INTELLIGENT SPECTRUM MOBILITY AND RESOURCE MANAGEMENT IN COGNITIVE RADIO AD HOC NETWORKS

A Dissertation by

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ABSTRACT

DAN WANG. Intelligent Spectrum Mobility and Resource Management in Cognitive Radio Ad Hoc Networks. (Under the direction of DR. YI SONG)

To alleviate the spectrum scarcity problem, the FCC has been suggested a brand new paradigm for dynamically accessing the allocated spectrum. Cognitive radio (CR) technology has emerged as a promising solution to realize dynamic spectrum access (DSA). With the capability of sensing the frequency bands in a time and location-varying spectrum environment and adjusting the operating parameters based on the sensing outcome, CR technology allows an unlicensed user to exploit the licensed channels which are not used by licensed users in an opportunistic manner.

In this research, an intelligent spectrum mobility and resource management framework in CR ad hoc networks is explored. In particular, five spectrum mobility and resource management issues in CR ad hoc networks are investigated: 1) global time synchronization in CR ad hoc networks; 2) spectrum sensing scheduling scheme to differentiate the signals from primary users (PUs) and secondary users (SUs); 3) power control scheme for concurrent transmissions of location-aware mobile cognitive radio ad hoc networks; 4) jointly power adaptation and spectrum handoff scheme in mobile cognitive radio networks; and 5) end-to-end congestion control scheme in multi-hop cognitive radio ad hoc networks.

The contributions of the research include: 1) fundamentally solving the global time synchronization problem for the CR ad hoc network in a time and location-varying spectrum environment. 2) Joint power control, frequency selection, and spectrum handoff is proposed in mobile CR ad hoc network. 3) Upper layer spectrum sensing scheme can differentiate the signals from PUs and SUs. 4) The proposed end-to-end congestion control protocol can significantly enhance the transport layer of the CR ad hoc networks. To the best of our knowledge, this is the first work that comprehensively investigate the spectrum mobility and resource management issues from the physical layer to the transport layer in mobile CR ad hoc networks.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHAPTER 1: Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Background on CR Networks</td>
<td>1</td>
</tr>
<tr>
<td>1.2 An Overview of Research in CRAHNs</td>
<td>1</td>
</tr>
<tr>
<td>1.3 Problem Identification</td>
<td>4</td>
</tr>
<tr>
<td>1.3.1 Global time synchronization in CR Ad Hoc Networks</td>
<td>4</td>
</tr>
<tr>
<td>1.3.2 Novel Spectrum Sensing Scheduling Scheme CRAHNs</td>
<td>7</td>
</tr>
<tr>
<td>1.3.3 Optimal Power Control Scheme in CRAHNs</td>
<td>11</td>
</tr>
<tr>
<td>1.3.4 Jointly Power Adaptation and Spectrum Handoff Scheme</td>
<td>14</td>
</tr>
<tr>
<td>1.3.5 End-to-End Congestion Control Scheme in CRAHNs</td>
<td>16</td>
</tr>
<tr>
<td>CHAPTER 2: Related Work</td>
<td>21</td>
</tr>
<tr>
<td>2.1 Existing Global time synchronization in CR Ad Hoc Networks</td>
<td>21</td>
</tr>
<tr>
<td>2.2 Existing scheme to differentiate the signals from PUs and SUs</td>
<td>21</td>
</tr>
<tr>
<td>2.3 Existing Power Control Scheme in CR Ad Hoc Networks</td>
<td>22</td>
</tr>
<tr>
<td>2.4 Existing Spectrum Handoff Scheme in Mobile CR Networks</td>
<td>23</td>
</tr>
<tr>
<td>2.5 Existing End-to-End Congestion Control Scheme</td>
<td>23</td>
</tr>
<tr>
<td>CHAPTER 3: Novel Global Time Synchronization in CR ad hoc network</td>
<td>26</td>
</tr>
<tr>
<td>3.1 Distributed Global Time Synchronization Protocol in CRAHNs</td>
<td>26</td>
</tr>
<tr>
<td>3.1.1 Root Node Selection</td>
<td>26</td>
</tr>
<tr>
<td>3.1.2 Global Time Synchronization</td>
<td>27</td>
</tr>
<tr>
<td>3.1.3 Periodical Global Time Synchronization</td>
<td>29</td>
</tr>
<tr>
<td>3.2 the Optimal Root Node Selection Scheme</td>
<td>29</td>
</tr>
<tr>
<td>3.2.1 Derivation of the Average Number of Available Channels</td>
<td>29</td>
</tr>
<tr>
<td>3.2.2 Calculation of the Distance to the Furthest Node</td>
<td>31</td>
</tr>
<tr>
<td>3.3 The Optimal Period of The Distributed Global Time Synchronization</td>
<td>34</td>
</tr>
<tr>
<td>3.3.1 Synchronization Overhead of the CR Ad Hoc Network</td>
<td>34</td>
</tr>
<tr>
<td>3.3.2 The Time Difference between Two Consecutive SSC</td>
<td>35</td>
</tr>
<tr>
<td>3.4 Performance Evaluation</td>
<td>37</td>
</tr>
<tr>
<td>CHAPTER 4: Novel Scheme to Differentiate PU and SU Signal</td>
<td>41</td>
</tr>
<tr>
<td>4.1 The Proposed Spectrum Sensing Scheduling Scheme</td>
<td>41</td>
</tr>
<tr>
<td>4.2 Derivation of the Optimal Sensing Duration and Sensing Period</td>
<td>44</td>
</tr>
<tr>
<td>4.2.1 Derivation of $p_d$</td>
<td>44</td>
</tr>
<tr>
<td>4.2.2 Derivation of $S(T_0)$</td>
<td>45</td>
</tr>
<tr>
<td>4.2.3 Derivation of $P_{pre}(N_p)$</td>
<td>51</td>
</tr>
<tr>
<td>4.3 Performance Evaluation</td>
<td>58</td>
</tr>
<tr>
<td>4.3.1 Performance Evaluation for the First Proposed Method</td>
<td>59</td>
</tr>
<tr>
<td>4.3.2 Performance Evaluation for the Second Proposed Method</td>
<td>59</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (continued)

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHAPTER 5: Concurrent Transmission Scheme in MCRAHNs</td>
<td>65</td>
</tr>
<tr>
<td>5.1 System Model and Problem Formulation for a mobile CRAHNs</td>
<td>65</td>
</tr>
<tr>
<td>5.2 Optimal Power Control for Single Pair CR Ad Hoc Networks</td>
<td>67</td>
</tr>
<tr>
<td>5.2.1 Feasibility of Optimal Power Control</td>
<td>67</td>
</tr>
<tr>
<td>5.2.2 Optimal Power Control for Mobility Scenarios</td>
<td>69</td>
</tr>
<tr>
<td>5.2.3 Shadowing Fading Effect</td>
<td>71</td>
</tr>
<tr>
<td>5.3 Optimal Power Control for Multi-CR and Multi-PR Ad Hoc Networks</td>
<td>72</td>
</tr>
<tr>
<td>5.3.1 Optimal Power Control for the Multi-CR Scenario</td>
<td>73</td>
</tr>
<tr>
<td>5.3.2 Optimal Power Control for the Multi-PR Scenario</td>
<td>77</td>
</tr>
<tr>
<td>5.4 Performance Results</td>
<td>80</td>
</tr>
<tr>
<td>5.4.1 Simulation Parameters for single pair CR user ad hoc network</td>
<td>80</td>
</tr>
<tr>
<td>5.4.2 Simulation Results for the Single Pair CR User Scenario</td>
<td>81</td>
</tr>
<tr>
<td>5.4.3 Simulation Result for Multi-CR scenario</td>
<td>85</td>
</tr>
<tr>
<td>5.4.4 Simulation Result for the Multi-PR Scenario</td>
<td>87</td>
</tr>
<tr>
<td>CHAPTER 6: Jointly Power Adaptation and Spectrum Handoff Scheme</td>
<td>89</td>
</tr>
<tr>
<td>6.1 The Proposed JOSH Scheme for Fixed Mobility Patterns</td>
<td>89</td>
</tr>
<tr>
<td>6.1.1 Network Model</td>
<td>89</td>
</tr>
<tr>
<td>6.1.2 The Proposed Scheme for Fixed Mobility Patterns</td>
<td>91</td>
</tr>
<tr>
<td>6.2 The Proposed JOSH Scheme for Random Mobile CRNs</td>
<td>98</td>
</tr>
<tr>
<td>6.2.1 The Details of The Sub-scheme I</td>
<td>100</td>
</tr>
<tr>
<td>6.2.2 The Details of Sub-scheme II</td>
<td>107</td>
</tr>
<tr>
<td>6.3 Performance Evaluation</td>
<td>110</td>
</tr>
<tr>
<td>6.3.1 Simulation results for mobile CR networks with constant speed</td>
<td>110</td>
</tr>
<tr>
<td>6.3.2 Simulation results for mobile CR networks with random speed</td>
<td>111</td>
</tr>
<tr>
<td>CHAPTER 7: Novel End-to-End Congestion Control in Multi-hop CRAHNs</td>
<td>116</td>
</tr>
<tr>
<td>7.1 The Proposed End-to-End Congestion Control Scheme</td>
<td>116</td>
</tr>
<tr>
<td>7.1.1 Step 1: Obtaining the Delay of ECN</td>
<td>118</td>
</tr>
<tr>
<td>7.1.2 Step 2: Deciding Whether to Use the ECN</td>
<td>118</td>
</tr>
<tr>
<td>7.1.3 Step 3: Avoiding the Incorrect Reaction</td>
<td>119</td>
</tr>
<tr>
<td>7.1.4 Step 4: Deriving the RTO Timer Value</td>
<td>120</td>
</tr>
<tr>
<td>7.2 The Derivation of the RTO Timer Value</td>
<td>121</td>
</tr>
<tr>
<td>7.2.1 The Derivation of the Channel Rendezvous Delay</td>
<td>122</td>
</tr>
<tr>
<td>7.2.2 The Derivation of the MAC Layer Delay</td>
<td>123</td>
</tr>
<tr>
<td>7.2.3 The Derivation of the Service Delay</td>
<td>123</td>
</tr>
<tr>
<td>7.2.4 The Derivation of the Queuing Delay</td>
<td>126</td>
</tr>
<tr>
<td>7.3 performance evaluation</td>
<td>132</td>
</tr>
<tr>
<td>CHAPTER 8: Conclusion</td>
<td>136</td>
</tr>
<tr>
<td>8.1 Conclusion</td>
<td>136</td>
</tr>
<tr>
<td>8.1.1 Published and finished work</td>
<td>137</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>139</td>
</tr>
</tbody>
</table>
CHAPTER 1: INTRODUCTION

1.1 Background on CR Networks

Recently, with an exponential growth of wireless devices, the radio spectrum resource becomes increasingly scarce. However, according to the Federal Communications Commission (FCC), up to 85% of the assigned radio spectrum is underutilized due to the current fixed spectrum allocation policy[1]. The underutilization of the radio spectrum has motivated the research on radio technologies which can support dynamic spectrum access (DSA). Recently, cognitive radio (CR) has emerged as the key technology to realize DSA[2][3]. CR technology enables unlicensed users (or, secondary users) to adaptively adjust their operating parameters and exploit the radio spectrum which is unused by licensed users (or, primary users) in an opportunistic manner[4]. Hence, the radio spectrum utilization can be greatly enhanced.

1.2 An Overview of Research in CRAHNs

In this research, we investigate novel spectrum mobility and resource management solutions in CR ad hoc networks. Figure 1.6 shows the overview of the proposed spectrum mobility and resource management schemes. In order to perform successful communication between nodes on the mobile CR ad hoc network, the global time synchronization is very important since all the other protocol needs it. After the global time synchronization successfully performed, the spectrum sensing should be performed to get the available channels for SUs to access. The accuracy of the spectrum sensing result is very important because it dramatically affect the throughput of the network. Then, the SUs access the available channels to transmit the data packets. In order to further increase the CR ad hoc network performance, we propose
Global time synchronization

PU and SU signals differentiation

PU and SU concurrent transmission

Joint power control and spectrum handoff

End to end congestion control

End to end congestion control

Joint power control and spectrum handoff

PU and SU concurrent transmission

PU and SU signals differentiation

Research Objectives

Intelligent mobility and resources management in CRAHNs

First, novel distributed global time synchronization protocol in CR ad hoc networks is proposed and evaluated.

Secondly, we propose a novel spectrum sensing scheduling scheme to solve the above issue without the need of PU PHY and MAC protocols. In our scheme, the PU and SU signal differentiation issue is investigated. The main contributions of this scheme are: 1) A novel spectrum sensing scheduling scheme to differentiate the signals from PUs and SUs is proposed. The proposed spectrum sensing scheduling scheme results in a more accurate spectrum sensing outcome than traditional spectrum sensing schemes. 2) Based on the proposed spectrum sensing scheduling scheme, the optimal sensing duration and sensing period are derived. A Markov model that characterizes
the activity of SUs, the performance of SUs, and the interference among multiple SUs is proposed.

Furthermore, we study a mobile CR network where each CR node has the power control capability. That is, each CR node can transmit at any power in the allowable transmit power range to achieve the maximum concurrent transmission region. Our main contribution is that we propose a location-aware sensing-free optimal power control algorithm for concurrent transmissions especially in mobile CR ad hoc networks. Under the proposed algorithm, the CR transmitter is able to conduct transmissions with the presence of the PR users while moving. Even if the CR users are in the area called “protected region” [5] where the CR users should not transmit, if the location information of both CR and PR receivers is known to the CR transmitter, the CR transmitter can adjust its transmit power to enable the concurrent transmission.

Moreover, we study a mobile CR network where each SU has the power adaptation capability[6]. That is, each SU can transmit at any power which is in the range of the maximum transmission power to keep the communication between the SUs [7]. Our proposed joint power adaptation and spectrum handoff strategy focuses on answering the following three questions: 1) how to adapt the SU transmission power based on the mobility information of the moving SU? For instance, how to ensure that the SU communication is not dropped due to the fact that the SUs move out of the transmission range of each other? 2) Whether there are any PUs who are currently active on the channel used by SUs in the additional transmission range caused by the increase of the transmission power? And 3) Whether to perform a spectrum handoff at the moment when the transmission power is adapted? The third issue is especially critical to the network performance and needs to be handled with care since the spectrum handoff terminates the on-going transmission and needs extra sensing time and delay due to the change of channels. In this paper, we design an intelligent strategy to decide whether the SUs should perform a spectrum handoff when the
transmission power is adapted.

In addition, a novel end-to-end congestion control scheme in multi-hop CR ad hoc networks is proposed. We compare the performance of our proposed scheme with the existing mechanisms. Through extensive simulation, it is shown that our proposed scheme outperforms other existing mechanism in terms of higher end-to-end throughput. More specifically, the main contributions of this paper are: 1) A novel end-to-end congestion control scheme is proposed in multi-hop CR ad hoc networks. The proposed scheme takes the spectrum sensing, PU activities, and channel rendezvous into consideration. We also compare the performance of our proposed end-to-end congestion control scheme with the traditional congestion control approaches. 2) Based on the proposed end-to-end congestion control scheme, the average RTT is calculated. A Markov model that characterizes the process of the SU packet transmission from the source node to the destination node is proposed. Then, the RTT of the multi-hop CR ad hoc network can be calculated based on the proposed Markov model. 3) Based on the calculated RTT, the optimal RTO timer value is derived in the proposed end-to-end congestion control scheme in the multi-hop CR ad hoc networks.

1.3 Problem Identification

1.3.1 Global time synchronization in CR Ad Hoc Networks

In wireless networks, one of the most critical functions is global time synchronization which enables all devices in a network to have a unified time and supports protocols that require time synchronization. In CR networks, global time synchronization is especially significant for several techniques such as the cooperative spectrum sensing protocols and the synchronous spectrum sharing protocols. Cooperative spectrum sensing usually involves several secondary users (SUs) to sense the channels cooperatively and exchange the sensing information among them[8, 9, 10]. Therefore, the global time synchronization ensures different SUs to sense the channels and
exchange the sensing information synchronously. In addition, global time synchronization allows SUs to adopt synchronous spectrum sharing techniques (e.g., time division multiple access (TDMA)-based spectrum sharing schemes) in CR networks which are considered to be more efficient than the contention-based spectrum sharing techniques. Due to the importance of global time synchronization, in this paper, we study the global time synchronization issue in CR ad hoc networks.

Currently, the global time synchronization issue has been studied extensively in both traditional wired and wireless networks. In traditional wired networks, there are some well-developed global time synchronization protocols such as Network Time Protocol (NTP). However, these protocols are not applicable in CR ad hoc networks where there is usually no centralized entity to control the time information exchange. Moreover, in traditional wireless networks (e.g., wireless ad hoc networks), the global time synchronization issue has also been investigated and several protocols have been proposed [11]. However, these protocols are under the assumptions that the channels are always available and the time synchronization process is not interrupted. Thus, they cannot be simply applied in CR ad hoc networks where the channel availability is dynamic and the time synchronization process may be interrupted due to the primary users (PUs) activity.

In CR ad hoc networks, the global time synchronization design is much more challenging than traditional wired and wireless networks due to the dynamic spectrum nature. There are two major challenges in designing global time synchronization protocols in CR ad hoc networks. First of all, the root node which constantly provides the reference time for the entire network is quite difficult to select. Fig. 1.2 demonstrates the difficulty to select the root node in CR ad hoc networks. As shown in Fig. 1.2, circles denote SUs and rectangles represent PUs. In addition, there are totally 3 channels in the network. Conventionally, only the network topology is considered to select the root node while the channel availability effect is ignored. That is, the node
which is located in the center of the network is selected as the root node. Thus, if the PU activity is not considered, $SU_1$ is chosen as the root node. However, as shown in Fig. 1.2, there are three pairs of active PUs in the transmission range of $SU_1$ which currently use channel 1, channel 2, and channel 3. Thus, there is no available channel for $SU_1$ to provide the reference time until the PUs finish their transmissions [12]. Therefore, the root node selection scheme needs to consider both the network topology and the PU activity, which is quite complicated and challenging.

Secondly, the \textit{period of the global time synchronization} is another challenging parameter that should be designed carefully. Since the global time synchronization process could be interrupted by PU activities, there exists a critical trade-off when determining the time synchronization period. On one hand, if the time synchronization period is too short, the overhead of the synchronization (i.e., the synchronization messages) is high. On the other hand, if the time synchronization period is too long, the impact of having one or more global synchronization cycles fail due to the activity of PUs is high. Therefore, the time synchronization period is affected by the trade-off between the synchronization overhead and the synchronization performance (i.e., the impact of the time errors caused by failed global time synchronization on network
performance). Thus, the design of the global time synchronization period in CR ad
hoc networks that considers the PU activities is also very challenging.

Considering the unique features of CR ad hoc networks, a novel distributed global
time synchronization protocol in CR ad hoc networks is proposed and evaluated.
There are three main contributions in our proposed distributed global time synchro-
nization protocol. Firstly, the proposed distributed global time synchronization pro-
tocol is designed to cope with the dynamic channel availability of SUs. The PU
behavior and topology are considered in our design. Secondly, an optimal root node
is selected considering both the network topology and the dynamic channel availabil-
ity, which can greatly reduce the synchronization delay. Thirdly, an optimal global
time synchronization period is calculated to balance the trade-off between the syn-
chronization overhead and the synchronization performance. Moreover, the proposed
synchronization protocol does not make impractical assumptions so that it can be
implemented in practical network scenarios. To the best of our knowledge, this is the
first work that addresses the unique challenges in the distributed global time syn-
chronization design in CR ad hoc networks that considers the unique features of CR
networks.

1.3.2 Novel Spectrum Sensing Scheduling Scheme CRAHNs

In CR networks, since primary users (PUs) should not be interfered by SUs,
spectrum sensing is proposed for SUs to detect whether there are PUs currently use
certain spectrum bands[13][14]. Due to its importance, the spectrum sensing issue has
been studied extensively in the research community [15][16]. The main goal of these
existing papers on spectrum sensing is to improve the accuracy of detecting PUs.
However, there is a serious problem with the current spectrum sensing techniques.
Almost all the previous studies on spectrum sensing are based on the assumption that
the detected signals only come from PUs. In fact, the detected signals could also come
from SUs, which may lead to an inaccurate the sensing result. In other words, the
existing spectrum sensing techniques have a drawback that they can only detect the existence of signals but they cannot differentiate whether the detected signals come from PUs or SUs. This drawback has a significant impact on the performance of CR networks.

Fig. 1.3 demonstrates the impact of this drawback. As shown in Fig. 1.3, $SU_0$ has a sensing range with a radius of $R$. In addition, there are SUs and PUs coexisting in the sensing range of $SU_0$ with totally 3 available channels. Suppose that $SU_1$, $SU_2$, $SU_3$, and $SU_4$ use channel 1 and channel 2 to communicate while $PU_1$ and $PU_2$ use channel 3 to communicate at the same time. Then, if $SU_0$ cannot differentiate the signals from SUs and PUs, the sensing result is that there is no available channel for $SU_0$. Thus, $SU_0$ cannot start any data transmission with its intended receiver (e.g., $SU_5$). However, in fact, only channel 3 is used by PUs. $SU_0$ can compete with other SUs to access channel 1 and channel 2 since SUs are of the same priority to access the spectrum. Hence, its communication is still possible. More importantly, some spectrum sharing techniques require the sensing history of PUs [13]. If SUs cannot differentiate the PU and SU signals, such sensing history is likely to be incorrect.
Thus, the designed spectrum sharing techniques are no longer feasible. Therefore, to differentiate PU and SU signals during spectrum sensing is extremely critical in CR networks.

To solve the PU and SU signal differentiation issue is very complicated. One possible method to differentiate PU and SU signals is to distinguish the signal features from the physical (PHY) layer (e.g., modulation schemes). In addition, another way is to differentiate different medium access control (MAC) protocols used by PUs and SUs. However, how to obtain the information of the PHY and MAC protocols is not an easy task in CR networks. Even though there are some methods to identify the protocol types [17], the condition is that the PU PHY and MAC protocols are known in advance and they are different from the protocols used by SUs. If SUs and PUs adopt the same PHY and MAC protocols, this kind of methods does not work anymore.

We propose a novel spectrum sensing scheduling scheme to solve the above issue without the need of PU PHY and MAC protocols. The main idea of the proposed scheme is that if a SU needs to perform spectrum sensing, all the other SUs within the sensing range of the SU have to temporarily stop their data transmissions. Since data transmissions of other SUs are terminated, the detected signals definitely come from PUs. In this way, the sensing result is only PU transmissions during spectrum sensing.

However, there are several challenges that need to be considered because of the termination of data transmissions of other SUs [18]. First of all, the throughput of SUs in the network may decrease since SUs are only allowed to transmit data while no SU performs spectrum sensing at the same time. Thus, SU data transmissions are affected by spectrum sensing operations from other SUs. Therefore, the SU throughput is highly related to the spectrum sensing duration (i.e., how long a SU performs one round of spectrum sensing) and the spectrum sensing period (i.e., the length
between two rounds of spectrum sensing). Then, how to optimize the spectrum sensing duration and the spectrum sensing period in order to obtain a satisfactory SU throughput of the network is critical. Secondly, the sensing accuracy for PU signals is also related to the spectrum sensing duration. Thus, we also need to consider the spectrum sensing accuracy in our designs.

Currently, research on how to differentiate SU and PU signals is still under-explored. There are only limited papers addressing how to optimize the spectrum sensing duration and spectrum sensing period [19] [20] [21] [22] [23] [24] [25]. In [19], a scheme on how to detect the available spectrum and improve the sensing robustness for avoiding interference to PUs is proposed. In [20], the effect of the average transmit and interference power constraints on the optimal spectrum sensing time is discussed. Additionally, a joint sensing time adaption and data transmission scheme is proposed in [21]. Moreover, in [22], the optimal spectrum sensing time considering spectrum handoffs is addressed. In [23], a method to improve the throughput of SUs in CR networks by dynamically adapting the spectrum sensing time is proposed. Furthermore, in [24], the allocation of the sensing period and the transmission time are optimized when the channel is modeled as an ON/OFF continuous time Markov chain [26]. In addition, a spectrum sensing scheme for CR networks in dynamic PU traffic environments where PUs might randomly depart or arrive during a spectrum sensing period is proposed in [25]. However, all these proposals are under the assumption that the detected signals during spectrum sensing are from PUs. Thus, it is unsuitable to use these methods to solve the problem in which the sensed signals can come from both SUs and PUs.

