

Minimising TTR for Frequency Rendezvous using Channel Hopping

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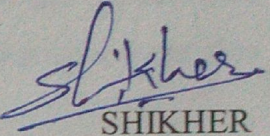
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DECLARATION

I Shikher, hereby, declare that the work presented in the thesis entitled “**Minimising TTR for Frequency Rendezvous using Channel Hopping**” by me in partial fulfilment of the requirements for the award of degree of Master of Engineering in Wireless Communication from Thapar University, Patiala, is an authentic record of my own work under the supervision of Dr. Surbhi Sharma, Assistant Professor, Electronics and Communication Engineering Department. The matter presented in this thesis has not been submitted in any other University/Institute for the award of any other degree.

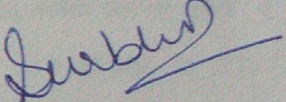
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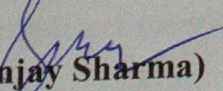
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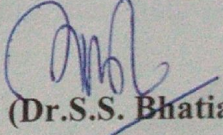
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ABSTRACT

With increasing number of users and limited frequency spectrum, the scarcity of the spectrum has been the real problem in the communication field. It has been analysed that most of the spectrum are not always occupied by the users. It introduces the concept of Dynamic spectrum Access (DSA). DSA is a smart way of using those spectrums which is not being currently used by any other user. This brings Secondary Users (SU) into the picture. SU are those which can use the currently vacant spectrum with a condition that they should leave the spectrum once the licensee of the spectrum comes again. Cognitive Radios are the smart radios which help to achieve DSA.

When DSA is implemented another problem of rendezvous comes. The SU don't have fixed spectrum, they occupy those which they find that are vacant. This leaves it and its peers to find each other in the band of frequency. Another important factor with rendezvous is Time to Rendezvous (TTR). TTR simply means how much time SUs take to rendezvous and it should be as low as possible. Many algorithms have been designed for rendezvous and to minimise TTR.

In this thesis optimized algorithm for low TTR is proposed with a guarantee of rendezvous. The algorithm is based on decentralised network with no control channel. This rendezvous process is also called blind rendezvous. It depends on the number of available channels and has been developed for shared model where radios have frequency numbering, number of available channels in common with no synchronisation with each other. Mathematical analysis has been done. Simulations results are compared with the proposed algorithm. Simulation show the performance of the proposed algorithm is much better than the other. For example, if we take 3 number of PUs, the TTR of the proposed algorithm is 3 but for the other one is 10.

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LIST OF ACRONYMS

PU	Primary User
SU	Secondary User
TTR	Time to Rendezvous
DSA	Dynamic Spectrum Access
FH	Frequency Hopping
CCC	Common Control Channel
MTTR	Maximum Time to Rendezvous
ETTR	Expected Time to Rendezvous

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INTRODUCTION

This chapter introduces with introductory concepts of Dynamic Spectrum Access (DSA). How DSA is achieved, DSA challenges, what is Frequency rendezvous, its strategies and models is discussed. This chapter concludes with introduction to Cognitive Radios and its importance in rendezvous.

1.1 Dynamic Spectrum Access

As the number of wireless users increase the spectrum gets to fill. With the increasing number of such users the spectrum has been filling very fast and such increase has led to the scarcity of the spectrum. This problem is becoming more serious with the way such users are increasing. Fig. 1.1 shows the spectrum utilization of frequency band.

As it can be observed from the Fig. 1.1, many frequencies are almost vacant. These spectrums are licensed, i.e. only those who have the licence are allowed to access their particular spectrum. When these licensed users are not active, these spectrum remain vacant as no other can use these spectrum. Looking onto the figure we could say that the spectrum is underutilized. The spectrum scarcity problem led to the solution to utilize these vacant spectrums when their licensed users are not active. This led to the concept of Dynamic Spectrum Access (DSA). When we talk about DSA [1], we have two types of users; one is Primary User (PU) and second is Secondary User (SU). Primary Users are those who have license to the use of spectrum. Secondary Users are those users who are allowed to use the spectrum when the Primary User is not active. Secondary users does not hold license to that spectrum. The condition for Secondary Users to use the spectrum is that they have to vacant the spectrum as soon as its original licensed user comes back to use its spectrum. After vacating the spectrum for Primary User, Secondary Users searches for another vacant spectrum to continue their communication. This flexible and dynamic method of establishing connection, accessing and using the spectrum in an efficient way is called Dynamic Spectrum Access (DSA).

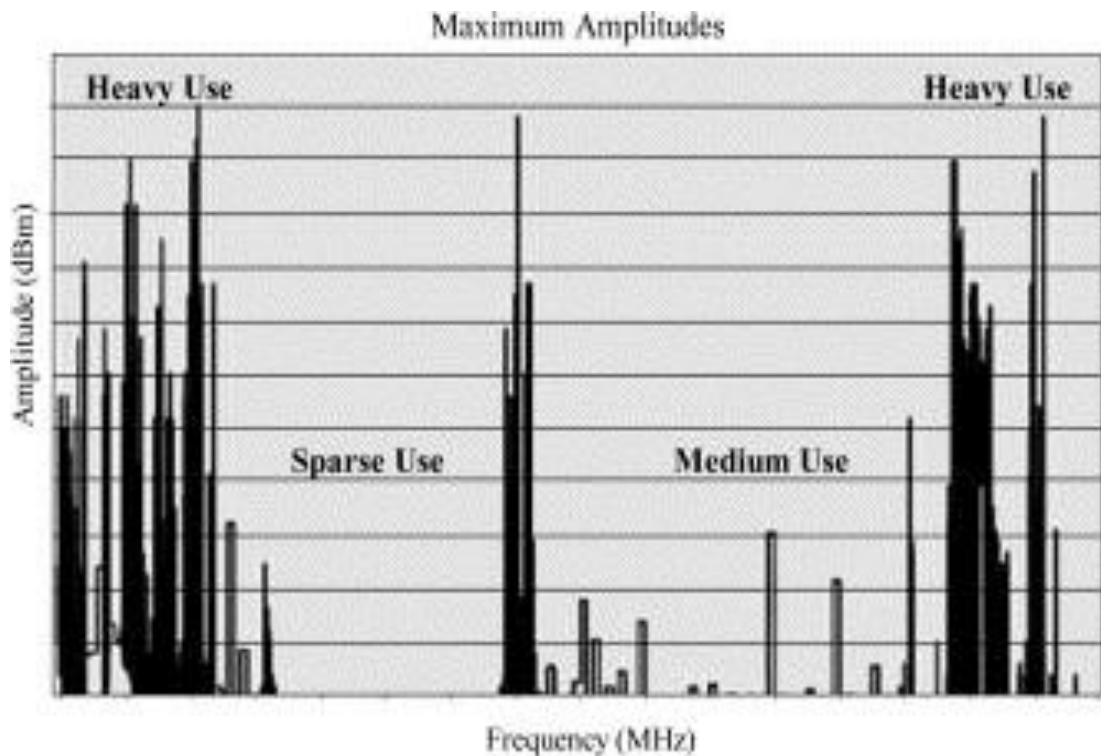


Fig. 1.1: Distribution of users in a frequency band [1].

1.2 How DSA is achieved?

Secondary User should be able to find vacant spectrum, it should also be able to sense when the Primary User has come back to its spectrum so that the Secondary User vacates the spectrum. This sensing and finding the vacant spectrum can be achieved by various ways. It can be centralized or decentralized. It can have dedicated control channel or it can be done without control channel.

When we talk about centralized DSA [2], it means having such a network which has a central hub which controls all the secondary radios and has the information about the spectrum vacancies. In short, in centralised network, central hub manages the entire network. When we talk about decentralised network, the secondary radios are on own to find the vacant spectrum to manage the connection. Centralised network can have control channel(s). Control Channels are used to exchange information between radios for the purpose of rendezvous. The problem with having a dedicated control channel in a network is that if the control channel fails the whole network will come to halt. Therefore, networks where the secondary radios are not dependent on control channels are required. The same problem arises with centralised network where if the central hub fails, the entire network will have to suffer. After researches, the best solution came out was that the secondary users should be smart enough to manage the connection on their

own by finding vacant spectrum. They should also be smart enough to sense the incoming Primary User so that it can vacate the spectrum for them and search for another vacant spectrum to continue their communication.

1.3 Dynamic Spectrum Access Models

Dynamic Spectral Access is the efficient technique to cope up with the problem of frequency spectrum scarcity due to the vastly increasing wireless users. Dynamic Spectrum Access must be able to utilise the vacant spectrum and Secondary User must leave the spectrum when it senses the Primary User coming. This can be achieved by using Cognitive Radios. Dynamic Spectrum Access is basically the smart sharing of spectrum between Primary Users and Secondary Users. Following are the three models [3] of Dynamic Spectrum Access (DSA):

- Interweave Model
- Underlay Model
- Overlay Model

Interweave DSA Model: Interweave DSA is one of the techniques of Dynamic Spectrum Access. In interweave technique the Secondary Users can only have access to the spectrum when the Primary User is absent. The Secondary User needs to vacate the spectrum when Primary User comes and search for next vacant space. The Fig. 1.3(a) illustrates interweave model of Dynamic Spectrum Access.

Underlay DSA Model: In underlay model of DSA, as shown in Fig. 1.3(b), the Secondary User can transmit in the presence of Primary User but with a constraint of signal strength. The Secondary User can use the spectrum even in the presence of Primary User but its signal strength should be well below enough so that it does not create interference for the Primary User. There is a defined threshold of power, below which the Primary User considers noise. This way if Secondary User transmits below that threshold, that will be considered as noise by the Primary User and not affect its performance.

Overlay DSA Model: Similar to underlay model, overlay model in Fig. 1.3 (c) also allows transmission of signal by Secondary User in the presence of Primary User. The basic

difference between the two is the constraint. In the underlay model, the constraint was signal power strength, so that Primary User doesn't get interfered but in overlay model the only thing needs to be taken care is that the performance of Primary User doesn't get deteriorated. The signal strength of the Secondary User transmission can be high, no need to be below a threshold level, if Primary User performance is not compromised. When Primary User sends a packet, the Secondary User captures its packets just to add half of its power to it. When Secondary User transmits its packets, it splits its power into two, half power for its own packet and half for Primary User packet. This way the performance of Primary User doesn't degrade, in fact it enhances. The SINR at the Primary User receiver increases. It can be said that with this overlay model of Dynamic Spectrum Access, both Primary User and the Secondary User get benefited.

