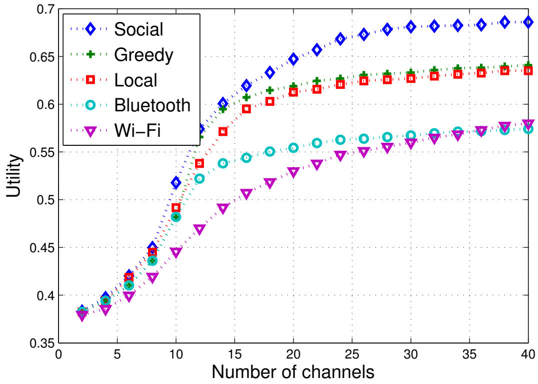


Figure 5.4: Average utility per user in the networks.

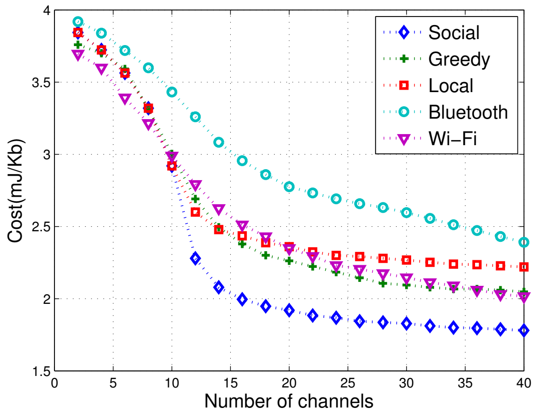


Figure 5.5: Average cost per user.

non-cooperative behavior though greedy has the same computational complexity. Correspondingly *local* is ahead because it can achieve similar utility but with lower complexity.

Another finding is that increasing the number of channels can reduce the cost for each pair, as depicted in Fig. 5.5. The cost is considered for each pair to transmit per kilobits (Kb) of data. For instance, when the number of channels increases the average cost per user reduces for all the schemes. Bluetooth has much higher cost compared to any other scheme as shown in Fig. 5.5, because of its lower bit rate. On the other hand, Wi-Fi shows significant improvement in the

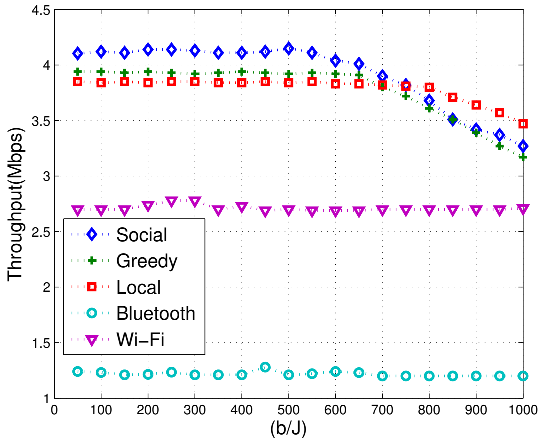


Figure 5.6: Average throughput per D2D pair.

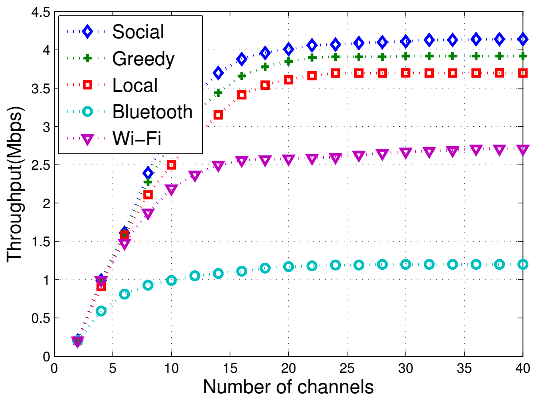


Figure 5.7: Average throughput as a function of the number of channels.

cost though totally outperformed by *social*. *Social* has an advantage in overall utility comparison which elevates the possibility of better output. With a lower number of channels *social* has a slightly higher cost, but it reduces significantly when the number of channels is more than 10 and it is less than 2mJ with 40 channels. Other two algorithms, *greedy* and *local* drain cost in the same manner for different numbers of channels. Nevertheless, we can claim that both schemes achieve better utility.

In Fig. 5.6 we can observe that the average throughput per user shows better performance than exclusive Wi-Fi and Bluetooth. This is obvious after the comparison of utility. Wi-Fi and Bluetooth show no impact with the increase of cost because these systems are biased to throughput. Hence, our proposed algorithms show reduction of throughput as the cost increases. When the cost is 10^3b/J, we can observe the throughput reduces by almost 22%. The average throughput per user with various numbers of channels is depicted in Fig. 5.7. All the proposed algorithms and Wi-Fi show an identical improvement till the number of channels is 10. After that Wi-Fi is completely outperformed by the proposed algorithms. Bluetooth has a very low throughput compared to the others. One reason is that it hops for another channel when there is interference on the current channel. On contrary Wi-Fi takes a backoff window when the channel is busy.

To investigate the efficiency by considering throughput and energy together, we considered 40 channels for various numbers of users as shown in Fig. 5.8. With the increase of the number of users, the efficiency declines. When the number of users is high, the backoff time of Wi-Fi increases and Bluetooth faces higher interference, which causes their lower efficiency compared to the proposed algorithms. *Social* has almost 70% improvement of efficiency when the number of users is 100.

