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DOCTORAL THESIS

TEMPORAL OPPORTUNISTIC SPECTRUM ACCESS SCHEME FOR WIRELESS NETWORKS

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ABSTRACT

The current spectrum management apparently leads to the spectrum underutilization issue. To address the problem, researchers propose an approach known as dynamic spectrum access. Dynamic spectrum access is a broad paradigm that encompasses many spectrum access and management approaches. Among them, there is an approach that called spectrum overlay access approach. The spectrum overlay access (also called opportunistic spectrum access) dictates that the secondary user is allowed to access the licensed spectrum of the primary user, provided with a condition that the secondary users’ access is not intrusive to the primary users. The current researches tend to focus on the exploitation of a licensed spectrum with rather slow temporal variation, such as TV channel bands. Meanwhile, a significant licensed channel is characterized by fast and dynamic temporal variation. In this fast varying temporal character, the primary users’ spectrum condition and opportunity are changing in relatively short duration, mostly, in term of seconds or milliseconds. Our research goal is to investigate and devise more effective secondary user access scheme to exploit the short and fast varying temporal opportunities under opportunistic spectrum access approach.

During the course of our study, we investigate the impact of utilizing multiple transmission rates and relays under fast varying time domain opportunistic spectrum access. From the investigation, we find the utilization of faster rate along with the relay assistance is actually lead to better temporal spectrum sharing performance compared with the direct transmission with the one hop optimal transmission rate. One caveat is that, for a system with diverse transmission rate selection, such as IEEE 802.11g or IEEE 802.11n system, not all the fast transmission rates results in the performance gain in the temporal spectrum sharing environment. The balance between a fast transmission rate and the number of the relay transmission need to be considered to improve the temporal spectrum sharing performance. As result, we observe that the proper exploitation of the
rate and relay diversity nature has the potential to improve the efficiency of temporal spectrum sharing between the primary and secondary users. We also devise an approach to put the application of this rate and relay diversity exploitation into practical wireless networks system by proposing an adaptive rate and relay approach. The adaptive rate and relay approach are composed of three components. As the main component, we propose Auto Rate Increase (ARI) and Receiver based Auto Rate Increase (R-ARI) as the rate adjustment algorithms. Secondly, we utilize the multi-rate GPSR routing algorithm as the mean to dynamically select the relay assistance. Lastly, we propose a rate limit formula as a metric to balance the transmission rate and the number of relays. We propose novel rate adaptation algorithms to address the weakness of the conventional WLAN rate adaptation algorithm. The current dynamic rate algorithms are designed for normal wireless networks environment without ever considering the existence of primary and secondary users. Our proposed rate adaptation algorithms consider, in addition to the channel condition, the effect of primary and secondary transmission collision and adjust the transmission rate so that the secondary users are able to efficiently exploit the temporal opportunity.

We evaluate the performance of our proposed approach through QualNet network simulator. The initial evaluation is aimed to compare the Auto Rate Increase (ARI) and Auto Rate Fallback (ARF) rate adaptation algorithm. The simulation parameters in this initial evaluation are modeled after the IEEE 802.11b model. The selectable rates are limited to 1, 2, 5.5, and 11 Mbps. We evaluate the algorithms under the connected network topology. The connected topology means for every transmission rate, a node is guaranteed to find the relay node to assist its transmission. The results show that the performance of ARI clearly outperforms ARF by wide margin. At most, we can expect around 56% improvement of the secondary throughput. Although the results show the superiority of Auto Rate Increase, the evaluation environment cannot be considered as
practical wireless networks with few selectable transmission rate and fully connected topology. As mentioned previously, we propose the adaptive rate and relay approach to exploit the rate and relay diversity nature and implement it into practical wireless. The next performance evaluation is to evaluate the feasibility of this adaptive rate and relay approach for various conditions and topologies. The simulation parameters are modeled from IEEE 802.11g with various selectable transmission rates from 6 to 54 Mbps. The performance metrics are the secondary users’ throughput and the primary-secondary transmission collision probability. We evaluate the performance for various primary protection thresholds, fractions of idle time, node density, and mobility factors. We also evaluate the performance under the connected and random node topology. The results show the proposed ARI and R-ARI algorithms outperform the conventional rate adaptation algorithms although the advantage of the proposed approaches diminishes under strict primary protection threshold. In conclusion, the performance evaluations through QualNet network simulator validate the feasibility of our adaptive rate and relay approach and show that our proposed rate adjustment algorithms are able to outperform the traditional dynamic rate adjustment algorithm and the optimal one hop transmission scheme under the temporal spectrum sharing environment. The performance gains are shown in the improvement of the secondary users’ throughput and lower primary and secondary transmission collisions probability.
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Chapter 1
Introduction