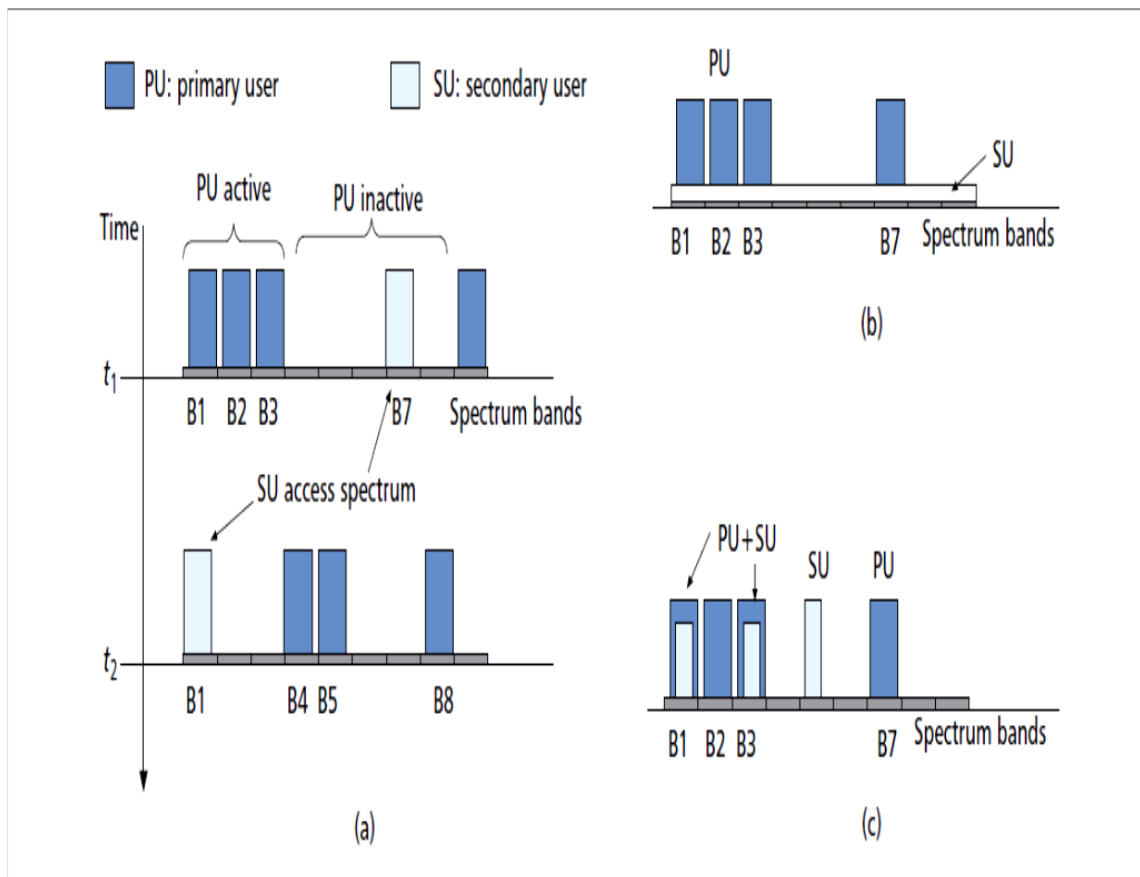


Fig. 1.2: (a) interweave DSA model (b) under lay DSA model and (c) overlay DSA model [3].

1.4 Challenges to DSA

To achieve the DSA, following are the roadblocks which need to be overcome [3]:

- First challenge is to correctly sense the presence of Primary Users: For secondary users to acquire a spectrum channel, a mandatory criterion is no presence of primary user on that particular channel. Therefore, before acquiring a channel, the secondary users must first sense the channel for any presence of primary user. Due to effect of multipath, fading, shadowing it becomes difficult for secondary user radio and it may not be able to detect a present primary user and create interference for it. Under such circumstances cooperative sensing may come to rescue and may be of some help but such sensing creates other sort of problems such as delay, security concerns, freshness of data is also a question here, all these concerns may lead secondary users to take incorrect decision.
- Ability of secondary user radio to distinguish between noise and primary user: The Cognitive Radio must be able to distinguish between a Primary User signal and noise signal. If the Secondary User scans a channel, which is vacant, but due to noise interprets it as occupied leads to incorrect decision.
- Third challenge is the scenario when secondary users are communicating and primary user comes. In such a case, the secondary users need to keep an eye on the primary user. While communicating, secondary user radio need to continuously sense for presence of primary user also. This only increases the overhead.
- If secondary user leaves the channel in between a communication for the primary user, the connection disrupts and secondary user has to re-establish the connection.
- Another challenge is Primary User Emulation (PUE). Whenever secondary user radio detects the incoming primary user, it vacates the channel for the primary user, or secondary user only takes on a channel if spectrum is vacant. PUE is

something where another radio other than Primary User, sends similar signal as primary user on the channels. In such case secondary user thinks primary user is present and it does not access the channel. Interweave DSA model is relief in such cases as secondary users can use the channel with primary user and it doesn't need to keep an eye on the primary user. This way no overhead and no PUE attack.

DSA is opportunistic access of channels in the absence of Primary Users. After finding vacant spectrum, the next step to establish connection for communication is finding the peer radios. This step is known as Frequency Rendezvous which is discussed in detail in following section.

1.5 Frequency Rendezvous

Frequency rendezvous [4] mean meeting at a particular frequency at a particular time. This is essential part for the secondary radios to establish network and to communicate. If two radios need to communicate, they both need to find the vacant spectrum where they can establish network, another task is to find the same spectrum at a particular time slot for both the radios. This is the only way they establish connection. To find the vacant spectrum on own, sensing the presence of Primary User and rendezvousing independently a smart radio is required. This job can be done using a smart radio called Cognitive Radio. In short we can say that to implement Dynamic Spectrum Access successfully, Cognitive Radio is required. Cognitive Radio helps to frequency rendezvous in decentralised networks without control channels.

1.5.1 Frequency Rendezvous strategies

To complete the process of rendezvous, various strategies [5] have been developed. Following are the three strategies mainly used for the rendezvous purpose.

Centralised controller: There is central control which enables radios to find vacant spectrum and find peer radios. This way radios are able to rendezvous. All radios share its information with the centralised controller. The controller stores all the information and guides the radios to achieve rendezvous.

Common control channel: A control channel is used which helps the radios to rendezvous. A common control channel is selected which is known to all the users. The control channel can be local or global. Global control channel is the one which is common to all the radios of the network but local control channels are those which are dedicated for some radios in a cluster.

Channel hopping: Radios hop from one channel to another channel in search of its peer radio. Radios trying to rendezvous hop from one channel to another channel. When the radios hop to the same channel in the same time slot, rendezvous completes.

1.6 Cognitive Radio

Cognitive Radios [2] are such smart radios which have the ability to sense and monitor the condition of the network. They are designed to have high intelligence level, which helps them to use the spectrum in a smart way. Cognitive Radios are able to change their parameters according to the network condition. They have the ability to sense the spectrum, analyze the condition of the network and respond accordingly. Cognitive Radios are always aware of its network and thus are widely used when Dynamic Spectral Access has to be achieved. They also have the knowledge of available bandwidth of spectrum available to the network. Cognitive Radios are smart enough to find for vacant spectrum in a network. It has helped to increase the efficiency of utilisation of the spectrum by providing technique to allow the users to share the spectrum band. With its ability to sense the spectrum, sense the other users, sense its target radio with which it has to communicate, it can rendezvous and establish connection. They are intelligent enough to also find its peer radio for establishing connection. Cognitive Radios have the capability to detect its nearby radios to work with them, to communicate with them to efficiently use the spectrum available to the network. Cognitive Radios are able to decide the strength of signal to transmit so that it does not interfere with the Primary User. There is threshold strength for Primary Users, below which they consider it as a noise. Cognitive Radios smartly communicate below this threshold, so that Primary User should not get interfered. Such smartness to identify vacant spectrum, identify Primary Users, calculate signal strength to ensure no interference to Primary Users can be found in Cognitive Radios. Following we discuss the characteristics of Cognitive Radios which is important to achieve the rendezvous [2], [6].

Cognitive Capability: The ability of the Cognitive Radios to gather the information about the network by sensing its surrounding is called Cognitive Capability. To decide the spectrum to switch to, to sense the Primary User's presence, such characteristic is necessary.

Spectrum Sensing: Spectrum sensing is the ability of the radios to find vacant spectrum and the presence of the Primary User (PU) using any technique of sensing discussed later.

Spectrum Decision: Ability to decide which spectrum to occupy in the available vacant spectrums based on channel capacity, channel bandwidth. It is the ability to choose best channel to establish the connection.

Configurability: After gathering information from the surroundings, after sensing the network its turn for the radio to adjust its parameter according to the network. Configuring its parameter such as signal strength, frequency of transmission according to the network condition at that particular time is called configurability.

Both the above characteristics of the Cognitive Radio make the radio work as it is made for.

1.6.1 Cognitive Radio Functions

Cognitive Radios have to perform various functions such as sensing for vacant spectrum, sensing Primary User to vacate the spectrum for them, coordinating with its peers for accessing same spectrum for communication, calculating the signal strength for transmission to not to create interference for the Primary Users. We can thus say Cognitive Radios have following functions to perform to achieve rendezvous [2]:

Spectrum sensing and analysis: Cognitive Radios should be able to detect vacant spectrums in the network, called as White Space, as shown in Fig. 1.3.

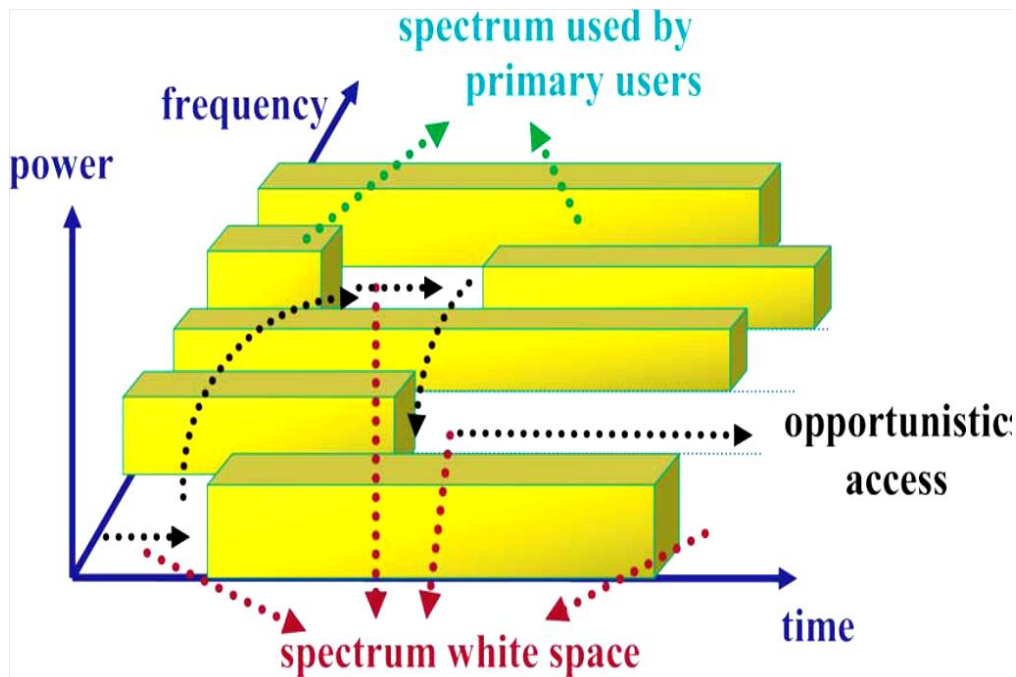


Fig 1.3: White spaces in frequency for opportunistic access [2].

Further, the Cognitive Radio must be able to sense incoming Primary User so that it can vacate the occupied spectrum for them.

Spectrum management and handoff: When the Primary User comes back to its spectrum, the Cognitive Radio must be able to jump to another available vacant channel in the network without breaking the connection. This process is called handoff.

Spectrum allocation and sharing: Spectrum allocation and sharing mechanism is very important when it comes to Dynamic Spectrum Access. Cognitive Radios allocate the frequency from the spectrum after sensing the vacancy. Sharing the same frequency spectrum with the Primary User is very important to use the spectrum efficiently.

1.7 Organisation of the Thesis

Chapter 1 (Introduction) is the introduction of Dynamic spectrum Access, Frequency Rendezvous, Frequency Rendezvous strategies, Cognitive Radio with its importance, characteristics and functions. The chapter concludes with the challenges in DSA.

Chapter 2 (Frequency Rendezvous and TTR) has explained the details of Frequency Rendezvous, methods, systems, models and classification. The chapter also includes the

introduction of spectrum sensing and its technique. The chapter wraps up with explanation of channel hopping, slotting and properties of frequency rendezvous.

Chapter 3 (Literature Survey) includes some of the literatures introducing algorithms and schemes for frequency rendezvous and TTR.

Chapter 4 (Methodology) has the complete explanation of the proposed algorithm with focuses on reducing TTR while frequency rendezvousing.

Chapter 5 (Simulation Result) shows the performance of the proposed algorithm. It shows how the algorithm performs in terms of expected and maximum TTR with increasing number of PUs and channels.

FREQUENCY RENDEZVOUS AND TTR

This chapter includes the detailed discussion on the topics mainly focused for the thesis. Frequency Rendezvous is explained with methods, systems, models and classification with some issues in decentralised network. The spectrum sensing is introduced with some techniques. This chapter concludes with slots in rendezvous, concept of Channel Hopping (CH), performance parameter and properties of frequency rendezvous.