Further we compare the cost with various numbers of D2D pairs considering $N = 100$ as shown in Fig. 5.9. We observe that the cost escalates with the number of pairs. Bluetooth consumes the most due to its hopping characteristics due to interference as explained before. For Wi-Fi it is obvious that more pairs will increase the backoff time which is reflected in the result. Only *social* shows significant improvement of cost as in the strategy all the pairs are not in Wi-Fi mode, which reduces the load. And finally we derive the average time to achieve a NE for our proposed schemes in Fig. 5.10. We considered a *tic-toc* operation to measure the elapsed time. Fig. 5.10 shows *social* takes much more time

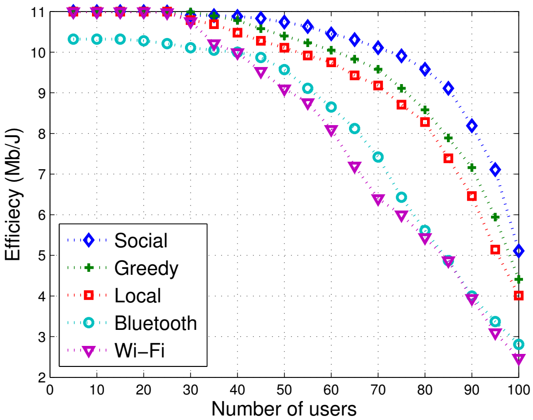


Figure 5.8: Average throughput per D2D pair.

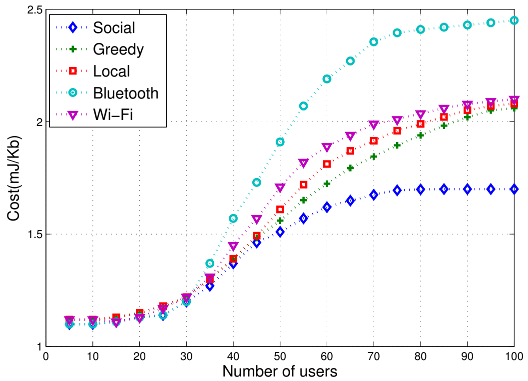


Figure 5.9: Average cost as a function of the number of users.

compared to other schemes, which is evident owing to the complexity explained earlier. *Greedy* has a similar complexity and the result justifies that property. Though *local* has the lowest utility and throughput, it consumes the least time to achieve a NE, because it does not deal with all the users and channels to make a decision for D2D communication.

5.6 Summary

Heterogeneous nature of modern wireless access networks has motivated us to study the process of *radio interface selection* in this chapter. In the light of non-

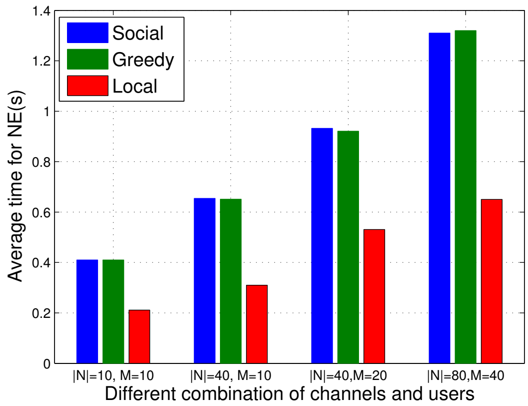


Figure 5.10: Average time to achieve a NE.

cooperative game theory we have modeled a competition among different available radio interfaces and channels. We have also studied Pareto optimality of the NE. Finally, we have provided three heuristic algorithm, namely *social*, *greedy* and *local* to achieve the efficient strategy to achieve a NE. The proposed algorithms work in different network models and parameter sets. In a practical network scenario, the proposed game model can be easily adopted to achieve critical impact.

The main observations of the analysis are:

1. proper radio *interface selection* can be modeled as a game that tends to convert in the form of NE solution, which is also Pareto optimal;

2. the equilibria are obtained based on an inverse relation of multi-parameter cost function and utility function;

3. the proposed approach and their comparison show the trade-off between utility, efficiency and cost with various sets of network parameters.

For future work, we will extend this current model to the case in which *interface selection* process accounts latency for applications running on the users.

In fact battery sojourn time can be considered as an influential factor for the decision. Last but not the least, we will also study to reduce the complexity of current approach.

Chapter 6

Final Remark

Wireless networks provide services that have become crucial to our everyday life. The recent evolution of wireless networks points towards decentralized wireless access: on the users' side, devices have become more sophisticated and programmable than before. It is essential to rendezvous for two or more users prior to data communication with each other. Therefore, users in the network successfully exchange management frames on the available channel tp achieve rendezvous.

The main focus of this thesis is to quantify the key-performance-limiting factors of the rendezvous process in CRNs with radio interface selection to establish pair wise communication. Rendezvous is a hard challenge in dynamic distributed networks due to variations in channel availability at different time and space. Several factors are identified that affect the performance of rendezvous. Among those asymmetric nature of channels, number of common channels between users and spectrum sharing process are highly significant. To achieve rendezvous, a CH sequence EAR was developed in this study based on channel ranking. Extensive simulation was conducted to evaluate the performance of proposed EAR over other CH sequences. However, EAR is mainly a mathematical CH sequence which fails to guarantee rendezvous due to collision prone nature of wireless channels. Proposed V-MAC protocol considered the collision issues during rendezvous and improved performance with simple but effective modification for CRNs. Upon rendezvous users connect to each other and this can be done with any wireless radio interfaces available in the device. Due to the limited battery power of users, it is important to select the proper radio interface in terms of energy consumption by considering the link quality and required quality fo service. Therefore a game theoretic model was proposed to select the proper radio interface between pairs to enable a communication link. The original contributions of this thesis are summarized below.