To sum up, in my work, the PU and SU signal differentiation issue is investigated. The main contributions of this paper are:

1. A novel spectrum sensing scheduling scheme to differentiate the signals from PUs and SUs is proposed. The proposed spectrum sensing scheduling scheme
results in a more accurate spectrum sensing outcome than traditional spectrum sensing schemes.

2. Based on the proposed spectrum sensing scheduling scheme, the optimal sensing duration and sensing period are derived. A Markov model that characterizes the activity of SUs, the performance of SUs, and the interference among multiple SUs is proposed.

To the best of our knowledge, this is the first work that studies the PU and SU signal differentiation issue in CR networks.

1.3.3 Optimal Power Control Scheme in CRAHNs

There exist many challenges in the deployment of CR networks. First of all, the transmission of CR users should not cause any harmful interference to primary (PR) users who have the license to use the spectrum band [27]. Secondly, the throughput of CR links should be maximized for reliable quality communications. Thirdly, the robustness of CR links becomes extremely difficult to achieve given the mobility of CR users. A number of studies have been conducted in order to address these challenges.

One commonly known technique to address the above challenges is spectrum sensing[4], where a CR transmitter can access a frequency band only if the PR transmission is detected to be inactive on that frequency band. Through spectrum sensing, CR users can exploit unused spectrum opportunistically in a dynamic radio environment [28]. Several spectrum detection techniques have been proposed in the literature, such as the detection of a PR transmitter through matched filter detection, energy detection, and cyclostationary feature detection [29], and the detection of a PR receiver through its local oscillator power [30].

We consider to achieve the above mentioned goals from a different perspective. Due to the non-zero probability of false detection and implementation complexity of spectrum sensing[30], we may raise a question: is there a way to achieve the goals of
CR networks without spectrum sensing? Hence, we study a new sensing-free solution to enable concurrent transmissions of mobile CR users in the legacy network and also guarantee non-interference to PR users [31]. Thus, the frequency utilization can be significantly enhanced. With such aim, we examine a location-aware spectrum sharing scenario, where a CR ad hoc network coexists with a legacy network [7]. CR users intend to operate over the same spectrum band which is licensed to PR users. The objective is to maximize the concurrent transmission region of CR users within which they can move, while at the same time maintaining non-interference to PR communications.

![Diagram](image)

(a) Without power control  (b) With power control

Figure 1.4: A spectrum sharing scenario of a two-node CR ad hoc network with a PR user.

To achieve the above objective, power control policies are important to guarantee the quality of both CR and PR communications. Fig. 1.4 demonstrates a spectrum sharing scenario without any power control scheme (in (a)) and the scenario with the power control scheme (in (b)). Fig. 1.4(a) indicates that without power control, when a PR user is within the interference range (i.e., the dotted circle) of a CR transmission, concurrent transmissions are not possible. However, in Fig. 1.4(b), with power control, concurrent transmissions become feasible by reducing the transmit power of the CR transmitter to ensure non-interference to the PR user. Hence, the concurrent transmission region defined in this paper refers to the circular area where the transmissions of CR users can be conducted without interfering PR users.
In addition, the optimal power is defined as the transmit power which makes the concurrent transmission region of a CR user the maximum so that the bandwidth efficiency and CR link throughput can be enhanced. Furthermore, we assume that every node has its own location information in the system through Global Positioning System (GPS) or other positioning algorithms [32], and every node is able to exchange location information via a common control channel with its neighboring nodes [33][34].

Currently, the related work on power control and concurrent transmissions of CR networks falls into two categories. First, the power control problem in CR networks is considered in terms of either improving network energy efficiency [35, 36, 37, 38], or supporting user communication sessions in multi-hop CR networks [39]. However, the concurrent transmission for CR users is not considered. Secondly, the sensing-free concurrent transmission region for CR users is considered only from a geometric point of view without taking power control into account[33][40][5]. In addition, in [40], the CR transmitters and receivers are geographically fixed and the mobility of CR users is ignored. Furthermore, the concurrent transmission area defined in [40] is an irregular area which is difficult to apply in mobile scenarios. In [33], a location-assisted medium access control (MAC) protocol is proposed to enable concurrent transmissions for exposed nodes. In [5], the power scaling constraint of a CR transmitter is studied.

Our proposed optimal power control algorithm differs from the related work in the original motivations. Most related work only considers fixed transmit power at each CR node without the power control capability [40] [41]. In this paper, we study a mobile CR network where each CR node has the power control capability. That is, each CR node can transmit at any power in the allowable transmit power range to achieve the maximum concurrent transmission region. Our main contribution is that we propose a location-aware sensing-free optimal power control algorithm for concurrent transmissions especially in mobile CR ad hoc networks. Under the proposed algorithm, the CR transmitter is able to conduct transmissions with the presence of
the PR users while moving. Even if the CR users are in the area called “protected region” [5] where the CR users should not transmit, if the location information of both CR and PR receivers is known to the CR transmitter, the CR transmitter can adjust its transmit power to enable the concurrent transmission.

1.3.4 Jointly Power Adaptation and Spectrum Handoff Scheme

One of the main goals of the opportunistic spectrum access in a CR network is to allow secondary users (SUs) to maintain satisfactory data transmission performance without causing harmful interference to primary user (PU) communications. Some commonly known techniques are proposed to achieve this goal, such as controlling the transmission power of SUs and changing the channel when PUs reuse it (i.e., spectrum handoff). However, most of these proposed techniques only focus on stationary cognitive radio networks (CRNs) where SUs are static [42][43][39]. More severely, the power adaptation and spectrum handoff techniques are investigated separately in the existing proposals, which is not suitable in mobile CRNs. This is because, in a mobile CR network, if SUs move away from each other, their relative distance changes. Thus, the SU transmission power needs to be adapted to maintain their communications. In the meantime, since the spectrum availability in CRNs is location-varying, SUs may also need to perform spectrum handoffs to avoid harmful interference to PUs. Therefore, solely considering one technique is not suitable when SUs are mobile.

Therefore, we consider to achieve the above goal by jointly considering the power adaptation and spectrum handoff in mobile CRNs. Fig. 1.5(a) illustrates the scenario where a SU receiver moves away from the SU transmitter before adapting its transmission power. The circle represents the transmission range of the SU transmitter under the current transmission power. It is shown that, without power adaptation [44], the continuous communication is not feasible when the SU receiver moves out of the transmission range. On the other hand, from Fig. 1.5(b), when using power adaptation, the continuous communication between the two SUs is feasible. However,
as shown in Fig. 1.5(b), there might be PUs that could potentially be interfered by the SU transmitter in the additional transmission range caused by the increase of the transmission power [36]. If those PUs already use the same channel as the SUs, the SUs have to perform a spectrum handoff to use another channel at the moment of power adaptation [45]. However, since the spectrum handoff terminates the on-going communication between the SUs, which degrades the SU performance [27], we need to design an optimal strategy that jointly considers power adaptation and spectrum handoff to maintain satisfactory SU transmission performance [46].

We study a mobile CR network where each SU has the power adaptation capability[6]. That is, each SU can transmit at any power which is in the range of the maximum transmission power to keep the communication between the SUs [7]. Our proposed joint power adaptation and spectrum handoff strategy focuses on answering the following three questions: 1) how to adapt the SU transmission power based on the mobility information of the moving SU? For instance, how to ensure that the SU communication is not dropped due to the fact that the SUs move out of the transmission range of each other? 2) Whether there are any PUs who are currently active on the channel used by SUs in the additional transmission range caused by the increase
of the transmission power? And 3) Whether to perform a spectrum handoff at the moment when the transmission power is adapted? The third issue is especially critical to the network performance and needs to be handled with care since the spectrum handoff terminates the on-going transmission and needs extra sensing time and delay due to the change of channels. In this paper, we design an intelligent strategy to decide whether the SUs should perform a spectrum handoff when the transmission power is adapted.

To sum up, the main contributions of this work are:

1. A power adaptation scheme is proposed to constantly maintain the continuous communication between the SU transmitting pair when the SU receiver is mobile.

2. An analytical model is developed to calculate the SU throughput under different scenarios during the power adaptation.

3. An intelligent scheme is proposed to make the optimal decision on whether the SUs should perform spectrum handoffs during the power adaptation based on the proposed analytical model.

1.3.5 End-to-End Congestion Control Scheme in CRAHNs

In the past decade, the CR technology has drawn tremendous attention in the research community. The majority of the existing research focuses on the issues on the lower layers in CR networks, e.g., spectrum sensing [47], spectrum sharing [48], and routing [49]. However, the transport layer issue in CR networks still remains underexplored. Although the transport layer issue on the Internet and in traditional wireless networks has been studied extensively [50, 51, 52, 53, 54], there are only limited papers addressing this issue in CR networks [55, 56, 57, 58, 59, 60, 61, 62, 63, 64]. Since the transport layer performance significantly influences the end-to-end communication services (e.g., reliability, congestion control, jitter control, and flow
control), there is a strong motivation to investigate it in CR networks. In this paper, we study the end-to-end congestion control issue since it plays a key role in transport layer protocols.

End-to-end congestion control, aiming to obtain how much traffic load offered by the source can be handled by a network, is an essential function of a transport layer protocol. Conventionally, Transmission Control Protocol (TCP) is the prevalent transport protocol to provide end-to-end congestion control on the Internet. Routers over the Internet indicate congestion by dropping packets (i.e., buffer over-flow). Therefore, the classic TCP protocol views all packet losses as being congestion related. In addition, packet round trip timeouts (RTOs) and duplicate acknowledgments (ACKs) are used as indicators for packet loss in TCP. However, in wireless ad hoc networks, packet losses may be contributed to various reasons such as interference or poor link quality. If packet losses are used as the indication of the congestion in wireless networks, the performance of the network will significantly degrade because the source node may mistakenly decreases the transmission rate in order to regulate the problem of congestion. Various efforts have been made to address this problem in traditional wireless ad hoc networks [65] [66].

However, these proposals for traditional wireless ad hoc networks do not consider the problems that may arise in end-to-end congestion control in CR ad hoc networks. First, in multi-hop CR ad hoc networks, the activity of primary users (PUs) may cause extra delay at intermediate nodes (e.g., sensing delay, rendezvous delay, and retransmission delay). Thus, the packet round trip time (RTT) may fluctuate dramatically which makes all the existing methods used to estimate the RTT infeasible [67]. If the RTT of the packet varies drastically, the source node may constantly encounter packet round trip timeouts. Thus, the end-to-end throughput using the timeout mechanism may suffer significant degradation.

Secondly, in traditional wireless ad hoc network, explicit congestion notification
(ECN) is proposed to indicate the congestion [68]. Generally speaking, there are two types of ECN mechanisms in multi-hop wireless ad hoc network: 1) the priority ECN mechanism (i.e., the ECN message is sent in a dedicated packet on data channels with the highest priority) and 2) the piggybacked ECN mechanism (i.e., the ECN message is piggybacked in the header of data packets on data channels). However, ECN is not effective in multi-hop CR ad hoc network. We show the problems of the ECN mechanisms in multi-hop CR ad hoc networks using the following figure.

Figure 1.6: A scenario of different ECN mechanisms in multi-hop CR ad hoc networks.

On one hand, as shown in Fig. 1.6, using the priority ECN mechanism, the congested node sends additional ECN signaling packets to the source to indicate the congestion in the network. However, the ECN message may not be able to reach the source node in time due to the long delay owing to PU activities, spectrum sensing, and channel rendezvous in the nodes between the source and the congested node. Moreover, since additional signaling messages are generated, the congestion in the networks may become more serious. Thus, the end-to-end throughput decreases significantly in multi-hop CR ad hoc network when the delay of the priority ECN message is excessively long. On the other hand, using the piggybacked ECN mechanism, the ECN information is piggybacked in the data packet header sent to the source to indicate the congestion in the network. However, because of the same defects in the priority ECN mechanism, the ECN message may not be able to reach the source node in time due to the long delay. Moreover, if the congested node is very close to the source node, the delay of the ECN information is extremely long. Thus, the end-to-end throughput decreases significantly in multi-hop CR ad hoc networks.
using piggybacked ECN mechanism when the congested node is very close to the source node. In extreme cases, the ECN message may even not be able to reach the source node due to the lack of available channels on the path. Thus, the end-to-end congestion control using the ECN mechanisms may fail.

Therefore, both the existing timeout and ECN mechanisms are not effective in multi-hop CR ad hoc networks. However, designing a novel end-to-end congestion control scheme to cope with the above problems in multi-hop CR ad hoc networks is not easy. First, due to the time and location varying PU activities, it is extremely difficult for the source node to obtain the congestion notification from the intermediate node. In addition, since the end-to-end transport layer delay consists all the delays at the lower layers (e.g., the data link delay in CR ad hoc networks), the RTT in multi-hop CR ad hoc networks in very challenging to estimate for the end-to-end congestion control scheme to decide whether to perform congestion control when using the timeout mechanism.

A novel end-to-end congestion control scheme in multi-hop CR ad hoc networks is proposed. We compare the performance of our proposed scheme with the existing mechanisms. Through extensive simulation, it is shown that our proposed scheme outperforms other existing mechanism in terms of higher end-to-end throughput. More specifically, the main contributions of this paper are:

1. A novel end-to-end congestion control scheme is proposed in multi-hop CR ad hoc networks. The proposed scheme takes the spectrum sensing, PU activities, and channel rendezvous into consideration. We also compare the performance of our proposed end-to-end congestion control scheme with the traditional congestion control approaches.

2. Based on the proposed end-to-end congestion control scheme, the average RTT is calculated. A Markov model that characterizes the process of the SU packet transmission from the source node to the destination node is proposed. Then,
the RTT of the multi-hop CR ad hoc network can be calculated based on the proposed Markov model.

3. Based on the calculated RTT, the optimal RTO timer value is derived in the proposed end-to-end congestion control scheme in the multi-hop CR ad hoc networks.

To the best of our knowledge, this is the first work that investigates the end-to-end congestion control issue in multi-hop CR ad hoc networks.
CHAPTER 2: RELATED WORK

2.1 Existing Global time synchronization in CR Ad Hoc Networks

Currently, in CR networks, there are only a few papers addressing the time synchronization issue [69] [70]. In [69], a synchronization protocol where a root node broadcasts the synchronization beacons to SUs based on the spanning tree is introduced. This protocol utilizes the potential spectrum holes to distinct channels for reducing the synchronization time. However, the impact of PUs on the time synchronization process is not considered in the design of the root node and the time synchronization period. In [70], two time synchronization protocols for the static CR networks and the mobile CR networks are proposed. However, it is assumed that each root node is equipped with a GPS receiver which is usually costly in CR ad hoc networks. In addition, in both [69] and [70], a dedicated common control channel (CCC) is needed to exchange the time synchronization messages, which is also not practical in CR ad hoc networks where a dedicated CCC usually does not exist.

To sum up, there is currently no paper addressing the unique challenges in global time synchronization in CR ad hoc networks considering PU activities. All the existing designs cannot be simply applied in CR ad hoc networks. In this paper, we address these issues and propose a novel distributed global time synchronization protocol in practical CR ad hoc networks.

2.2 Existing scheme to differentiate the signals from PUs and SUs

Currently, research on how to differentiate SU and PU signals is still under-explored. There are only limited papers addressing how to optimize the spectrum sensing duration and spectrum sensing period [19] [20] [21] [22] [23] [24] [25]. In [19],
a scheme on how to detect the available spectrum and improve the sensing robustness for avoiding interference to PUs is proposed. In [20], the effect of the average transmit and interference power constraints on the optimal spectrum sensing time is discussed. Additionally, a joint sensing time adaption and data transmission scheme is proposed in [21]. Moreover, in [22], the optimal spectrum sensing time considering spectrum handoffs is addressed. In [23], a method to improve the throughput of SUs in CR networks by dynamically adapting the spectrum sensing time is proposed. Furthermore, in [24], the allocation of the sensing period and the transmission time are optimized when the channel is modeled as an ON/OFF continuous time Markov chain [26]. In addition, a spectrum sensing scheme for CR networks in dynamic PU traffic environments where PUs might randomly depart or arrive during a spectrum sensing period is proposed in [25]. However, all these proposals are under the assumption that the detected signals during spectrum sensing are from PUs. Thus, it is unsuitable to use these methods to solve the problem in which the sensed signals can come from both SUs and PUs. To the best of our knowledge, this is the first paper that studies the PU and SU signal differentiation issue in CR networks.

2.3 Existing Power Control Scheme in CR Ad Hoc Networks

Currently, the related work on power control and concurrent transmissions of CR networks falls into two categories. First, the power control problem in CR networks is considered in terms of either improving network energy efficiency [35, 36, 37, 38], or supporting user communication sessions in multi-hop CR networks [39]. However, the concurrent transmission for CR users is not considered. Secondly, the sensing-free concurrent transmission region for CR users is considered only from a geometric point of view without taking power control into account [33][40][5]. In addition, in [40], the CR transmitters and receivers are geographically fixed and the mobility of CR users is ignored. Furthermore, the concurrent transmission area defined in [40] is an irregular
area which is difficult to apply in mobile scenarios. In [33], a location-assisted medium access control (MAC) protocol is proposed to enable concurrent transmissions for exposed nodes. In [5], the power scaling constraint of a CR transmitter is studied.

2.4 Existing Spectrum Handoff Scheme in Mobile CR Networks

One of the main goals of the opportunistic spectrum access in a CR network is to allow secondary users (SUs) to maintain satisfactory data transmission performance without causing harmful interference to primary user (PU) communications. Some commonly known techniques are proposed to achieve this goal, such as controlling the transmission power of SUs and changing the channel when PUs reuse it (i.e., spectrum handoff). However, most of these proposed techniques only focus on stationary cognitive radio networks (CRNs) where SUs are static [42][43][39]. More severely, the power adaptation and spectrum handoff techniques are investigated separately in the existing proposals, which is not suitable in mobile CRNs. This is because, in a mobile CR network, if SUs move away from each other, their relative distance changes. Thus, the SU transmission power needs to be adapted to maintain their communications. In the meantime, since the spectrum availability in CRNs is location-varying, SUs may also need to perform spectrum handoffs to avoid harmful interference to PUs. Therefore, solely considering one technique is not suitable when SUs are mobile.

2.5 Existing End-to-End Congestion Control Scheme

Currently, there are only very limited papers focusing on the end-to-end congestion control issue. For single hop CR ad hoc networks, in [55], the characteristics of CR networks including channel unavailability and imperfect spectrum sensing which lead to the obvious reduction of the TCP performance are investigated. Moreover, an expression of the end-to-end effective TCP throughput in CR networks is derived. However, this paper is based on single hop CR networks with a base station (BS) and no solution is proposed to address the problem of the TCP performance degradation.
In [56], a cross-layer design approach is proposed to optimize the TCP performance in CR networks without modifying the standard TCP. In addition, the main idea of this approach is that TCP uses the information from the physical layer to decide whether to access the channel. Moreover, the modulation scheme, coding scheme, and the link layer protocol are optimized to maximize the TCP throughput. However, this approach is also based on the single hop scenario with a BS which is not feasible in multi-hop CR ad hoc networks. For instance, the optimized parameters for physical layer cannot be obtained when several nodes access the same channel in multi-hop CR ad hoc networks since different optimized parameters for the same channel may be obtained by different nodes. A novel modular architecture for the TCP in CR networks including the knowledge module and the cognitive module in each layer is proposed in [57], which can help the TCP utilize available bandwidth efficiently. However, this paper is also based on single hop CR networks, which is not effective in multi-hop CR ad hoc networks. In [58], two approaches are proposed to improve the TCP performance in CR networks. The main idea of these two approaches is that the local recovery is performed at the BS because the BS can store all the TCP traffic. In addition, a new timer is introduced in the BS to decrease the number of timeouts due to spectrum sensing in CR networks. However, this paper is still based on single hop CR network with the BS. The designs in [59, 60, 61] are all based on the single hop scenario with the BS, which cannot be utilized in the multi-hop scenario.

For multi-hop CR ad hoc networks, there are only a few papers focusing on the transport layer issue. In [62], a window-based transport protocol for CR ad hoc networks is proposed to improve the TCP performance by making a combination of the explicit feedbacks from the intermediate nodes and the destination. However, this method is not effective when the delay of the feedback is too long due to spectrum sensing and PU activities. In addition, the increase in the amount of the feedback information could cause significant TCP performance degradation. In order to solve
these problems, a TCP friendly rate control (TFRC) protocol is proposed in [63], which uses the recent FCC mandated spectrum database (DB) information instead of relying on any intermediate node feedback. The main idea of this method is that the sender can change the sending rate in time by using the information obtained from the spectrum DB. However, the access to the DB may become dramatically frequent when the PU traffic is heavy, which makes the quick and appropriate control of data transmission extremely difficult. In [64], a method named CoBA is proposed to improve the TCP performance by updating the congestion window appropriately in response to the change in the bottleneck bandwidth and RTT which is obtained through the feedback information from the intermediate node. However, it suffers the same problem as [62] when the delay of the feedback is long. Thus, the existing mechanisms on end-to-end congestion control cannot be used in multi-hop CR ad hoc networks because they do not consider the unique features of multi-hop CR ad hoc networks in their designs.
CHAPTER 3: NOVEL GLOBAL TIME SYNCHRONIZATION IN CR AD HOC NETWORK

3.1 Distributed Global Time Synchronization Protocol in CRAHNs

In this section, the proposed distributed global time synchronization protocol for CR ad hoc networks is presented. Our proposed protocol has the following advantages which enable it to be implemented in practical scenarios: 1) it does not need a dedicated CCC to exchange synchronization messages; 2) the network topology information is not needed; 3) an external positioning equipment (e.g., GPS) is not needed; and 4) the synchronization overhead of the network (i.e., the total time synchronization messages) is low. As long as each SU can perform channel rendezvous with its neighboring SUs[71], our proposed protocol can be implemented in CR ad hoc network under the above practical scenarios. There are majorly three steps in the proposed protocol. We introduce the details of these three steps in this section.

3.1.1 Root Node Selection

The first step is to select a root node that constantly provides the reference time for the entire network. Conventionally, the number of hops from one node to other nodes is considered for the root node selection in traditional wireless ad hoc networks. However, as mentioned in Section ??, solely studying the number of hops is not enough for the root node selection in CR ad hoc networks. The impact of the dynamic channel availability due to the PU activity should also be taken into consideration [72]. In this paper, the average numbers of available channels of SUs are jointly investigated to select the optimal root node. The details of the root node selection are introduced in Section 3.2.
3.1.2 Global Time Synchronization

The second step is the global time synchronization. During the global time synchronization step, we define two cases: the *successful pairwise synchronization case* and the *denied pairwise synchronization case*. The synchronization process of these two cases are shown in Fig. 3.1 and Fig. 3.2, respectively. In Fig. 3.1 and Fig. 3.2, the SU who initializes the pairwise synchronization process by sending a synchronization inquiry message is the master node while the SU who receives the message is the slave node. In addition, there are four types of messages defined: 1) the *synchronization inquiry message* (SIQM) which is used by the master node to inquire whether the time synchronization is finished for the SUs who receive the SIQM message; 2) the *synchronization request message* (SRQM) which is used by the slave node to request a time synchronization process; 3) the *synchronization response message* (SRPM) which is used by the master node to reply the time synchronization process; and 4) the *synchronization refuse message* (SRFM) which is used by the slave node to refuse the time synchronization process if the SU has already been synchronized.

![Figure 3.1: The successful pairwise synchronization case.](image1)

![Figure 3.2: The denied pairwise synchronization case.](image2)

Next, we briefly introduce the process of the above two cases and show how these two cases are implemented in CR ad hoc networks. The successful pairwise synchronization process is shown in Fig. 3.1. Firstly, the master node (i.e., the root node or the node who has been synchronized) sends a SIQM including its ID, a time
synchronization inquiry symbol, and a sequence number. Then, the slave node (i.e., the node who has not been synchronized) will reply a SRQM including its ID, the synchronization request symbol, and a sending time stamp (i.e., T1). The master node records the receiving time (i.e., T2) and sends back a SRPM including the root node ID, the synchronization response symbol, the receiving time stamp (T2), and its sending time stamp (i.e., T3). Then, the receiving time (i.e., T4) is recorded by the slave node when it receives the SRPM. After collecting all the time stamps, the slave node can be synchronized to the master node based on the propagation delay (i.e., \( \Delta = (T_2 - T_1) + (T_4 - T_3) \)) and the clock offset (i.e., \( \delta = (T_2 - T_1) - (T_4 - T_3) \)).