In a DSA network, when two radios want to communicate they need to find each other after finding a vacant spectrum. Whenever a radio enters a network, first of all it needs to find a vacant spectrum. Another task is to find its peer radio to establish a connection for communication. This process in which a radio meets its peer radio on a specific vacant spectrum is called Frequency Rendezvous. When we talk about Dynamic Spectrum Access, only Frequency Rendezvous is not important. It's very important that radios find each other in minimal time to establish a fast connection. The faster the establishment is, the faster the rendezvous occur more efficient and more the good the system is considered. So, after entering the network the radios take some finite time to complete rendezvous. This finite time taken by the radios to rendezvous is known as Time to Rendezvous (TTR). We will start this chapter with frequency rendezvous, but before that we will have a look at some assumptions regarding DSA networks and user's hardware:

- All rendezvous channels in a DSA network are known to all the nodes in the network. Information about rendezvous channels of a DSA network can be announced by regulation authorities such that all secondary users wishing to join the network will have this information.
- Each node is equipped with a single transceiver, which means at a certain time point a node can only engage in a channel for communication. This assumption is in accordance with the ability of most commodity wireless devices.
- Each node is able to switch its working channels with negligible overhead. This assumption is valid because most wireless hardware manufacturers claim that the channel switching delay is of the order of 80-90 micro sec. This delay is negligible compared to the length of a slot in a hopping sequence.

2.1 Frequency Rendezvous based on Network

In Dynamic Spectrum Access network, Frequency Rendezvous can be achieved in centralised and decentralised network [5], [7].

Centralised Network: Centralised means there is a central system which controls the network and helps the radios to rendezvous. A central hub is present which has control over the network and contains information about the availability of the network spectrum. Radios trying to rendezvous are helped by this hub to find each other on same spectrum and establish connection. This central hub type network has its own demerit. The entire network would come to halt, if the central hub fails because the entire network is dependent on it. Centralised networks can be used with common control channel also. Common control channel eases the connection between the radios and the rendezvous process. Using common control channel has also many disadvantages like

- Congestion
- Maintenance is hard and sometimes impractical
- Attack on the network through the common control is easy e.g. jamming attack, attack on information etc.

Using common control channel increases risk of failure because whole system will come to halt if the control channel fails.

Decentralised Network: As in the case of centralised network where the entire network was dependent of a central system, opposite to that in decentralised network the radios are on their own to find vacant spectrum and rendezvous. When the radios in network have no help from something like central system, when radios are in not in control of anything called central system, the system is called as decentralised one. There are two ways of creating decentralised network:

- With Control Channel
- Without Control Channel

Decentralised Systems using control channel: Control channel helps the radios to rendezvous, but it also has the demerit of being the failure point. In a control channel

utilising network, radios rendezvous with the help of control channel but the control channel again has the same demerit as the central hub has. If the control channel fails, the radios will not be able to rendezvous and the communication network will come to halt. Moreover when the network is very large, the concept of common control channel becomes tedious.

Decentralised Systems without control channel: Radios in network without control channel will have to rely on their intelligence and ability to sense the network to find the vacant channel and its peer radio to establish the connection. Also called blind rendezvous when radios try to rendezvous in such networks. The basic technique used in such systems is channel hopping technique. Channel hopping technique is the technique in which radios hops from one channel to another. When two radios hops onto same channel in the same time slot the rendezvous occur.

2.1.1 Issues with Decentralised Networks

With advantages over centralised networks, decentralised networks also have some issues with them which need to be taken care of. Control channel is one of the issues related to decentralised network. Dedicate control channels to the network do help in finding vacant channel for rendezvous, but it always has risk of failure. Its failure will result in complete network failure.

When we talk about rendezvous, radios need to visit the frequency spectrum one by one in search of vacant spectrum and in search of its peer radio. The order in which the radio visits the frequencies needs to be flexible. If the visiting order is predefined and fixed, the flexibility doesn't remain.

Therefore, we should look for such a network which does not depend on control channel. In such a case the radios should be smart enough to assess the network for vacant spectrum.

2.2 Rendezvous based on number of SU

The rendezvous algorithms can be classified in two different operations based on the number secondary users involved in the process of rendezvous at the same time [8].

Unicast Rendezvous: The unicast algorithm is designed when only two users want to rendezvous with each other in a network.

Multicast Rendezvous: When more than two secondary users want to rendezvous with themselves in a network in same time slot, then such designed algorithm is called as multicast rendezvous. Following are some methods to achieve such rendezvous

- Designing different frequency hopping sequence that overlaps at common slots.
- Using a series of unicast rendezvous to make secondary users tune to common slot.

Such multicast algorithms have security issues. If any one of the secondary user gets attacked or compromised then all the nodes will be exposed because they all are sharing same frequency hopping sequence. The remedy can be using different frequency hopping sequence for different pairs of secondary user; this way if one secondary user gets attacked other secondary users are not affected.

2.3 Properties of Frequency Rendezvous

To evaluate a rendezvous algorithm, following are the criterion used [9]:

Asynchronous Rendezvous support: When we are dealing with decentralised network, achieving time synchronisation is difficult, therefore, the algorithm designed for rendezvous purpose should work well when radios are not synchronised.

Guaranteed Rendezvous: The algorithm should be able to complete the rendezvous process in finite number of time slots. There may be some algorithms which, on an average, give good result in terms of TTR but the maximum time taken to rendezvous is infinite. That is, there is a possibility that the radios keep on finding themselves for infinite time or never able to find each other. Guaranteed rendezvous is the property of any algorithm that assures there is not any chance that the radios will not be able to find themselves, even if TTR goes high.

Asymmetric Model support: The algorithms for rendezvous should not fail if different users observe different number of channels. Algorithms should equally support asymmetric model.

Low TTR: The rendezvous process should be able to complete in minimum number of time slots. Delay in connection is the problem which is not an option in today's communication system thus the rendezvous should be completed in as minimum time slots as possible.

2.4 Rendezvous Methods

Various researches have been done to formulate rendezvous methods. Some of the rendezvous methods have been discussed below:

Common Control Channel: Control channel [4] helps the radios to rendezvous and establish link for communication. The control channel can be dedicated and cluster based. The dedicated control channel is shared by all the users in the network whereas cluster based control channel is used by users arranged in clusters. The problem with control channels is that it is a single failure point for the users.

Grid Based quorum system: In Grid based quorum system [4], the channels are arranged in a square matrix as shown in the Fig. 2.1. K number of channels are selected from the total number of available channels, where $K = 2\sqrt{N}$, and N is total number of available channels.

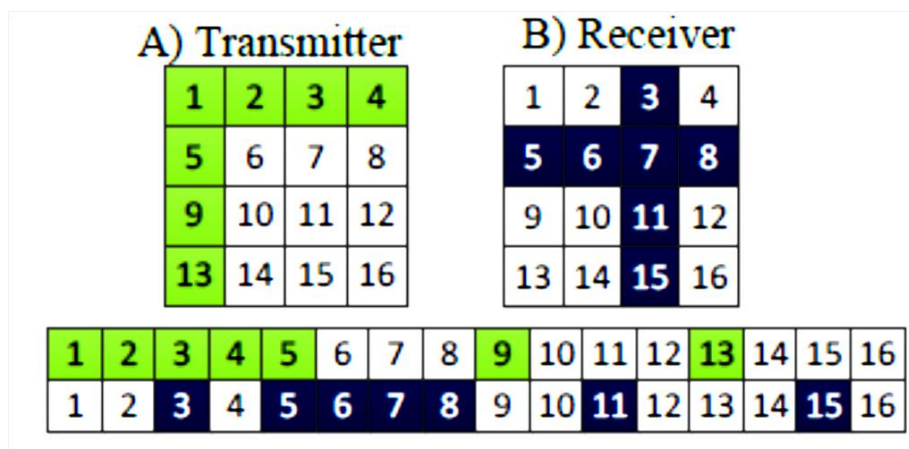


Fig. 2.1: Frequency Hopping sequence for transmitter and receiver using Grid based quorum system [4].

Torus quorum system: $R+S/2$ elements are selected from a matrix of $R \times S$. A column is selected and one element from other column is selected in backward and forward direction as shown in the Fig. 2.2.

Forward					
0	1	2	3	4	5
6	7	8	9	10	11
12	13	14	15	16	17

Backward					
0	1	2	3	4	5
6	7	8	9	10	11
12	13	14	15	16	17

Fig. 2.2: Torus quorum system sequence model [4].

Uniform k-arbiter method: Above methods are not applicable for multicast networks. This method, k-arbiter [4], is used for multicast networks.

Modular clock Method: In Modular clock method [7], a hopping sequence is prepared according to a random jump pattern. Radios hop from one channel to the other until both radios fall onto same channel is same time slot.

Cluster Method: In cluster [5], Radios find the other target radio where the population of radios is more. Finding of target radio in most populated region is more.

Ring Walk: The available channels are arranged in vertex of a circle [10], where users hop with different velocities. The faster user is always able to catch the slower one or stopped one. This guarantees the rendezvous.

Short Sequence: All the users have same labels for the channels in short sequence [11]. Every user has the same start channel and end channel in the sequence of available channels. The user hops from origin of the sequence till the end, and then again in backward direction from end to the origin. This way they may find its peer. If not, they will stay at the origin for one time slot and then again start the hopping in the same pattern. The radio which started later will be found by the other when returning back

from end channel to original channel. This algorithm works well for symmetric and asymmetric models.

Multiple Radios- More than one radio is used to speed up the rendezvous process [12]. Different radios scan different frequency channel to speed the rendezvous process. One of the many radio can also wait on a particular channel while all other scan the channels.

Channel Hopping: The radios are made to hop from one channel to the other in a random or predefined manner. The hopping can also depend on various conditions. The hopping continues until radios to rendezvous hop to a common channel in the same time slot.

2.5 Rendezvous Network Models

We can classify networks into different models on the basis of various features such as roles, naming network conditions etc. The various models are as follows [7]:

	Assisted	Roles	Shared	Individual	Free-for-all
Synch available	●	●			
Heterogeneous roles	●	●			
Number radios	n	2	2	2	n
Common naming	●	●	●		
Wideband	●				
Fairness	●	●	●	●	
Control channels	●				
Master controller	●				
Common spectrum	●	●	●		
No detection errors	●	●	●	●	
No malicious radios	●	●	●	●	

Fig. 2.3: Rendezvous network models [7].

Assisted Model: Assisted models have synchronisation between radios. When one radio transmits other radio doesn't miss the transmission nor causes interference to other radios. These models have heterogeneous roles of radios, i.e., radios can perform different roles for rendezvous process. For example if one radio is broadcasting a beacon to send its presence signal, other radio may be in searching process for this beacon. This way, if one broadcasts its presence and one search for such broadcast, rendezvous can occur. The number of radios in assisted model can be more than two. The rendezvous is considered successful in assisted type model if all the radios are able to rendezvous. Assisted model bears same name for all frequency spectrum. The index name of each frequency spectrum is common. If one radio has named a particular spectrum as 1, then all the radios have named that same frequency spectrum as 1. In such network model, all radio names the frequency channel commonly. Only this model has the facility in which radios can broadcast itself or search for its peer radio on multiple channels. This simplifies the rendezvous process at the cost of hardware. As far as this model is considered, radios can rendezvous on any of the observed channel. Each of the observed channels has equal probability of rendezvous. Rendezvous can be done on any vacant rendezvous channel of the network. Assisted model also offer control channel. Control channels are those which help in rendezvous. These models can also have a master controller which can help in finding vacant spectrum and spectrum allocation. It is not necessary that all radios can observe same number of available channels or exactly same channels. The spectrum common to all the radios are only considered for rendezvous purpose. This assisted model says all radios sense common spectrum. The spectrums observed by all its radios are common to all the radios. When finding for vacant spectrum, there is a possibility that radios considers a spectrum vacant even when a PU is present or other SU is already present. Such problem does not occur in assisted model because it has no detection error. The possibility of having malicious radios trying to interrupt the rendezvous process is also nil in this rendezvous model.