The proliferation of wireless technology innovations has lead to the belief that radio spectrum is getting scarcer. This phenomenon is observable, especially, in the unlicensed Industrial, Scientific, and Medical (ISM) radio spectrum bands. The increasing popularity of the Wi-Fi technology and mobile devices (e.g., notebook, smartphones, etc) results in the over crowdedness of the ISM bands, which strains the overall wireless networking performance. The growing quality of service demand of the wireless performance makes this spectrum scarcity issue as one urgent problem that needs an immediate solution.

The question is that are we really running out of radio spectrum resource? According to the actual spectrum measurements conducted by FCC [1], the current spectrum management policy causes the radio spectrum resource shortage rather than the actual physical scarcity of the usable frequency. At any given time and location, most of the licensed spectrum lies idle and unused, while the unlicensed spectrum suffers from over crowdedness. This underutilization issues can be solved with better spectrum management policies and techniques. Efficient radio spectrum resource allocation and usage should boost the wireless network performance and, at the same time, able to accommodate future wireless technology innovation.
1.1 Dynamic Spectrum Access

One solution to address the spectrum resource underutilization is Dynamic Spectrum Access (DSA). As opposed to the current static spectrum management, dynamic spectrum access is a new paradigm that focuses on the flexible spectrum allocation. As illustrated in Fig. 1.1, dynamic spectrum access is a broad paradigm that comprises many different spectrum allocations, managements, and access approaches to realize spectrum allocation and management reform. In this section, we provide a brief further introduction to each of the dynamic spectrum access strategy to give a glance...
of the dynamic spectrum access research field boundary.

1.1.1 Dynamic Exclusive Use Model

This first model maintains the structure of the current spectrum policy, where each spectrum band is licensed for each different wireless technology. It retains the exclusive usage of the spectrum bands but introduces the dynamic aspect. In broader case, this dynamic exclusive use model are comprised of two approaches: spectrum property rights and dynamic spectrum allocation.

Spectrum property rights approach allows licensees to lease, sell, trade, and share the spectrum for the usage of other wireless technology [3]. This approach is more flexible than the current command and control spectrum policy, where rigid exclusive use and no spectrum sharing policy are defined. Spectrum property right approach treats radio spectrum as a property, which can be leased, traded, shared, and sold just like common property. This paradigm shifting gives radio spectrum resource more flexibility feel. In short, the economic demand plays an important role on the application of the spectrum property rights approach.

Dynamic spectrum allocation approach’s purpose is to improve spectrum inefficiency by dynamic spectrum assignment, which varies according to the spatial and temporal factor [4]. Exploiting the fact that at any given time and space, the spectrum usage statistic for many different services varies a lot, allocating the spectrum dynamically improves the spectrum utilization efficiency. This approach retains the exclusive use of the spectrum but the main difference with the current spectrum policy is that the spectrum assignment varies dynamically with spatial and temporal factor.
1.1.2 Open Sharing Model

This spectrum model mimics the unlicensed industrial, scientific, and medical (ISM) band, where the radio spectrum is open to be shared with many different technologies [5]. Researchers propose centralized and distributed approach to manage sharing the common spectrum.