On the other hand, the denied pairwise synchronization process is shown in Fig. 3.2. Firstly, the master node sends a SIQM which is the same as in the successful pairwise synchronization case. Since the slave node has already been synchronized, it will reply a SRFM with its ID, a synchronization refuse symbol, and a received sequence number. After that, the master node will not synchronize with the slave node again in the current time synchronization cycle in order to reduce the synchronization messages.

Then, we present how these two cases are implemented in CR ad hoc networks. First of all, the root node starts the global time synchronization by sending a SIQM to one of its neighboring SUs. Then, the root node and its neighboring SU will start a successful pairwise synchronization process where the root node is considered as the master node and its neighboring node is the slave node. Using the same method, the root node will synchronize with other neighboring SUs sequentially. Then, each synchronized SU sends the SIQM to its own neighboring SUs except its master node. If the slave SU identifies a new time synchronization cycle via a new sequence number, the two SUs will start the successful pairwise synchronization process. Otherwise, if the sequence number has been received, this means that the SU has been synchronized in the current time synchronization cycle. Then, they start a denied pairwise
3.1.3 Periodical Global Time Synchronization

In the third step, the root node initiates the global time synchronization process periodically. As mentioned earlier, the time synchronization period is a critical factor for the global time synchronization performance in CR ad hoc networks. If the time synchronization period is too long, when one or more synchronization cycles fail due to the PU activity, the network performance may be severely affected. However, if the time synchronization period is too short, the synchronization overhead of the whole CR ad hoc networks becomes heavy. Therefore, the design of the synchronization period needs to be considered carefully. The derivation of the optimal time synchronization period in CR ad hoc networks is introduced in Section 3.3.

3.2 the Optimal Root Node Selection Scheme

In this section, the optimal root node selection scheme for the global time synchronization protocol in CR ad hoc network is presented. Conventionally, only the network topology is used to select the root node. That is, the root node is usually located in the center of the network so that the distance from the root node to the furthest nodes is the shortest. However, in CR ad hoc networks, the channels availability of a SU should also be considered for the selection of the root node.

In this paper, we use two metrics to select the root node: 1) the average number of available channels of a SU and 2) the distance to the furthest SU. Thus, two criteria are designed for the root node selection: 1) the average of available channels of a SU is larger than a threshold and 2) the distance to the furthest SU is minimized.

3.2.1 Derivation of the Average Number of Available Channels

First of all, the average number of available channels of each SU is derived. We assume that there are $K$ PUs distributed in the network area (denoted as $A_L$) as a Poisson point process [73]. Then, the probability that $p$ PUs are within the trans-
mission coverage (denoted as $A^*$) could be calculated by

$$Pr(p) = \frac{(\lambda A^*)^p e^{-(\lambda A^*)}}{p!},$$

(3.1)

where $\lambda = \frac{K}{A_L}$ represents the PU node density. Moreover, $A^* = \pi r^2$ and $r$ is the radius of the SU transmission coverage. In addition, we define the probability that a PU is active, $\rho$, as:

$$\rho = \frac{E[\text{ON duration}]}{E[\text{ON duration}] + E[\text{OFF duration}]},$$

(3.2)

where $E[\cdot]$ represents the expectation of the random variable [74]. Therefore, given that there are $p$ PUs within $A^*$, the probability that there are $b$ PUs active is

$$Pr(b|p) = \binom{p}{b} \rho^b (1 - \rho)^{p-b}.$$  

(3.3)

Furthermore, given that there are $p$ PUs and $b$ active PUs within $A^*$, the probability that there are $c$ available channels is denoted as $Pr(c|p, b)$. Since the number of available channels is only related to the number of active PUs, $c$ is independent of $p$. In addition, since an active PU randomly selects a channel from $M$ channels in the band, $Pr(c|p, b)$ is equivalent to the probability that there are exactly $c$ empty boxes given that $b$ balls are randomly put into a total of $M$ boxes and a box can have more than one ball (because we do not limit a channel to only on PU). Thus, $Pr(c|p, b)$ can be expressed as

$$Pr(c|p, b) = \binom{K}{p} (M - c)! \frac{(S(b, M - c))}{M^b},$$

(3.4)

where $S(b, M - c)$ is the Stirling number of the second kind. In addition, $S(b, M - c)$
is defined as

\[ S(b, M - c) = \frac{1}{(M - c)!} \sum_{i=0}^{M-c} (-1)^i \binom{M - c}{i} (M - c - i)^b. \]  

Then, the probability that there is an available channel for a SU is

\[ P_{\text{avail}} = \frac{1}{M} \sum_{p=0}^{K} \sum_{b=0}^{p} \sum_{c=\max(0,M-b)}^{M} \frac{c(M)! S(b, M - c)}{M^b} \cdot \binom{p}{b} \rho^b (1 - \rho)^{p-b} (\lambda A^*)^p e^{-(\lambda A^*)} \frac{p!}{p!}. \]  

Therefore, the average number of the available channels for a SU is given by

\[ N_{\text{ave}} = \sum_{i=1}^{M} (1 - P_{\text{avail}})^{(M-i)} P_{\text{avail}}^i. \]  

3.2.2 Calculation of the Distance to the Furthest Node

Secondly, we calculate the distance to the furthest node for each SU. A distributed clustering-based method is used. Although there are many papers addressing the clustering issue in wireless networks [75][76], the clustering algorithm is out of scope of this paper. In fact, we can use any clustering method to calculate this metric. In this paper, the Highest Connectivity Clustering algorithm (HCC) [76] is adopted. To be more specific, every SU first broadcasts its ID to the nodes within its radio coverage. The node with the local maximum number of neighboring nodes is selected as the cluster head. As shown in Fig. 3.3, node 2 and node 8 with the largest numbers of neighboring nodes are selected as the cluster head in their local clusters. After the selection of cluster heads, each cluster head broadcasts its ID to its neighboring nodes in the local cluster. Moreover, the nodes which can receive more than one cluster head IDs are the gateway nodes, such as the node 4 in Fig. 3.3.

Next, each local cluster head communicates with other local cluster heads through
the gateway node between them. If the connection is set up successfully, the two local cluster heads exchange the local connectivity information with each other to form a new connectivity relationship. According to the exchanged connectivity relationship, the two local cluster heads use the following method to calculate the distance (i.e., number of hops) between two nodes. First of all, the local cluster heads set up the relationship matrix whose sequences of the row and column are assigned according to the IDs of the nodes. Moreover, the value is set to 1 in the cross point of the two nodes in the matrix if they have a neighboring relationship. Otherwise, the value is set to 0. An example is shown in (10) where $n_i$ represents node $i$. The relationship
matrix for the two local clusters in Fig. 3.3 is

\[
Q = \begin{pmatrix} 
  n1 & n2 & n3 & n4 & n5 & n6 & n7 & n8 \\
  n1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
  n2 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\
  n3 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
  n4 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
  n5 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\
  n6 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
  n7 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
  n8 & 0 & 0 & 0 & 1 & 1 & 1 & 0 
\end{pmatrix}
\]

(3.8)

Secondly, the distance between any two nodes is calculated. According to the relationship matrix \( Q \), the distance between any two nodes can be calculated using the graph theory. In this paper, we use the Floyd-Warshall algorithm to calculate the distance between two nodes. Therefore, the numbers of hops started from each node to any other node are calculated. Then, we can obtain the matrix of the maximum number of hops which expresses the number of hops from one node to the furthest node. For example, the matrix of the number of hops to the furthest node in Fig. 3.3 is shown as follows

\[
Y = \begin{pmatrix} 
  n1 & n2 & n3 & n4 & n5 & n6 & n7 & n8 \\
  4 & 3 & 4 & 2 & 4 & 4 & 4 & 3 
\end{pmatrix}
\]

(3.9)

Finally, we apply the constraint of the average number of available channels. The root SU node is selected based on the proposed two criteria. If more than one node satisfies the criteria, the node with the maximum average number of available channels will become the root SU node.
3.3 The Optimal Period of The Distributed Global Time Synchronization

As mentioned earlier, the global time synchronization period should be designed carefully so that the network is not significantly affected by the interrupted synchronization cycles or burdened by the synchronization overhead. In this section, the optimal period of the global time synchronization in CR ad hoc networks is studied. We consider two performance metrics: 1) the time difference between two consecutive successful global time synchronization cycles and 2) the synchronization overhead of the CR ad hoc network (i.e., the total number of time synchronization messages in a unit time). Thus, two criteria are designed: 1) the synchronization overhead of the CR network is lower than a threshold and 2) the time difference between two consecutive successful global time synchronization cycles is minimized.

3.3.1 Synchronization Overhead of the CR Ad Hoc Network

Based on the proposed protocol in Section 3.1, every synchronized SU node (except the root node) tries to initiate the synchronization process with its neighboring SU nodes excluding its master node. In addition, the synchronization process has two scenarios: the successful pairwise synchronization process and the denied pairwise synchronization process. Therefore, if there are $N$ SUs in the CR ad hoc network, the total number of the synchronization processes for the whole CR network in one time synchronization cycle is

$$\hat{N}_{total} = \sum_{i=1}^{N} (N_i - 1) + 1,$$

(3.10)

where $N_i$ is the total number of the neighbor nodes for SU $i$.

Moreover, the number of successful pairwise synchronization processes for each regular node is one. Thus, the number of the successful pairwise synchronization
process for the whole CR network in one time synchronization cycle is

\[ N_{\text{succ}} = N - 1. \] (3.11)

Therefore, according to (3.10) and (3.11), the number of the denied pairwise synchronization process for the whole CR network in one synchronization cycle is

\[ N_{\text{denied}} = N_{\text{total}} - N_{\text{succ}}. \] (3.12)

In addition, based on the proposed protocol, three messages are required in a successful pairwise synchronization process (i.e., SIQM, SRQM, and SRPM) and there are two messages are required in a denied pairwise synchronization process (i.e., SIQM and SRFM). Therefore, the number of the synchronization messages for the whole CR ad hoc network in one time synchronization cycle is

\[ N_{\text{sync}} = 3N_{\text{succ}} + 2N_{\text{denied}}. \] (3.13)

Denoted the synchronization period as \( \tau \). Therefore, the synchronization overhead of the CR ad hoc network is

\[ X = \frac{N_{\text{sync}}}{\tau}. \] (3.14)

3.3.2 The Time Difference between Two Consecutive SSC

In CR ad hoc networks, some global time synchronization cycles fail due to the impact of PUs. In order to find the optimal time synchronization period, we propose an algorithm to calculate the time difference between two consecutive successful synchronization cycles.

In this paper, we consider a CR ad hoc network where \( N \) SUs and \( K \) PUs co-exist in an area. The SUs opportunistically access the licensed channels. Moreover, an \( M/D/1 \) queuing model is used to characterize the PU channel usage [27]. Based on
this model, the difference between two consecutive successful time synchronization cycles can be derived.

![Figure 3.4: Calculation of the synchronization period.](image)

As shown in Fig. 3.4, after one successful cycle, we study the probability that the next time synchronization cycle is also successful. Denote the time needed to transmit one PU packet as $T_p$. We divide $\tau$ into $D$ segments, where $D = \text{mod} (\tau, T_p) + 1$. Thus, there are $D - 1$ segments which are equal to $T_p$ and one additional part $\Delta t$ left (i.e., $\Delta t = \tau - D T_p$), as shown in Fig. 3.4. If the time synchronization is successful in Cycle 1, there should be no PU packet arrival during the first segment. In addition, there should be no more than one PU packet arrival during the second segment and so on so forth. Therefore, two conditions should be satisfied: 1) the largest number of the PU packet arrivals during the $i$-th segment is no more than $i - 1$ and 2) the largest number of the arrival packets during $\tau$ is no more than $D - 1$.

Furthermore, we assume that there are $k$ PUs ($k \leq K$) located in the transmission coverage of $SU_i$. Moreover, the arrival rates of the $k$ PUs are $\lambda_1, \lambda_2, \ldots, \lambda_k$. Since the PU arrival follows the Poisson process, the equivalent arrival rate of PUs in the coverage of $SU_i$ is $\lambda_{\text{sum}} = \sum_{i=1}^{k} \lambda_i$. In addition, based on the $M/D/1$ model, the probability of arriving $q$ PU packets during one segment is given by

$$P = \frac{(\lambda_{\text{sum}} T_p)^q e^{-\lambda_{\text{sum}} T_p}}{q!}. \quad (3.15)$$
Define $P_i$ as the probability that the PU packets successfully transmitted during the $i$th segment ($i \in [1,D-1]$). Thus, $P_i$ is

$$P_i = \sum_{q=0}^{i-1} \frac{\left(\lambda_{sum}T_p\right)^q e^{-\lambda_{sum}T_p}}{q!}.$$  \hspace{1cm} (3.16)

Define $P_D$ as the probability that the PU packets successfully transmitted during $\Delta t$. Then, $P_D$ is

$$P_D = \sum_{q=0}^{D-1} \frac{\left(\lambda_{sum}\Delta t\right)^q e^{-\lambda_{sum}\Delta t}}{q!}.$$  \hspace{1cm} (3.17)

Define $P_1$ as the probability that the time synchronization is successful in Cycle 1. We have

$$P_1 = \sum_{i=1}^{D-1} P_i + P_D.$$  \hspace{1cm} (3.18)

Therefore, the average time difference between two consecutive successful time synchronization cycles in CR ad hoc networks is

$$T_{diff} = \sum_{i=1}^{\infty} (1 - P_1)^{i-1} P_1 i \tau.$$  \hspace{1cm} (3.19)

Finally, according to (3.14) and (3.19), the optimal time synchronization period can be obtained.

3.4 Performance Evaluation

In this section, we evaluate the network performance of the proposed distributed global time synchronization protocol in different scenarios via simulations in Matlab. We first compare the network performance under the proposed optimal root node selection scheme with the randomly selected root node. Then, the network performance under the propose optimal synchronization period with the randomly selected synchronization period is compared and analyzed. The default simulation parameters are given in Table I.

The topology of the CR ad hoc network used in the simulation is randomly gen-
Table 3.1: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The number of PUs</td>
<td>50</td>
</tr>
<tr>
<td>The probability that a PU is active</td>
<td>0.3</td>
</tr>
<tr>
<td>The PU arrival rate</td>
<td>10 packet/s</td>
</tr>
<tr>
<td>The packets length of PU</td>
<td>100 ms</td>
</tr>
<tr>
<td>The number of SU</td>
<td>8</td>
</tr>
<tr>
<td>The synchronization messages length</td>
<td>10 ms</td>
</tr>
<tr>
<td>The synchronization period of SUs</td>
<td>2000 ms</td>
</tr>
<tr>
<td>The number of channels</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 3.5: The synchronization delay under different number of channels.

erated. Fig. 3.5 shows the simulation results of the synchronization delay of the global time synchronization under different numbers of channels. We compare the network performance under the proposed optimal root node selection algorithm with randomly selected root nodes. As shown in Fig. 3.5, the synchronization delay under the optimal root node is always lower than the randomly selected root node by up to 50%. This is because that the proposed optimal root node always leads to the shortest distance to the furthest node and constantly provides the reference time. In addition, it is shown that the synchronization delay decreases as the number of
channels increases.

![Graph showing the time difference between two consecutive successful synchronization cycles with different synchronization periods.](image)

Figure 3.6: The time difference between two consecutive successful synchronization cycles with different synchronization periods.

Fig. 3.6 shows the simulation results of the time difference between two consecutive successful synchronization cycles under different synchronization periods with the different numbers of PUs. It is shown that the time difference increases as the synchronization period increases. Moreover, the time difference increases when the number of PUs increases.

In addition, Fig. 3.7 shows the overhead of the time synchronization process under different synchronization periods when the number of PUs changes. As we can see, the overhead decreases as the synchronization period increases. Moreover, the overhead increases when the number of PUs increases.

Therefore, using the proposed optimal synchronization period criteria, the optimal synchronization period is obtained. As shown in Fig. 3.8, the time difference between two consecutive successful synchronization cycles is much lower under the optimal synchronization period than the random selected synchronization period.
Figure 3.7: The overhead under different synchronization periods.

Figure 3.8: The optimal synchronization period under different number of channels.
CHAPTER 4: NOVEL SCHEME TO DIFFERENTIATE PU AND SU SIGNAL

4.1 The Proposed Spectrum Sensing Scheduling Scheme

In this section, we introduce the proposed spectrum sensing scheduling scheme to differentiate PU and SU signals in CR networks.

![Frame structure of CR networks.](image)

First of all, we illustrate the frame structure considered in this paper. As shown in Fig. 4.1, the frame structure of SUs in CR networks consists of a spectrum sensing phase and a data transmission phase. The durations of the sensing phase and the data transmission phase are $\tau$ and $T - \tau$, respectively. A SU senses for available spectrum during the sensing phase. Then, after detecting the PU activity, the SU can either share the spectrum with PUs in a way that it does not interfere with PUs, or the SU performs a spectrum handoff in order to use another channel to transmit data during the data transmission phase. However, in order to differentiate PU and SU signals during the spectrum sensing phase, when a SU performs spectrum sensing, all the other SUs in the sensing range of this SU should stop the on-going data transmissions. This issue causes further complexity when multiple SUs try to sense the spectrum. We use Fig. 4.2 to illustrate this problem.

We assume that there are three SUs who have sensing ranges with the same radius of $R$. In addition, $SU_1$ and $SU_2$ are in the sensing range of $SU_0$. Since the distance between $SU_1$ and $SU_2$ are larger than $R$, they are out of the sensing ranges of each
Moreover, we assume that the sensing durations of $SU_0$, $SU_1$ and $SU_2$ are $\tau_0$, $\tau_1$, and $\tau_2$, respectively. As shown in Fig. 4.3, the shaded rectangle for each SU represents the spectrum sensing duration. Thus, initially, the silent duration of these SUs are $\tau_0$, $\tau_1$, and $\tau_2$, respectively. In addition, we assume that the starting time of the observed frame is $t_p$ and the starting sensing times for these three SUs are different. Then, the silent duration for $SU_0$ increases from $\tau_0$ to $\tau_0 + \tau_1 + \tau_2$ because $SU_0$ cannot transmit data when $SU_1$ and $SU_2$ perform spectrum sensing. In addition, for $SU_1$, the silent duration increases from $\tau_1$ to $\tau_0 + \tau_1$ because $SU_0$ is in the sensing range of $SU_1$. Finally, the silent duration for $SU_2$ increases from $\tau_2$ to $\tau_0 + \tau_2$ since $SU_0$ is in the sensing range of $SU_2$. Therefore, if the sensing starting time for SUs are different, it results in longer silent durations for SUs.

Therefore, to solve this problem, we propose to let all SUs who are within the sensing ranges of each other start to perform spectrum sensing at the same time. In addition, the sensing duration of these SUs is the same. Then, the silent duration for each SU dramatically decreases. Fig. 4.4 indicates that the silent duration for all
three SUs is only $\tau_s$. One issue to let all the SUs sense at the same time is to obtain synchronization. However, synchronization is not difficult to achieve in infrastructure-based CR networks. Even in ad-hoc CR networks, it is also not a serious issue since there are existing papers on time synchronization in ad-hoc CR networks [77].

Since all SUs within the sensing ranges of each other perform spectrum sensing simultaneously, the sensing duration design is quite critical. To be more specific, a short sensing duration leads to the decrease of the PUs detection accuracy which re-
sults in the potential interference to the PUs. However, a long sensing duration results in less time for data transmissions which may adversely affect the SU throughput.

Moreover, we also have to take the sensing period into consideration. At the beginning of each frame, the SU senses the channel and then a specified period of data transmission time is allocated. A smaller sensing period causes lower SU throughput. However, a longer sensing period leads to higher SU throughput but less accuracy of detecting the PU activity. Therefore, a suitable spectrum sensing period $T_0$ should be chosen. More importantly, the sensing duration and the sensing period are related to the SU traffic and the number of SUs which are difficult to obtain. In the next section, we derive the optimal sensing duration and sensing period.

4.2 Derivation of the Optimal Sensing Duration and Sensing Period

In this section, we derive the optimal sensing duration and sensing period for the proposed spectrum sensing scheduling scheme. Moreover, we propose two methods to obtain optimal sensing period. The first one is to obtain the appropriate $\tau_s$ and $T_0$ that maximizes the SU throughput $S(T_0)$ with respect to $p_d \geq p_0$, where $p_d$ is the probability to detect PUs and $p_0$ is a pre-defined threshold.

4.2.1 Derivation of $p_d$

In order to obtain a good accuracy for the PU detection, a proper sensing duration of SUs is needed. Firstly, the relationship between the spectrum sensing duration and the accuracy for detecting PUs is presented in [78]. Suppose that the carrier frequency is $f_c$, the bandwidth is $W$, and the received signal is sampled at a sampling frequency of $f_s$. The probability of detecting PUs can be approximated by

$$p_d(\epsilon, \tau_s) = Q((\frac{\epsilon}{\sigma \mu})^2 - \gamma - 1) \sqrt{\frac{\tau_s f_s}{2\gamma + 1}},$$

(4.1)
where \( Q(x) \) is the complementary cumulative distribution function of the standard Gaussian distribution. In addition, \( \varepsilon \) is the threshold for signal detection while \( (\sigma_\mu)^2 \) is the variance of the Gaussian distribution. Moreover, \( \gamma \) is the signal-to-noise ratio. Fig. 4.5 shows the relationship between the sensing duration and the PU detection probability. Therefore, we can obtain the proper sensing duration which ensures the PU detection probability greater than the threshold \( p_0 \).

![Figure 4.5: The detection probability of PU under varying sensing durations.](image)

**4.2.2 Derivation of \( S(T_0) \)**

Another important parameter that needs to be determined is the sensing period, \( T_0 \). In this section, we propose a Markov model to obtain the relationship between \( T_0 \) and the SU throughput. Based on the time slotted channels, any action of a SU can only be taken at the beginning of a time slot. In addition, the status of a SU in the current time slot only relies on its immediate past time slot. Such discrete-time
characteristics allow us to model the status of a SU using the Markov model [79]. SUs adopt a carrier sense multiple access (CSMA)-based MAC protocol to access the channels that are not used by PUs. There are four states of a SU during a time slot. The definitions of these four states are

1. Transmission: the SU transmits a packet and no collision with PU packets occurs.

2. Sense: SU performs spectrum sensing.

3. Backoff: The SU starts its backoff timer when it tries to access a channel.

4. Collision: the SU transmits a packet and a collision with the transmission of PU packets occurs.

![Diagram of the state transition diagram of the Markov model.](image)

Figure 4.6: The state transition diagram of the Markov model.

Fig. 4.6 shows the state transition diagram of the proposed Markov model. We use $t$, $b$, $c$, and $s$ to represent the Transmission, Backoff, Collision, and Sense states,
respectively. The state of the proposed Markov model at time slot \( t_0 \) is denoted as \( N(t_0) \). To be more specific, we denote the one-step state transition probability from time slot \( t_0 \) to time slot \( t_0 + 1 \) as \( p(k|m) = p(N(t_0 + 1) = k|N(t_0) = m) \). Therefore, the probability \( p(k|m) \) represents the transition probability between the four states of a SU. In order to obtain the steady-state probabilities of the Markov model in Fig. 4.6, we first calculate all the state transition probabilities. The notations used in the derivation of the transition probabilities are presented in Table 7.1.

Next, we calculate the state transition probabilities of the proposed Markov model. First of all, starting from the Sense state, \( p(t|s) \) is the probability that the SU transits from the Sense state to the Transmission state. The conditions are that the channel is idle and the SU accesses the channel successfully. Therefore, we have,

\[
p(t|s) = \frac{1}{\tau_s} p_{idle} (1 - p) p_s.
\]  

Then, \( p(s|s) \) is the probability that the SU stays in the Sense state from the previous slot to the current slot. We have,

\[
p(s|s) = 1 - \frac{1}{\tau_s}.
\]  

Next, \( p(c|s) \) is the probability that a PU packet arrives after the SU finishes the spectrum sensing. Thus, we have,

\[
p(c|s) = (1 - \frac{1}{\tau_s}) p.
\]  

Table 4.1: Notations used in the Markov model

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )</td>
<td>Probability that a PU packet arrives in a time slot</td>
</tr>
<tr>
<td>( p_{idle} )</td>
<td>Probability that a SU does not perform any action</td>
</tr>
<tr>
<td>( p_s )</td>
<td>Probability that a SU accesses the channel successfully</td>
</tr>
<tr>
<td>( L_s )</td>
<td>The average length of a SU packet</td>
</tr>
<tr>
<td>( T_0 )</td>
<td>The length of the sensing period</td>
</tr>
<tr>
<td>( \tau_s )</td>
<td>The length of the sensing duration</td>
</tr>
</tbody>
</table>
Finally, \( p(b|s) \) is the probability that the SU fails to access the channel after sensing, which is expressed as
\[
p(b|s) = p_{idle} \frac{1}{T_s} (1 - p)(1 - p_s).
\] (4.5)

Starting from the Collision state, \( p(s|c) \) is the probability that the SU transits into the Sense state after the collision ends due to the start of a new sensing period. That is,
\[
p(s|c) = \frac{1}{T_0} p_{idle}(1 - p).
\] (4.6)

In addition, \( p(c|c) \) is the probability that the SU collides with the PU. Once the collision occurs, the SU will stay in the collision state until the new sensing period starts. We assume that \( p(c|c) \) is known and denoted as \( p_{cc} \).