Roles Model: Roles models have synchronisation between radios. When one radio transmits other radio doesn't miss the transmission nor causes interference to other radios. These models have heterogeneous roles of radios, i.e., radios can perform different roles for rendezvous process. For example if one radio is broadcasting a beacon to send its presence signal, other radio may be in searching process for this beacon. This way, if one broadcasts its presence and one search for such broadcast, rendezvous can

occur. The number of radios in roles model can be only two. Roles model bears same name for all frequency spectrum. The index name of each frequency spectrum is common. If one radio has named a particular spectrum as 1, then all the radios have named that same frequency spectrum as 1. In such network model, all radio names the frequency channel commonly. Radios can broadcast it and search for peer model on one single frequency at one time. As far as this model is considered, radios can rendezvous on any of the observed channel. Each of the observed channels has equal probable of rendezvous. Rendezvous can be done on any vacant rendezvous channel of the network. Roles model does not offer control channel. Control channels are those which help in rendezvous. This model also does not have a master controller which can help in finding vacant spectrum and spectrum allocation. It is not necessary that all radios can observe same number of available channels or exactly same channels. The spectrum common to all the radios are only considered for rendezvous purpose. This roles model says all radios sense common spectrum. The spectrums observed by all its radios are common to all the radios. When finding for vacant spectrum, there is a possibility that radios considers a spectrum vacant even when a PU is present or other SU is already present. Such problem does not occur in roles model because it has no detection error. The possibility of having malicious radios trying to interrupt the rendezvous process is also nil in this rendezvous model.

Shared Model: Shared model does not have synchronisation between radios. These models also don't have heterogeneous roles of radios, i.e., radios cannot perform different roles for rendezvous process. The number of radios in shared model can be only two. Shared model bears same name for all frequency spectrum. The index name of each frequency spectrum is common. If one radio has named a particular spectrum as 1, then all the radios have named that same frequency spectrum as 1. In such network model, all radio names the frequency channel commonly. Radios can broadcast it and search for peer model on one single frequency at one time. As far as this model is considered, radios can rendezvous on any of the observed channel. Each of the observed channels has equal probable of rendezvous. Rendezvous can be done on any vacant rendezvous channel of the network. Shared model does not offer control channel. Control channels are those which help in rendezvous. This model also does not have a master controller which can help in finding vacant spectrum and spectrum allocation. It is not necessary that all radios can observe same number of available channels or exactly same channels. The spectrum

common to all the radios are only considered for rendezvous purpose. This shared model says all radios sense common spectrum. The spectrums observed by all its radios are common to all the radios. When finding for vacant spectrum, there is a possibility that radios considers a spectrum vacant even when a PU is present or other SU is already present. Such problem does not occur in shared model because it has no detection error. The possibility of having malicious radios trying to interrupt the rendezvous process is also nil in this rendezvous model.

Individual Model: Individual model does not have synchronisation between radios. These models also don't have heterogeneous roles of radios, i.e., radios cannot perform different roles for rendezvous process. The number of radios in individual model can be only two. Individual model does not bear same name for all frequency spectrum. The index name of each frequency spectrum is not common. In such network model, all radio does not names the frequency channel commonly. Radios can broadcast it and search for peer model on one single frequency at one time. As far as this model is considered, radios can rendezvous on any of the observed channel. Each of the observed channels has equal probable of rendezvous. Rendezvous can be done on any vacant rendezvous channel of the network. Individual model does not offer control channel. Control channels are those which help in rendezvous. This model also does not have a master controller which can help in finding vacant spectrum and spectrum allocation. It is not necessary that all radios can observe same number of available channels or exactly same channels. The spectrum common to all the radios are only considered for rendezvous purpose. This individual model says all radios cannot sense common spectrum. The spectrums observed by all its radios are not common to all the radios. When finding for vacant spectrum, there is a possibility that radios considers a spectrum vacant even when a PU is present or other SU is already present. Such problem does not occur in individual model because it has no detection error. The possibility of having malicious radios trying to interrupt the rendezvous process is also nil in this rendezvous model.

Free for all Model: Just like assisted model, it can have more than two radios for rendezvous. Rendezvous process will only be considered completed when all the radios have rendezvoused. Besides, this model has no synchronisation. These models also don't have heterogeneous roles of radios, i.e., radios cannot perform different roles for rendezvous process. This model does not bear same name for all frequency spectrum. The

index name of each frequency spectrum is not common. In such network model, all radio does not names the frequency channel commonly. Radios can broadcast it and search for peer model on one single frequency at one time. As far as this model is considered, radios cannot rendezvous on any of the observed channel. There is no fairness amongst the channels. This model also does not offer control channel. Control channels are those which help in rendezvous. This model also does not have a master controller which can help in finding vacant spectrum and spectrum allocation. It is not necessary that all radios can observe same number of available channels or exactly same channels. The spectrum common to all the radios are only considered for rendezvous purpose. This model says all radios cannot sense common spectrum. The spectrums observed by all its radios are not common to all the radios. The problem of false detection can occur in this model, when finding for vacant spectrum, there is a possibility that radios considers a spectrum vacant even when a PU is present or other SU is already present. The possibility of having malicious radios trying to interrupt the rendezvous process is also present in this rendezvous model.

Other than these given rendezvous models, different models can be classified as symmetric and asymmetric models

Asymmetric model: When all the radios trying to rendezvous observe different channels for rendezvous, then it is called asymmetric model. Due to various reasons and different capabilities of the radio, the radios are not able to recognise all the available channels of the spectrum. All radios observe the available channel differently. Some particular channel is observed by some but not by some others. When this situation occurs, this type of network is called asymmetric model.

Symmetric model: When radios trying to rendezvous observe same channels for rendezvous, then it is called symmetric model. When an assumption is made that all the radios have equal capability and ability to observe the spectrum, all radio observe the available channel exactly in same way. Some rendezvous algorithms are specifically for symmetric model that do not run for asymmetric model.

2.6 Time Slot in Rendezvous

The rendezvous is a process which has to be followed to complete it. In rendezvous, the radios transmit beacon and listen for others beacon. The basic purpose is to tell other radio about its presence and listen to other radios if there is radio present at any certain frequency or not. Radios tell about its presence by transmitting a beacon signal which other radios can listen. If some radio listens to this beacon they can understand that a radio is present at this particular frequency. Radios must also go to listen mode if want to find other radios. In listen mode [7] they can hear the beacon if any radio is transmitting it. This transmitting of beacon [7] and listening to the beacon helps the radios to find each other. When the radios find each other then they can check if it's the target radio which it was searching for or not. If that radio is the target radio they can proceed with the handshake process or else again start searching for other radio by continuing transmitting beacon and continuing listening to other beacon. The Fig. 2.4 explains the rendezvous process in terms of time slot.

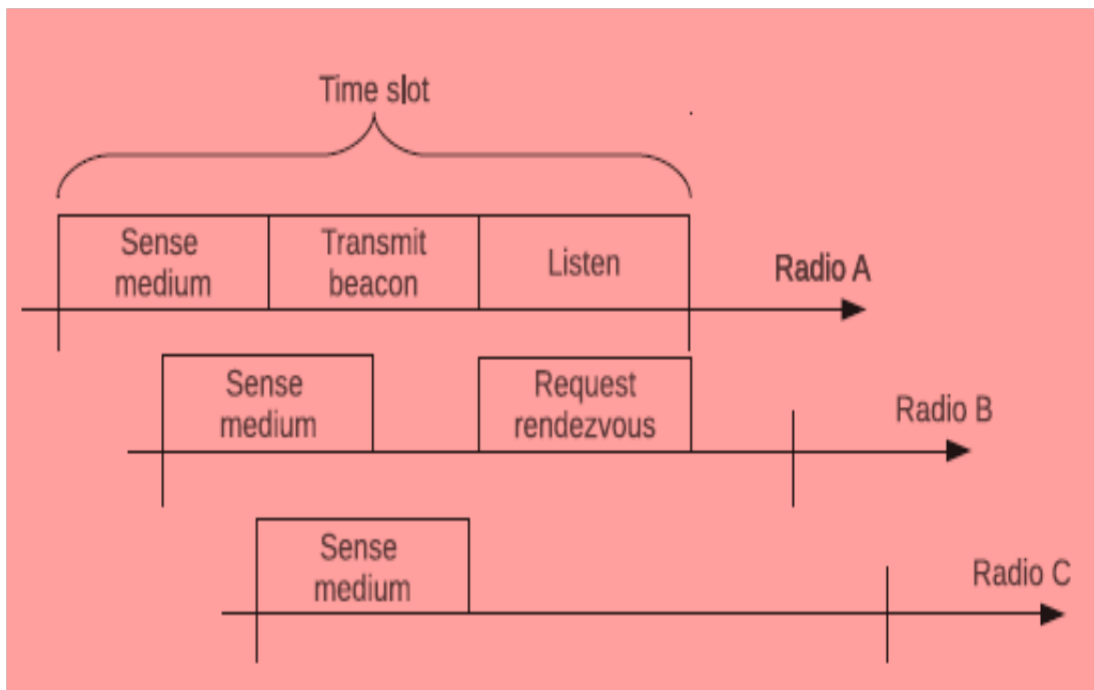


Fig. 2.4: Modes of one time slot [7].

In the Fig. 2.4, radios are first sensing the medium, then transmitting beacon and then entering the listen mode. The entire three modes are done only in one time slot. The first mode is sensing of medium. In this mode, the radio first senses if there is any PU or SU already present in the channel. The radios visit each channel and first sense the medium.

If any PU or SU is already present in that channel, it moves on to other channel and senses again. If the radio finds no other radio already occupying the channel, it transmits its beacon to make its presence known for other radios. After transmitting the beacon, it enters the listen mode, to listen if other radio is transmitting its beacon or other radio is transmitting the response after listening to its beacon. All these three modes occur in one single time slot. All the radios follow same mechanism and this results in successful rendezvous.

The Fig. 2.4 shows that for rendezvous synchronisation in time slot is not necessary. If we take radio B, we can see from the Fig. 2.4 that it can hear the radio A's beacon even if its time slot is not synchronised with radio A. Same goes for radio C. Radio C can also hear the beacon of radio A even though its time slot is not synchronised with that of radio A and rendezvous can occur. This proves that for rendezvous to occur, synchronisation in time slot is not necessary.

2.7 Channel Hopping

Channel hopping is the technique radios use to rendezvous when the network is decentralised and is without any control channel. In channel hopping, radios jump from one channel to another in search of vacant spectrum and its peer radio. When two radios jump to a same channel in the same time slot, the rendezvous completes. The channel hopping can be random, predefined or based upon any particular condition. The channel hopping sequence falls under following categories [13]:

Random sequence: There is no predefined sequence for the radios nor there is any algorithm through which radios can derive the sequence of hopping. Radios randomly hop from one channel to the other.

Predefined sequence: The sequence in which radios have to hop from one channel to another is already known to the radio. The sequence is strictly followed by the radios. The radios always follow the same predefined sequence until rendezvous occurs.

Sequence based on condition: The hopping sequence of the radios is decided by following an algorithm. The radios decide its own algorithm according to the conditions such as number of channels.

Sequence with synchronisation: Such hopping sequence requires time synchronisation between the radios looking to rendezvous. The start time of time slots of the radios to rendezvous and end time of time slots of the radios to rendezvous should match to guarantee the rendezvous.

Sequence without synchronisation: These hopping sequences do not require any time synchronisation in the time slots of the radios.

The Channel Hopping (CH) sequence designing should follow some specific rules so that rendezvous is possible. Therefore, the design requirement for CH can be summarised as follows [14]:

Overlap Requirement: The CH sequences of two radios must overlap so that in order to ensure that the radio will fall on to the common channel in one time slot to complete rendezvous process.

Full Utilization of Rendezvous Channels: The nodes must be able to utilise the entire available channels for rendezvous purpose.