Two users can start communicating after rendezvous in a decentralized networks, therefore rendezvous is much desired in CRNs. In literature there are several research works that considered rendezvous based on CCC. Due to several issues regarding CCC, it is impossible to guarantee rendezvous on a predetermined CCC. Moreover, existing rendezvous suffers from higher TTR and homogeneous characterization of channel behavior. To overcome these problems, we developed enhanced adaptive rendezvous (EAR) to guarantee rendezvous considering channels are heterogeneous and channel lists ae asymmetric. Multiple-radio interfaces were adopted to achieve rendezvous. In this work, with a novel strict partition we guarantee that user will attempt to rendezvous more on channel with higher rank. The performance of the CH sequences, V-MAC and radio interface selection game was evaluated using MATLAB simulation package. Additionally, we presented another CH sequence V-HS which reduces the expected time to rendezvous.

In a CRNs multiple CR users opportunistically access channels alloted for PUs without creating any interference. Hence, an efficient MAC protocol is necessary to facilitates rendezvous attempt and channel access. In Chapter 4, a MAC protocol namely V-MAC for multi channel was developed. This work discussed issues during rendezvous considering CSMA/CA protocol, and proposed effective modification. First, a sensing period was introduced right after RTS NAV for SUs. This strategy can reduce the possibility of false blocking. Secondly, multiple probe request with a modified contention window was proposed to reduce collisions that render loss of rendezvous opportunity. This model also protects the incumbent PU transmission. Finally, the performance is quantified for V-MAC that supports

In Chapter 5 the rendezvous task was extended to a radio interface selection problem, where users can select any of the available radio interfaces to establish a D2D link. In the model a D2D pair is defined as a combination fo two rendezvoused node. We discuss about the fact that there is no proper radio interface to guarantee controlled interference, spectrum efficiency and quality of service (QoS). A non-cooperative game was modeled where a rendezvoused pair can selfishly select a radio interface while optimizing a utility function that captures various involved trade-offs between communication performance and associated costs. Three heuristic algorithm namely *social*, *greedy* and *local* were proposed to achieve the NE. With equilibrium strategy our schemes can increase the utility, lower the cost and lead to higher efficiency in terms of achievable throughput per consumed energy.

On account of the results reported above, we can realize that radio interface selection has an impressive impact to initialize a decentralized networks. EAR and V-MAC allows to hop on different channels based on the ranked channel list and finally establish a connection with a selected radio interface.

Bibliography

[1] I. Akyildiz, Y. Altunbasak, F. Fekri and R. Sivakumar, “Adaptnet: an adaptive protocol suite for the next-generation wireless internet” *IEEE Communications Magazine*, vol. 42, no. 3, pp. 128-136, Mar 2004.

[2] FCC, “Spectrum policy task force report”, *ET Docket*, no. 02-1555, Nov 2002.

[3] A. Ghassemi, S. Bavarian and L. Lampe, “Cognitive radio for smart grid communications” *IEEE International Conference on Smart Grid Communications (SmartGridComm)*, pp. 297-302, Oct 2010.

[4] A. Gorcin and H. Arslan, “Public safety and emergency case communications: Opportunities from the aspect of cognitive radio”, *DySPAN*, pp. 1-10, Oct 2008.

[5] M. Mueck, A. Piipponen, K. Kalliojarvi, G. Dimitrakopoulos, K. Tsagkaris, P. Demestichas, F. Casadevall, J. Perez-Romero, O. Sallent and G. Baldini “Etsi reconfigurable radio systems: status and future directions on software defined radio and cognitive radio standards” *IEEE Communications Magazine*, vol. 48, no. 9, pp. 78-86, 2010.

[6] T. Kamakaris, M. M. Buddhikot and R. Iyer, “A case for coordinated dynamic spectrum access in cellular networks” *DySPAN*, pp. 289-298, 2005.

[7] I. Akyildiz, W. -Y. Lee, M. C. Vuran and S. Mohanty, "A survey on spectrum management in cognitive radio networks" *IEEE Communications Magazine*, vol. 46, no. 4, pp. 40-48, April 2008.

[8] R. Chavez-Santiago, K. Nolan, O. Holland, L. De. Nardis, J. Ferro, N. Barroca, L. Borges, F. Velez, V. Goncalves, and I. Balasingham, "Cognitive radio for medical body area networks using ultra wideband", *IEEE Wireless Communications*, vol. 19, no. 4, pp. 74-81, Aug 2012.

[9] L. Ma, X. Han and C.-C. Shen, "Dynamic open spectrum sharing mac protocol for wireless ad hoc networks", *DySPAN*, vol. 8774712, 203-213, 2005.

[10] Y. Zhang, Q. Li, G. Yu and B. Wang, "Etch: Efficient channel hopping for communication rendezvous in dynamic specrtum access network", *IEEE INFOCOM*, pp. 2471-2479, June 2011.

[11] J. Zhao, H, Zheng and G.-H. Yang, "Distributed coordination in dynamic spectrum allocation networks", *DySPAN*, pp. 259-268, 2005.

[12] L. Ma, X. Han and C.-C. Shen, "Dynamic open spectrum sharing mac protocol for wireless networks", *DySPAN*, pp. 203-213, 2005.

[13] J. Jia, Q. Zhang and X. Shen, "Hc-mac: A hardware-constrained cognitive mac for efficient spectrum management", *IEEE JSAC*, vol. 26, no. 1, pp. 106-117, 2008.

[14] C. Cordeiro, K. Challapali, D. Birru and S. S. N, "IEEE 802.22: the first worldwide wireless standard based on cognitive radios", *Journal of Communications*, vol. 1, no. 1, pp. 38-47, 2006.