Next, starting from the Backoff state, \( p(c|b) \) is the probability that the SU collides with the PU after the Backoff state. Then, we have
\[
p(c|b) = p.
\] (4.7)

Moreover, \( p(b|b) \) is the probability that the SU stays in the Backoff state. Thus, it can be expressed as
\[
p(b|b) = (1 - p)(1 - p_s).
\] (4.8)

Then, the \( p(s|b) \) is the probability that the SU enters a new sensing period after the Backoff state in the previous slot. We assume that \( p(s|b) \) is known and denoted as \( p_{bs} \). Furthermore, \( p(t|b) \) is the probability that the SU finishes the backoff process and access the channel successfully in the next slot. That is,
\[
p(t|b) = (1 - p)p_s.
\] (4.9)
Last, starting from the Transmission state, $p(s|t)$ is the probability that the SU transits into the Sense state after it finishes the data transmission in the previous slot. Thus, we have,

$$p(s|t) = \frac{1}{L_s} \frac{1}{T_0} (1 - p)p_{idle}. \quad (4.10)$$

Next, $p(c|t)$ is the probability that the SU collides with the PU during a data transmission and the SU collides with the PU after it finishes the data transmission in the previous slot. Hence,

$$p(c|t) = [(1 - \frac{1}{L_s})p + \frac{1}{L_s} p_s p] (1 - \frac{1}{T_0}). \quad (4.11)$$

Then, $p(b|t)$ is the probability that the SU enters the backoff procedure after it finishes the data transmission in the previous slot. Therefore,

$$p(b|t) = \frac{1}{L_s} (1 - p)(1 - p_s)(1 - \frac{1}{T_0}). \quad (4.12)$$

Finally, $p(t|t)$ is the probability that the SU stays in the Transmission state which is shown as

$$p(t|t) = [(1 - \frac{1}{L_s})(1 - p) + \frac{1}{L_s} (1 - p)p_s)](1 - \frac{1}{T_0}). \quad (4.13)$$

Now, we have obtained the non-zero one-step state transition probabilities for all four states in the proposed Markov model. Let $\pi(t) = \lim_{t_0 \to +\infty} p(N(t_0) = \text{transmission})$ be the steady-state probability of the Transmission state of the Markov model. Similarly, the other three steady-state probabilities can be presented as $\pi(b)$, $\pi(c)$, and $\pi(s)$. Based on the conservation law, we can get the balance equation for the Transmission state as

$$[p(s|t) + p(c|t) + p(b|t)]\pi(t) = p(t|s)\pi(s) + p(t|b)\pi(b) + p(t|t)\pi(t). \quad (4.14)$$
Then, for the Sense state, we have

\[
[p(t|s) + p(c|s) + p(b|s)]\pi(s) = p(s|s)\pi(s) + p(s|b)\pi(b) + p(s|t)\pi(t) + p(s|c)\pi(c).
\] (4.15)

For the Collision state, we have

\[
p(s|c)\pi(c) = p(c|s)\pi(s) + p(c|b)\pi(b) + p(c|t)\pi(t) + p(c|c)\pi(c).
\] (4.16)

Then, for the Backoff state, the balance equation is represented as

\[
[p(c|b) + p(s|b) + p(t|b)]\pi(c) = p(b|s)\pi(s) + p(b|b)\pi(b) + p(b|t)\pi(t).
\] (4.17)

Since \(\pi(t) + \pi(s) + \pi(b) + \pi(c) = 1\), we can calculate the steady-state probability of every state in the proposed Markov model. We only show the closed-form of \(\pi(t)\). Other steady state probabilities can be represented using \(\pi(t)\). In order to make the closed forms of the steady-state probabilities simpler, we use the following notations

\[
C_1 = p(s|t) + p(p(c|t) + p(b|t) - p(t|t)
C_2 = p(t|s) + p(c|s) + p(b|s) - p(s|s)
C_3 = p(s|c) - p(c|c)
C_4 = p(c|b) + p(s|b) + p(t|b) - p(b|b).
\] (4.18)
Then, we can use the steady-state probability of the state transmission \( \pi(t) \) to represent the other three steady-state probabilities. That is,

\[
\begin{align*}
\pi(s) &= \frac{C_4 C_1 - p(t|b)p(b|t)}{C_4 p(t|s) + p(b|s)p(t|b)} \pi(t) \\
\pi(b) &= \frac{p(b|s)C_1 + p(t|s)p(b|t)}{p(b|s)p(t|b) + p(t|s)C_4} \pi(t). 
\end{align*}
\]

(4.19)

If we denote that 

\[
A = \frac{C_4 C_1 - p(t|b)p(b|t)}{C_4 p(t|s) + p(b|s)p(t|b)} \text{ and } B = \frac{p(b|s)C_1 + p(t|s)p(b|t)}{p(b|s)p(t|b) + p(t|s)C_4},
\]

\( \pi(c) \) can be written as

\[
\pi(c) = \frac{p(c|s)A + p(c|t) + p(c|b)B}{C_3} \pi(t). 
\]

(4.20)

Finally, from (4.14)-(7.18), \( p(t) \) can be represented as

\[
\pi(t) = \frac{C_3}{C_3(A + B + 1) + p(c|s)A + p(c|t) + p(c|b)B}.
\]

(4.21)

As described above, it is noted that \( \pi(t) \) is a function of \( T_0 \). Based on (4.21), we can obtain the optimal \( T_0 \) to maximize the transmission probability. Fig. 4.7 illustrates the relationship between the transmission probability and the sensing period. It clearly shows that there exists an optimal sensing period for the maximum transmission probability.

4.2.3 Derivation of \( P_{pre}(N_p) \)

In this section, the second method is proposed to obtain the optimal sensing period \( N_p \) to maximize the probability of the prediction for PUs \( P_{pre}(N_p) \). Based on the time slotted channels, we use Fig. 4.8 to show the channel model used in this section. To be more specific, the start time of sensing duration is \( N_0 \) while the sensing duration and sensing period is represented by \( N_s \) and \( N_p \), respectively. The definitions of four states for the proposed channel model in one sensing period are

1. \( S_B \): the state of the sensing duration is busy, which means that there is at least one slot is busy in the sensing duration \( N_s \).
2. $S_I$: the state of the sensing duration is idle, which means that all the slots in the sensing duration $N_s$ are idle.

3. $A_B$: the state of the transmission duration is busy, which means that at least one slot in the duration $[N_0 + N_s, N_p]$ is busy.

4. $A_I$: the state of the transmission duration is idle, which means that all the slots in the duration $[N_0 + N_s, N_p]$ are idle.

Figure 4.7: The transmission probability under vary sensing period.

Figure 4.8: The time slotted channel model.
In order to obtain the relationship between $N_p$ and $P_{pre}(N_p)$, the definitions of four condition probabilities are

1. $P(A_B|S_B)$: the probability that the duration of the transmission on the channel is actually busy while the SU sensing result for the channel is busy.

2. $P(A_I|S_B)$: the probability that the duration of the transmission on the channel is actually idle while the SU sensing result for the channel is busy.

3. $P(A_I|S_I)$: the probability that the duration of the transmission on the channel is actually idle while the SU sensing result for the channel is idle.

4. $P(A_B|S_I)$: the probability that the duration of the transmission on the channel is actually busy while the SU sensing result for the channel is idle.

Where $P(A_B|S_B)$ and $P(A_I|S_I)$ are the accurate prediction probabilities, which means that the state of the transmission duration is the same as the sensing result. $P(A_I|S_B)$ and $P(A_B|S_I)$ are the inaccurate prediction probabilities, which means that the state of the transmission duration is different from the sensing result. We have

$$\begin{cases} 
    P(A_B|S_B) + P(A_I|S_B) = 1 \\
    P(A_I|S_I) + P(A_B|S_I) = 1.
\end{cases} \tag{4.22}$$

The goal of our proposed method is to maximize the accurate prediction probabilities and minimize the inaccurate prediction probabilities. However, according to 4.22, we have $P(A_I|S_B) = 1 - P(A_B|S_B)$ and $P(A_B|S_I) = 1 - P(A_I|S_I)$. Then, the goal of our proposed method is simplified to maximize the accurate prediction probabilities. In this section, we consider that the threshold for the sensing duration should meet the requirement $p_d(N_{th}) \geq p_d$. We denote the probability threshold for $P(A_B|S_B)$ as $P_{th}$. The optimal sensing period problem for accurate prediction probabilities is formulated as following:
Maximize: \( P_{pre}(N_p) = P(A_I|S_I) \)

Subject to:

\[
P(A_B|S_B) \geq P_{th} \\
N_s \geq N_{th} \\
N_p > N_s,
\]

(4.23)

4.2.3.1 the derivation of \( P(A_B|S_B) \)

In this section, \( P(A_B|S_B) \) is derived. We use Fig. 4.9 to further show the scenario where the SU sensing result is busy. The light blue rectangles represent the PU packets and the length of the PU packet is denoted by \( L_p \). If we assume the arrive time of the \( k \)th PU packet is \( N_{str}^k \), we have \( N_{str}^k \in [N_0 + L_p + 1, N_0 + N_s - 1] \).

In order to calculate the probability \( P(A_B|S_B) \), two cases are introduced. The case I is that \( N_{str}^k \in [N_0 + L_p + 1, N_0 + N_s - L_p] \) while the case II is \( N_{str}^k \in [N_0 + L_p + 1, N_0 + N_s - 1] \). The details about the case I can be seen in Fig. 4.10. \( X_k \) denotes the \( k \)th PU packet and \( X_k' \) is the \( k \)th PU packet with the arrive time \( N_0 + N_s - 1 \). \( X_{k+1} \) is the \( k + 1 \)th PU packet. The interval between the arrive time of \( k \)th and \( k + 1 \)th PU packet is denoted by \( \Delta k \). In case I, \( \Delta k \) should be in \([N_s - 1, N_p]\).

Then, the case II is introduced. As shown in Fig. 4.11, the arrive time of the \( k \)th PU packet \( N_{str}^k \) is \([N_0 + L_p + 1, N_0 + N_s - 1]\). In this case, the state of the transmission is always busy since some slots of the \( k \)th PU packet are in duration \([N_0 + N_s, N_0 + N_p]\).

Finally, we can calculate the \( P(A_B|S_B) \) with the combination of the case I and II.
We have

\[
P(A_B|S_B) = P_{\text{busy}} \frac{1}{N_s + L_p - 2} \left( \sum_{i=1}^{N_s-1} \int_{N_s-i}^{L_p+N_p-1} \lambda e^{-\lambda T_s t} dt \right) \\
+ P_{\text{busy}} \frac{L_p - 1}{L_p + N_s - 2},
\]

where \( T_s \) is the time duration for each slot. \( P_{\text{busy}} \) is the probability that the channel is busy during \([N_0, N_0 + N_s]\). Then, we have

\[
P_{\text{busy}} = 1 - (1 - \rho_0)^{N_s}.
\]

where \( \rho_0 = \frac{\lambda}{\mu} \) is the average probability that the channel is busy.

4.2.3.2 the derivation of \( P(A_I|S_I) \)

In this section, the derivation of the probability \( P(A_I|S_I) \) is introduced. Here, we calculate \( P(A_B|S_I) \) because \( P(A_I|S_I) \) is equal to \( 1 - P(A_B|S_I) \). Fig. 4.12 shows the scenario that the state of the transmission duration is busy when the sensing result is idle.
Figure 4.12: The scenario that the transmission duration state is busy when the sensing result is idle.

As shown in Fig. 4.12, \( t = N_{str}^m \ (m \in [1, \infty]) \) is the arrive time of the \( m \)th PU packet. In order to calculate \( P(A_B|S_I) \), we have \( t \in [N_0 + N_s, N_0 + N_p] \). Thus, we have

\[
P(A_B|S_I) = P_{idle} \sum_{m=1}^{N_p-N_s} P_r(m|m-1)p_0\frac{N_p-N_s}{N_p}.
\]  

(4.26)

where \( P_r(m|m-1) \) is the probability that the \( m \)th slot is busy after \( m-1 \) consecutive idle slots. The probability that there are \( m \) consecutive idle slots is derived first. We use “0” and “1” to represent that the channel is idle and busy, respectively. Denote \( D(t) \) as the status of the channel at time slot \( t \). In addition, \( R(t) \) is the number of consecutive idle slots before the first busy slot. Fig. 4.13 shows three examples with different number of consecutive idle slots.

![Figure 4.13: Three examples with different number of consecutive idle slots.](image)

Based on the channel status of two consecutive time slots, we define the following four conditional probabilities: 1) \( p_{00} = P_r(D(t) = 0|D(t-1) = 0) \); 2) \( p_{01} = P_r(D(t) = 1|D(t-1) = 0) \); 3) \( p_{10} = P_r(D(t) = 0|D(t-1) = 1) \); 4) \( p_{11} = P_r(D(t) = 1|D(t-1) = 1) \). Therefore, from Fig. 4.13, the probability that there are \( m \) consecutive idle time slots can be expressed as \( P_r(R(t) = m) = P_r(D(t) = 1, D(t-1) = 0, \cdots, D(t-m) = 0) \). Then, since the PU arrival process is memoryless, using the Bayes’ theorem and
the Markov property, we have

\[ P_t(R(t) = m) = P_t(D(t) = 1|D(t-1) = 0, \cdots, D(t-m) = 0) \cdot P_t(D(t-1) = 0|D(t-2) = 0, \cdots, D(t-m) = 0) \cdots \]

\[ = P_t(D(t) = 1|D(t-1) = 0) \cdot P_t(D(t-1) = 0|D(t-2) = 0) \cdots \]

\[ = \prod_{m=0}^{m} p_{00} p_{01} D(t) = 1 \]

\[ = p_{00}^m p_{01} P_t(D(t) = 1) \]

\[ = p_{00}^m p_{01} \rho_0, \]

where \( \rho_0 \) is the probability that the channel is busy in a time slot. Note that 4.27 is the probability that there are \( m \) idle slots before one busy slot. Thus, the probability that the transmission duration is busy when the sensing result is idle is

\[ P(A_B|S_I) = P_{idle} \sum_{m=1}^{N_p - N_s} p_{00}^m p_{01} \rho_0 \frac{N_p - N_s}{N_p}. \] (4.28)

where \( P_{idle} \) is the probability that each slot of the sensing duration is idle. We have \( P_{idle} = (1 - \rho_0)^{N_s} \).

![Figure 4.14: The channel state transition diagram.](image)
Next, we calculate the conditional probabilities \( p_{ij} \), where \( i, j = 0, 1 \). A Markov model is proposed to describe the change of the channel state. The channel state transition diagram is shown in Fig. 4.14. According to the Markov property, we have

\[
\begin{cases}
    p_{00} + p_{01} = 1 \\
    p_{10} + p_{11} = 1 \\
    P_r(idle) = p_{00}P_r(idle) + p_{10}P_r(busy) \\
    P_r(busy) = p_{11}P_r(busy) + p_{01}P_r(idle),
\end{cases}
\] (4.29)

where \( P_r(idle) \) is the probability that the channel is idle in a time slot and \( P_r(busy) \) is the probability that the channel is busy in a time slot. Thus, we have \( P_r(idle) = 1 - \rho_0 \) and \( P_r(busy) = \rho_0 \). According to 4.29, we have

\[
p_{01} = \frac{(1 - p_{11})\rho_0}{1 - \rho_0}.
\] (4.30)

where \( p_{11} = \rho_0 \frac{L - 1}{L_p} \). Since the sum of the conditional probabilities \( p_{01} \) and \( p_{00} \) is one, we have \( p_{00} = 1 - p_{01} \).

4.3 Performance Evaluation

In this section, we evaluate the performance of the proposed spectrum sensing scheduling scheme with two different methods for the derivation of the optimal spectrum sensing period. The advantage of our proposed spectrum sensing scheduling scheme is that it can differentiate the signals from PUs and SUs. Therefore, the channels used only by PUs can be obtained. Since other spectrum sensing methods cannot differentiate the signals from PUs and SUs, the sensing result is not accurate no matter how perfect the spectrum sensing method is. Thus, we use a arbitrary spectrum sensing technique to compare with our proposed spectrum sensing scheduling scheme via simulation.
4.3.1 Performance Evaluation for the First Proposed Method

In this section, the performance of the proposed spectrum sensing scheduling scheme with the first method for the derivation of the optimal spectrum sensing period is evaluated.

Fig. 4.15 shows the average SU throughput using the proposed scheme and without the proposed scheme. In the simulation, we run five times with the increasing packet arrive rates. In addition, we assume that there are two pairs of PUs and three pairs of SUs in the simulation area. Moreover, there are totally four channels available in the network. It is shown that our proposed spectrum sensing scheduling scheme outperforms the scenario without the proposed scheme in terms of higher SU throughput. This is because that only two channels used by two pairs of PUs from the proposed spectrum sensing scheduling scheme. Thus, the three pairs of SUs can compete the other two available channels. However, when the proposed spectrum sensing scheduling scheme is not used, SUs cannot differentiate SU and PU signals. Thus, the sensing result is that four channels are all used when two pairs of PUs and two pairs of SUs access four channels. Thus, there is always one pair of SUs that cannot access the channel successfully. Therefore, the SU throughput is low.

Fig. 4.16 and Fig. 4.17 show that the average SU throughput under the proposed spectrum sensing scheduling scheme is higher than the scenario without the proposed scheme when the numbers of SU pairs are four and five.

4.3.2 Performance Evaluation for the Second Proposed Method

In this section, we will introduce the performance evaluation for our proposed spectrum sensing scheduling using the second proposed optimal spectrum sensing period derivation method. First, we show the simulation results about the performance comparison between our proposed method for optimal spectrum sensing duration and period and the random selection method.
Figure 4.15: The average SU throughput (three pairs of SUs).

Fig. 4.18 shows the $P(I|I)$ under different PU arrive rates. In the simulation, we compare the $P(I|I)$ under different spectrum sensing durations and periods. To be more specific, the $P(I|I)$ under the optimal spectrum sensing duration and period is compared to the other two $P(I|I)$ under two randomly selected spectrum sensing durations and periods. As shown in Fig. 4.18, the performance of our proposed method for the optimal spectrum sensing duration and period is much better than the other two random selections.

Fig. 4.19 shows the SU throughput comparison under different PU arrive rates. In this simulation, there are 8 pairs of PUs in the networks and the SU packet arrive rate is 40 packets/s. As shown in Fig. 4.19, the SU throughput under our optimal spectrum sensing durations and periods is much higher than the other two random selections. The SU throughput decreases as the PU packet arrive rate increases.

Fig. 4.20 shows the SU throughput comparison under different SU arrive rates.
In this simulation, there are 8 pairs of PUs in the networks with the PU packet arrive rate 40 packets/s and the SU packet arrive rate varies from 10 packets/s to 70 packets/s. As shown in Fig. 4.20, the SU throughput under our optimal spectrum sensing durations and periods is much higher than the other two random selections. The SU throughput increases as the SU packet arrive rate increases.

Fig. 4.21 shows the SU throughput comparison using the proposed spectrum sensing scheme and without the proposed spectrum sensing scheme. In this simulation, the second method to obtain the optimal spectrum sensing duration and period is used. Both the proposed spectrum sensing scheme and the scheme without the proposed spectrum sensing scheme use the optimal spectrum sensing duration and period. As shown in Fig. 4.21, the SU throughput of the proposed spectrum sensing scheme is much higher than the scheme without the proposed spectrum sensing scheme. This is because that more channels can be used to transmit SU packets in our
Figure 4.17: The average SU throughput (five pairs of SUs).

The proposed spectrum sensing scheme performs better than other spectrum sensing schemes. In addition, the SU throughput increases as the SU packet arrive rate increases.
Figure 4.18: The P(I—I) comparison under different PU arrive rates.

Figure 4.19: The SU throughput comparison under different PU arrive rates.
Figure 4.20: The SU throughput comparison under different SU arrive rates.

Figure 4.21: The SU throughput comparison under different spectrum sensing schemes.
5.1 System Model and Problem Formulation for a mobile CRAHNs

In this section, a spectrum sharing scenario where a mobile CR ad hoc network coexisting with a PR network (e.g., a TV network) is considered. Fig. 5.1 shows the system model, where the shaded triangle and square represent the PR transmitter and receiver, respectively. The white circles are the CR transmitter (denoted as CTx) and receiver (denoted as CRx). They form an ad hoc network to share the same spectrum band with the primary network [80]. Without loss of generality, we assume that the PR base station (e.g., TV base station) is at the origin of the coordinate axes, and the PR receiver (e.g., TV receiver) does not move. Let the location of the PR and CR receiver be \((r_1, \varphi_1)\) and \((r_2, \varphi_2)\), respectively. In addition, \(d_{12}\) represents the distance between the CTx and the PR receiver, and \(d_{22}\) represents the distance between the CTx and CRx. The decodable radius of the TV base station is \(R\). Thus, the distance between the PR and CR receiver is \(d_{pc} = \sqrt{r_1^2 + r_2^2 - 2r_1r_2 \cos \theta_{pc}}\), where \(\theta_{pc}\) is the relative angle of the PR and CR receivers. Therefore, the concurrent transmission region of CRx is shown in Fig. 2.

In addition, we use the two-ray ground propagation model in this paper[81][82]. Based on the two-ray ground propagation model, the received signal power \(P_r\) can be written as \(P_r = \frac{P_t G_t G_r h_t^2 h_r^2}{r^\alpha}\), where \(P_t\) is the transmit power, \(G_t\) and \(G_r\) are the gains of the transmitter and receiver antennas, respectively; \(h_t\) and \(h_r\) are the heights of the transmitter and receiver antennas, respectively; \(r\) is the distance between the transmitter and the receiver; and \(\alpha\) is the path loss factor [83].

In this paper, we consider that the concurrent transmission for CR users must
Figure 5.1: System model of a mobile CR ad hoc network coexisting in a primary network.

satisfy the co-channel signal-to-interference ratio (SIR) requirements for both PR and CR receivers. We denote the SIR thresholds for the PR and CR receivers as $\tau_p$ and $\tau_c$, respectively; and the SIRs for the PR and CR receivers are $SIR_p$ and $SIR_c$, respectively. The optimal power control problem for the concurrent transmission region maximization is formulated as follows:

Maximize: the area of concurrent transmission region

Subject to:

\[
\begin{align*}
SIR_p &> \tau_p \\
SIR_c &> \tau_c \\
&\quad P_{ct} \leq P_{c} \leq P_{c}^{\text{max}},
\end{align*}
\]  \hspace{1cm} (5.1)

where $P_{ct}$ is the transmit power of the CTx, $P_{c}^{\text{min}}$ and $P_{c}^{\text{max}}$ are the minimum and maximum allowable transmit power of the CTx, respectively.
5.2 Optimal Power Control for Single Pair CR Ad Hoc Networks

In this section, the proposed optimal power control algorithm for the concurrent transmission region maximization in a single-pair CR ad hoc network is presented. We first consider the feasibility of the proposed optimal power control algorithm. Then, we consider the implementation of the algorithm in a mobility scenario. Finally, the impact of the shadowing fading effect on the optimal power control algorithm is investigated for the mobility scenario.