Raman, et al., proposes a centralized spectrum server to coordinate transmission between each group of links that share a common spectrum [6], while Ileri, et al., use spectrum policy server to regulate the competition between operators who operate in common spectrum [7]. For distributed approach, researchers use game theoretic approach to handle the policy of each user in a distributed manner to handle the spectrum sharing [8, 9].

1.1.3 Hierarchical Access Model

The main idea of this model is to allow the unlicensed user to utilize the licensed user radio spectrum as long as the performance of the licensed user is kept to minimal. The model refers to the unlicensed user as secondary user (SU) and licensed user as primary user (PU). There are two approaches of spectrum sharing in this hierarchical access model, which are spectrum underlay and spectrum overlay.

The spectrum underlay approach gives strict requirement to the transmission power of the secondary users so that they can operate in parallel with the primary users without seriously affecting their performance. This approach enables secondary users to share the spectrum even with the worst case assumption that the primary users transmit all the time. [10, 11] propose joint rate and power allocation for the secondary user to utilize the spectrum underlay access. Under the spectrum underlay access, the secondary user does not need to concern with white space and spectrum opportunity detection.
The spectrum overlay access relies on the detection of the spectrum white space in space, frequency, and time domain. The main sharing method in this approach is exploitation of the underutilized primary user spectrum white space by the secondary users. Software defined radio\[12\] enables the detection and exploitation of the white space by the secondary users. There is no strict transmission power limitation in this model but the secondary users need to carefully choose when and where to transmit in order to not intrude the primary users. Under this spectrum access method, the definition of the spectrum white space or spectrum hole is extremely important so that the identification of the spectrum hole is accurate.

The hierarchical model is more compatible with the current spectrum management policy compared to the dynamic exclusive and the open sharing model. This model can be viewed as one strong candidate for transition phase before any ideal dynamic spectrum access can be realized. Researchers also refer to this access method as opportunistic spectrum access (OSA), which stems from the fact that the secondary users try to find an opportunity to use the primary user spectrum and transmit opportunistically.

1.2 Software Defined Radio

As mentioned in the section \[1.1.3\], software defined radio plays important role in the hierarchical model. This section introduces a brief background to the software defined radio and shows the importance of the software defined radio as the enabling technology for both spectrum underlay and overlay access approach.

Software-defined radio is generally a multi-band radio that supports multiple air interfaces and protocols along with the ability to be reconfigured through software run on Digital Signal Processing (DSP) or general purpose microprocessors \[13\]. Within dynamic spectrum access, a software defined radio is the basis to realize the cognitive
radio technology.

[14] defines cognitive radio as an intelligent wireless communication system that is aware of its surrounding environment and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:

- highly reliable communications whenever and wherever needed
- efficient utilization of the radio spectrum

The unique features for cognitive radio are the following: Awareness, intelligence, learning, adaptivity, reliability, efficiency, and reconfigurability. For both the spectrum access underlay and overlay model of the dynamic spectrum access, cognitive radio task can be summarized as below:

1. Radio-scene analysis, which consist of:
   - estimation of interference temperature of the radio environment

![Fig. 1.2: Basic cognitive cycle](image)
1. Detection of spectrum white spaces

2. Channel identification, which consist of:
   - estimation of channel state information
   - prediction of channel capacity for transmitter use

3. Transmit-power control and dynamic spectrum management

These three tasks form a cognitive cycle as shown in Fig. 1.2. Radio-scene analysis and channel identification tasks are carried out in the receiver, while transmit-power control and dynamic spectrum management are carried out in the transmitter side.

The secondary users, equipped with a cognitive radio, are able to identify the spectrum white space opportunity and adapt their parameters to exploit the spectrum white space. Environment awareness and fast reconfigurability of the radio parameters features are the basis on why the cognitive radio is the enabling technology for the opportunistic spectrum access scheme.