[15] K. Bian and J.-M. Park, “Asynchronous channel hopping for establishing rendezvous in cognitive radio networks”, *IEEE INFOCOM Miniconference*, pp. 236-240, 2011.

[16] L. DaSilva and I. Guerreiro, “Sequence-based rendezvous for dynamic spectrum access”, *DySPAN*, pp. 1-7, Oct 2008.

[17] Y. Kondareddy and P. Agrawal, “Synchronized mac protocol for multi-hop cognitive radio networks”, *IEEE International Conference on Communications*, pp. 3198-3202, 2008.

[18] P. Bahl, R. Chandra and J. Dunagan, “Ssch: slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks”, *Proceedings of the* 10*th Annual International Conference on Mobile Computing and Networking*, ACM, pp. 216-230, 2004.

[19] C. Cormio and K. R. Chowdhury, “Common control channel design for cognitive radio wireless ad hoc networks using adaptive frequency hopping”, *Ad Hoc Networks*, vol. 8, 430-438, 2010.

[20] D. Yang, J. Shin and C. Kim, “Deterministic Rendezvous Scheme in Multichannel Access Networks”, *Electronics Letters*, vol. 46, no. 20, pp. 1402-1404, 2010.

[21] J. Shin, D. Yang and C. Kim, “A Channel Rendezvous Scheme for cognitive radio networks”, *IEEE Comm. Letters*, vol. 14, no. 10, pp. 954-956, Oct 2010.

[22] H. Garcia-Molina and D. Barbara, “How to assign votes in a distributed system”, *Journal of the ACM*, vol. 32, 841-860, 1985.

[23] N. Theis, R. Thomas and L. DaSilva, “Rendezvous for cognitive radios, *IEEE Transactions on Mobile Computing*, vol. 10, 216-227, 2011.

[24] K. Bian, J.-M. Park and R. Chen, "A quorum-based framework for establishing control channels in dynamic spectrum access networks", *Proc. of the ACM MobiCom*, pp. 25-36, 2009.

[25] S. Romaszko and P. Mahonen, "Grid-based channel mapping in cognitive radio ad-hoc networks", *PIMRC*, pp. 438-444, Sept 2011.

[26] M.J. Abdel Rahman, H. Rahbari and M. Krunz, "Adaptive frequency hopping algorithms for multi-cast rendezvous in DSA networks", *DySPAN*, 517-528, 2012.

[27] Z. L. Lin, H. Liu, X. Chu and L. Yiu-Wing, "Jump-stay based channel-hopping algorithm with guaranteed rendezvous for cognitive radio networks", *IEEE INFOCOM*, 2444-2452, 2011.

[28] I. Chuang, H.-Y. Wu, K.-R. Lee and Y.-H. Kuo, "Alternate hop-and-wait channel rendezvous method for cognitive radio networks", *IEEE INFOCOM*, pp. 746-754, April 2013.

[29] Y. Kondareddy, P. Agrawal and K. Sivalingam, "Cognitive radio network setup without a common control channel", *IEEE MILCOM*, vol. 10466200, pp. 1-6, 2008.

[30] B. Horine and D. Turgut, "Link rendezvous protocol for cognitive radio networks", *DySPAN*, vol. 9869727, 444-447, 2007, doi:10.1109/DYSPAN.2007.64.

[31] Tefek and U. Teng Joon Lim, "Channel-hopping on multiple channels for full rendezvous diversity in cognitive radio networks", *IEEE Global Communications Conference (GLOBECOM)*, 4714-4719, Dec 2014.

[32] N. Balasubramanian, A. Balasubramanian, and A. Venkataramani, "Energy consumption in mobile phones: A measurement study and implications for network applications", *ACM SIGCOMM*, pp. 280–293, 2009.

[33] M. A. Viredaz, L. S. Brakmo and W. R. Hamburgen, "Energy management on hand-held devices", *ACM Queue*, vol. 1, no. 7, pp. 44–52, 2003.

[34] N. Fourty, T. Val, P. Fraissem and J.-J.Mercier, "Comparative analysis of new high data rate wireless communication technologies from Wi-Fi to WiMAX", *IEEE ICAS/ICNS*, pp. 66–71, 2005.

[35] J. Ploennigs, V. Vasyutynskyy and K. Kabitzsch, "Comparative study of energy-efficient sampling approaches for wireless control networks", *IEEE Trans. Ind. Informat.*, vol. 6, no. 3, pp. 416–424, 2010.

[36] Roy friedman, Alex Kogan and Yevgeny Krivolapov, "On power and throughput trade-offs of Wi-Fi and Bluetooth in smart-phones", *IEEE Transactions on Mobile Computing*, vol. 12, no. 7, 2013.

[37] Shuo Deng, Ravi Netravali, Anirudh Sivaraman and Hari Balakrishnan, "WiFi, LTE or Both? Measuring multi-homed wireless internet performance", *ACM IMC*, pp. 181–194, 2014.

[38] T. Pering, Y. Agarwal, R. Gupta, and R. Want, "CoolSpots: Reducing the power consumption of wireless mobile devices with multiple radio interfaces", *ACM MobiSys*, pp. 220–232, 2006.

[39] A. Rahmati and L. Zhong, "Context-for-Wireless: Context-Sensitive Energy-Efficient Wireless Data Transfer", *MobiSys*, 2007.

[40] L. Georgiadis, M. J. Neely, and L. Tassiulas, "Resource allocation and cross-layer control in wireless networks" *Foundation and Trends in Netw.*, vol. 1, no. 1, pp. 1–144, 2006.