5.2.1 Feasibility of Optimal Power Control

Without loss of generality, we assume that the transmit power of the TV base station is \( P_{bs} \); the gains of the transmitter and receiver antennas are unity; the heights of the antennas are the same; the path loss factors of the PR and CR transmissions are the same; and the Gaussian noise is negligible. Based on these assumptions, the SIRs at both CR and PR receivers can be written as \( SIR_c = \frac{P_{ct} \tau_c}{P_{bs} d_2^\alpha} \) and \( SIR_p = \frac{P_{bs} d_1^\alpha}{P_{ct} \tau_p} \), respectively. Since the SIRs must satisfy (5.1), we have

\[
\begin{align*}
    d_2^\alpha &< r_2 \left( \frac{P_{ct}}{\tau_c P_{bs}} \right)^{1/\alpha} \\
    d_1^\alpha &> r_1 \left( \frac{\tau_p P_{ct}}{P_{bs}} \right)^{1/\alpha}.
\end{align*}
\]

The first constraint in (5.2) means that the CTx which can concurrently transmit to the CRx must be physically within the disk centered at the CRx with a radius of \( r_2 \left( \frac{P_{ct}}{\tau_c P_{bs}} \right)^{1/\alpha} \), as shown in Fig. 5.1. The second constraint means that the CTx must not fall into the disk which is centered at the TV receiver with a radius of \( r_1 \left( \frac{\tau_p P_{ct}}{P_{bs}} \right)^{1/\alpha} \), as shown in Fig. 5.1. Therefore, the concurrent transmission region reaches the maximum when the following equation is satisfied:

\[
    r_1 \left( \frac{\tau_p P_{ct}}{P_{bs}} \right)^{1/\alpha} + r_2 \left( \frac{P_{ct}}{\tau_c P_{bs}} \right)^{1/\alpha} = d_{pc}.
\]
Hence, given $r_1$, $r_2$, and $\theta_{pc}$, the optimal power for the concurrent transmission region maximization can be derived by solving equation (6.26).

However, considering (5.1), the solution of (6.26) may not lie in the allowable range $[P_c^{\text{min}}, P_c^{\text{max}}]$. So we consider two extreme cases by letting $P_{ct}$ be $P_c^{\text{min}}$ and $P_c^{\text{max}}$, respectively. We have the following two extreme functions of $r_2$ and $\theta_{pc}$:

$$f(r_2, \theta_{pc}) = r_1 \left(\frac{P_{c}^{\text{min}}}{P_{bs}}\right)^{1/\alpha} + r_2 \left(\frac{P_{c}^{\text{min}}}{\tau_c P_{bs}}\right)^{1/\alpha}$$

$$- \sqrt{r_1^2 + r_2^2 - 2r_1 r_2 \cos \theta_{pc}}$$

(5.4)

$$g(r_2, \theta_{pc}) = r_1 \left(\frac{P_{c}^{\text{max}}}{P_{bs}}\right)^{1/\alpha} + r_2 \left(\frac{P_{c}^{\text{max}}}{\tau_c P_{bs}}\right)^{1/\alpha}$$

$$- \sqrt{r_1^2 + r_2^2 - 2r_1 r_2 \cos \theta_{pc}}.$$  

(5.5)

If $f(r_2, \theta_{pc}) > 0$, as shown in Fig. 5.2(a), the two disks overlap and increasing the transmit power $P_{ct}$ cannot make these two disks separate, therefore, the optimal transmit power of $P_{ct}$ can never be reached. Similarly, if $g(r_2, \theta_{pc}) < 0$, as shown in Fig. 5.2(b), there will not be an optimal power either. Hence, the existence of the optimal $P_{ct}$ power relies on $r_2$ and $\theta_{pc}$. If the optimal power control is feasible, the two cases shown in Fig. 5.2 should be avoided. That is, to let the optimal power exist, $r_2$ and $\theta_{pc}$ must be in the set

$$\{(r_2, \theta_{pc}) | f(r_2, \theta_{pc}) \leq 0 \cap g(r_2, \theta_{pc}) \geq 0\}.$$  

(5.6)

Fig. 4 presents the proposed optimal power control algorithm for the scenario when the CRx is in a fixed location, where $r_{\text{max}}$ is the maximum decodable range of the CTx. Recall that the location information of both the CR and PR receivers is available to the CTx. The proposed algorithm first evaluates the feasibility of the optimal power control for concurrent transmissions. Then, the optimal power can be computed using any numerical method when the optimal power control is feasible.
Figure 5.2: Two possible cases that there will be no solution for (6.26). (a) $f(r_2, \theta_{pc}) > 0$. (b) $g(r_2, \theta_{pc}) < 0$.

update $r_1$, $\varphi_1$, $r_2$ and $\varphi_2$;
calculate $\theta_{pc}$, $d_{22}$, $f(r_2, \theta_{pc})$ and $g(r_2, \theta_{pc})$;
if ($f(r_2, \theta_{pc}) \leq 0$) AND ($g(r_2, \theta_{pc}) \geq 0$) AND ($d_{22} \leq r_{max}$)
calculate optimal power; //optimal power could apply
transmit with optimal power;
elseif ($g(r_2, \theta_{pc}) < 0$) AND ($d_{22} \leq r_{max}$)
transmit with maximum power; //concurrent transmission will not affect primary user
elseif ($f(r_2, \theta_{pc}) > 0$)
stop transmitting; //concurrent transmission is not allowed
endif

Figure 5.3: Power control algorithm for fixed CRx in a single-pair CR ad hoc network.

The last case checks the availability of concurrent transmissions and the CTx will not conduct transmissions unless the condition is violated.

5.2.2 Optimal Power Control for Mobility Scenarios

We now extend our model to the scenario where the mobility of the CRx is considered. Because of the mobility of the CRx, $r_2$ and relative angle $\theta_{pc}$ change with the movement of the CRx. Thus, the optimal power and the concurrent transmission region also change. Fig. 5.4 shows the scenario where the concurrent transmission region evolves with the movement of the CRx from A to B.

Without loss of generality, we assume that the CTx is static in a location $(r_3, \varphi_3)$, and the CRx is moving from a starting point $(R_2, \Phi_2)$ with a velocity of $\vec{v} = s\vec{u}$, where $s$ is the speed and $\vec{u} = (\cos \gamma, \sin \gamma)$ is the unit directional vector. Therefore,
the polar coordinates of the CRx can be written as:

\[
\begin{align*}
    r_2(t) &= \sqrt{(R_2 \cos \Phi_2 + st \cos \gamma)^2 + (R_2 \sin \Phi_2 + st \sin \gamma)^2} \\
    \varphi_2(t) &= \arctan \left( \frac{R_2 \sin \Phi_2 + st \sin \gamma}{R_2 \cos \Phi_2 + st \cos \gamma} \right).
\end{align*}
\]

If the movement pattern of the CRx does not change (i.e., the direction and velocity remain the same) or the movement pattern is deterministic, the coordinates of the CRx are just functions of time. Therefore, the CTx can “predict” the location of the CRx, thus adjust its transmit power using exactly the same optimal power control algorithm shown in Fig. 4.

On the other hand, if the movement pattern of the CRx keeps changing randomly, the CRx should update its location to the CTx for computing the optimal power control. Fig. 6 demonstrates the proposed optimal power control algorithm for a mobile CRx that changes movement patterns randomly, where \( r_{CT} \) is the radius of the concurrent transmission region.
update \( r_1, \phi_1, R_2, \Phi_2, r_3, \phi_3, s \) and \( \vec{u} \);
calculate \( r_2, \phi_2, \theta_{pc} \) and \( d_{22} \);
if \( (d_{22} \leq r_{CT}) \text{AND}(d_{22} \leq r_{max}) \)
  //the distance between CTx and CRx
  is still in concurrent transmission region
  transmit power remains the same;
else
  calculate \( f(r_2, \theta_{pc}) \) and \( g(r_2, \theta_{pc}) \);
  if \( (f(r_2, \theta_{pc}) \leq 0) \text{AND}(g(r_2, \theta_{pc}) \geq 0) \text{AND}(d_{22} \leq r_{max}) \)
    calculate optimal power;
    calculate concurrent transmission radius \( r_{CT} \);
    transmit with optimal power;
  elseif \( (g(r_2, \theta_{pc}) < 0) \text{AND}(d_{22} \leq r_{max}) \)
    transmit with maximum power; //concurrent transmission
    will not affect primary user
  elseif \( (f(r_2, \theta_{pc}) > 0) \)
    stop transmitting; //concurrent transmission is not
    allowed
endif
endif

Figure 5.5: Power control algorithm for the mobile CRx in a single-pair CR ad hoc network.

5.2.3 Shadowing Fading Effect

In this subsection, we consider the impact of the shadowing fading effect on the optimal power control algorithm. Since the antenna of the TV transmitter is usually hundreds of meters higher than that of the CR transmitter, we loose the assumption that the path loss factors of the PR user and CR user are the same, and assume that \( \alpha_1 < \alpha_2 \), where \( \alpha_1 \) and \( \alpha_2 \) are the path loss factors of the PR user and CR user, respectively. Using log-distance path loss model [81], the path loss of PR transmissions can be written as:

\[
PL_p(r_1)[dB] = PL_p(d_0) + 10\alpha_1 \log\left(\frac{r_1}{d_0}\right) + X_\sigma,
\]

where \( d_0 \) is the reference distance and \( X_\sigma \) is a zero-mean Gaussian random variable with standard deviation \( \sigma \) which is location and distance dependent. Therefore, the received power of the PR receiver is \( P_{pr}(r_1) = P_{bs} - PL_p(r_1) \), and interference from
the CTx is $P_t(d_{12}) = P_{ct} - PL_c(d_{12})$. Hence, the SIR at the PR receiver is $SIR_p = P_{pr}(r_1) - P_t(d_{12})$. Similarly, the SIR at the CR receiver is $SIR_c = P_{cr}(d_{22}) - P_t(r_2)$. Since the SIRs must satisfy the constraints in (5.1), we have

$$d_{12}[dB] > \frac{P_{ct} + \alpha_1 r_1 + \tau_p + X'_\sigma - P_{bs} \log_{10} 2}{\alpha_2}$$  \hspace{1cm} (5.7)$$

$$d_{22}[dB] < \frac{P_{ct} + \alpha_1 r_2 - \tau_c - X'_\sigma - P_{bs} \log_{10} 2}{\alpha_2},$$  \hspace{1cm} (5.8)$$

where $X'_\sigma \sim N(0, \sqrt{2}\sigma)$. Similar to (6.26), the optimal power is achieved when the following equation is satisfied.

$$10 \left( \frac{P_{ct} + \alpha_1 r_1 + \tau_p + X'_\sigma - P_{bs} \log_{10} 2}{\alpha_2} \right) + 10 \left( \frac{P_{ct} + \alpha_1 r_2 - \tau_c - X'_\sigma - P_{bs} \log_{10} 2}{\alpha_2} \right) = \sqrt{r_1^2 + r_2^2 - 2r_1r_2 \cos \theta_{pc}}.$$  \hspace{1cm} (5.9)$$

The solution of (5.9) can be expressed as

$$P_{ct}[dB] = 10\alpha_2 \log \left( \frac{\sqrt{r_1^2 + r_2^2 - 2r_1r_2 \cos \theta_{pc}}}{10 \left( \frac{P_{ct} + \alpha_1 r_1 + \tau_p + X'_\sigma - P_{bs} \log_{10} 2}{\alpha_2} \right) + 10 \left( \frac{P_{ct} + \alpha_1 r_2 - \tau_c - X'_\sigma - P_{bs} \log_{10} 2}{\alpha_2} \right)} \right).$$  \hspace{1cm} (5.10)$$

Hence, the optimal transmit power to maximize the concurrent transmission region in a single-pair CR ad hoc network is obtained. Next, we consider the multi-CR and multi-PR scenario.

5.3 Optimal Power Control for Multi-CR and Multi-PR Ad Hoc Networks

In this section, the proposed optimal power control algorithm for the concurrent transmission region maximization in a multi-CR and multi-CR single-PR scenario is presented. We first consider the proposed power control algorithm for the multi-PR ad hoc networks. Then, the proposed power control algorithm for multi-CR and multi-PR scenario is introduced.
5.3.1 Optimal Power Control for the Multi-CR Scenario

We now consider the network model where there are multiple pairs of CR users in the networks. For instance, Fig. 5.6 shows the scenario where there are three pairs of CR users in a CR ad hoc network.

![System model of a CR ad hoc network with three pairs of CR users.](image)

Figure 5.6: System model of a CR ad hoc network with three pairs of CR users.

In our system model for the multi-CR scenario, we assume that there are $N_s$ pairs of CR users which are denoted as $CT_{xi}$ and $CR_{xi}$ ($i \in [1, N_s]$). The distance between each $CT_{xi}$ and $CR_{xi}$ pair is $D_i$ while the distance between the $CT_{xi}$ and the PR receiver is $L_i$. In addition, $r_s^i$ is the distance between the PR base station and the $CR_{xi}$. Finally, $r_p$ is the distance between the PR base station and the PR receiver. Then, the $SIR$ at the PR receiver is

\[
SIR_p = \frac{P_{bs}}{\sum \frac{P_{ct}^i}{r_s^i \alpha}}.
\] (5.11)

where $P_{ct}^i$, $i \in [1, N_s]$ is the transmit power of the $CT_{xi}$. Moreover, the SIR at the $CR_{xi}$ receiver can be written as $SIR_c^i = \frac{P_{bs}}{P_{ct}^i (r_s^i \alpha)}$. In order to maximize the total concurrent transmission region for all $N_s$ pairs of CR users, the sum of the $SIR^i_{c}, i \in [1, N_s]$ need to be maximized. Therefore, the optimal power control problem for the concurrent
transmission region maximization in the multi-CR scenario is formulated as follows:

Maximize: \( SIR_{\text{sum}} = \sum_{i=1}^{N_s} \frac{P_i^{c}(r_i)^{\alpha}}{P_{ba}D_i^{\alpha}} \)

Subject to:

\[
\begin{align*}
SIR_p &> \tau_p \\
SIR_{ci} &> \tau_c & i \in [1, N_s] \\
P_{ci}^{\text{min}} &\leq P_{ci} \leq P_{ci}^{\text{max}} & i \in [1, N_s],
\end{align*}
\]

where \( SIR_{\text{sum}} \) is the sum of the SIRs at all CR receivers. From (5.11) and (5.12), we have

\[
\frac{P_1^{\text{ct}}}{L_1^\alpha} + \frac{P_2^{\text{ct}}}{L_2^\alpha} + \frac{P_3^{\text{ct}}}{L_3^\alpha} + \cdots + \frac{P_{N_s}^{\text{ct}}}{L_{N_s}^\alpha} < \frac{P_{ba}}{\tau_p r_p^\alpha},
\]

(5.13)

Since \( SIR_{ci} > \tau_c \), we have \( \frac{P_i^{\text{ct}}(r_i)^{\alpha}}{P_{ba}D_i^{\alpha}} > \tau_c \). Then, we obtain

\[
P_i^{\text{ct}} > \tau_c \frac{P_{ba}D_i^{\alpha}}{\tau_p r_p^\alpha}.
\]

(5.14)

However, considering (5.14), the solution of (5.12) does not exist when \( \tau_c \frac{P_{ba}D_i^{\alpha}}{\tau_p r_i^{\alpha}} > P_{ci}^{\text{max}} \).

So, we only consider the case where \( \tau_c \frac{P_{ba}D_i^{\alpha}}{\tau_p r_i^{\alpha}} < P_{ci}^{\text{max}} \). According to (5.12) and (5.13), we modified the above formulation as follows:

Maximize: \( SIR_{\text{sum}} = \sum_{i=1}^{N_s} \frac{P_i^{c}(r_i)^{\alpha}}{P_{ba}D_i^{\alpha}} \)

Subject to:

\[
\begin{align*}
\frac{P_1^{\text{ct}}}{L_1^\alpha} + \frac{P_2^{\text{ct}}}{L_2^\alpha} + \frac{P_3^{\text{ct}}}{L_3^\alpha} + \cdots + \frac{P_{N_s}^{\text{ct}}}{L_{N_s}^\alpha} &< \frac{P_{ba}}{\tau_p r_p^\alpha} \\
P_i^0 &\leq P_i^{\text{ct}} \leq P_{ci}^{\text{max}} & i \in [1, N_s],
\end{align*}
\]

(5.15)

where \( P_i^0 = \max(\frac{\tau_c P_{ba}D_i^{\alpha}}{\tau_p r_i^{\alpha}}, P_{ci}^{\text{min}}), i \in [1, N_s] \). In order to obtain the standard optimization problem, we introduce variables \( P_{ci}^{N+j}, j \in [1, 2N_s] \). Then, using simple mathematical manipulation, the formulation for the optimal power control problem for the multi CR scenario can be written as:
Minimize: $-\left[ \frac{(r_1^1)^\alpha P_{bs}^1}{P_{bs}D_1^a} + \frac{(r_2^2)^\alpha P_{bs}^2}{P_{bs}D_2^a} + \cdots + \frac{(r_N^N_s)^\alpha P_{bs}^{N_s}}{P_{bs}D_{N_s}^a} \right]$

Subject to:

\[
\frac{P_1^{c_1}}{L_1^a} + \frac{P_2^{c_2}}{L_2^a} + \frac{P_3^{c_3}}{L_3^a} + \cdots + \frac{P_{N_s}^{c_{N_s}}}{L_{N_s}^a} + P_{c_{N_s+1}} = \frac{P_{bs}}{\tau_{p^a}}
\]

\[
P_1^{c_1} - P_{c_{N_s+2}} = P_0^1
\]

\[
P_2^{c_2} - P_{c_{N_s+3}} = P_0^2
\]

\[
\vdots \quad \vdots 
\]

\[
P_N^{c_{N_s}} - P_{c_{2N_s+1}} = P_0^{N_s}
\]

Then, in order to obtain the solution of the above standard optimization problem, we define the coefficient matrix for the objective function as

\[
\vec{c} = -\left[ \frac{(r_1^1)^\alpha}{P_{bs}D_1^a} \quad \frac{(r_2^2)^\alpha}{P_{bs}D_2^a} \quad \frac{(r_3^3)^\alpha}{P_{bs}D_3^a} \quad \cdots \quad \frac{(r_N^N_s)^\alpha}{P_{bs}D_{N_s}^a} \quad 0 \cdots 0 \right]_{1 \times 3N_s}.
\]
\[
A = \begin{bmatrix}
\frac{1}{L_1} & \frac{1}{L_2} & \frac{1}{L_3} & \cdots & \frac{1}{L_{N_s}} & 1 & 0 & 0 & \cdots & 0 \\
1 & 0 & 0 & \cdots & 0 & 0 & -1 & 0 & \cdots & 0 \\
0 & 1 & 0 & \cdots & 0 & 0 & 0 & -1 & \cdots & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & \cdots & 1 & 0 & \cdots & -1 & \cdots & 0 \\
1 & 0 & 0 & \cdots & 0 & 0 & 0 & 1 & \cdots & 0 \\
0 & 1 & 0 & \cdots & 0 & 0 & 0 & 0 & 1 & \cdots \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & \cdots & 1 & 0 & 0 & 0 & \cdots & 1 \\
\end{bmatrix}_{3N_s \times 3N_s}
\] (5.18)

\[
\vec{b} = \begin{bmatrix}
P_{bs} \tau_p r_p^a & P_0^1 & P_0^2 & \cdots & P_0^{N_s} & P_c^{max} & \cdots & P_c^{max}
\end{bmatrix} \begin{bmatrix}
1 \\
1 \\
0 \\
\vdots \\
0 \\
1 \\
0 \\
\vdots \\
0 \\
\end{bmatrix}_{3N_s}. \tag{5.19}
\]

Then, we can rewrite (5.16) as

\[
A \vec{X} = \vec{b}, \tag{5.20}
\]

where \( \vec{X} = [P_{ct}^1 \quad P_{ct}^2 \quad P_{ct}^3 \quad \cdots \quad P_{ct}^{3N_s}]^T \). Here, \( Z^T \) means the transpose of vector \( Z \).

The matrix \( A \) can be rewritten as

\[
A = [\vec{M}_1 \quad \vec{M}_2 \quad \vec{M}_3 \quad \vec{M}_4 \quad \cdots \quad \vec{M}_{3N_s}], \tag{5.21}
\]

where \( M_k, k \in [1, 3N_s] \) are the column vectors of the matrix \( A \). We use \( U \) to denote the rank of \( A \) and \( U = rank(A) \). Then, we choose \( U \) linear independent column vectors from \( A \) to form a matrix \( B \) while the remaining vectors in \( A \) form a matrix \( W \). Thus, the matrix \( A \) can be rewritten as \( A = (B, W) \). Moreover, we choose the elements in \( \vec{c} \) which have the same column index as the \( U \) linear independent column vectors to form a vector \( \vec{c}_B \) while the remaining elements in \( \vec{c} \) form a vector \( \vec{c}_W \). Therefore, the vector \( \vec{c} \) can be rewritten as \( \vec{c} = [\vec{c}_B \quad \vec{c}_W] \). According to the linear
optimization theory [84], when \( c^T B^{-1} b - c^T N \leq 0 \), we obtain the optimal solution

\[
\bar{x}_{opt} = [B^{-1} b, 0]^T
\]  

(5.22)

where \( T \) means the transpose of the vector \([B^{-1} b, 0]\).

5.3.2 Optimal Power Control for the Multi-PR Scenario

Next, we consider the optimal power control for the Multi-PR scenario. Fig. 5.7 shows the system model for a multi-PR CR ad hoc network, where the shaded triangles and squares represent the PU transmitter and receivers (denoted as PU1, PU2, PU3 and PU4), respectively. The shaded circles are the CR transmitter (denoted as CTx) and receiver (denoted as CRx). The distance between the PU base station and the CRx is \( r_0 \).

![Figure 5.7: System model of a multi-PR CR ad hoc network.](image)

We assume that there are \( N \) PR receivers and one pair of CR transmitter and receiver in our system model. In addition, \( PU_i, i \in [1, N] \) represent the \( N \) PR receivers in the system and \( r_i, i \in [1, N] \) is the distance between the PR base station and the \( PU_i \). Furthermore, the distance between the CTx and \( PU_i \) is \( d_i, i \in [1, N] \) while the distance between the CTx and the CRx is represented by \( d_{tr} \). We use \( SIR_{pi} \),

77
$i \in [1, N]$ to denote the SIRs at the $PU_i$. The optimal power control problem for the concurrent transmission region maximization for the multi-PR CR ad hoc network is formulated as follows:

Maximize: $SIR_c$

Subject to:

$$SIR_{pi} > \tau_p \quad i \in [1, N]$$
$$SIR_c > \tau_c$$

$$P_{c}^{min} \leq P_{ct} \leq P_{c}^{max},$$

(5.23)

where $SIR_c = \frac{P_{ct}r_0^\alpha}{P_{bs}d_{tr}^\alpha}$ and $SIR_{pi} = \frac{P_{bs}d_{tr}^\alpha}{P_{ct}r_0^\alpha}$ are the SIRs at CR and PR receiver, respectively. Using simple mathematical manipulation, we can rewrite the formulation as

Maximize: the $SIR_c = \frac{P_{ct}r_0^\alpha}{P_{bs}d_{tr}^\alpha}$

Subject to:

$$P_{ct} < \frac{P_{bs}d_{tr}^\alpha}{\tau_p r_i^\alpha} \quad i \in [1, N]$$

$$P_1 \leq P_{ct} \leq P_{c}^{max},$$

(5.24)

where $P_1 = max(\frac{P_{bs}d_{tr}^\alpha}{r_0^\alpha}, P_{c}^{min})$. Similar to the multi-CR scenario, in order to obtain the standard optimization problem, we introduce the variables $P_{ct}^k k \in [2, N + 3]$. Then, the formulation of the optimal power control problem for the multi-PR CR ad hoc network can be written as

Minimize: $-\frac{r_0^\alpha P_{ct}^k}{P_{bs}d_{tr}^\alpha}$

Subject to:
\[ P_{ct}^1 + P_{ct}^2 = \frac{P_{bs}d_1^\alpha}{\tau_{p}r_1^\alpha} \]
\[ P_{ct}^1 + P_{ct}^3 = \frac{P_{bs}d_2^\alpha}{\tau_{p}r_2^\alpha} \]
\[ P_{ct}^1 + P_{ct}^4 = \frac{P_{bs}d_3^\alpha}{\tau_{p}r_3^\alpha} \]
\[ \vdots \]
\[ P_{ct}^1 + P_{ct}^{N+1} = \frac{P_{bs}d_N^\alpha}{\tau_{p}r_N^\alpha} \]
\[ P_{ct}^1 + P_{ct}^{N+2} = P_{c}^{\text{max}} \]
\[ P_{ct}^1 - P_{ct}^{N+3} = P_1. \]  

Then, we define the coefficient matrix for the objective function as

\[ \vec{c}_1 = -[r_{0k}^\alpha \quad 0 \quad 0 \quad \cdots \quad 0]_{1 \times (N+2)}, \]  

In addition, coefficient matrix for the constraints is defined as

\[ A_1 = \begin{bmatrix}
1 & 1 & 0 & 0 & \cdots & 0 \\
1 & 0 & 1 & 0 & \cdots & 0 \\
1 & 0 & 0 & 1 & \cdots & 0 \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
1 & 0 & 0 & \cdots & 1 & 0 \\
1 & 0 & 0 & \cdots & 0 & 1 \\
1 & 0 & 0 & \cdots & 0 & 0 & -1
\end{bmatrix}, \]  

\[ \vec{b}_1 = [\frac{P_{bs}d_1^\alpha}{\tau_{p}r_1^\alpha} \quad \frac{P_{bs}d_2^\alpha}{\tau_{p}r_2^\alpha} \quad \cdots \quad \frac{P_{bs}d_N^\alpha}{\tau_{p}r_N^\alpha} \quad P_{c}^{\text{max}} \quad ax_c \quad P_1]_{1 \times (N+2)}. \]

Then, we can rewrite (5.25) as

\[ A_1 \vec{X}_1 = \vec{b}_1. \]  

Finally, we use the same method for the above optimization problem to obtain the
optimal solution for (5.29). Then, the optimal transmit power for the multi-PR scenario is obtained.