1.3 Research Focus

In response to the broad research field for the dynamic spectrum access topic, this section explain more detail on our research focus. We decide to put our focus on the hierarchical access model. Specifically, we are interested in researching the spectrum overlay method, where the secondary users try to identify and exploit the primary users spectrum white space. In the spectrum overlay approach, the spectrum white space or spectrum hole refers to the opportunity for the secondary users to exploit the primary users’ spectrum with no intrusion to the primary users system. These opportunities appear in several domains, such as, space, frequency, power, and time domain. Fig 1.3
Fig. 1.3: Spectrum white spaces illustration

depicts the illustration of the spectrum white spaces found under the time, power, and frequency domain [15].

Along the years, there have been intensive researches in this opportunistic spectrum access field [16, 17, 18, 19, 20, 21, 22, 23, 24]. Dominantly, the works focus on the identification of the spectrum opportunities, or also known as spectrum sensing, and the exploitation of the spectrum white space in the spatial and frequency domains. There are not so many researches address the temporal aspect of the opportunistic spectrum access.

The current researches tend to focus on the exploitation of a licensed spectrum with rather slow temporal variation, such as TV channel bands. Meanwhile, a significant licensed channel is characterized by fast and dynamic temporal variation. In this fast varying temporal character, the primary users’ spectrum condition and opportunity are changing in relatively short duration, mostly, in terms of seconds or milliseconds duration. This licensed spectrum characteristic emphasizes the importance to investigate more on temporal aspect in the opportunistic spectrum access approach. This background is further put more focus on our research to concentrate on the temporal aspect of the opportunistic spectrum access approach. In summary, Our research goal is to
investigate and devise more effective secondary user access scheme to exploit the short and fast varying temporal opportunities under opportunistic spectrum access approach.

1.4 Organization of thesis

The outline of this thesis is described as follows. Chapter 2 explains the preliminary investigation of our study. We start our research by reviewing some relevant studies in the following fields: The secondary user’ access scheme for opportunistic spectrum access environment and the rate adaptation approach under opportunistic spectrum access and normal wireless local area network environment. Then, we describe the overall system model and assumptions that we use for the rest of our study. We also explain the detail of our proposed observation and argument that the use of faster rate and relay transmission are may able to improve the performance of the temporal opportunistic spectrum sharing. We close this chapter with the investigation of the rate and relay impact to the secondary users’ access in the temporal spectrum sharing environment. The results support our proposed argument that a faster rate and relay transmission can benefit secondary users access under temporal spectrum sharing environment.

Chapter 3 provides details of our proposed adaptive rate and relay approach. In this chapter, we devise an access method for secondary user to better exploit the temporal white space of primary user spectrum. Our access method relies on two factors: transmission rate and relay transmission. We use the observation from the chapter 2 to propose a new approach for efficient utilization of the primary user spectrum temporal white space. In this chapter, we propose auto rate increase (ARI) and receiver-based auto rate increase (R-ARI) scheme. ARI and R-ARI are rate adjustment scheme that aim to exploit faster rate in a temporal spectrum sharing scenario. We define all the necessary components required to exploit the rate-relay diversity in temporal opportunistic
spectrum access environment as one novel adaptive rate and relay approach.

The performance evaluations of the proposed approach are presented in the chapter 4. In this chapter, we evaluate the feasibility and the performance of the adaptive rate and relay approach. The performance evaluations are all done by simulation evaluation under QualNet simulator. We conduct two stages evaluation. The first one is the initial evaluation that aims to compare the performance of the ARI and ARF. The simulation parameter configuration follows IEEE 802.11b with limited selectable rates and secondary users node topology environment. The second stage is the general evaluation. In this stage, we evaluate a more general secondary users node topology and the simulation parameters follow IEEE 802.11g with more transmission rate selection. Lastly, chapter 5 marks the conclusion of this thesis.
CHAPTER 2

Preliminary

This chapter describes the preliminary study of our research. We start our research by reviewing some relevant studies in the following fields: The secondary user’ access scheme for opportunistic spectrum access environment and the rate adaptation approach under opportunistic spectrum access and wireless local area network environment. Then, we describe the overall system model and assumptions that we use for the rest of our study. We also explain the detail of our proposed observation and argument that the use of faster rate and relay transmission are may able to improve the performance of the temporal opportunistic spectrum sharing. We close this chapter with the investigation of the rate and relay impact to the secondary users’ access in the temporal spectrum sharing environment. The results support our proposed argument that a faster rate and relay transmission can benefit secondary users access under temporal spectrum sharing environment.