[41] M. J. Neely, "Energy optimal control for time-varying wireless networks", *IEEE Transactions on Information Theory*, vol. 52, no. 7, pp. 2915–2934, 2006.

[42] S. Chareen, H. Xie and P. Cole, "WINA: A framework to conserve energy in mobile wireless communications", *ICACT*, 13–16, pp. 132–137, Feb 2011.

[43] F. Bari and V. C. M. Leung, "Automated network selection in a heterogeneous wireless network environment", *IEEE Network*, vol. 21, no. 1, pp. 34-40, Jan 2007.

[44] J. Hou and D. C. O'Brien, "Vertical handover decision making algorithm using fuzzy logic for the integrated Radio-and-OW system", *IEEE Transactions on Wireless Communications*, vol. 5, no. 1, pp. 176-185, Jan 2006.

[45] D. Niyato and E. Hossain, "Dynamics of network selection in heterogeneous wireless networks: an evolutionary game approach", *IEEE Transactions on Vehicular Technology*, vol. 58, no. 4, pp. 2008-2017, May 2009.

[46] D. Mariz, I. Cananea, D. Sadok and G. Fodor, "Simulative analysis of access selection algorithms for multi-access networks", *WoWMoM*, pp. 219-227, 2006.

[47] E. Stevens-Navarro, Y. Lin and V. W. S. Wong, "An MDP-based vertical handoff decision algorithm for heterogeneous wireless networks", *IEEE Transactions on Vehicular Technology*, vol. 57, no. 2, pp. 1243-1254, March 2008.

[48] C. Sun, E. Stevens-Navarro and V. W. S. Wong, "A Constrained MDP-based vertical handoff decision algorithm for 4G wireless networks", *ICC*, pp. 2169-2174, 2008.

[49] L. Scalia and J. Widmer and I. Aad, "On the side effects of packet detection sensitivity in IEEE 802.11 interference management", *IEEE WoWMoM*, vol. 978-1-4244-7264-2, 1-7, 2010.

[50] D. Camps-Mur, A. Garcia-Saavedra and P. Serrano, "Device-to-device communications with Wi-Fi Direct: overview and experimentation", *Wireless Communications*, vol. 20, 96 - 104, 2013, doi:10.1109/MWC.2013.6549288.

[51] Do-Yun Kim, Young-June Choi, Kyung-yul Cheon and Chang-Joo Kim, "Overhead analysis on beacon broadcasting for self-organizing MIMC ad-hoc networks", *IEEE ICUFN*, vol. 2165-8528, 724-728, 2013.

[52] Hansraj Gupta, "Patition-A Survey", *JOURNAL OF RESEARCH of the National Bureau of Standards-B. Mathematical Sciences*, vol. 74B, no. 1, 1970.

[53] P802.22/D2.0, Feb 2011 - IEEE Draft Standard for Information Technology -Telecommunications and information exchange between systems - Wireless Regional Area Networks (WRAN) - Specific requirements - Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV Bands.

[54] IEEE 802.11 Standard [Online]. Available: http://standards.ieee.org.getieee802/download/802.11-2007.pdf, 2007.

[55] Dongmin Yang, Jongmin Shin, Jeonggyu Kim and Cheeha Kim, "An energy optimal scheme for neighbor discovery in opportunistic networking", *Consumer Communications and Networking Conference (CCNC)*, 2009.

[56] Q. Liu, X. Wnag, B. Han, X. Wang and X. Zhou, "Access delay of cognitive radio networks based on asynchronous channel-hopping rendezvous

and CSMA/CA MAC", *IEEE Transactions on Vehicular Technology*, vol. 64, 2015.

[57] Y. Choi and S. Choi, "Service charge and energy-aware vertical hand- off in integrated IEEE 802.11e/802.11 Networks", *IEEE INFOCOM*, pp. 589-597, 2007.

[58] S. Yan, Y. Zhuo and S. Wu, "An adaptive RTS threshold adjust algorithm based on minimum energy consumption in IEEE 802.11 DCF", *Communication Technology Proceedings ICCT*, pp. 1210-1214, 2003.

[59] Guiseppe Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function", *IEEE Journal on Selected Areas in Communications*, vol. 18, 2000.

[60] R. Paul, Y. Z. Jembre and Y. J. Choi, "Multi-interface rendezvous in self-organizing cognitive radio networks", *IEEE DySPAN*, pp. 531-540, April 2014.

[61] B. Insight, "Handset connectivity technologies", *second ed.*, http://www.berginsight.com/ReportPDF/Summary/bi-hct2-sum.pdf, 2011.

[62] Cisco, "Cisco visual networking index: Global mobile data traffic forecast update", *Whitepaper*, Feb 2011.

[63] A. Asadi, Q. Wang and V. Mancuso, "A survey on device-to-device communication in cellular networks", *IEEE Comm. Surveys & Tutorials*, 2014.

[64] T. Q. S. Quek, G. de la Roche, I. Guvenc, and M. Kountouris, *Small cell networks: deployment, PHY techniques, and resource management*, Cambridge University Press, 2012.

[65] 3GPP TR 36.843 "Study on LTE device to device proximity services: radio aspects",*v. 12.0.1*, 2012.

[66] "LTE direct always-on device-to-device proximal discovery", *Qualcomm Inc.*, 2014.

[67] D. Camps-Mur, A. Garcia-Saavedra and P. Serrano, "Device to device communications with WiFi Direct: overview and experimentation", *IEEE Wireless Communications*, vol. 20, issue. 3, pp. 96 - 104, June 2013.