Even Use of Rendezvous Channel: All the channels must occur with equal probability in any CH sequence. If any channel occurs for more number of times than other, the user at that channel will lose contact with other users if that channel is occupied by a Primary User (PU).

2.8 Performance Parameter

As discussed, best way for radios to rendezvous is adopting channel hopping algorithm. Different algorithms have been proposed in frequency rendezvous, some better than the other in one way or the other. The ways these algorithms are compared are based on some parameters. To judge which algorithm is better than the other, following parameters are considered [14], [15], [16]:

Maximum TTR: MTTR is upper bound for time to rendezvous. It denotes the maximum time an algorithm can take to complete the rendezvous process once the radios enter the network. For a good algorithm, MTTR should be as low as possible.

Average TTR: Average or expected TTR is the average time taken by the radios to rendezvous. The time to rendezvous is always counted from the time the radios have joined the network till the rendezvous process gets complete.

Rendezvous channel diversity rate: It is the ratio of number of channels where radios can attempt to rendezvous to the total number of available channels. Hence, it ranges from 0 to 1. Channel diversity rate should be as high as possible and close to 1. We want that the radios can attempt to rendezvous on any channel because of many problems like congestion, eavesdropping, attack etc. Hence, it is important that radios have many options of channels to rendezvous to minimise such problems.

Average Rendezvous channel load: The average number of users meets at a particular rendezvous channel. The average rendezvous channel load should be as low as possible because lower the rendezvous channel load lower is the traffic collision and more is the available communication bandwidth.

Rendezvous channel utilization ratio: Ratio between the number of channels which are available as control channel in a hopping slot among the rendezvous channel and total number of rendezvous channel. Higher the utilization ratio more is the network capacity. It should be as high as possible.

Rendezvous Interval: The number of time slots between two consecutive rendezvous is known as Rendezvous interval.. Ideally the Rendezvous interval should be as low as possible.

Number of Rendezvous: The total number of rendezvous in a given time slot. The more the number of rendezvous in a given time slot, the better the system is considered. It shows the ability of the system, how it is able to manage multiple numbers of rendezvous.

LITRETURE SURVEY

This chapter contains the reviews of different schemes and algorithms proposed in the literature on Frequency Rendezvous, Channel Hopping and TTR.

Nick C. Theis, Ryan W. Thomas and Luiz A. DaSilva in [7] proposed modular clock algorithm which is a frequency hopping algorithm for cognitive radios. The cognitive radios hops through the channel making a certain number of channel jump. After every time slot radio jumps r channels, using wrapping around, until it finds its target radio. If radio is not able to rendezvous in $2p$ time slots, then radios change it r , where p is smallest prime number greater than m , which is number of observed channels. The performance of this algorithm is analysed using both shared and individual model. Modified Modular clock is also proposed which ensures guarantees rendezvous under all circumstances in individual model.

In [5], **Di Pu, Alexander M. Wyglinski and Mike McLernon** proposed a frequency rendezvous algorithm which uses pilot tone and spectrum sweeping to find its target radio. Channels with pilot tones are scanned for target radio. It is proved that the cluster scanning sequence takes lesser time to rendezvous than other given scanning sequences such as pilot tone strength scanning and frequency sequence scanning using simulations and mathematical derivations. The algorithm has been simulated in three scenarios, one using uniform distribution of radios, second using Gaussian distribution of radios and last being the actual spectrum measurement of paging band signal. It is proved that in any scenario cluster scanning of the radios takes lesser time than the other two.

In jump and stay algorithm proposed by **Zhiyong Lin, Hai Liu, Xiaowen Chu and Yiu-Wing Leung** in [13] for rendezvous makes radio to be in jump mode where they jump from one channel to other and then in stay mode where they stay in a particular channel. Rendezvous can occur between radios in any of four permutations, i.e. jump-jump, stay-stay, jump-stay and stay-jump. It provides guaranteed rendezvous without synchronisation between nodes. For multiuser and 2 user scenario maximum and average TTR is derived. Theoretical and simulations are done to show TTR.

Uniform k-arbiter and Chinese remainder theorem is used to develop frequency hopping sequence for multicast rendezvous in [8] by **Mohammad J. Abdel-Rahman, Hanif Rahabari and Marwan Krunz**. Fast PU dynamics, i.e., time a PU occupies its channel, is considered while designing the frequency hopping algorithm. Low average TTR and security is traded off in the proposed frequency hopping algorithm. The algorithm developed is for asynchronous heterogeneous DSA system.

In [16], **Lin Chen, Shuyu Shi, Kaigui Bian and Yusheng Ji** optimised the maximum TTR and average TTR. A hybrid hopping sequence is proposed which has property of both random hopping, which provide best average TTR but no guarantee of rendezvous, and sequence based hopping which provides maximum TTR. The radios work in two modes awake and sleep mode. In awake mode it follows sequence based hopping and random hopping in sleep mode. The algorithm has been simulated to prove that both average TTR and maximum TTR has improved.

Ram Narayan Yadav and Rajiv Mishra in [17] developed an algorithm for both symmetric and asymmetric algorithm. The sender and the receiver generates independent hopping sequence. The sender jumps every channel one by one from starting to end and then again from end to start making complete on cycle in $(2M-1)$ time slots where M is the number of channels. The receiver's one cycle is $M(2M-1)$ time slots long, it hops from start to end channel spending $(2M-1)$ time slots on each channel. It guarantees rendezvous with upper bound of $(2M-1)$ in symmetric model and $M(2M-1)$ time slots in asymmetric model. Mathematically and through simulation, it is proved that average TTR is $(M-1)$.

Sequence based Rendezvous for DSA is proposed by **Luiz A. DaSilva and Igor Guerreiro** in [18]. The radios visit the channels in predefined sequence. The channel selected permutation appear $N+1$ times in a cycle, N is number of channels. N times permutation appear contiguously and once the permutation appear interspersed with the other N permutations. Given algorithm doesn't require synchronization in radios. Closed form expression has been derived for average and maximum TTR. Probability of rendezvous for best and worst channel is also derived. Simulations have been done for expected and maximum TTR.

In [19], **Milan Nosovic and Terence D. Todd** worked on scheduled rendezvous using RFID technology. It uses low power wakeup mechanism and uses very low power. The power utilization of RFID scheduled and general scheduled rendezvous is compared.

Link Rendezvous approach proposed by **Brent Horine and Dalma Turgut** in [20] minimises unintentional interference during rendezvous using low power attention signal. Attention signal can be detected even if in a high noise environment if its length is equivalent to one FFT frame. The attention signal is of low bandwidth.

Nicola Baldo, Alfred Asterjadhi and Micheel Zorzi in [21] presented an algorithm for DSA based on network coded cognitive control channel. It is a distributed model DSA algorithm. Proposed algorithm creates very low interference for Primary User and provides efficient spectrum utilization.

I-Hsun Chuang, Hsiao-Yun Wu, Kuan-Rong Lee and Yau-Hwang Kuo in [22] proposed hop and wait algorithm. One of the two radios to rendezvous hops around the channel and the other one waits at one channel. The hopping radio meets the waiting radio at one channel to rendezvous. The other radio must be in the waiting mode until M time slots, where M is the number of channels, to guarantee rendezvous. This algorithm is applicable to symmetric and asymmetric models. It shows low average and maximum TTR in simulations and theoretical proofs. Analysis shows hop and wait algorithm performs well in all scenarios.

In [23], **Zhaoquan Gu, Qiang-Sheng Hua and Weiguo Dai** proposed local sequence based algorithm. In general global sequence, redundant channels are used which increases the TTR and does not help in rendezvous. In local sequences this redundancy is removed.

Dhananjay Kumar, A. Magesh and U.Mohammed Hussain in [24] predicts the local of the target radio by using time of previous rendezvous. Every radio has a stay value, which is the number of time slots that radio stays at a channel. It also has last channel and time of rendezvous with that target radio in its memory. Using its memory and time

elapsed since its last rendezvous it calculates the channel at which the target radio might be. It also shows that the probability of rendezvous in its very first attempt is very high.

Sutton P.D., Nolan K.E. and Doyle L.E. in [25] proposed rendezvous technique using cyclostationary signatures. It is a water mark embedded in the transmitted signal so that when the signal is received, it can be distinguished and detected by its peers. They have shown it the best mechanism when it comes to OFDM signals in DSA. They have introduced the technique to generate the cyclostationary signatures using OFDM and have shown that OFDM is the best technique to generate cyclostationary signatures.

Sequence detection algorithms of Markov sources in noise for spectrum sensing in rendezvous in DSA has been developed in [26] by **Zhanwei Sun, J.Nicholas Laneeman and Glenn J. Bradford.** Different algorithms have been studied by them which can help in minimising the false and missed detection. They have compared the proposed algorithm with energy detection and coherent detection using simulation and mathematics.

Majid Altamimi, Kashirasagar Naik and Xuemin Shen in [27] proposed Mac protocol to achieve frequency rendezvous without common control channel (CCC) and synchronisation using the concept of Balanced Incomplete block design. Their algorithm distributes the network load on the channels and the nodes uniformly. Using simulations they have shown their algorithm performs well in terms of TTR, channel utilisation, network throughput and collision between PUs and SUs.

Yifan Zhang, Qun Li and Gexin Yu presents ETCH in [14] which a channel hopping algorithm for rendezvous. They have presented two Mac protocols SYNC-ETCH and ASYNC-ETCH. SYNC-ETCH has a global clock to synchronise. All nodes start shopping at the same time. ASYNC-ETCH don't have such global clock. Both the protocols can achieve good TTR.

Li Zhang, Kefeng Tan, Kai Zeng and Prashant Mohapatra in [28] uses power leakage of adjacent channel for rendezvous to speed up the rendezvous process. If radios can detect adjacent channel radios, it can find its peer with a local channel search. The

proposed algorithm is for 2 user and multiuser. Analytical and simulative results are shown to support their idea.

Short sequence based rendezvous algorithm is proposed by **Vitalio Alfonso Reguera, Erik Ortiz Guerra, Richard Demo Souza, Evelio M.G. Fernandez and Glauber Brante** in [11] for symmetric and asymmetric models. Simulative and theoretical analysis has been presented to prove their algorithm's performance in terms of maximum and expected TTR. All the users' starts hopping from the origin of sequence till the end of the sequence and returns in the opposite direction along the same sequence. The radio may find its peer along its way. *If it doesn't find its peer along its way back, it remains on the origin from one time slot and again starts hopping. This will guarantee the rendezvous. Closed form expression has also been derived for MTTR and ETTR.*

Enhanced hop and wait hopping algorithm is proposed by **I-Hsung Chuang, Hsiao-Yun Wu and Yau-Hwang Kuob** in [15]. Each user is assigned unique hopping sequence. The channels are arranged as the vertex of a channel and one user starts hopping and other stays on the channel leading to rendezvous. Each sequence pattern is of $3P$ time duration, where P is smallest prime number greater than number of channels. The sequence pattern can be hop-hop-wait, wait-hop-hop etc. where for first P user is in wait mode and for next $2P$ user is in hop mode.

Mohammad J. Abdel-Rahman and Marwan Krunz considers two SUs in the presence of a jammer for rendezvous in [29]. They consider both synchronised and asynchronised case. Two SUs tries to minimise the time slots required to rendezvous and jammer tries to maximize the slots. They have shown that the performance is good when the receiver and the jammer are time synchronised.

Proposed algorithm by **Francisco Hugo Costa Neto, Igor M. Guerreiro and Tarcisio F. Maciel** in [30] is based on vectorization of a Toeplitz matrix built from a list of channels available. They have shown that the mean TTR, maximum TTR and the probability of rendezvous have exact closed expression. The proposed algorithm also guarantees rendezvous.

In [31], **Osamu Takyu, Takayuki Yamakita, Takeo Fujii, Fumihito Sasamori and Shiro Handa** consider learning assisted rendezvous channel. They derived optimal learning time with taking sensing errors into account.

An asynchronous and symmetric channel hopping scheme has been proposed in [32] by **Chih-Min Chao, Chien-Yu Hsu and Yun-Ting Ling** called staggered channel hopping. They have proved that this scheme guarantees rendezvous problem. It provides more number of rendezvous and smaller TTR.