2.1 Related Work

The current spectrum management apparently leads to an inefficient spectrum resources allocation [1]. However, with the advent of the cognitive radio (CR) [12], the opportunistic spectrum access has emerged as a promising solution to this problem. The opportunistic spectrum access follows a hierarchical spectrum access model, whereby the SU and PU notations are defined [2]. In order to exploit the spectrum opportuni-
ties, an SU (cognitive user) is allowed to access the PU (legacy user) spectrum, provided that it is not intrusive to the PU. The primary spectrum opportunities can be found in spatial and temporal domains. Over the years, a number of researchers have studied the OSA/CR\textsuperscript{1} environment. In this section, we review some of their works that are relevant to our study.

Several efforts has been made to design an SU access scheme to exploit the primary spectrum effectively. A decentralized cognitive media access control (DC-MAC) has been proposed in \cite{16}. To choose the optimal channel to be sensed and accessed, the DC-MAC uses the partially observable Markov decision process (POMDP) approach. A hardware constrained MAC (HC-MAC) protocol has been designed in \cite{17} to access the unused primary spectrum. It derives an optimized sensing and transmission decision to maximize the secondary throughput. On the other hand, an efficient MAC protocol called opportunistic spectrum MAC (OS-MAC) has been proposed in \cite{18}. In OS-MAC, the SUs decide and negotiate the data channel (DC) they can access via a common control channel (CCC). A comprehensive survey of the MAC strategies in cognitive network can be found in \cite{19}. The SUs contention and access method in most of the works follows a scheme similar to that of the IEEE 802.11 DCF. The control packets, such as request-to-send (RTS) and clear-to-send (CTS), are often used to reserve the primary channel and synchronize the SU sender and receiver. Most works model the primary system occupancy in the channel with a certain probability of the busy-idle state. The busy state means that the channel is currently being used by the PUs, while the idle state means the otherwise. However, such a model does not capture the temporal dynamic variation impact.

A different approach has been taken in works \cite{25, 26, 27}. In these works, the fundamental performance of the OSA is analyzed. Moreover, the temporal aspect of OSA

\textsuperscript{1}The term CR and OSA are often used interchangeably to denote a general dynamic spectrum access environment.
has been better represented in their system models. In [25], the performance capacity
of the SU under generally distributed busy duration and exponentially distributed idle
duration has been analyzed. Three SU random access schemes have also been evaluated.
Moreover, the secondary throughput, primary collision, and overlapping time have been
taken as the performance metrics. The work of [26] extends that of [25] by adding
multiple PU constraints, while [26] analyzes and derives the SU optimal transmission
policy under a heterogeneous environment. In [27], the secondary performance has been
analyzed under different PU traffics. Based on the characteristics of the PU traffic, an
optimal transmission scheme can be derived. None of these works, however, addresses
the SU multi-rate-relay impact on the temporal OSA.