5.4 Performance Results

In this section, the performance of the proposed optimal power control algorithms is evaluated via simulations and compared with the power control algorithm with fixed transmit power.

5.4.1 Simulation Parameters for single pair CR user ad hoc network

The parameters used in our simulations are listed in Table 5.1. We assume that the transmit power of the TV base station is 100 kW [85], the transmit power range of the CTx is [1W, 100W] [85], and the SIR thresholds for the TV and CR receivers are 30dB and 3dB, respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TV base station transmit power</td>
<td>100kW</td>
</tr>
<tr>
<td>Maximum transmit power of CTx</td>
<td>100W</td>
</tr>
<tr>
<td>Minimum transmit power of CTx</td>
<td>1W</td>
</tr>
<tr>
<td>Coordinates of TV receiver</td>
<td>(50km, 0°)</td>
</tr>
<tr>
<td>Coordinates of CTx</td>
<td>(50km, 60°)</td>
</tr>
<tr>
<td>SIR threshold for PR receiver</td>
<td>30dB</td>
</tr>
<tr>
<td>SIR threshold for CR receiver</td>
<td>3dB</td>
</tr>
<tr>
<td>Path loss factor</td>
<td>3</td>
</tr>
<tr>
<td>Simulation time</td>
<td>1000s</td>
</tr>
</tbody>
</table>

The mobility characteristics of the CRx are modeled using the random waypoint mobility model [86][87]. The CRx changes its movement pattern every $ts$ seconds, where $ts$ is uniformly distributed between 0 and 30s. The average speed of the CRx $s$ is chosen at 10, 20, 30, 40 m/s. The heading angle of the CRx is selected to be uniformly distributed between 0 and $2\pi$. The average pause time of the CRx is set to be 5 seconds. The starting position of the CRx is (50km, 60°). The time-based update mechanism is used in our simulations with the time threshold 1 second.

Moreover, the length of packets sent from the CTx is exponentially distributed
with the mean length of 100 bytes. The packets are sent in a Poisson stream fashion with the average arrival rate of 10 packets/s.

5.4.2 Simulation Results for the Single Pair CR User Scenario

![Figure 5.8: Optimal transmit power of CTx for maximum concurrent transmission.](image)

First, from (6.26) we obtain the plane of the optimal power with respect to $r_2$ and $\theta_{pc}$, as shown in Fig. 5.8. It is observed that when $\theta_{pc}$ is within a certain range, the optimal power is constant at $P_{c}^{max}$. This is because that if the solution of (6.26) is greater than the maximum allowable transmit power of the CTx, the optimal power will be limited to the maximum transmit power.

Fig. 5.9 along with Fig. 5.10 illustrate the relationship between the radius of the concurrent transmission region $r_{CT}$ and the transmit power of the CTx under different $r_2$. Fig. 5.9 is obtained from Fig. 5.8 when $\theta_{pc}$ is fixed to be 60°, while Fig. 5.10 is obtained through the simulation based on the constraints in (5.1). It is noted that when $r_2$ is in the interval [47km, 51km] as shown in Fig. 5.9, the optimal power in these two figures match perfectly, which indicate the analytical and
Figure 5.9: Optimal transmit power when $\theta_{pc} = 60^\circ$.

Figure 5.10: Simulation results of concurrent transmission radius vs. transmit power of CTx.

Simulation results coincided well. From the proposed optimal power control algorithm shown in Fig. 6, the distance between the CTx and the CRx $d_{22}$ must be smaller
Figure 5.11: Packet delivery ratio using fixed power algorithm and the proposed power control algorithm under different average speeds.

than the maximum decodable radius of the CTx to let the concurrent transmission be feasible. According to (5.2), the maximum decodable radii of the CTx are 3.7km when \( r_2 \) is 47km and 4.2km when \( r_2 \) is 54km. So if \( r_2 \) is out of the neighborhood of 50km (i.e., [47km, 54km]), \( d_{22} \) is larger than the maximum decodable radius of the CTx. Hence, the concurrent transmission radius is zero, which means that the concurrent transmission is not allowed. From Fig. 5.9, the radius of the concurrent transmission region increases as the transmit power of the CTx increases. When the transmit power reaches the optimal power, the concurrent transmission radius reaches the maximum, and then it decreases drastically.
Fig. 5.11 shows the simulation results of packet delivery ratio of the mobile CR ad hoc network using fixed transmit power of the CTx and the proposed optimal power control algorithm with different moving speeds of the CRx. The mobility characteristics are given in Section 5.4.1. First of all, it is observed that the overall packet delivery ratio suffers degradation as the moving speed of the CRx increases. Secondly, with the same moving speed, the packet delivery ratio increases as the transmit power of the CTx increases. When the fixed transmit power of the CTx exceeds 80W, the packet delivery ratio decreases to zero. This is because that the $SIR_p$ can never be satisfied when the transmit power of the CTx exceeds 80W. However, it is noted that the packet delivery ratio using the proposed optimal power control algorithm is always higher than that of the fixed power algorithm at any speed.

Finally, Fig. 5.12 shows the simulation results of the packet delivery ratio under different power control algorithms with the impact of the shadowing fading effect.
The mobility characteristics are the same as used for Fig. 5.11. The path loss factors of PR and CR transmissions are 3 and 4, respectively. The average speed of the CRx is set to be 30 m/s, and the standard deviation \( \sigma \) is chosen to be 6 dB. Compared to Fig. 5.11(c), the overall packet delivery ratio decreases significantly. However, with the shadowing fading effect, the SIR\(_p\) can be satisfied with certain probability when the transmit power of the CTx exceeds 80W. It is observed from the simulation results that the proposed optimal power control algorithm also outperforms the fixed power algorithm under the shadowing fading effect.

5.4.3 Simulation Result for Multi-CR scenario

Then, we show the performance result of the multi-CR scenario. The parameters used in our simulation for the multi-CR scenario are the same as the parameters shown in Table 7.1 except the location of the PR and CR user pairs. We assume that there are three CR user pairs in our simulation region.
Fig. 5.14: Packet delivery ratio using fixed power algorithm and the proposed power control algorithm under different average speeds of CR receivers.

Fig. 5.13 shows the simulation results of the obtained optimal sum of SIRs for the multi-CR scenario using the proposed optimal power control algorithm. The optimal sum of SIR decreases when the distance between the basestation and the PR receivers increases. In addition, the optimal sum of SIRs decreases when $\tau_c$ increases.

Then, Fig. 5.14 shows the simulation results of the packet delivery ratio of the mobile multi-CR scenario using fixed transmit power of the CR transmitters and the proposed optimal power control algorithm with different average moving speeds of the three CRx. The mobility characteristics are given in Section 5.4.1. First of all,
it is observed that the packet delivery ratio of the proposed power control algorithm for multi-SU CR ad hoc network is much higher than the fixed $SIR_{sum}$ algorithm. Secondly, the packet delivery ratio decreases when the moving speed of the three CR receivers increases.

5.4.4 Simulation Result for the Multi-PR Scenario

Finally, we show the performance result of the multi-PR scenario. The parameters used in our simulation for the multi-PR scenario are the same as the parameters shown in Table 7.1 except the location of the PR receivers. We assume that there are 20 PR receivers randomly distributed in our simulation region.

Next, Fig. 5.15 shows the simulation results of the obtained optimal SIR for the multi-CR scenario using the proposed optimal power control algorithm. The SIR first increases then decreases when the distance between CR receiver and the base station
The power of the CR transmitter (w)
Packet delivery ratio
(a) Average speed = 10m/s
(b) Average speed = 20m/s
(c) Average speed = 30m/s
(d) Average speed = 40m/s

Figure 5.16: Packet delivery ratio using fixed power algorithm and the proposed power control algorithm under different average speeds of PUs.

At last, Fig. 5.16 shows the simulation results of the packet delivery ratio of the mobile multi-PR CR using the fixed power control policy of the CR receivers and the proposed optimal power control algorithm with different moving speeds of the 20 PR receivers. The mobility characteristics are the same in Section 5.4.1. First of all, it is observed that the packet delivery ratio of the proposed power control algorithm for the multi-PR ad hoc network is much higher than the fixed optimal power control algorithm. Secondly, the packet delivery ratio decreases when the moving speed of the 20 PUs increases.

(BS) increases. In addition, the SIR increases when $\tau_p$ decreases.
6.1 The Proposed JOSH Scheme for Fixed Mobility Patterns

In this section, the power adaptation scheme for mobile CR networks with fixed mobility patterns is proposed. Our goal is to maintain the communication between the SUs when they are mobile.

6.1.1 Network Model

We assume that there are two SUs communicating with each other. In addition, there are PUs distributed in the network area and $M$ channels available. Fig. 6.1 shows the network model where the triangle represents the PUs and the circles represent the CR users. The shaded circle stands for the initial SU transmission range. First of all, we assume that the distance between the SU transmitter (denoted as Tx) and the SU receiver (denoted as Rx) is $d_0$. Then, the SU receiver keeps moving away from the SU transmitter in the direction shown in the Fig. 6.1. The A shows the next location of the SU receiver after moving for a certain amount of time. Then after the same period of time, the SU Rx reaches location B. In addition, the information about the speed of the SU Rx is known to the SU transmitter [88]. In this paper, we assume that the SU transmitter and PUs do not move. Moreover, as shown in Fig. 6.1, the speed of the SU Rx is $v$ and the moving angle is $\theta$ with respect to the radial direction.

Based on the two-ray ground propagation model [80], the received signal power,
Figure 6.1: The network model of mobile CR networks with fixed mobility patterns.

\( P_r \), can be written as follows:

\[
    P_r = \frac{P_t G_t G_r h_t^2 h_r^2}{d^a}, \tag{6.1}
\]

where \( P_t \) is the transmission power; \( G_t \) and \( G_r \) are the gains of the transmitter and receiver antennas, respectively; \( h_t \) and \( h_r \) are the heights of the transmitter and receiver antennas\[^{[89]}\], respectively; \( d \) is the distance between transmitter and the receiver; and \( a \) is the path loss factor. Here, we assume that the SU receiver must maintain the received power above a predefined threshold \( P_r \). Therefore, the required
power of the SU transmitter can be given in the following equation:

\[ P_t = \frac{P_r d^n}{G_t G_r h_t^2 h_r^2}. \]  \hspace{1cm} (6.2)

Since the process of adapting the SU transmission power in order to maintain continuous communications takes time [90], we need to perform the power adaptation periodically. We design to address this problem by changing the power at an equal interval time. That is, the SU performs power adaptation every \( \delta_t \) seconds. Then, the power adaptation formulation can be given as follows:

\[ P_t(n) = \frac{P_r \left(d_0 + nvcos\theta\delta_t\right)^a}{G_t G_r h_t^2 h_r^2}, \]  \hspace{1cm} (6.3)

\[ P_t(n + 1) = \frac{P_r \left[d_0 + (n + 1)vcos\theta\delta_t\right]^a}{G_t G_r h_t^2 h_r^2}, \]  \hspace{1cm} (6.4)

\[ P'_t = P_t(n + 1) - P_t(n), \]  \hspace{1cm} (6.5)

where \( P_t(n) \) is the transmission power after the \( n \)-th power adaptation and \( P'_t \) is the difference of the two consecutive rounds of power adaptation. Since the SU starts performing power adaptation when the distance is \( d_0 \), \( n \) starts with 0.

Therefore, after increasing the transmission power, the transmission range of the SU transmitter becomes larger. However, as shown in Fig. 6.1, the SUs may interfere the communication of PUs. Therefore, in order to avoid the interference to PUs, spectrum handoff also needs to be considered.

6.1.2 The Proposed Scheme for Fixed Mobility Patterns

In this section, the proposed joint power adaptation and spectrum handoff scheme for mobile CR user with fixed mobility pattern is presented. Since the SU receiver may move out of the transmission range of the SU transmitter, we need to use the previously described power adaptation to increase the transmission range of the SU transmitter [83]. However, there may exist active PUs which may be interfered by the
SUs in the additional transmission range caused by the increase of the transmission power. Therefore, a spectrum handoff is necessary to avoid the collision between PUs and SUs.

6.1.2.1 The probability of having the active PUs in the additional transmission range

In this section, we present the derivation process of the probability of having active PUs in the additional transmission range. First of all, the additional transmission
range caused by the increase of the SU transmission power can be obtained by

\[ A^* = \pi [d_0 + n v \Delta t]^2, \]  

(6.6)

Then, we need to calculate the probability of having active PUs within \( A^* \). The size of the total network area is denoted as \( A_L \) (i.e., \( A_L = L^2 \)). Since the locations of PUs are evenly distributed [92], the probability that \( p \) PUs are within \( A^* \) is

\[ \Pr(p) = \binom{K}{p} \left( \frac{A^*}{A_L} \right)^p \left( \frac{A_L - A^*}{A_L} \right)^{K-p}, \]  

(6.7)

where \( \binom{K}{p} \) represents the total combinations of \( K \) choosing \( p \). In addition, we define the probability that a PU is active, \( \rho \), as:

\[ \rho = \frac{E[\text{ON duration}]}{E[\text{ON duration}] + E[\text{OFF duration}]}, \]  

(6.8)

where \( E[\cdot] \) represents the expectation of the random variable. Therefore, given that there are \( p \) PUs within \( A^* \), the probability that there are \( b \) PUs active is

\[ \Pr(b|p) = \binom{p}{b} \rho^b (1 - \rho)^{p-b}, \]  

(6.9)

where \( \binom{p}{b} \) represents the total combinations of \( p \) choosing \( b \). In addition, we define the probability that an active PU uses a channel, \( f = 1/M \). Therefore, given that there are \( b \) active PUs using a channel, the probability that there are \( m \) PUs using the same channel is

\[ \Pr(m|b) = \binom{b}{m} f^m (1 - f)^{b-m}. \]  

(6.10)

Finally, we have the probability that at least one PU using the same channel as
SUs in the additional transmission range as follows

\[ P_r = \sum_{p=1}^{K} \sum_{b=1}^{p} \sum_{m=1}^{b} Pr(p)Pr(b|p)Pr(m|b). \]  

(6.11)

6.1.2.2 The condition for spectrum handoff

Based on the above analysis, we propose the condition to decide whether the SUs should perform the spectrum handoff. We denote that the throughput of SUs with spectrum handoff when there is a collision is \( S_2 \). In addition, the throughput of SUs without spectrum handoffs when there is no collision is \( S_1 \). If there is a collision without spectrum handoff, we use \( S_3 \) to represent the SU throughput in this scenario. Finally, the proposed spectrum handoff scheme is formed as a hypothesis test problem given in the following inequality,

\[ S_2 \overset{H_1}{\geq} S_3Pr + S_1(1 - Pr), \]  

(6.12)

where \( H_1 \) means that the SUs should perform a spectrum handoff and \( H_0 \) means that the spectrum handoff is not applied.

Then, we calculate the \( S_1, S_2, \) and \( S_3 \). Firstly, since we assume that the SU packets arrive in a Poisson stream fashion, the inter-arrival time of SU packets is exponentially distributed with the average arrival rate of \( k \) packets per second [93]. Fig. 6.2 illustrates the scenario where the SUs collides with a PU. Then, the SUs have to use another channel in order to avoid the interference.

In order to obtain the value of \( S_1 \) and \( S_2 \), we consider two SU traffic scenarios: 1) the SU traffic is unsaturated and 2) the SU traffic is saturated (i.e., SU transmitter always has packets in its buffer to be transmitted). To be more specific, Fig. 6.3 illustrates the scenario where the SU traffic is unsaturated, where Fig. 6.3(a) shows the case where there is no collision between SU and PU transmissions and Fig. 6.3(b) shows the case where there is a collision and SUs need to perform a spectrum handoff.
Hence, since the SU traffic is unsaturated, we have $\bar{X}_s\lambda_s < 1$, where $\bar{X}_s$ is the average service time and $\lambda_s$ is the average arrival rate of SUs. Thus, the SU throughput is equal to the arrival rate. That is,

$$S_1 = S_2 = \lambda_s.$$  \hspace{1cm} (6.13)

On the other hand, when the SU traffic is saturated, we have $\bar{X}_s\lambda_s \geq 1$. Then, the formulations for $S_1$ and $S_2$ are as follows:

$$S_1 = \frac{1}{\bar{X}_s} = \frac{1}{L_s}$$ \hspace{1cm} (6.14)

$$S_2 = \frac{1}{\bar{X}_s} = \frac{1}{L_s + \text{delay} + \frac{L_s}{2}},$$ \hspace{1cm} (6.15)

where $L_s$ is the average SU packet length and \textit{delay} is the time delay for SU to perform the spectrum handoff.
Next we derive the throughput when SUs do not perform a spectrum handoff and have a collision with PU transmission. If there is a collision with the PU and the SU transmission, the SUs have to stop the on-going transmission [26]. Fig. 6.4 illustrates this scenario.

![Figure 6.4: The SUs transmission has a collision with the PUs.](image)

We assume that the number of the PU packets which collide with the SU packets is \( C \). Then, we can get the formulation for \( S_3 \) as follows:

\[
S_3 = \frac{1}{C \times \frac{L_s}{2} + C \times L_p + L_s},
\]

where \( L_p \) is the average packet length of PUs.

According to (6.12), the threshold \( P_{th} \) to decide whether to perform a spectrum handoff is obtained as follows

\[
P_{th} = \frac{S_1 - S_2}{S_1 - S_3}.
\]

Therefore, the spectrum handoff is performed when \( P_r \geq P_{th} \). However, the calculation of \( P_r \) results in computation overhead. The time complexity for each \( \Delta t \) is \( O(K^3T_c) \) (where \( K \) is the total number of channels in the network and \( T_c \) is the time needed to calculate the combinations). Since the calculation of all the combinations here includes a huge amount of multiplication and division, the time consumption increases dramatically as \( K \) increases. The total time of the calculation is

\[
\sum_{i=1}^{N_u} O_i(K^3T_c)
\]

where \( N_u \) is the times of power adaptation. Thus, significant energy consumption is introduced, which is quite detrimental to the lifetime and service duration of mobile ad hoc networks. In order to reduce the energy consumption, we obtain a threshold \( A_{th} \) for the transmission range. Then, we only need to calculate
the transmission range each $\Delta t$ and compare the transmission range with the threshold $A_{th}$. Thus, the computation time complexity reduces to $O(1)$. The spectrum handoff is performed when $A^* \geq A_{th}$. According to (6.6-6.11), we have $P_r = F(A^*)$. As shown in Fig. 6.5, one $P_r$ is obtained for each transmission range. Therefore, we have $A^* = F^{-1}(P_r)$. Then, we obtain $A_{th} = F^{-1}(P_{th})$.

![Graph](image_url)

Figure 6.5: The $P_r$ varies with the transmission range.

Fig. 6.6 presents the proposed joint power adaptation and spectrum handoff scheme algorithm for the scenario where the SU receiver is mobile, where $t$ is the total simulation time. The SU performs the power adaptation every $\delta_t$. The proposed algorithm first computes the throughput $S_1$ and $S_2$ based on the current transmission scenario of SUs (i.e., saturated or unsaturated). Then, the probability of the potential PUs transmitting on the same channel with SUs can be computed using 6.11. The last step is to check whether it is time to the perform power adaptation and decides whether the spectrum handoff should be performed based on 6.12.
update t and d;
If(SU unsaturated)
calculate S1 and S2;
else
calculate S1 and S2;
endif
calculate S3;
If(mod(t, ∆t) == 0)
calculate ∆P_t; //power control should apply
calculate A*; //spectrum handoff decision should use
If(A* > A_th)
perform spectrum handoff;
change the packet arrival time;
else
continue to use the current channel;
endif
endif

Figure 6.6: The joint power adaptation and spectrum handoff scheme algorithm.

6.2 The Proposed JOSH Scheme for Random Mobile CRNs

In this section, the joint power adaptation and spectrum handoff scheme for mobile CR networks with random mobility patterns is proposed. In our system model, the SU receiver moves based on the Random Waypoint mobility model. Fig. 6.7 shows the movement of the SU receiver in the Random Waypoint mobility model. We use the yellow circles A, B, and C to denote the Waypoints chosen by the SURx. As seen in the figure, the SURx first randomly choose A as the next location, then, a random moving speed for the SURx to reach A is chosen. After location A is reached and a short stop at A, B is randomly chosen as the next location and a random speed is chosen. Then, the same actions are performed as the previous movement until the location SURx’ is reached. Obviously, the distance between the SU Tx and SU Rx varies with the movement of the SU Rx. In addition, the available channels for SU change due to the movement of the SU Rx. Therefore, we have to design a
novel scheme to perform the power adaptation and spectrum handoff according to the movement of the SU Rx.

![Figure 6.7: An example of random mobility model of SU receiver.](image)

In our random waypoint mobility model, we assume the random location can be chosen is \((x, y)\) where \(x \in [X_{\text{min}}, X_{\text{max}}]\) and \(y \in [Y_{\text{min}}, Y_{\text{max}}]\). The speed of the SU Rx is \(v\) where \(v \in [V_{\text{min}}, V_{\text{max}}]\). In addition, the speed \(v\) is divided into the horizontal direction \(v_x\) and vertical direction \(v_y\) where we have

\[
\begin{align*}
    v_x &= v \cos \theta \\
    v_y &= v \sin \theta \\
    \theta &= \tan^{-1}\left(\frac{y_n - y_c}{x_n - x_c}\right),
\end{align*}
\]  

(6.18)

where \((x_n, y_n)\) is the coordinate of the location chosen as the next Random Waypoint and \((x_c, y_c)\) is the coordinate of the current location. We use the coordinates \((x_{tr}, y_{tr})\) to denote the location of the SU transmitter. The initial location of the SU Rx is denoted by \((x_0, y_0)\).

The main processes of our proposed scheme can be seen in Fig. 6.8. We use \((x_{\text{cur}}, y_{\text{cur}})\) to denote the current location of the SU Rx. \((x_{\text{new}}, y_{\text{new}})\) denotes the
location of the new waypoint that is randomly chosen during the random waypoint movement. Therefore, the transmission ranges of the SU Tx are denoted by $A_{\text{cur}}$ and $A_{\text{new}}$ when the SU Rx is located at $(x_{\text{cur}}, y_{\text{cur}})$ and $(x_{\text{new}}, y_{\text{new}})$ respectively. The comparison result between the transmission range of current and next location is used to decide which sub-scheme needed to be performed in our proposed scheme. Sub-scheme I and sub-scheme II are introduced in the following.

![Figure 6.8: The flow chart for the proposed scheme.](image)

6.2.1 The Details of The Sub-scheme I

As described above, the sub-scheme I is used when the $A_{\text{new}}^i \geq A_{\text{cur}}$. In this scenario, the SU Rx chooses a new location which is further away from the SU Tx compared to the current location. If the transmission range of the new location $A_{\text{new}}^i > A_{\text{th}}$, the spectrum handoff is performed. If the transmission range of the new location $A_{\text{new}}^i \leq A_{\text{th}}$, the spectrum handoff is not performed. Then, the method to decide when to perform the power adaptation is proposed. The power adaptation is performed each single $\Delta t_i$. The whole process of the sub-scheme I is shown in Fig. 6.9.
Therefore, the most important step in the sub-scheme I is how to update $\Delta t_i$. $\Delta t_i$ is the power adaptation interval to be updated when the $i$th new location is chosen. First, the scenario with $A_{cur} \geq A_{th}$ is considered. As shown in Fig. 6.10, the transmission range in the red inner circle is $A_{th}$ while $A_{cur}$ denotes the current transmission range in the green intermediate circle. In addition, the transmission range of the SU Tx for the next location SU Rx' in the back circle is $A_{new}^i$.