[68] Jia Liu, Canfeng Chen, Yan Ma and Ying Xu, "Adaptove device discovery in bluetooth low energy networks", *IEEE Vehicular Technology Conference (VTC Spring)*, pp. 1-5, 2013.

[69] M. Felegyhazi, M. Cagalj, S. S. Bidokhti and J. P. Hubaux, "Non-cooperative multi-radio channel allocation in wireless networks", *IEEE International Conference on Computer Communications (INFOCOM)*, pp. 1442–1450, 2007.

[70] F. Wu, N. Singh, N. Vaidya and G. Chen,"On adaptive-width channel allocation in non-cooperative, multi-radio wireless networks", *IEEE INFOCOM*, pp. 2790–2798, 2011.

[71] B. Hajek and G. Sasaki, "Link scheduling in polynomial time", *IEEE Transactions on Information Theory*, vol. 34, no. 5, pp. 910–917, Sep 1988.

[72] P. Gupta and P. Kumar, "The capacity of wireless networks", *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 388–404, Mar 2000.

[73] M. Alicherry, R. Bhatia and L. Li, "Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks", *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 11, Nov 2006.

[74] S. Avallone and I. Akyildiz, "A channel assignment algorithm for multi-radio wireless mesh networks", *International Conference on Computer Communications and Networks (ICCCN)*, pp. 1034-1039, 2007.

[75] M. J. Osborne and A. Rubenstein,"A course in game theory", em The MIT Press, 1994.

[76] Roy Friedman, Alex Kogan and Yevgeny Krivolapov, "On power and throughput trade-offs of WiFi and Bluetooth in Smartphones", *IEEE Transactions on Mobile Computing*, vol. 12, no. 7, July 2013.

[77] S. Deng, R. Netravali, A. Sivaraman and H. Balakrishnan, "WiFi, LTE, or both? Measuring multi-homed wireless internet performance", *Internet Measurement Conference (IMC)*, pp. 1–14, Nov 2014.

Appendix A

V-HS

A.1 Hopping Sequence Generator

We now present the proposed hopping sequence, V-HS, for symmetric and asymmetric models. Any two users individually generate their own sequence following the same set of rules.

The set of available channel is denoted by $C = \{c_1, c_2 \ldots, c_N\}$. Let $C_n \subseteq C$ denote the set of available channels of user $n, n = \{1, 2, \ldots\}$. Let G denote the number of common available channels between users, i.e., $G = C_1 \cap C_2$. In symmetric model, all the users have the same available channels, i.e, $C_1 = C_2$. In asymmetric model, all the users have different available channels. It is assumed that there is at least one common channel between users, i.e., $G \neq 0$. Otherwise, there is no feasible solution for rendezvous of the users.

While users have their N channels, they require to select another parameter related to N. Let P be the smallest prime number greater than N. Each round lasts for $2P$ time slots. For every $2P$ time slots, users will generate a sequence based on some predefined parameters. Theorem A.1.1 and Theorem A.1.4 will explain how the sequence is generated consecutively for both the symmetric and asymmetric models.

A.1.1 Channel Hopping Sequence Generator

Theorem A.1.1. *1* (Channel hopping sequence for symmetric model) Let N be the number of channels and P be the smallest prime number greater than N. Let $s(t)$ be the hopping sequence of period $2P$ defined as

$$f(x) = \begin{cases} ((rt/2 \ + \ i) \ mod \ P) + 1 & for \ t \ \equiv \ 0 \ mod \ 2 \\ r & for \ t \ \equiv \ 1 \ mod \ 2 \end{cases}$$

where r is the index of the best channel which is naturally a position integer indicating a channel number such that $1 \leq r < P$ and $gcd(r, P) = 1$ and i is time difference between users given as a random positive integer less than P. Then, two users will appear on the same channel within $2P$ time slots.

Suppose the channel indices are [1 2 3 4], then $N = 4$ and $P = 5$. When $f(x)$ generates a number that exceeds the indices, $f(x) > N$, both users replace each exceed number with the same index. For instance $f(x) = 5$ and both users change $f(x)$ to the same number a such as $1 \leq a \leq 4$.

To prove the above theorem, we should consider the following lemmas first. Here, $s(t)$ is the channel hopping sequence of a symmetric system.

Lemma A.1.2. *(Lin, Liu, Chu, and Leung [27]) Given a positive integer n, if $r \in [1, n]$ is relatively prime to n, i.e., the common factor between them is* 1*, then for any $t \ \in \ [0, n]$ the sequence $s(t) =< t\%(n+1), (t+r)\%(n+1), \ldots, (x+(n-1)r)\%(n+1)$ is a permutation of $< 1, 2, \ldots, n >$.*

Lemma A.1.3. *(Lin, Liu, Chu, and Leung [27]) Given a prime P, if r_1 and r_2 are two different numbers in $(1, P)$, then for any $x_1 \in [1, P]$ and $x_2 \in [1, P]$, there must be an integer $k \ \in \ [1, P]$ such that $(x_1 \ + \ kr_1)\%P = (x_2 \ + \ kr_2)\%P$.*

Proof of Theorem A.1.1: The proof is given for three cases.

Case 1) Time difference i between two users is odd. Since r is a position integer less than or equal to P and assigned to all odd time slots which meet the even time slot of other users. There should be time slots of other users with channel index r. Therefore, a rendezvous occurs within $2P$ time slots.

Case 2) Time difference between two users in even and r of two users are different. According to the result of Lemma A.1.2 and Lemma A.1.3, there should be a rendezvous in an even time slot within $2P$ time slots (P even time slots).