Lu Yu, Hai Liu, Yiu-Wing Leung, Xiaowen Chu and Zhiyong Lin in [33] proposed an algorithm to speed up the rendezvous process by using multiple radios per user. They generalised the existing algorithm to use multiple radios. If there are multiple radios then all the radios will scan different channel to speed up the process. They also came up with new algorithm where all radios except one scans the frequency channel, called general radio, and the one waits on a particular channel called as dedicated channel. Through simulations and theoretical proofs they showed multiple radios can reduce ETTR and MTTR. They also showed even distribution of radios increases performance.

Channel hopping sequence is proposed by **Hai Liu, Zhiyong Lin, Xiaowen Chu and Yiu-Wing Leung** in [34] which is based on ring walk. All the channels are arranged in a circle with channels as vertices on the circle. Different users walk on the circle with different velocities. This algorithm provides guarantee in rendezvous because slower user will always be caught by the faster user. This algorithm works for 2 user and multiuser scenarios and does not need synchronisation. Simulations results have been shown about the superiority of the algorithm with maximum and expected TTR.

METHODOLOGY

This chapter introduces to the proposed algorithm for frequency rendezvous and Time to Rendezvous (TTR). Only able to rendezvous is not important, the time taken by the radios to find each other so that they can establish connection is equally important. If two radios are able to rendezvous but they take large amount of time to find each other then such communication fails. Thus this chapter explains proposed algorithm which guarantees rendezvous with minimised TTR.

4.1 System Model

Our algorithm is based on the sequence in which the radios will visit the channels. The sequence will not be predefined but the radios will themselves decide the order in which they have to visit the channel depending on the available channels. We are assuming shared model for rendezvous where all radios have common observed channels and common labelling. We have also considered PUs, hence the radios will look for vacant spectrum for rendezvous.

Radios will first select a set of channels S_1 from the available channels and check for vacant spectrum. If no spectrum is vacant the radios will select another set of channels S_2 from the remaining available channels and this process will continue until a vacant channel is found.

Now the question arises how the radios will select channel set S_i . For this radios need a jump factor J_i , which is the rate at which the radios hop between the channels. The radios know the number of available channels, say N . The radios will factorize N and say that the factors are $1, F_1, F_2, F_3, N$ and so on (all in increasing order). To find jump factor the radio will divide N by factor F_1 . Starting from first channel the radio will keep hopping J_1 channels forward in search of vacant channel. When the channel index exceeds the total number of channels, the radio will generate new jump factor by dividing N by F_2 . Now starting from the first non visited channel the radio will hop through the channel excluding already visited channels in search of vacant channel. The process continues until radio finds the first vacant channel as given in example 4.1:

EXAMPLE 4.1: Let the number of available channels are $N=10$. The factors of 10 are 1, 2, 5 and 10. N (i.e. 10) will first be divided by 2, therefore, $J_1=5$. The first set of sequence (S_1) will be 1, 6. If neither 1 nor 6 is vacant, N will next be divided by 5 giving jump factor $J_2=2$ and the next set will be (S_2) 3, 5, 7 and 9 (1 will be excluded as already visited in previous set). Even now if the radio hasn't found any vacant spectrum, N will be divided by 10 giving $J_3=1$ and the new set will be (S_3) 2, 4, 6, 8 and 10 (excluding 1, 3, 5, 7 and 9).

The flow graph for finding the vacant channel is shown in Fig 4.1.

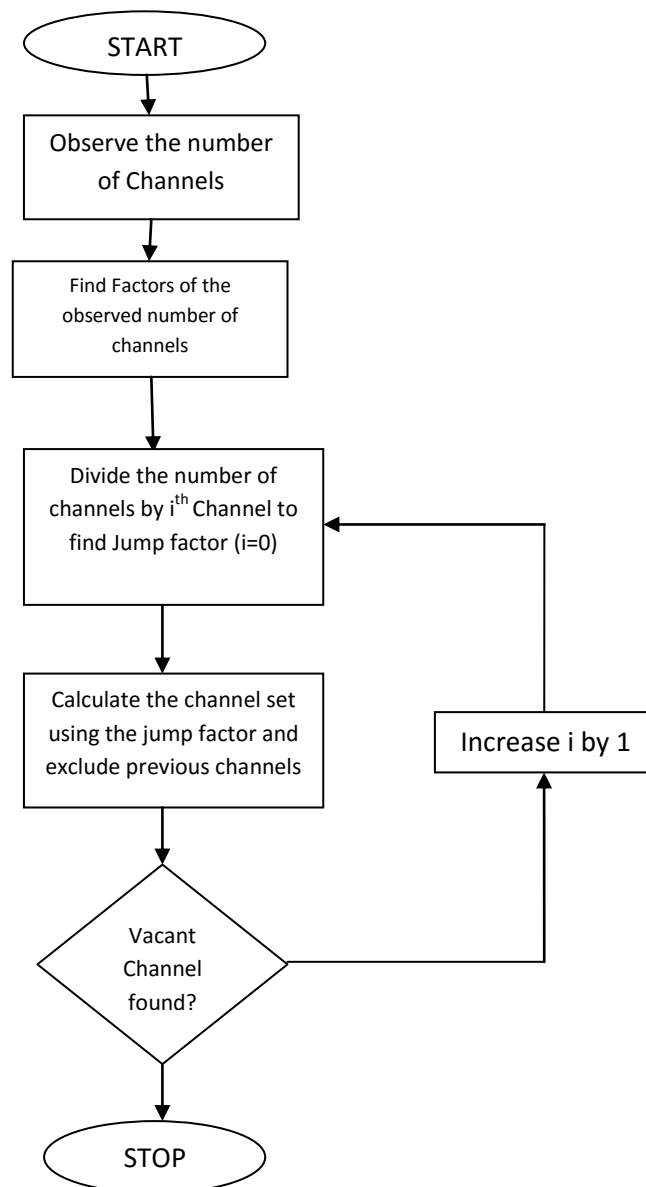


Fig. 4.1: Flow graph to find the set of channel with vacant channel.

After finding the first vacant channel, the radio will wait for the other radio to find this vacant channel as there can be a delay for other radio to join the network. Once they both reach the same vacant channel they can establish connection. Other radios will also try to find the first vacant channel using the same algorithm. As the total number of available channels is same for all radios they all will visit the channels in the same order. At the first vacant channel the two radios will establish a connection.

There will also be a limit for the radios to wait at a particular channel in waiting mode for other radios to arrive for connection because there is a possibility that the channel found occupied by one radio becomes vacant when some other radio arrives. In such case radios will keep on waiting at their vacant channel if there is no time limit. Therefore, when radios find the first vacant channel, they will wait there for time slots equal to the number of channels in S_i , where S_i is the set in which the vacant channel is found, and then start hopping again until it finds its target radio. The next time radio will go to wait mode is when it again reaches the same vacant channel or it finds another vacant channel before that vacant channel where it was in waiting mode previously. It can be explained by example 4.2:

EXAMPLE 4.2: Suppose there are 5 channels in a set as shown in Fig 4.2.

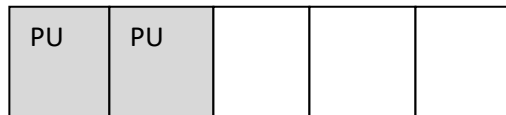


Fig. 4.2: Channels occupied by PU in channel set S_i .

Let first radio entering the channel set at time $t=0$ (first time slot) and finds first channel and second channel occupied, so it will go to third channel at time $t=2$ (third time slot) and enter wait mode for 5 time slots. Suppose second radio (target radio for the first) enters the network with an offset of 2 time slots i.e. at $t=2$ and by the time first channel of the set is now vacant as shown in Fig 4.3.

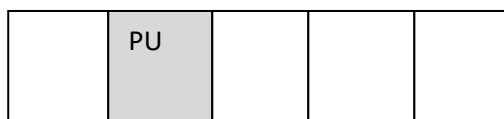


Fig. 4.3: Channels occupied by PU in channel set S_i .

Target radio enters to wait mode for 5 time slots as it gets onto the first channel. At the end of 7 time slots, both radios will start hopping simultaneously. When they reach fifth channel of the set they again come to the first channel of the same set because this set still have vacant channels. When the first radio now finds the first channel of the set to be vacant it goes in to the waiting mode because this channel comes before the vacant channel where the radio was in waiting mode. If the first channel of the set is again occupied, the radio will enter waiting mode in the third channel where target radio will follow.

There is also a possibility that by the time third channel of the set also get occupied, in such a case the radio will enter waiting mode in the very next vacant channel. This will guarantee rendezvous. One important point to note is that, we the number of channels is divided by its factors to find the set of channel to search for a vacant spectrum. If the number of available channel is a prime number, then it cannot be divided because a prime number does not have a factor. So, it will be can be divided by only 1 or itself. The channel set in this set will the all the observed channels. Hence in this scenario the TTR will be higher than any other number of channels which will be composite number. Later in the next chapter graph has been shown, which shows TTR for different number of channels. At channel number which is a prime, the TTR graph will show spikes which will prove that TTR in that particular case will be on the higher side. But the graph will also prove that in that case also our TTR will be lesser than any other algorithm proposed in the literature.

4.2 Time to Rendezvous

The time taken by the radios to find each other on the same frequency spectrum is called Time to Rendezvous (TTR). Time to Rendezvous is the parameter of measuring efficiency of any rendezvous algorithm. Lesser the TTR better is the rendezvous algorithm because it would take lesser time for the radios to establish connection.

Let the total number of channels in the network be C . Factors of C be $1, F_1, F_2 \dots C$. The sets of channels formed be $S_1, S_2 \dots S_n$ with number of channels in each be $N_1, N_2 \dots N_n$ after excluding common channels from succeeding channels. The amount of delay with which second radio joins the network can be $[0, 2N_i-2]$, where $i=1, 2, 3 \dots n$, because

delay of $2N_i-1$ will be equivalent to delay of 0, delay of $2N_i$ will be equivalent to delay of 1 and so on if TTR is concerned.

We can divide delay into two parts, first $[0, N_i-1]$ and second $[N_i, 2N_i-2]$. If delay is $[0, N_i-1]$ the TTR will be T time slots after entering the set N_i , where T is the number of first vacant channel in the set N_i . For e.g. if Fig. 4.2 is set N_i , then value of T is 3 time slots. If delay is $[N_i, 2N_i-2]$, the TTR will be $(T+1), (T+2) \dots (T+N_i-1)$ time slots (after entering set N_i) for $(2N_i-2)$ delay, $(2N_i-3)$ delay... N_i delay respectively. For simplicity we will write N_i as N .

Let any delay is equal probable, so probability for each delay (P_d) will be $\frac{1}{2N-1}$

$$E[TTR] = (N \times T)P_d + (N + T - 1)P_d + (N + T - 2)P_d + \dots (N + T - (N - 1))P_d \quad (1)$$

In equation (1), the probability of delay P_d is multiplied by time taken by the radios finding each other for any possible delay. For delays equal to 0 to $(N-1)$ the time will be equal, hence the time T is multiplied by N in the first term of the equation (1). Rest of the terms depend on the delays from $(N$ to $2N-2)$. For the delays from N to $(2N-2)$ the time to find each other will be $(N+T-1), (N+T-2), (N+ T-3) \dots (N+T- (N-1))$.