We define the coordinates of the new location and current location are $(x_i, y_i)$ and $(x_{i-1}, y_{i-1})$, respectively. The randomly chosen speed is $(v_{x_{i-1}}^i, v_{y_{i-1}}^i)$. Then, we have

$$t_i = \frac{d_{cn}}{v_{cn}} = \sqrt{\frac{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}{(v_{x_{i-1}}^i)^2 + (v_{y_{i-1}}^i)^2}}. \quad (6.19)$$

where $d_{cn}$ is the distance between the current location and new location. $v_{cn}$ is the
speed of the SU Rx which equals $\sqrt{(v_x^{i-1})^2 + (v_y^{i-1})^2}$. Then, the times of the power adaptation during the $i$th random movement is $M_i$. We have $M_i = ceil(t_i/\Delta t_i)$. Here, we use $\Delta P_i$ to denote the power difference between the actually needed power and the power consumed by our proposed power control scheme during the $i$th movement of SU Rx. We have

$$\Delta P_i = \sum_{l=1}^{M_i} \left\{ \int_{T_i+l\Delta t_i}^{T_i+(l-1)\Delta t_i} \left[ P_{r0}(d_{i-1} + \Delta d_i)^\alpha - P_{r0}(d_{i-1} + \Delta d_{i-1} + d_i)^\alpha \right] dt \right\},$$

(6.20)

where $d_{i-1}$ is the distance between the start location of the $i$th random movement of SU Rx and the location of SU Tx. $d_i$ is the distance between the SU Rx and SU Tx during the $i$th movement of SU Rx. The distance that SU Rx moves during every
\( \Delta t_i \) in the \( i \)th random movement is represented by \( \Delta d_l \) \( (l \in [1, M_i]) \). We have

\[
d_{i-1} = \sqrt{(x_{i-1} - x_{tr})^2 + (y_{i-1} - y_{tr})^2},
\]

\[(6.21)\]

\[
d_t = \sqrt{(x_t - x_{tr})^2 + (y_t - y_{tr})^2},
\]

\[(6.22)\]

where \((x_t, y_t)\) is the coordinates of the SU Rx, we have

\[
x_t = x_{i-1} + v_{x}^{i-1}(t - T_i)
\]

\[
y_t = y_{i-1} + v_{y}^{i-1}(t - T_i),
\]

\[(6.23)\]

\( \Delta d_l \) is the transmission range increase in the \( l \) the power adaptation. We have

\[
\Delta d_l = \sqrt{(x_l^i - x_{tr})^2 + (y_l^i - y_{tr})^2} - \sqrt{(x_{l-1}^i - x_{tr})^2 + (y_{l-1}^i - y_{tr})^2}.
\]

\[(6.24)\]

where \((x_l^i, y_l^i)\) is the coordinates of the SU Rx after the \( l \)th power adaptation during the \( i \)th random movement, we have

\[
x_l^i = x_{i-1} + v_x^{i-1}l\Delta t_i
\]

\[
y_l^i = y_{i-1} + v_y^{i-1}l\Delta t_i,
\]

\[(6.25)\]

Here, we consider that the duration of the power adaptation \( \tau \) must satisfy the transmission duration requirements for SU Tx. We denote the transmission duration threshold for SU Tx as \( \tau_L \). The optimal power adaptation interval problem for power difference minimization is formulated as follows:

Minimize: the power difference \( \Delta P_i \)
Subject to:

\[
\Delta t_i - \tau \geq \tau_L
\]
\[
\Delta t_i \leq t_i.
\]  

Second, the scenario with \( A_{\text{cur}} \leq A_{\text{th}} \) is considered. As shown in Fig. 6.11, there are two cases in this scenario. \( \Delta t_{i1} \) and \( \Delta t_{i2} \) should be updated in case I as shown in Fig. 6.11(a). \( \Delta t_i \) needs to be updated in case II shown in Fig. 6.11(b). The method to update \( \Delta t_i \) for case II in this scenario is the same as the described scenario where \( A_{\text{cur}} > A_{\text{th}} \). Therefore, we only need to find the method to update \( \Delta t_{i1} \) and \( \Delta t_{i2} \) for case I. The intersection of the random movement with the red circle is defined as \( I(x_{th}, y_{th}) \). we have,

\[
\begin{cases}
(y_{th} - y_{i-1})(x_i - x_{i-1}) = (y_i - y_{i-1})(x_{th} - x_{i-1}) \\
(x_{th} - x_{tr})^2 + (y_{th} - y_{tr})^2 = \frac{A_{th}}{\pi} \\
x_{\min} < x_{th} < x_{\max} \\
y_{\min} < y_{th} < y_{\max},
\end{cases}
\]  

where \( x_{\min} = \min(x_{i-1}, x_i) \) and \( y_{\min} = \min(y_{i-1}, y_i) \). We define that the duration
for the SU Rx to reach \( I \) is \( t_{i1} \) and the duration for the SU Rx moving from \( I \) to SU Rx' is \( t_{i2} \). We have

\[
\begin{align*}
t_{i1} &= \sqrt{\frac{(x_{th} - x_{i-1})^2 + (y_{th} - y_{i-1})^2}{(v_{y}^{i-1})^2 + (v_{x}^{i-1})^2}}, \\
t_{i2} &= \sqrt{\frac{(x_i - x_{th})^2 + (y_i - y_{th})^2}{(v_{y}^{i-1})^2 + (v_{x}^{i-1})^2}},
\end{align*}
\] (6.28)

In addition, we use \( M_{i1} = \text{ceil}(\frac{t_{i1}}{\Delta t_{i1}}) \) to denote the times of power adaptation needed when the transmission range increases from \( A_{\text{cur}} \) to \( A_{th} \). \( M_{i2} = \text{ceil}(\frac{t_{i2}}{\Delta t_{i2}}) \) represents the times of power adaptation needed when the transmission range increases from \( A_{th} \) to \( A_{new}^{i} \). We have

\[
\Delta P_{i1} = \sum_{l=1}^{M_{i1}} \left\{ \int_{T_i + l\Delta t_{i1}}^{T_i + (l-1)\Delta t_{i1}} [P_{r0}(d_{i-1} + \Delta d_{i1}^l)^\alpha - P_{r0}(d_{i-1} + \Delta d_{i1}^{l-1} + d_{i1}))^\alpha] dt \right\}.
\] (6.29)

where \( d_{i1} \) is the distance between the SU Rx and SU Tx when the SU Rx moves to the location \( I \). The distance that SU Rx moves during every \( \Delta t_{i1} \) before reaching location \( I \) is represented by \( \Delta d_{i1}^l \). We have

\[
d_{i1} = \sqrt{(x_{i1} - x_{tr})^2 + (y_{i1} - y_{tr})^2},
\] (6.30)

where \((x_{i1}, y_{i1})\) is the coordinates of the SU Rx, we have

\[
\begin{align*}
x_{i1} &= x_{i-1} + v_{x}^{i-1}(t - T_i) \\
y_{i1} &= y_{i-1} + v_{y}^{i-1}(t - T_i),
\end{align*}
\] (6.31)

\( \Delta d_{i1}^l \) is the transmission range increase in the \( l \) the power adaptation. We have

\[
\Delta d_{i1}^l = \sqrt{(x_{i1}^{i1} - x_{tr})^2 + (y_{i1}^{i1} - y_{tr})^2} - \sqrt{(x_{i1}^{i1} - x_{tr})^2 + (y_{i1}^{i1} - y_{tr})^2}.
\] (6.32)
where \((x_i^l, y_i^l)\) is the coordinates of the SU Rx after the \(l\)th power adaptation during the \(i\)th random movement, we have

\[
\begin{aligned}
x_i^{i+1} &= x_i - 1 + v_x^{i-1} l \Delta t_i \\
y_i^{i+1} &= y_i - 1 + v_y^{i-1} l \Delta t_i,
\end{aligned}
\] (6.33)

Then, \(\Delta P_{i2}\) is calculated. We have

\[
\Delta P_{i2} = \sum_{l=1}^{M_2} \int_{T_i+t_{i1}+l\Delta t_{i2}}^{T_i+t_{i1}+(l-1)\Delta t_{i2}} [P_{r0}(d_{th} + \Delta d_{i2}^2)^\alpha - P_{r0}(d_{th} + \Delta d_{i-1}^2 + d_{t2})^\alpha] dt,
\] (6.34)

where \(d_{th} = \sqrt{(x_{th} - x_{tr})^2 + (y_{th} - y_{tr})^2}\). \(d_{t2}\) is the distance between the SU Rx and SU Tx when the SU Rx moves from the location \(I\) to the location SU Rx’. The distance that SU Rx moves during every \(\Delta t_{i2}\) before reaching location SU Rx’ is represented by \(\Delta d_{i2}^2\). We have

\[
d_{t2} = \sqrt{(x_{t2} - x_{tr})^2 + (y_{t2} - y_{tr})^2} - \sqrt{(x_{th} - x_{tr})^2 + (y_{th} - y_{tr})^2},
\] (6.35)

where \((x_{t2}, y_{t2})\) is the coordinates of the SU Rx, we have

\[
\begin{aligned}
x_{t2} &= x_{th} + v_x^{i-1}(t - T_i - t_{i1}) \\
y_{t2} &= y_{th} + v_y^{i-1}(t - T_i - t_{i1}),
\end{aligned}
\] (6.36)

\(\Delta d_{i2}^2\) is the transmission range increase in the \(l\)th power adaptation. We have

\[
\Delta d_{i2}^2 = \sqrt{(x_{i2}^2 - x_{tr})^2 + (y_{i2}^2 - y_{tr})^2} - \sqrt{(x_{i-1}^2 - x_{tr})^2 + (y_{i-1}^2 - y_{tr})^2}.
\] (6.37)

where \((x_{i2}^2, y_{i2}^2)\) is the coordinates of the SU Rx after the \(l\)th power adaptation when
the SU Rx moves from location $I$ to location SU Rx', we have

\[
\begin{align*}
x_i^{t_2} &= x_{th} + v_{x_i}^{i-1} l \Delta t_{i2} \\
y_i^{t_2} &= y_{th} + v_{y_i}^{i-1} l \Delta t_{i2},
\end{align*}
\]

Then, the optimal power adaptation interval problem for power difference minimization is formulated as follows:

Minimize: the power difference $\Delta P_{i1} + \Delta P_{i1}$

Subject to:

\[
\begin{align*}
\Delta t_{i1} - \tau &\geq \tau_L \\
\Delta t_{i2} - \tau &\geq \tau_L \\
\Delta t_{i1} &\leq t_{i1} \\
\Delta t_{i2} &\leq t_{i2}
\end{align*}
\]

(6.39)

6.2.2 The Details of Sub-scheme II

In this section, the sub-scheme II is introduced. The whole process of the sub-scheme II is shown in Fig. 6.12. Since the same condition as sub-scheme I is used to decide whether to perform the spectrum handoff, the optimal adaptation interval problem is to be solved here.

First, the scenario where $A_{cur}<A_{th}$ is considered. In this scenario, the SU Rx is in the range with no spectrum handoff. We use $\Delta P_i'$ to denote the power difference between the actually needed power and the power consumed by our proposed power adaptation scheme during the movement of SU Rx. We have

\[
\Delta P_i' = \sum_{l=1}^{M_i} \left\{ \int_{T_i + (l-1)\Delta t_i}^{T_i + l\Delta t_i} [P_{r0}(d_{i-1} - \Delta d'_{i-1})^\alpha - P_{r0}(d_{i-1} - \Delta d'_{i-1} - d_i)^\alpha] dt \right\},
\]

(6.40)
where $\Delta d_i'$ is the transmission range decrease in $l$th $\Delta t_i'$. We have

$$\Delta d_i' = \sqrt{(x_{i-1}^l - x_{tr})^2 + (y_{i-1}^l - y_{tr})^2} - \sqrt{(x_i^l - x_{tr})^2 + (y_i^l - y_{tr})^2}. \quad (6.41)$$

Then, the optimal power adaptation interval problem for power difference minimization is formulated as follows:

Minimize: the power difference $\Delta P_i'$

Subject to:

$$\Delta t_i' - \tau \geq \tau_L \quad (6.42)$$

$$\Delta t_i' \leq t_i.$$
Second, the scenario where $A_{cur} \geq A_{th}$ is considered. In this scenario, there are two cases which are $A_{new} > A_{th}$ and $A_{new} < A_{th}$. The solution for the optimal power adaptation interval problem is the same as the first scenario when $A_{new} > A_{th}$. Therefore, we only need to obtain the optimal power adaptation interval for the case when $A_{new} < A_{th}$. As shown in Fig. 6.12, $\Delta t_{i1}'$ and $\Delta t_{i2}'$ need to be updated when $A_{new} < A_{th}$. We have

$$\Delta P_{i1}' = \sum_{l=1}^{M_{i1}'} \left\{ \int_{T_i + (l-1)\Delta t_{i1}'}^{T_i + l\Delta t_{i1}'} [P_{r0}(d_{i-1} - \Delta D_{1l-1}')^\alpha - P_{r0}(d_{i-1} - \Delta D_{1l-1}' - d_{i1}')]^\alpha dt \right\}, \quad (6.43)$$

$$\Delta P_{i2}' = \sum_{l=1}^{M_{i2}'} \left\{ \int_{T_i + (l-1)\Delta t_{i2}'}^{T_i + l\Delta t_{i2}'} [P_{r0}(d_{i-1} - \Delta D_{2l-1}')^\alpha - P_{r0}(d_{i-1} - \Delta D_{2l-1}' - d_{i2}')]^\alpha dt \right\}, \quad (6.44)$$

where $M_{i1}' = t_{i1}' / \Delta t_{i1}'$ and $M_{i2}' = t_{i2}' / \Delta t_{i2}'$. Moreover, we have $D_{1l}' = -d_{i1}'$ and $D_{2l}' = -d_{i2}'$. In addition, $v_{x-1}^i$ and $v_{y-1}^i$ is replaced by $-v_{x-1}^i$ and $-v_{y-1}^i$ in 6.31 6.33 6.36 6.38. Then, the optimal power adaptation interval problem for power difference minimization is formulated as follows:

Minimize: the power difference $\Delta P_{i1}' + P_{i2}'$

Subject to:

$$\Delta t_{i1}' - \tau \geq \tau_L$$

$$\Delta t_{i2}' - \tau \geq \tau_L$$

$$\Delta t_{i1}' \leq t_{i1}$$

$$\Delta t_{i2}' \leq t_{i2}. \quad (6.45)$$
6.3 Performance Evaluation

In this section, the performance of the proposed joint power adaptation and spectrum handoff strategy is evaluated using software simulations. In addition, we also compared our proposed scheme with the scheme that does not consider the spectrum handoff.

6.3.1 Simulation results for mobile CR networks with constant speed

The parameters used in our simulations are listed in Table I. We assume that the SU received power is 1W in order to maintain the transmission. The initial distance between SU transmitter and SU receiver, \(d_0\) is 3m. The simulation area \(L\) is 300m. We assume that a time-slotted system is adopted.

<table>
<thead>
<tr>
<th>Number of SUs (N)</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of PUs (K)</td>
<td>20</td>
</tr>
<tr>
<td>Number of channels (M)</td>
<td>10</td>
</tr>
<tr>
<td>The side length of the simulation area (L)</td>
<td>300 (unit length)</td>
</tr>
<tr>
<td>The initial distance (d_0)</td>
<td>3 (unit length)</td>
</tr>
<tr>
<td>The interval time of power adaptation (\delta_t)</td>
<td>0.2 (second)</td>
</tr>
<tr>
<td>The probability that a PU is active (\rho)</td>
<td>0.9</td>
</tr>
<tr>
<td>The time slot (\beta)</td>
<td>0.002 (second)</td>
</tr>
<tr>
<td>The total simulation time (t)</td>
<td>1</td>
</tr>
</tbody>
</table>

The mobility characteristics of the SU receiver are assumed that the speed is constant and \(\theta = 0\). The average speed of the SU receiver is 10 m/s. The length of packets sent from the SU transmitter is exponentially distributed with the mean length of 50 time slot. The packets are sent in a Poisson stream fashion with the average arrive rates of 2, 5, 10, 15, and 20 packets/s.

First of all, Fig. 6.13 shows the simulation results of packet delivery ratio of the mobile CR network. We set \(\lambda_s\) as 2, 5, 10, 15, and 20 packet/s. Since the packet length is 50 time slot and every time slot is 0.002s, the service time \(X_s\) is 0.1s. From Fig. 6.13, we can see when the arrive rate is 2 or 5 packet/s, \(S_2\) is equal to \(S_1\). This
is because that since the SU is unsaturated, the packet delivery rate is equal to $\lambda_s$. When $\lambda_s$ is 10, 15 and 20 packets/s, we have $\lambda_s \times X_s > 1$. According to 6.14 and 6.15, the throughput $S_2$ is less than $S_1$, which is shown in Fig. 6.13. From Fig. 6.13(c), the throughput $S_3$ is much less than $S_1$ and $S_2$. This is because that if there is a collision with the PUs, the SUs have to wait for the end of the PUs transmission before retransmitting the collided packet. If the PUs always utilize the channel which is currently used by the SUs, the transmission of the SUs is significantly affected so that the throughput is much lower.

In Fig. 6.13, we use the $P_{th}$ as the threshold to decide whether to perform a spectrum handoff. We can calculate the optimal threshold $P_{th}$ using (17) which is equal to 0.4. SUs use this threshold to decide whether they should perform a spectrum handoff. Then, we compare the SU throughput under the optimal threshold with the SU throughput under the thresholds that are either greater than or less than the optimal threshold.

Fig. 6.14 illustrate the throughput in terms of the moving speed. It is shown that $S_2$ decreases as the speed increases. As the speed increases, the probability of the potential PUs rises due to the increase of $A^*$.  

6.3.2 Simulation results for mobile CR networks with random speed

First, the parameters for the simulation are introduced. The range of the random mobility movement is $x \in [0, 100]$ and $y \in [0, 100]$. The speed range is $v_x \in [0, 10]$ and $v_y \in [0, 10]$.

As shown in Fig. 6.15, the throughput of the mobile CR networks with our proposed scheme is close to the throughput where there is no collision. The throughput of the mobile CR networks is quite low when there is collision with the PU traffic without our proposed scheme.

Fig. 6.16(a) shows the power wasted using our proposed scheme is much better than the other two random selection scheme. In addition, as shown in Fig. 6.16(b),
(a) The throughput without spectrum handoff and no collision.

(b) The actual throughput under the optimal strategy.

(c) The throughput with collision and no spectrum handoff.

Figure 6.13: The SUs transmission throughput with the optimal threshold.

the throughput of the proposed scheme is much better than the other random schemes.

As shown in Fig. 6.17, the throughput of the randomly mobile CR networks
Figure 6.14: Comparison between throughput under different speeds.

(a) The throughput without spectrum handoff and no collision.
(b) The actual throughput under the optimal strategy.
(c) The throughput with collision and no spectrum handoff.

Figure 6.15: The SUs transmission throughput comparison for randomly mobile CR networks.
Figure 6.16: The power wasted and throughput comparison for randomly mobile CR networks.
Figure 6.17: Comparison between throughput under different power adaptation duration.

decreases as the duration for power adaptation increases.
CHAPTER 7: NOVEL END-TO-END CONGESTION CONTROL IN
MULTI-HOP CRAHNS

7.1 The Proposed End-to-End Congestion Control Scheme

In this section, the proposed novel end-to-end congestion control scheme in multi-hop CR ad hoc networks is presented. The main idea of our proposed end-to-end congestion control scheme is to combine the ECN and timeout mechanism to make the optimal decision to handle the congestion in the network. Our proposed scheme has the following advantages compared with the existing congestion control approaches: 1) it does not need a dedicated common control (CCC) to exchange or transmit the congestion notification; 2) no other control messages is needed except ECN; 3) the end-to-end congestion control can be performed faster than the traditional timeout mechanism; 4) the congestion control can be performed correctly even if the ECN message never reaches the source node; and 5) the end-to-end throughput of the network is high.

Before we introduce the congestion control scheme details, a comprehensive end-to-end congestion control framework for multi-hop CR ad hoc networks under practical scenarios is proposed, as shown in Fig. 7.1. Our proposed framework considers the interactions from the physical (PHY) layer to the transport layer in a network. More importantly, the components at each layer are necessary for SU to work in a CR ad hoc network without a CCC. Then, we illustrate how the components at different layers are systematically integrated in the proposed framework. First of all, the objectives of the PHY layer are spectrum sensing, modulation, and coding. The spectrum sensing helps each SU to obtain the availability information of the current
channel as an input for the higher layers. Secondly, at the link layer, there are two sub-layers including the medium access control (MAC) layer and the logic link control (LLC) layer. There are two objectives for the LLC layer: 1) the channel rendezvous (the method tries to find a common available channel for communications) and 2) the link error control scheme. In addition, the MAC layer protocol is the IEEE 802.11 DCF CSMA/CA while the stop-and-wait automatic repeat request (ARQ) protocol is used in LLC layer as a link error control scheme. Thirdly, a routing protocol for wireless ad hoc network is used to find a path from the source to the destination at the network layer. Finally, at the transport layer, the proposed end-to-end congestion control scheme is implemented. Next, we present the details of our proposed congestion control scheme on the transport layer.

Figure 7.1: The proposed end-to-end congestion control framework of multi-hop CR ad hoc networks.
7.1.1 Step 1: Obtaining the Delay of ECN

There are four steps in the proposed scheme, the first step is to obtain the delay of ECN in multi-hop CR ad hoc network. Conventionally, the delay of ECN is short in traditional wireless ad hoc networks. However, as mentioned in Section II, the delay of ECN may be extremely long due to the spectrum sensing, PU activities, channel rendezvous, and channel switching, which makes the ECN mechanisms not effective for the congestion control in multi-hop CR ad hoc network. Therefore, the delay of ECN should be properly obtained in order to decide whether the ECN is effective or not. In order to obtain the delay of ECN, an extra byte used to store the delay of ECN is added in the priority ECN packets and the header of the piggybacked ECN message. The delay of ECN is updated each time when each intermediate node receives the ECN packet. Denote the delay of ECN as $D_{ECN}$. We have

$$D_{ECN} = t - t_{con},$$

(7.1)

where $t$ and $t_{con}$ represent the time when the ECN message is received and the time when the congestion occurs, respectively. $D_{ECN}$ is added into the extra byte of the priority ECN packets and the header of the piggybacked ECN packets.

7.1.2 Step 2: Deciding Whether to Use the ECN

Then, the second step is to decide whether the ECN can be used as the congestion indication. The process of deciding whether the ECN can be used as the congestion indication is performed at intermediate nodes. Moreover, the flow chart of the process is shown in Fig. 7.2.

In Fig. 7.2, we use $D_{pECN}$ and $D_{bECN}$ to denote the priority ECN delay and piggybacked ECN delay, respectively. In addition, $RTO_r$ denotes the remaining duration
Figure 7.2: The flow chart of the ECN delay updated process.

of the RTO timer. Therefore, the $RTO_r$ is

$$RTO_r = RTO - \lfloor t_{\text{con}} - \text{start}(\text{packet}_c) \rfloor,$$  \hspace{1cm} (7.2)

where $t_{\text{con}}$ is the time when the congestion occurs in the network and $\text{start}(\text{packet}_c)$ is the time that the current packet starts being transmitted in the network. Thus, the priority ECN packet is dropped and the bits for piggybacked ECN in the header of data packets are cleared when $D_{pECN} \geq RTO_r$ and $D_{bECN} \geq RTO_r$, respectively. This means that the timeout mechanism will be used as the indication of congestion. If $D_{pECN} < RTO_r$ and $D_{bECN} < RTO_r$, the decision for congestion control will be made at the source node, which is described in the following section.