The rate adaptation scheme under cognitive networks has also been studied. The works
of [20, 21, 22, 23, 24] study the joint rate and power allocation for a cognitive network.
To maximize the secondary performance, an optimal rate and transmission power alloca-
tion scheme can be derived under various constraints. These works study the multi-rate
aspect in terms of joint-rate-power allocation. Its impacts on the temporal OSA and
rate-relay aspect, however, have not been considered. In contrast with cognitive envi-
ronments, the multi-rate adaptation scheme has more been explicitly studied in wireless
local area network environments. Under a wireless local area network (WLAN) scenario,
a number of works address the rate adjustment issue. Thus, [28] designs an auto-rate
fallback (ARF) algorithm to exploit the multi-rate capability. The ARF tries to in-
crease the rate after consecutive successful transmissions and decreases it, otherwise. A
receiver based auto-rate (RBAR) has been proposed in [29]. An optimal transmission
rate between the sender and the receiver can be decided by piggybacking the receiver
channel quality information in the CTS packet. If we bring the rate adaptation issue
to the temporal OSA environment, the optimal rate allocation can be modeled after
this RBAR scheme. However, being designed for a normal environment, the ARF and
RBAR do not consider any PU activity.

In sum, through this research, we try to bridge the gaps between the temporal, multi-rate, and multi-relay aspects for an opportunistic spectrum access environment. We observe that the use of a relay assisted, faster transmission rate can be beneficial for the SU to exploit the temporal opportunity of the PU. Hence, the contributions of our work is two-fold. First, it brings out the impact of the multi-rate and relay assistance on temporal aspect of an opportunistic spectrum access, and secondly, it derives a distributed rate-relay adjustment scheme for a temporal opportunistic spectrum access environment.

Fig. 2.1: Primary and secondary user networks
2.2 Temporal Spectrum Sharing Model

In accordance to section 1.3, we focus on the temporal aspect of the opportunistic spectrum access scheme. Overall, we use the similar assumptions and model for temporal

Fig. 2.2: Aggregated primary user traffics

Fig. 2.3: Temporal spectrum sharing
opportunistc spectrum access environment [25, 27, 26]. Consider a network with \( N \) primary users (PUs) and \( M \) secondary users (SUs) where the secondary users try to exploit the primary channel of primary users. Under the temporal sharing scheme, secondary users objective is to exploit the idle period of the primary users and to keep the interference between the primary and secondary users under a certain threshold value. From the viewpoint of a secondary user, the primary channel is busy if it is used by one or more primary users, and idle otherwise. In this case, we can treat the aggregated busy and idle periods of multiple primary users as one primary user. Fig. 2.2 illustrates the traffic of this aggregated primary users can be modeled as alternating busy and idle periods. The idle period distribution is exponential while the busy period is general. We assume there is no coordination between primary and secondary users. Primary user channel access is not affected by the secondary users transmission. We also assume the system is stationary and ergodic. The radio range of the primary users is assumed to be far exceed the secondary users radio range [30] considering the difference in transmission power for primary and secondary user. Fig 2.1 illustrates the primary and secondary users networks.

Fig. 2.3 shows the illustration of how the secondary users exploit the temporal opportunity of the primary users spectrum. Let \( I_p \) and \( B_p \) denote the idle and busy period for the primary channel, respectively. And let \( i_p = E[I_p] \) and \( b_p = E[B_p] \) denote the expected value for the idle and busy period, respectively. Approximately, SUs can utilize \( \alpha \) fraction of time for transmission, where \( \alpha = \frac{i_p}{i_p + b_p} \). In this work, we assume that SUs form a wireless ad hoc network and their characteristic is similar to the wireless local area network (WLAN) system. SU channel access scheme follows IEEE 802.11 DCF scheme where listen-before-talk (LBT) mechanism is employed. An SU performs spectrum sensing before transmission and only transmits when the primary channel is idle. We assume the spectrum sensing duration (\( \tau \)) is equal to the total of distributed
Fig. 2.4: Comparison of throughput versus distance for different modulation schemes inter-frame space (DIFS) and back-off (BO) duration, where $\tau = DIFS + BO$. The spectrum sensing results are also assumed to be perfect. Due to the hardware limitation, SU cannot sense the channel while transmitting. In general, the objective of an OSA scheme can be summarized into two parts:

- To maximize the secondary throughput
- To keep the intrusion to PU as minimum as possible

The second objective necessitates some PU protection scheme.