Case 3) Time difference between two users is even and r's of two users are the same. Since every odd time slot has channel index r, if two users have the same r then a rendezvous occurs in every odd time slot.

Using the channel hopping sequence for symmetric model in Theorem A.1.1, we can generate a channel hopping sequence for asymmetric model as in the following theorem.

Theorem A.1.4. (Channel hopping sequence for asymmetric system) Let N be the number of channels in communication environment, G be the number of common channels between two users, and P be the smallest prime greater than N. Let r_1 and r_2 be the index of the best channel of user 1 and 2 such that $1 \le r_1, r_2 < P$. Let the channel hopping sequence $q_i(t)$ for user $i (i = 1, 2)$ be defined as follows

$$q_i(t) = \begin{cases} ((r_i t/2 + \lfloor \frac{t}{4P} \rfloor) \bmod P) + 1, & \text{for } t \equiv 0 \bmod 2 \\ ((r_i + \lfloor \frac{t}{4P} \rfloor) \bmod P) + 1, & \text{for } t \equiv 1 \bmod 2 \end{cases}$$

Then a rendezvous occurs within $4P(P - G + 1)$ time slots.

When $q_i(t)$ generates a number that exceeds the indices, $q_i(t) > G$, the number is replaced with the index of $r_i, (i = 1, 2)$. For instance $q_i(t) = 5$ and it will be changed to $q_i(t) = 2$ if $r_i = 2$.

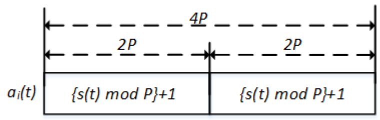


Figure A.1: Relation between $a_i^k(t)$ and $s(t)$.

Proof: For an integer k such that $1 \le k < P$, let $a_i^k(t)$ is defined as follows.

$$a_i^k(t) = \begin{cases} ((r_i t/2 + k) \bmod P) + 1, & \text{for } t \equiv 0 \bmod 2 \\ ((r_i + k) \bmod P) + 1, & \text{for } t \equiv 1 \bmod 2. \end{cases}$$

In the above equation, $a_i^k(t)$ has the repeated form of the sequence in Theorem A.1.1. Using $a_i^k(t)$ we can rewrite $q_i(t)$ as follows:

$$q_i(t) = a_i^k(t), \text{for } k = 1, 2, \cdots, P - 1,$$

where $a_i^k(t)$ can be rewritten by using $s(t)$ in Theorem A.1.1 as in Fig. A.1.

Let i_1 and i_2 be the initial time for user 1 and 2, respectively. Without loss of generality, we can say $i_1 \le i_2$. Then we can define $i'_1 = 0$ and $i'_1 = i_2 - i_1$ and these can be seen as initial time for user 1 and 2, respectively. Fig. A.2 shows the sequence $q_1(t)$ and $q_2(t)$ with the time difference i'_2.

Let us think about the first $4P$ slots of $q_i(t)$ with the existence of time difference i'_2. In the first $4P$ time slots, $a_1^0(t)$ meets $a_2^k(t)$ with the time difference i'_2. Without loss of generality, we can set $0 \le i'_2 < 4P$. As seen in Fig. A.2, there always exist $2P$ time slots that contain $s_1(t)$ and $s_2(t) + k \bmod P$.

From the result of Theorem A.1.1, there must be the same symbol in $2P$ time slots. Since $a_i^k(t) \equiv a_i^0 + k \bmod P$, if there is a time slot with the same symbol at $a_1^0(t)$ and $a_2^k(t)$, then $a_1^m(t)$ and $a_2^{k+m}(t)$ also have the same symbol at the same time slot with the value increased by m.

Therefore, user 1 and 2 show all channels in the environment simultaneously within $4P^2$ time slots. Since two users have G common channels, a rendezvous occurs within $4P(P-G+1)$ time slots by using $q_i(t)$ as channel hopping sequence.

A.1.2 Expected TTR of Symmetric Model

Based on Theorem:A.1.1, we get the following corollary, which provides an upper-bound of the expected TTR of V-HS in the symmetric model.

Corollary A.1.5. *1* The expected TTR of the system using V-HS in Theorem A.1.1 is $(2P^2 - P + 1)/(2P)$.

Proof: To calculate the expected TTR, we should think the following three cases.

Case 1) $r_1 = r_2$ with even time difference.

It is clear that the probability of this case is $1/(2P)$. When $r_1 = r_2$, two users have the same symbol in even time slots. Therefore, a rendezvous occurs at time slot 0. So the expected TTR is 1.

Case 2) $r_1 \neq r_2$ with even time difference.

It is clear that the probability of this case is $(P-1)/(2P)$. When $r_1 \neq r_2$, two

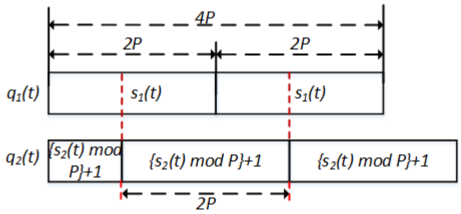


Figure A.2: Channel hopping sequence in first $4P$ time slots.

users have different symbol in even time slots. Therefore, a rendezvous cannot occur at even time slots. For odd time slots, the probability of rendezvous is equal to every time slot. So, the expected TTR is

$$\frac{1}{P}\sum_{i=1}^{P}(2i-1) = \frac{P(P+1)}{P} - 1 = P. \tag{A.1}$$

Case 3) Odd time difference.