7.1.3 Step 3: Avoiding the Incorrect Reaction

In the third step, the source node has to avoid the incorrect end-to-end congestion control reaction in one RTT. As mentioned earlier, the decision for congestion control
is made at the source node when $D_p^{ECN} < RTT_r$ and $D_b^{ECN} < RTT_r$, which means that
the source node receives both the priority ECN and piggybacked ECN. Thus, the
source node reacts to the congestion if there is no further indication to the congestion. We use \textit{flag}_a to indicate whether the congestion control is already performed by the
source node. In addition, the flow chart of the reaction avoidance process is shown in
Fig. 7.3. As shown in Fig. 7.3, the source node performs congestion control only when
\textit{flag}_a is zero. Thus, after the source node has performed congestion control if the RTT
exceeds the RTO timer, it will not perform congestion control again in the current RTT
duration even it receives the ECN.

![Flow chart of the end-to-end congestion control reaction avoidance](image)

Figure 7.3: The flow chart of the end-to-end congestion control reaction avoidance.

### 7.1.4 Step 4: Deriving the RTO Timer Value

The fourth step is to obtain the RTO timer value. The RTO timer value is a critical
factor for the timeout mechanism, which impact the end-to-end congestion control
performance significantly. If the RTO timer value is too long, the congestion control
is almost never performed since there is no timeout. Thus, the CR network becomes
increasingly congested and cannot function properly. If the RTO timer value is too
short, the congestion control is frequently performed. Thus, the transmission rate is
always low and the network bandwidth is wasted. Therefore, the RTO timer value is essentially critical for the network performance. However, the existing approaches used to estimate RTO timer value cannot be used in the multi-hop CR ad hoc network due to the unique features of CR networks. A new method to derive the RTO timer value is needed. The derivation of the RTO timer value of our proposed scheme is introduced in Section IV.

7.2 The Derivation of the RTO Timer Value

In this section, our proposed method to calculate the RTO timer value is presented. Conventionally, the average RTT can be calculated using the following equation [67]:

\[ R = \alpha R + (1 - \alpha)T_1, \]  

(7.3)

where \( R \) us the average estimated RTT and \( T_1 \) is the RTT measured from the most recent ACKed segment. Moreover, \( \alpha \) is a smoothing factor. Once the estimated RTT is updated, the RTO timer value for the next segment is set to \( \beta R \) [67]. However, this algorithm is not useful in the multi-hop CR ad hoc network. As mentioned earlier, due to the extra delay caused by PU activities, the RTO timer value obtained from the traditional timeout algorithm is not effective for the congestion control in multi-hop CR ad hoc network. This is because if the estimated RTT for the current segment is small due to the light PU activities at intermediate nodes, then the calculated RTO timer value for the next segment is small. However, if the RTT of the next segment is long due to heavy PU activities, the source node is likely to trigger timeout even there is no congestion. Thus, the correct calculation of the RTO timer value is essential important when using the timeout mechanism to perform the end-to-end congestion control.

Then, in our proposed approach, the calculation of the average RTT value includes four components: 1) the channel rendezvous delay, 2) the MAC layer delay, 3) the
service delay, and 4) the queuing delay. Moreover, we use $RTO$ to indicate the RTO timer value while $D_{red}$, $D_{mac}$, $D_{ser}$, and $D_{queue}$ represent these four kinds of delay, respectively. $N$ denotes the number of SU nodes in multi-hop CR ad hoc network. Then, we have

$$RTO = \beta [ (N - 1)(D_{red} + D_{mac} + D_{ser}) + D_{queue}]. \quad (7.4)$$

### 7.2.1 The Derivation of the Channel Rendezvous Delay

First of all, the channel rendezvous scheme considered in this paper is Common Hopping [94], which is a very straightforward and effective scheme. Fig. 7.4 shows the procedure of Common Hopping, where the SU channels are time-slotted and SUs communicate with each other in a synchronous manner. Based on Common Hopping, all the SUs in the network have the same hopping sequence. There are two phases in a frame. The first phase is called the *Sensing Phase* where all SUs are required to perform spectrum sensing during this phase. Following the sensing phase is the *Transmission Phase* where SUs may transmit packets in this phase.

![Figure 7.4: An example of the Common Hopping channel rendezvous scheme.](image)

We assume that there are $M$ channels available in the network. Moreover, the probability that the SU successfully accesses the channel is denoted by $P_1$ while the size of the one frame including the sensing phase and the transmission phase is $T_{fr}$. 


Then, the channel rendezvous delay is

$$D_{\text{red}} = \sum_{i=1}^{M} (1 - P_1)^{i-1} P_1 (i - 1) T_{fr}.$$  \hfill (7.5)

### 7.2.2 The Derivation of the MAC Layer Delay

Secondly, the MAC layer delay calculated is the average delay. In addition, the MAC layer delay calculated in our proposed method is the contention delay. This is the duration from the moment that a packet reaches the head of the queue to the moment that the sender can transmit the packet. Thus, the average MAC layer delay is

$$D_{\text{mac}} = P_{\text{idle}}(T_{\text{sense}})(T_{\text{sense}} + \text{ave}_b + T_{\text{RTS}} + T_{\text{CTS}})$$

$$+ T_{\text{MACK}} + [1 - P_{\text{idle}}(T_{\text{sense}})](T - T_s),$$  \hfill (7.6)

where $P_{\text{idle}}(T_{\text{sense}})$ indicates that the channel is idle during the sensing time and $T_{\text{sense}}$ is the sensing duration. In addition, $T$ is the sensing period while $\text{ave}_b$ is the expected delay encountered in the backoff stage and $\text{ave}_b = \frac{CW_{\text{min}}}{2} T_{\text{slot}}$. $T_{\text{RTS}}$ and $T_{\text{CTS}}$ denote the duration of the RTS and CTS, respectively. $T_{\text{MACK}}$ is the duration of the MAC ACK. Moreover, the $T_{\text{slot}}$ represents the time of a slot and $P_{\text{idle}}(t) = e^{-\lambda p t}$, where $t$ is the idle period of the channel.

### 7.2.3 The Derivation of the Service Delay

Thirdly, we calculate the service delay that a SU packet is successfully transmitted. We use Fig. 7.5 to show a realization of traffic transmission of SUs on channel $j$ ($j = 1, 2, ..., M$), where $M$ is the number of the channels. As shown in Fig. 7.5, $S(i)$ ($i = 1, 2, ...$) represents the invalid transmission time of SU packet due to the interruptions caused by the PU traffic. In addition, $U(i)$ ($i = 1, 2, ...$) represents the busy period of the channel when the PU accesses the channel to perform transmissions. Moreover, $L$ represents the time that SU transmits a packet successfully without interruptions and
$T_s$ denotes the duration that SUs complete a successful transmission of the packet including the interruption due to the PU traffic.

![Figure 7.5: A SU data transmission on one channel.](image)

As indicated in Fig. 7.5, we can obtain the following equation

$$T_s = \sum_{i=1}^{n} [S(i) + U(i)] + L,$$

where $n$ is the times of unsuccessful transmission of the SU data packet.

Furthermore, the PU traffic on the channel is a Poisson process with the rate $\lambda_p$ while the PU traffic transmission on the channel is regarded as an M/M/1 queue. In addition, the PU packet transmission time follows the exponential distribution with the expected value $L_p$. Then, the service rate of the PU traffic is $\mu_p = \frac{1}{L_p}$. We obtain the expected value of a busy period on one channel [95] as

$$E[U] = \frac{1}{\mu_p - \lambda_p}.$$  

Then, since the idle period of the licensed channel $j$ has the same distribution as the PU traffic arrivals [95], the idle period of the channel is exponentially distributed with the rate $\lambda_p$, where its accumulated distribution function (CDF) is

$$F(I) = 1 - e^{-\lambda_p I}, \quad I \geq 0.$$  

Thus, the condition for the SU transmission interruption due to the PU traffic is that the idle period on the channel should be smaller than the SU packet length $L$.  

124
We assume that \( m \) is the duration, then we obtain the interruption probabilities of SU transmissions as follows

\[
P(n = N_c|m) = (1 - e^{-\lambda_p m})^n e^{-\lambda_p m}, n = 0, 1, 2, \ldots
\]  

(7.10)

where \( N_c \) represents the number of collisions. The expected value of \( N_c \) is

\[
E[N_c] = \int_0^\infty (e^{-\lambda_p m} - 1)f(m)dm
\]  

= \( E[e^{-\lambda_p L} - 1] \),

(7.11)

where \( f(m) \) denotes the probability density function (pdf) of \( L \). Then, the expected value of \( T_s \) is

\[
E[T_s|m] = E\left[\sum_{i=1}^{n} (S(i)|m + U(i)|m) + m\right]
\]  

= \( E[N_c](E[S|m] + E[U|m]) + m \),

(7.12)

where

\[
E[U|m] = E[U] = \frac{1}{\mu_p - \lambda_p},
\]  

(7.13)

and

\[
E[T_s|m] = E[I|I \leq m]
\]  

= \( \frac{1}{\lambda_p} - m \frac{e^{-\lambda_p m}}{1 - e^{-\lambda_p m}} \).

(7.14)

Therefore, the expected value of the service delay \( T_s \) is

\[
D_{ser} = E[T_s] = E[E[T_s|m]]
\]  

= \( E[N_c](E[E[L|m]] + E[U|m]) + E[m] \)

= \( (\frac{1}{\lambda_p} + \frac{1}{\mu_p - \lambda_p})E[e^{-\lambda_p L} - 1] \).

(7.15)
7.2.4 The Derivation of the Queuing Delay

Finally, the calculation of the queuing delay in multi-hop CR ad hoc networks is introduced. Fig. 7.6 shows the initial queue state of the source and the destination nodes. In addition, both the source and destination nodes have a First In First Out (FIFO) forward buffer. We assume that there are \( w \) packets in the buffer of the source node and the buffer size is \( V \). Moreover, the data packets are represented by the number \( i \) \((i = 1, 2, 3, \ldots)\). As shown in Fig. 7.6, the initial state of the destination node buffer is empty since there is no packet received by the destination node.

![Figure 7.6: The initial queue state of the source and destination nodes in a multi-hop CR ad hoc network.](image)

Next, Fig. 7.7 shows the communication process of the end-to-end transport layer connection. As shown in Fig. 7.7, the destination node generates ACK 1' and ACK 2' after receiving the packet 1 and packet 2. Then, the destination node successfully accesses the channel and sends the ACK 1' to the source node. Based on the sliding window mechanism in most end-to-end congestion control scheme, a new data packet
can be queued in the source node buffer after receiving one ACK from the destination node, which can be seen in Fig. 7.7. The data packet $w + 1$ comes to the buffer of the source node when it receives the ACK $1'$. Moreover, the queuing delay refers to the duration from the moment when the packet is ready to be sent to the moment when the ACK of this packet is received by the source. Actually, the queuing delay varies dramatically. Obviously, the delay for the situation that the source node and the destination node send the packet successfully one after another is totally different from the case that the source node consecutively sends several data packets and the destination node sends ACK packet after this. Therefore, we need to calculate the average queuing delay.

![Diagram](image)

Figure 7.7: The queue state of during the data transmissions.

As described above, we have to take all different kinds of queuing delay into consideration in order to calculate the average queue delay. We propose a Markov chain model to solve this problem. First, a discrete Markov chain is formed for the case when the source and destination is single hop away. The Markov chain is then extended to the general case when there are multiple hops existing in the network.

First, the Markov chain model for the signal-hop CR ad hoc network is introduced. The state of the proposed Markov chain model is defined by two parameters: the
number of data packets and the number of ACK packets in the network. We assume that the congestion control window side is \( w \) (i.e., the source node can send at most \( w \) packets at one time) and the initial state of the network is that there are already \( w \) data packets in the buffer of the source node while the destination node buffer is empty. In addition, the queuing delay is the duration from the moment the packet is queued in the source node buffer to the moment the corresponding ACK packet is received by the source node. Then, the state transition diagram of the proposed Markov chain model is shown in Fig. 7.8.

![State Transition Diagram of Proposed Markov Chain](image)

Figure 7.8: The state transition diagram of the proposed Markov chain.

As shown in Fig. 7.8, we use \( P_s \) to denote the probability that no data packets is transmitted in the current slot while \( P_p \) is the probability that the source node sends a data packet to the destination node. In addition, \( P_a \) denotes the probability that the destination node sends a TCP ACK packet to the source node. There are three cases of the channel usage between the source node and the destination node: 1) none of the node accesses the channel successfully where the probability \( p_s \) is used to denote the probability of this case; 2) the source node accesses the channel successfully where we use \( p_p \) to represent the probability of this case; and 3) the destination node gets the successfully accesses to the channel where \( p_a \) is used to denote the probability of this case. In addition, we use \( \pi_i \) (\( i=0,1,2...M \)) to denote the steady state probabilities.
for all the states. Then, based on the conservation law, we have

\[
\begin{align*}
\pi_0 &= p_0 \pi_0 + p_a \pi_1 \\
\pi_1 &= p_p \pi_0 + p_s \pi_1 + p_a \pi_2 \\
\pi_2 &= p_p \pi_1 + p_s \pi_2 + p_a \pi_3 \\
&\quad \vdots \\
\pi_{w-1} &= p_p \pi_{w-2} + p_s \pi_{w-1} + p_a \pi_w \\
\pi_w &= p_p \pi_{w-1} + p_1 \pi_w \\
\pi_0 + \pi_1 + \pi_2 + \cdots + \pi_w &= 1.
\end{align*}
\] (7.16)

Next, we can calculate the \(p_s\), \(p_a\), and \(p_p\) through the above equations. Then, the queuing delay is

\[
D_{\text{queue}} = p_p L_d + p_a L_a + p_p^2 2 L_d + p_p^2 p_a L_a + \cdots + p_p^w L_d + p_p^w p_a L_a,
\] (7.17)

where \(L_d\) represents the length of the SU packet and \(L_a\) is the length of the ACK packet.

Secondly, for the multi-hop CR ad hoc network scenario, an accurate Markov model would be based on the state space \((K_0, A_0), (K_1, A_1), (K_2, A_2), \ldots, (K_N, A_N)\), where \((K_i, A_i)\) represents the numbers of data and ACK packets at node \(i\). This multi-dimensional Markov chain model considers the number of data packets and ACK packets at the source, the destination, and the intermediate nodes in multi-hop CR ad hoc networks. The transition diagram of the proposed Markov model is shown in Fig. 7.9.

As shown in Fig. 7.9, \((w, 0, 0)\) denotes the initial state of the network where \(w\) is the congestion window size. To be more specific, \((w, 0, 0)\) indicates that there are \(w\) packets in the source node ready to be sent and no packets in the intermediate
Figure 7.9: The state transition diagram of the proposed Markov model in the multi-hop scenario.

and destination node. Moreover, we use \((K_0, (K_1, A_1), A_2)\) to represent that there are \(K_0\) data packets in the source node, \(A_2\) ACK packets at the destination node, and \(K_1\) data packets and \(A_1\) ACK packets at the intermediate node. In addition, in order to make the notations more readable, we use \(Num\) and \(Num'\) to indicate the data packet and its corresponding ACK packets, respectively. For example, \((1, 2')\) means the number of data packets and ACK packets at the intermediate node is 1 and 2 respectively. Based on the above definition, the state of the proposed Markov model at time slot \(t\) is defined by a vector \(\{N_s(t), (N_m(t), N'_m(t)), N_d(t)\}\), where \(N_s(t)\), \((N_m(t), N'_m(t))\), and \(N_d(t)\) denote the number of data packets at the source node, the
number of data packets and ACK packets at the intermediate node, and the number of ACK packets at the destination node at time $t$, respectively.

Then, we calculate the queuing delay. First, according to the state transition diagram, we have the one-step transition probability. We denote the one-step state transition probability from time slot $t$ to $t + 1$ as $P(i_1, (j_1, k_1), l_1|i_0, (j_0, k_0), l_0) = P(N_s(t+1) = i_1, N_m(t+1) = j_1, N'_m(t+1) = k_1, N_d(t+1) = l_1|N_s(t) = i_0, N_m(t) = j_0, N'_m(t) = k_0, N_d(t) = l_0)$. Thus, the non-zero one-step state transition probabilities for this state transition diagram are

$$
P(w - i - 1, i + 1, 0, 0|w - i, i, 0, 0) = p_p$$
$$P(w - 1, 0, 0, 1'|w - 1, 1, 0, 0) = p_p$$
$$P(w - 1, 0, 0, 1'|w - 1, 0, 1', 0) = p_a$$
$$P(w - 1, 0, 1', 0|w, 0, 0, 0) = p_a$$
$$P(w - 2, 1, 0, 1|w - 2, 2, 0, 0) = p_p$$
$$P(w - 2, 1, 1', 0|w - 2, 1, 0, 1) = p_p$$
$$\vdots$$
$$P(0, 0, w - 3', 3'|0, 0, w - 2', 2') = p_a$$
$$P(0, 0, w - 2', 2'|0, 0, w - 1', 1') = p_a$$
$$P(0, 0, w', 0'|0, 0, w - 1', 1'|) = p_a$$
$$p(i_0, j_0, k_0, l_0|i_0, j_0, k_0, l_0) = p_s.$$

Then, we use the probability calculated through the single-hop scenario to derive the queuing delay in the multi-hop CR ad hoc networks since the probability $p_p$, $p_a$ and $p_s$ are the same when the number of hops varies. In order to calculate the queuing delay, we divide the state transition diagram into $w$ levels. The first level is
the queuing delay with the initial state \((w - 1, (1, 0), 0)\), which is

\[
D_{queue}(1) = p_p L_p + p_p^2 2L_p + p_p^3 L_a + p_p^2 p_a 2L_a. \tag{7.19}
\]

Then, the queuing delay of the second level is

\[
D_{queue}(2) = p_p L_p + p_p^2 2L_p + p_p^3 3L_p + p_p^3 p_a 3L_a +
\]

\[
p_p^3 p_a^3 2L_a + p_p^3 p_a^3 3L_a. \tag{7.20}
\]

Next, the queuing delay of the third level is

\[
D_{queue}(3) = p_p L_p + p_p^2 2L_p + p_p^3 3L_p + p_p^4 L_p + p_p^4 p_a 4L_a +
\]

\[
p_p^4 p_a^3 2L_a + p_p^4 p_a^3 3L_a + p_p^4 p_a^4 4L_a + p_p^4 p_a^5 5L_a. \tag{7.21}
\]

Thus, the queuing delay of the \(w\) level is

\[
D_{queue}(w) = \sum_{i=1}^{w+1} p_p^i L_p + p_p^{w+1} \sum_{i=1}^{2w-1} p_a^i L_a. \tag{7.22}
\]

Hence, the totally queuing delay is,

\[
D_{queue} = \sum_{j=1}^{w} \left( \sum_{i=1}^{j+N-1} p_p^i L_p + p_p^{w+1} \sum_{i=1}^{2j+N-1} p_a^i L_a \right). \tag{7.23}
\]

Finally, we successfully derive all the components and the RTO timer value can be obtained.

7.3 performance evaluation

In this section, we evaluate the network performance of the proposed novel end-to-end congestion control scheme in multi-hop CR ad hoc network. The main advantage of our proposed end-to-end congestion control scheme is that the source node can perform the end-to-end congestion control in time. To evaluate the performance of
the proposed end-to-end congestion control scheme, we conduct extensive software simulation using MATLAB and compare with existing the end-to-end congestion control mechanisms. We consider a 5-hop CR ad hoc network with a chain topology, as shown in Fig. 1.6. Each SU has a circular transmission range with a radius of $r_c$. The normal buffer size of each SU is 50 TCP packets while the buffer size of the congested nodes is 3 TCP packets. Other parameters used in our simulation are listed in Table I.

<table>
<thead>
<tr>
<th>Number of PUs</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of channels in the spectrum band</td>
<td>5</td>
</tr>
<tr>
<td>Side length of the network area</td>
<td>1400 m</td>
</tr>
<tr>
<td>Radius of the SU transmission range</td>
<td>250 m</td>
</tr>
<tr>
<td>Length of the sensing phase</td>
<td>1 ms</td>
</tr>
<tr>
<td>Length of the transmission phase</td>
<td>10 ms</td>
</tr>
<tr>
<td>Data rate of the channels</td>
<td>2 Mbps</td>
</tr>
<tr>
<td>Size of RTS packets</td>
<td>240 bits</td>
</tr>
<tr>
<td>Size of CTS packets</td>
<td>240 bits</td>
</tr>
<tr>
<td>Size of MAC ACK packets</td>
<td>240 bits</td>
</tr>
<tr>
<td>Size of SU TCP segments</td>
<td>1460 bytes</td>
</tr>
<tr>
<td>Size of SU TCP ACK packets</td>
<td>20 bytes</td>
</tr>
<tr>
<td>Size of dedicated packets marked with ECN</td>
<td>20 bytes</td>
</tr>
<tr>
<td>Size of PU packets</td>
<td>1460 bytes</td>
</tr>
</tbody>
</table>

Fig. 7.10 shows the simulation results of the end-to-end throughput of our proposed end-to-end congestion control scheme and other mechanisms. As shown in Fig. 7.10, the end-to-end throughput using our proposed end-to-end congestion control scheme is always higher than all the other mechanisms by up to 30%. This is because our proposed end-to-end congestion control scheme always performs the congestion control in time when congestion occurs.

Fig. 7.11 depicts the simulation results of the congestion control efficiency of our proposed end-to-end congestion control scheme and other mechanisms. The congestion control efficiency is defined as the ratio of the number of non-congested received packets (i.e., received packets that are not dropped due to congestion) to the total
number of received packets. As shown in Fig. 7.11, the congestion control efficiency under the timeout mechanism is the highest. Our proposed end-to-end congestion control scheme achieves almost the same congestion control efficiency with the timeout mechanism. However, as shown in Fig. 7.10, the end-to-end throughput under the timeout mechanism is much lower than our proposed scheme.
Figure 7.11: The congestion control efficiency comparison between our proposed scheme and other existing mechanisms.
8.1 Conclusion

In this research, the unique challenges in the global time synchronization design challenges in CR ad hoc networks have been addressed for the first time. A practical global time synchronization protocol is proposed considering the unique features of CR ad hoc networks. Moreover, using the proposed optimal root node selection and the proposed time synchronization period, the synchronization delay and the proposed impact of PUs in the global time synchronization are reduced dramatically. Simulation results show that the root selection and the calculated synchronization period can significantly reduce the synchronization delay and reduce the impact of PUs during the global time synchronization process.

We investigate how to differentiate the signals between PUs and SUs in CR networks. A novel spectrum sensing scheduling scheme is proposed to solve this issue. By using the proposed spectrum sensing scheduling scheme, the signals from SUs and PUs can be differentiated and the sensing result of the channel information is more accurate. In addition, in order to obtain the optimal spectrum sensing duration and sensing period for the proposed scheduling scheme, a Markov model is proposed. Simulation results show that our proposed spectrum sensing scheduling scheme outperforms the scenario without signal differentiation in terms of higher SU throughput.

In this research, an optimal power control algorithm for concurrent transmissions of location-aware mobile CR ad hoc networks is proposed. The proposed algorithm incorporates the mobility characteristics of the CR receiver in the algorithm design.
and is aimed to maximize the concurrent transmission region of CR users, hence improving the throughput of CR links. Simulation results demonstrate that the packet delivery ratio of the proposed optimal power control algorithm can be effectively improved, as compared to that of the fixed power algorithm. The impact of the shadowing fading effect on the proposed algorithm is also considered. It is shown that the proposed power control algorithm also outperforms the fixed power control algorithm under the shadowing fading effect.

A joint power adaptation and spectrum handoff scheme for mobile CR network is proposed. The proposed scheme incorporates the power adaptation in order to maintain transmission when SU receiver is mobile. In addition, the spectrum hand-off scheme aims to alleviate the interference to the PUs caused by the increase of the transmission power. Simulation results demonstrate that the throughput of the SUs with the proposed algorithm can be effectively improved, as compared to that of algorithm without spectrum handoff. The proposed joint power adaptation and spectrum handoff scheme is a fundamentally indispensable part to the protocol design in mobile CRNs.

The unique challenges in the end-to-end congestion control scheme design in multi-hop CR ad hoc networks have been addressed for the first time. A novel end-to-end congestion control scheme is proposed considering the features of multi-hop CR ad hoc networks. Moreover, using the proposed end-to-end congestion control scheme, the end-to-end throughput and the congestion control efficiency of the network increase dramatically. The results of this paper will have a significant impact on the transport layer protocol design as well as the realization of multi-hop CR ad hoc networks.

8.1.1 Published and finished work


REFERENCES

[1] FCC. (2003, November) Et docket no. 03-289 notice of proposed rule making and order.