The last term of the equation (1) can be written as $(T+1) P_d$ and the second term of the same equation can be written as $(T+ (N-1))$. Thus equation (1) can be rearranged to equation (2).

$$E[TTR] = (N \times T)P_d + (T + 1)P_d + (T + 2)P_d + \dots (T + (N - 1))P_d \quad (2)$$

$$E[TTR] = (T \times P_d) + P_d + (T \times P_d) + 2P_d + \dots (T \times P_d) + (N - 1)P_d + (N \times T)P_d \quad (3)$$

$$E[TTR] = ((N - 1) \times T \times P_d) + (P_d + 2P_d + 3P_d + \dots (N - 1)P_d) + (N \times T)P_d \quad (4)$$

After rearranging the terms of equation (3), it can be seen that the second term of the equation (4) makes an arithmetic progression.

$$E[TTR] = (N \times T \times P_d) - (T \times P_d) + P_d(1 + 2 + 3 + \dots (N - 1)) + (N \times T \times P_d) \quad (5)$$

The arithmetic progression with first element 1 and number of elements (N-1) and common difference of 1 is $\frac{(N-1)N}{2}$.

$$E[TTR] = (2 \times N \times T \times P_d) + P_d \left(\frac{(N - 1)N}{2} \right) - (T \times P_d) \quad (6)$$

$$E[TTR] = ((2N - 1)(T \times P_d)) + P_d \left(\frac{N^2 - N}{2} \right) \quad (7)$$

$$E[TTR] = \left[(2N - 1)P_d + \left(\frac{N^2 - N}{2} \right) \right] P_d \quad (8)$$

$$E[TTR] = \left[\frac{(2N - 1)T + \left(\frac{N^2 - N}{2} \right)}{2N - 1} \right] \quad (9)$$

(As $P_d = \frac{1}{2N-1}$)

The equation (9) is the final equation which is the Expected TTR for our proposed algorithm. The given equation depends on N, which is the number of channels in a given set, and T, which is the number of first vacant channel in the set. The set is obtained by

dividing the total number of available channels by its factor. T will always be lesser than or equal to N.

The E [TTR] for other algorithm such as modular clock algorithm is

$$E[TTR] = \frac{N^4 + 2N^2 + 6N - 3}{3N(N + 1)} \quad (10)$$

The efficiency of the proposed algorithm can be proved by subtracting equation (9) by equation (10). The result of subtraction is a positive value, which proves that equation (10) is higher than equation (9). Let the d is the value of difference between the two equations.

$$d = \frac{N^4 + 2N^2 + 6N - 3}{3N(N + 1)} - \left[\frac{(2N - 1)T + \left(\frac{N^2 - N}{2}\right)}{2N - 1} \right] \quad (11)$$

After solving equation (11), it can be rewritten as (12)

$$d = \frac{2N^5 - 2.5N^4 + 4N^3 + 11.5N^2 - 12N + 3 + (3N - 3N^2 - 6N^3)T}{(3N^2 + 3N)(2N - 1)} \quad (12)$$

Now we will try to find out the value of T for which d is a positive value.

$$\frac{2N^5 - 2.5N^4 + 4N^3 + 11.5N^2 - 12N + 3 + (3N - 3N^2 - 6N^3)T}{(3N^2 + 3N)(2N - 1)} \geq 0 \quad (13)$$

We find the value T for which equation (13) is satisfied. Equation (13) is an inequality equation.

Equation (13) can be rearranged to get equation (14).

$$T \leq \frac{2N^5 - 2.5N^4 + 4N^3 + 11.5N^2 - 12N + 3}{(6N^3 + 3N^2 - 3N)} \quad (14)$$

To prove our algorithm's efficiency, the equation (12) should be positive, i.e., equation (13) should be satisfied or we can say that equation (14) should be satisfied. The probability that the equation (14) will be satisfied is very high and in almost all the occasion equation (14) will be true. On an average the algorithm will outperform modular clock algorithm as shown through simulations in the next chapter.

SIMULATION RESULTS

This chapter presents the results of the proposed algorithm with comparison with other algorithm. Expected TTR (ETTR) with increasing number of channels and increasing number of PUs is given along with Maximum TTR (MTTR) with increasing number of PUs.

In the previous chapter, mathematical analysis was done of the proposed algorithm. The proposed algorithm will be further proved with the help of simulations. The proposed algorithm was implemented in MATLAB. The Modular clock algorithm is used as the base to compare the proposed algorithm.

In Fig. 5.1, TTR is calculated by varying the number of available channels from 1 to 20. Both the algorithm's, proposed and Modular clock, TTR is calculated against varying number of available channel. For both the algorithms the occupancy of Primary User is 50%, i.e., half of the available channels is occupied by the Primary Users. In the MATLAB, the PUs are distributed among the channels randomly. For Modular clock algorithm also, the jump factor and the starting channel was decided randomly. As can be seen in the Fig 5.1, for only one available channel, the TTR for both the algorithms is 1 unit of time, it is because for only one available channel, rendezvous will take place only if that channel is vacant, i.e., no PU is present. Hence, for both the algorithms the TTR will be same for only one available channel, but as the number of available channel increases the proposed algorithm outperforms the other one. The blue line indicates the graph of proposed algorithm and the black line indicates the graph of Modular clock algorithm.

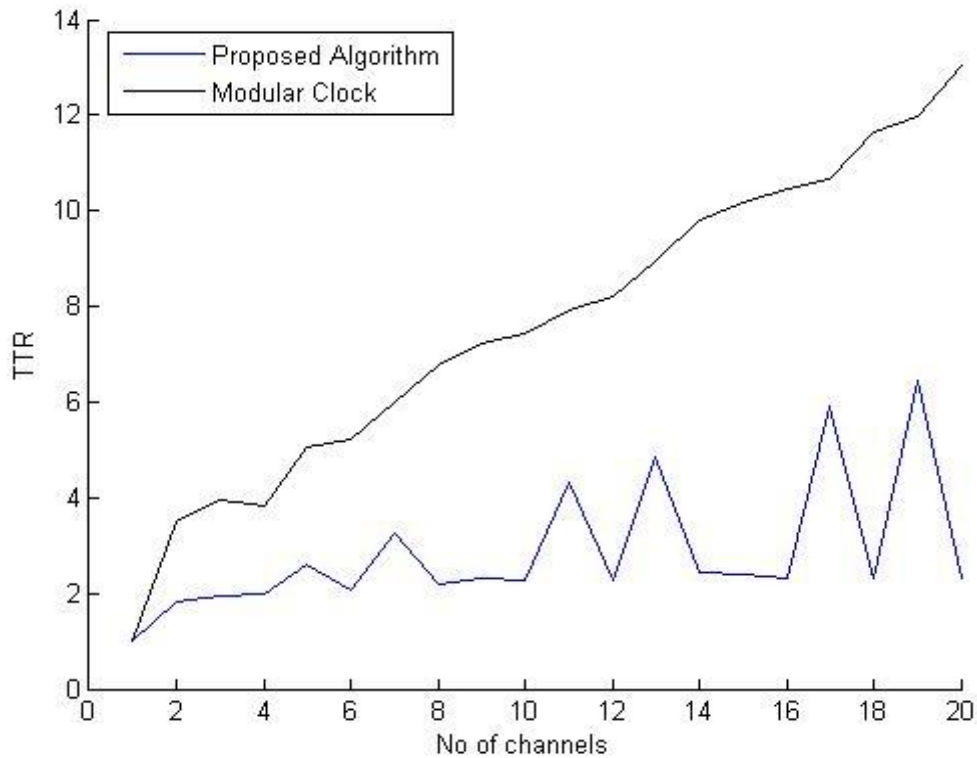


Fig. 5.1: Comparison of proposed algorithm and modular clock algorithm with respect to TTR and number of channels.

Observation: From the Fig. 5.1, it is observed that

- For any number of channels, the TTR from proposed algorithm is lower than that of modular's clock. For any number of available channels, proposed algorithm performs better than the modular clock's.
- When the number of channel is a prime number, the TTR graph goes high. This is because prime number cannot be factorised and the algorithm is based on factorisation.
- When number of channel is a composite number the TTR doesn't increase too much with increasing number of channel.

In the Fig 5.2, the comparison is made with increasing number of Primary Users. The number of channels has been fixed to 10. To make rendezvous possible the maximum number of Primary User can be 9 for 10 channels. The TTR has been calculated for no Primary User and for increasing Primary Users from 1 to 9. The Primary Users have been

randomly distributed and the delay by which second radio joins the network has also been chosen randomly. For Modular clock, the jump factor and the starting channel has been chosen randomly.

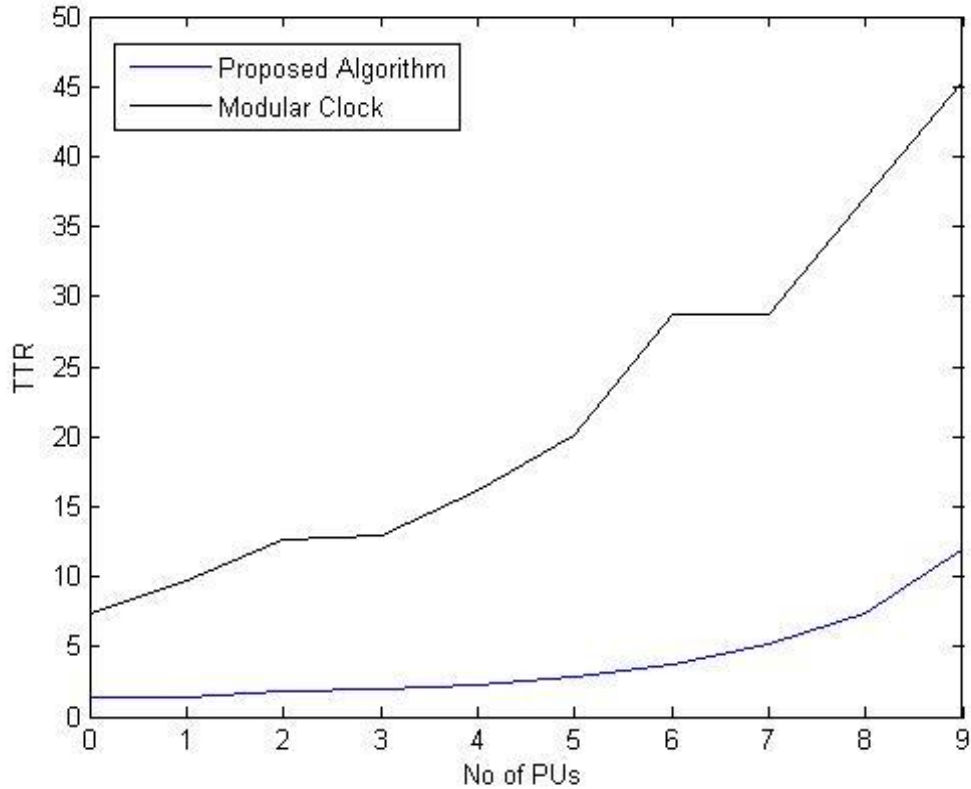


Fig. 5.2: Comparison of proposed algorithm and modular clock algorithm with respect to TTR and number of PUs.

Observation: It can be observed from the Fig. 5.2 that

- For any number of Primary User, the proposed algorithm performs better than the other one.
- For increasing Primary User, there is not very high increment in TTR in the proposed algorithm.
- Even for no Primary User, the performance of the proposed algorithm is better than the other.

Fig. 5.3 shows the graph between maximum TTR vs. number of Primary Users. The following graph will give the maximum bound of TTR. The number of Primary Users has been varied from no Primary User to the maximum number of users for any number of

channels. The number of channels is varied from 2 to 10. The maximum number of Primary User can be 1 less than the number of channel because for rendezvous to be possible, at least one channel should be vacant. The Fig. 5.3 provides with the guarantee of maximum time taken for rendezvous using this algorithm for any number of Primary Users.