It is clear that the probability of this case is $1/2$. In this case, one user's odd time slot always meets the other user's even time slot. So, a rendezvous occurs at the time slot that user 1's odd time slot has the value r_2 or user 2's odd time slot has the value r_1. The probability of rendezvous is equal to every time slot in this case. Therefore, expected TTR in this case is P.

From the results of Case 1) – Case 3), the expected TTR can be calculated as

$$\begin{aligned}
\mathbf{E}[\mathrm{TTR}^{\mathrm{s}}_{\mathrm{sym}}] &= \frac{1}{2P} \times 1 + \frac{P-1}{2P} \times P + \frac{1}{2} \times P \\
&= \frac{1}{2P} + \frac{P(P-1)}{2P} + \frac{P^2}{2P} \\
&= \frac{2P^2 - P + 1}{2P}.
\end{aligned} \tag{A.2}$$

A.1.3 Expected TTR for Asymmetric Model

Based on Theorem A.1.4, we get the following theorem, which provides an upper-bound of the expected TTR in the asymmetric model.

$$\mathbf{E}[TTR^s_{asym}] = \sum_{k=1}^{P} \left\{ 4P(k-1) + \frac{4P^2 - P + 1}{2P} \right\} \left\{ G(P-G)^{k-1} \prod_{j=0}^{k-1} \frac{1}{P-j} \right\}. \tag{A.3}$$

Theorem A.1.6. The expected TTR of the system using V-HS in Theorem A.1.4 is calculated as Eq.(A.3).

Before beginning to prove the above theorem, we should see the following lemma.

Lemma A.1.7. Let N be the number of channels in the system, P be the smallest prime greater than N, G be the number of common channels between two users who want to rendezvous. Then the probability of the system using the channel hopping sequence in Theorem:A.1.4 that a rendezvous occurs at $a_i^k(t)$-k-th component sequence- is calculated as

$$G(P-G)^{k-1} \prod_{j=0}^{k-1} \frac{1}{P-j}. \tag{A.4}$$

Proof: Since the number of common channels is G, it is clear that the probability that a rendezvous occurs at 1st component sequence is G/P.

Let us think about the case that a rendezvous occurs at 2nd component sequence. This means that a rendezvous does not occur at 1st component sequence. Therefore, the channel index that locates at the same time slot for both users' channel hopping sequences is not on the list of common channels. So, we should remove this channel to calculate the probability of rendezvous at 2nd component sequence. With this process, we can calculate the probability that a rendezvous does not occur at 1st component sequence is $(P-G)/P$ and a rendezvous occurs at 2nd component sequence is $G/(P-1)$.

With the similar process of 2nd component sequence, we can calculate that the probability of rendezvous at the k-th component sequence as

$$G(P-G)^{k-1} \prod_{j=0}^{k-1} \frac{1}{P-j}.$$

Proof of Theorem A.1.6: According to Theorem A.1.4, the channel hopping sequence $q_i(t)$ consists of the component sequence $a_i^k(t),\ k = 0, \cdots, P-1$ and $a_i^k(t)$ is a duplication of $s_i(t)$ in Theorem A.1.1. As seen in Fig. 2, average time frame slot until the rendezvous is started in $s_i(t)$ is P. Using the result of Corollary A.1.5, if $a_i^k(t)$ has a common channel between both users, the average TTR in $a_i^k(t)$ is $(2P^2 - P + 1)/(2P) + P = (4P^2 - P + 1)/(2P)$. Since $a_i^k(t)$ is k-th component sequence of $q_i(t)$, the actual expected TTR for $a_i^k(t)$ is $4P(k-1) + (4P^2 - P + 1)/(2P)$. From the result of Lemma A.1.7 the probability of rendezvous at $a_i^k(t)$ is $G(P-G)^{k-1}\prod_{j=0}^{k-1} 1/(P-j)$. Therefore, the expected TTR for asymmetric model using the channel hopping sequence in Theorem A.1.4 can be calculated as Eq. (A.3).

Appendix B

Publications

B.1 Conference

- RPaul and YJ Choi, "Two Step softened decision for cooperative spectrum sensing in cognitive radio network", *ICUFN*, pp. 242-246, 2012.
- YZ Jembre, RPaul, YJ Choi, K-Y Cheon and C-J Kim, "Channel assignment and jammer mitigation for mil33itary MANETs with multiple interfaces and multiple channels", *ACM IMCOM (ICUIMC)*, 2014.
- RPaul, YZ Jembre and YJ Choi, "Multi-Interface Rendezvous in Self-Organizing Cognitive Radio Networks", *IEEE DySPAN*, pp. 531-540, 2014.
- JW Jang, YJ Choi, R Paul and YS Kim, "New channel hopping sequence for cognitive radio systems using p-ary m-sequence", *ICUFN*, pp. 632-634, 2016.
- RPaul, YJ Choi, "Interface selection for D2D communication", submitted in DySPAN, 2017.

B.2 Journal

- RPaul, W. Pak and YJ Choi, "Selectively triggered cooperative sensing in cognitive radio networks", *IET Communications*, vol. 8, issue 15, pp.

2720-2728, 2014.

- YZ Jembre, YJ Choi, RPaul, W Pak and Z Li, "Informed spectrum discovery in cognitive radio networks using proactive out-of-band sensing", *KSII Transactions on Internet and Information Systems*, vol. 8, no. 7, pp. 2212-2230, 2014.

- RPaul and YJ Choi, "Adaptive rendezvous for heterogeneous channel environments in cognitive radio networks", *IEEE Transactions on Wireless Communications*, vol. 15, issue 11, pp. 7753 - 7765, Nov. 2016.