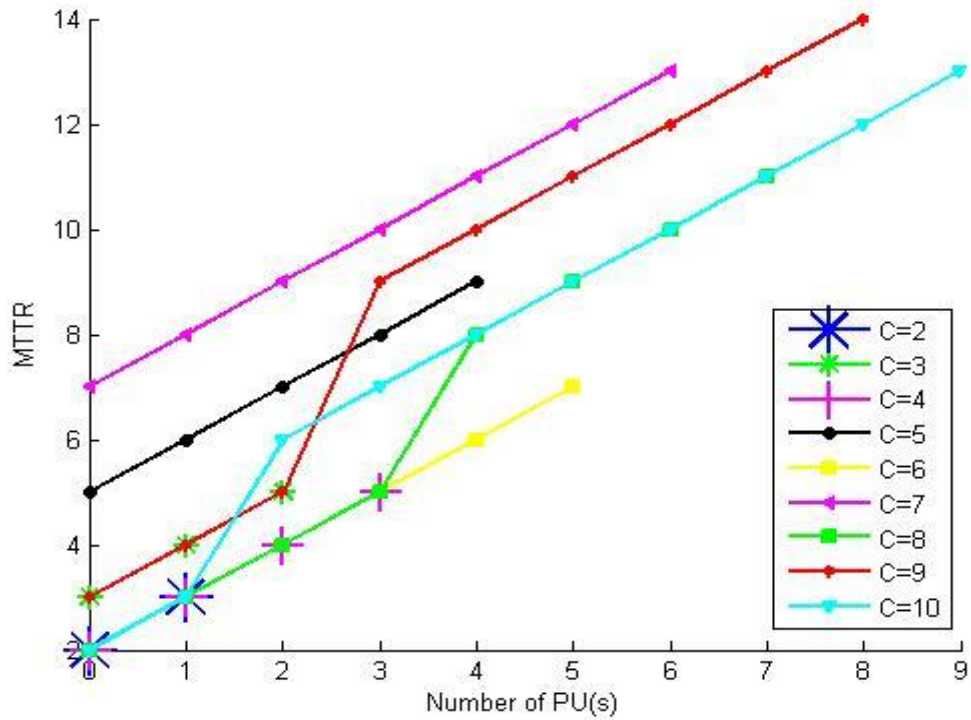


Fig. 5.3: Maximum TTR of proposed algorithm with increasing number of PUs for various numbers of channels.

CONCLUSION AND FUTURE SCOPE

This chapter contains the concluding remarks of the work proposed in the chapter 4. The results obtained will be discussed and the results will be analysed. The further work that can be done in this area is added to conclude this chapter.

The proposed algorithm works on minimising the Time to Rendezvous (TTR) while doing frequency rendezvous. The work is compared with other algorithm and graphs of comparison have been shown in chapter 5.

Fig. 5.1 shows the comparison by comparing TTR with increasing number of channels. It can be seen the proposed method outperforms the other. It can be observed that the TTR for both the algorithm is same for only one available channel. When only one channel is available, the rendezvous is possible only if it is not occupied by any Primary User. If that channel is vacant, the TTR will always be 1 unit of time for any algorithm. Other observation from Fig 5.1 is the spikes in the graph. It shows that the TTR is on the higher side when the number of channels is a prime number. This happens because the prime numbers have no factor, on which our whole algorithm is dependent.

Fig 5.2 is again a comparison graph but this time TTR is compared with increasing number of Primary Users (PUs). As can be observed from the graph, TTR of the proposed algorithm is very low compared to the other one. For example, for 3 number of PUs the TTR in the proposed algorithm is 3, but for the other TTR is 10.

Fig 5.3 shows the upper bound for the rendezvous. This shows maximum Time to Rendezvous (MTTR) with increasing number of Primary Users for different number of channels.

As it can be observed, in all the algorithms available in the literature the TTR increases with the increasing number of available channels. Thus the basic concept of the proposed algorithm is to virtually decrease the number of available channels by taking only few channels from the available channels at a time. If vacant spectrum is found in the first set, rendezvous will complete, else another set will be picked up to check for vacant channel. In this way, on an average, the TTR will be lesser than considering all the available channels at a time.

In future, work can be extended to develop such an algorithm which can also support independent model. In the given algorithm, all the radios are able to observe all the available channels equally. In some scenarios, it may not be possible for all the radios to observe equal number of channels. In such a case, common channels of the radio pair need to be deduced first.

REFERENCES

- [1] Shantidev Mohanty, Mehmet C. Vuran, Won-Yeol Lee and an F. Akyildiz, “Next Generation Dynamic Spectrum Access Cognitive Radio Wireless Networks: A Survey”, *Computer Networks*, Elsevier, vol. 50, no.13, pp. 2127-2159, September 2006.
- [2] Beibei Wang and K.J. Ray Liu, “Advances in Cognitive Radio Networks: A survey”, *IEEE journal of selected topics in signal processing*, vol. 5, no.1, pp 5-23, February 2011.
- [3] Min Song, Chunsheng Xin, Yanxiao Zhao and Xiuzhen Cheng, “Dynamic Spectrum Access: From Cognitive Radio to Network Radio”, *IEEE Wireless communications*, vol. 19, no. 1, pp 23-29, February 2012.
- [4] Swetha Reddy, Robin Grodi, Nimish Sharma and Danda B. Rawat, “Rendezvous Methods for Opportunistic spectrum Access in Cognitive Wireless Networks: Analysis and Implementation”, *IEEE proceedings of Southeastcon*, pp 1-2, April 2015.
- [5] Di Pu, Alexander M. Wyglinski and Mike McLernon, “An Analysis of Frequency Rendezvous for Decentralised Dynamic Spectrum Access”, *IEEE Transactions on vehicular technology*, vol. 59, no. 4, pp 1652-1658, May 2010.
- [6] Anita Garhwal and Partha Pratim Bhattacharya, “A Survey on Dynamic Spectrum Access Techniques for Cognitive Radio”, *International Journal of Next-Generation Networks*, vol.3, no.4, pp. 15-32, December 2011.
- [7] Nick C. Theis, Ryan W. Thomas and Luiz A. DaSilva, “Rendezvous for Cognitive Radios”, *IEEE Transactions on mobile computing*, vol. 10, no. 2, pp 216-227, February 2011.
- [8] Mohammad J. Abdel-Rahman, Hanif Rahbari and Marwan Krunz, “Multicast Rendezvous in Fast-Varying DSA Networks”, *IEEE transactions on mobile computing*, vol. 14, no. 7, pp 1449-1462, July 2015.

- [9] Ram Narayan Yadav and Rajiv Mishra, "Periodic Channel-Hopping Sequence for Rendezvous in Cognitive Radio Networks", International conference on advance computing, pp. 1787-1792, August 2015.
- [10] Hai Liu, Zhiyong Lin, Xiaowen Chu and Yiu-Wing Leung, "Ring-Walk Based Channel-Hopping Algorithms with Guaranteed Rendezvous for Cognitive Radio Networks", IEEE Green Computing and Communication, pp. 755-760, December 2010.
- [11] Vitalo Alfonso Reguera, Erik Ortiz Guerra, Richard Demo Souza, Evelio M.G. Fernandez and Glauber Brante, "Short Channel Hopping Sequence Approach to Rendezvous for Cognitive Networks" IEEE communications letters, vol. 18, no. 2, February 2014.
- [12] Lu Yu, Hai Liu, Yiu-Wing Leung, Xiaowen Chu and Zhiyong Lin, "Multiple Radios for Fast Rendezvous in Cognitive Radio Networks", IEEE Transaction on Mobile Computing, vol. 14, no. 9, pp. 1917-1931, September 2015.
- [13] Hai Liu, Zhiyong Lin, Xiaowen Chu and Yiu-Wing Leung, "Jump-Stay Rendezvous Algorithm for Cognitive Radio Networks", IEEE transaction on parallel and distributed systems, vol. 23, no. 10, pp 1867-1881, October 2012.
- [14] Yifan Zhang, Qun Li, Gexin Yu and Baosheng Wang, "ETCH: Efficient Channel Hopping for Communication Rendezvous in Dynamic Spectrum Access Networks", IEEE Infocom 2011, pp. 2471-2479, April 2011.
- [15] I-Hsun Chuang, Hsiao-Yun Wu and Yau-Hwang Kuo, "A Fast Blind Rendezvous Method by Alternate Hop-and-Wait Channel Hopping in Cognitive Radio Networks", IEEE Transaction on Mobile Computing, vol. 13, no. 10, pp. 2171-2184, October 2014.
- [16] Lin Chen, Shuyu Shi, kaigui Bian and Yusheng Ji, "Optimizing Average-Maximum TTR trade-off for Cognitive Radio Rendezvous", IEEE ICC 2015- Cognitive Radio and Network Symposium, pp. 7707-7712, June 2015.

- [17] Ram Narayan Yadav and Rajiv Mishra, "Periodic Channel-Hopping Sequence for Rendezvous in Cognitive Radio Networks", International conference on advance computing, pp. 1787-1792, August 2015.
- [18] Luiz A. DaSilva and Igor Guerreiro, "Sequence-based Rendezvous for Dynamic Spectrum Access", IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks 2008, pp. 1-7, October 2008.
- [19] Milan Nosovic and Terence D. Todd, "Scheduled Rendezvous and RFID Wakeup in Embedded Wireless Networks", IEEE International Conference on Communication, vol. 5, pp. 3325-3329, April 2002.
- [20] Brent Horine and Damla Turgut, "Link Rendezvous Protocol for Cognitive Radio Networks", IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, pp 444-447, April 2007.
- [21] Nicola Baldo, Alfred Asterjadhi and Micheel Zorzi, "Dynamic Spectrum Access Using a Network coded Cognitive Control Channel, IEEE transaction on wireless communications, vol. 9, no. 8, pp 2575-2587, August 2010.
- [22] I-Hsun Chuang, Hsiao-Yun Wu, Kuan-Rong Lee and Yau-Hwang Kuo, "Alternate Hop-and-wait Channel Rendezvous method for Cognitive Radio Networks", IEEE Proceedings Infocom, pp 746-754, April 2013.
- [23] Zhaoquan Gu, Qiang-Sheng Hua and Weiguo Dai, "Local Sequence Based Rendezvous Algorithms for Cognitive Radio Networks", IEEE International Conference on Sensing, Communication and Networking, pp 194-202, June 2014.
- [24] Dhananjay Kumar, A. Magesh and U. Mohammed Hussain, "Prediction Based Channel-Hopping Algorithm For Rendezvous in Cognitive Radio Networks", Journal of Communication Technology, vol. 03, no. 04, pp 619-625, December 2012.
- [25] Sutton P.D., Nolan K.E., Doyle L.E., "Cyclostationary Signatures for Rendezvous in OFDM-based Dynamic Spectrum Access Networks", IEEE International Symposium on New Frontiers in Dynamics Spectrum Access Networks, pp. 220-231, April 2007.

- [26] Zhanwei sun, J. Nicholas Laneman and Glenn J. Bradford, "Sequence Detection Algorithms for Dynamic Spectrum Access Networks", IEEE Symposium on New Frontiers in Dynamic Spectrum, pp 1-9, April 2010.
- [27] Majid Altamini, Kshirasagar Naik and Xuemin Shen, "Parallel link Rendezvous in Ad Hoc Cognitive Radio Networks", IEEE GlobeCom 2010 proceedings, pp 1-6, December 2010.
- [28] Li Zhang, Kefeng Tan, Kai Zeng and Prasant Mohapatra, "Fast Rendezvous for Cognitive Radios by Exploiting Power Leakage at Adjacent Channels" IEEE 23rd International Symposium on Personal, Indoor and Mobile radio communications, pp 185-190, September 2012.
- [29] Mohammad J. Abdel-Rahman and Marwan Krunz, "Game-theoretic Quorum-based Frequency Hopping for Anti-jamming Rendezvous in DSA Networks", IEEE International Symposium on Dynamic Spectrum Access Networks, pp 248-258, April 2014.
- [30] Francisco Hugo Costa Neto, Igor M.Guerreiro and Tarcisio F.Maciel, "Toeplitz-structured Sequence for Rendezvous in Dynamic Spectrum Access", Proceedings of European Wireless 2014, pp. 1-5, May 2014.
- [31] Osamu Takyu, Takayuki Yamakita, Takeo Fujii, Fumihito Sasamori and Shiro Handa, "Learning Assisted Rendezvous Channel in Cognitive Radio System", IEEE International Conference of Communication System, pp.452-456, November 2014.
- [32] Chih-Min Chao, Chien-Yu Hsu and Yun-Ting Ling, "Efficient Asynchronous Channel Hopping Design for Cognitive Radio Networks", IEEE Transaction on Vehicular Technology, vol. pp, no. 99, pp. 1-13, October 2015.

LIST OF PUBLICATIONS

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