A secondary user is also equipped with the knowledge of $k$ numbers of modulation schemes at the PHY layer. This also can be mapped into $k$ numbers of physical data
rate capability. Let $\mathbf{R}$ denote the set of selectable physical data rate, where $\mathbf{R} = \{R_1, R_2, \ldots, R_k\}$. The transmission rate order are as follows, $R_k > \cdots > R_2 > R_1$, where $R_k$ is the fastest and $R_1$ is the slowest. The higher and the faster $R_i, \forall R_i \in \mathbf{R}$, the higher the signal-to-interference-plus-noise ratio (SINR) needed at the receiver to decode correctly the packet. Let $Th_{R_i}$ as the SINR threshold needed to decode the packet transmitted at data rate $R_i$. The order of $Th_{R_i}$ similarly follows the order of the rate $R_i$, where $Th_{R_k} > \cdots > Th_{R_2} > Th_{R_1}$, with $Th_{R_k}$ value being the highest and $Th_{R_1}$ being the lowest. [29] conduct a performance evaluation to validate the relationship between transmission rate and distance. The result is shown by Fig. 2.4 and it shows that a faster transmission rate necessitates a better channel condition or closer proximity distance between source and destination node [29].

2.3 Primary Protection Scheme

As mentioned before, one of the objective for the temporal spectrum sharing is to keep PU intrusion minimum. In temporal opportunistic spectrum access, the challenge to achieve those objective is that an SU cannot precisely knows the value of the current $I_p$. Aggressive SU transmission is most likely will interfere with the PU transmission. One example for this problem can be seen in Fig. 2.3, where spectrum sensing result returns that the primary channel is idle but the remaining $I_p$ is not enough for SU transmission where it results in the collision between secondary and primary packet. For this reason, a mean to protect the PU transmission is needed, we refer this as primary protection scheme. In this thesis, we introduce two primary protection schemes based on the assumption whether the PU idle distribution is known or not.
2.3.1 Hard Protection

This protection scheme is based on the assumption that no PU idle distribution is known. Under this assumption, PU needs to be able to tolerate a certain degree of interference from SU. Let $T_{MAX}$ be the maximum interference duration that PU can tolerate. Let $T_s$ denotes the duration for one SU packet transmission. With SU LBT mechanism, only one SU packet at most will collide with the PU. Hence, as long as SU can keep $T_s \leq T_{MAX}$, PU can always tolerate SU interference \[.\] Hard protection scheme is more efficient and reasonable if we assume $T_s \leq T_{MAX} << B_p$. Under this protection scheme, SU is allowed to transmit aggressively without any restriction.

2.3.2 Interference Threshold Protection

If the PU idle distribution is known, then the interference threshold protection scheme can be utilized. This protection scheme dictates that the PU interference should be below some threshold value $\eta$. Referring to Fig. 2.3, let $t$, $t'$, and $T_s$ denote the start of idle period time instance, the time instance when an SU is ready to transmit the packet, and the duration for SU transmission, respectively. For exponentially distributed idle period, the probability of secondary and primary packet collision $P_{pc}$ can be written as

$$P_{pc} = 1 - \int_{T_{exp}}^{\infty} \frac{1}{t_p} e^{-\frac{t}{t_p}} dt = 1 - e^{-\frac{T_{exp}}{t_p}}$$

Where $T_{exp}$ is the expected duration of the idle period which is able to accommodate the current SU transmission, it can be calculated as $T_{exp} = (t' - t) + T_s$. Under the interference threshold protection, the system can set the following constraint $P_{pc} \leq \eta$. The constraint will keep the interference to the PU below a specified threshold $\eta$. In short, stricter $\eta$ will make SU transmits more conservatively.
2.4 Observation: Rate and Relay Diversity

In our quest to find an efficient access method for a secondary user to better exploit the temporal opportunity in primary users spectrum, we stumble upon observation on how multiple transmission rate affect the temporal spectrum sharing.

Simple illustration of this observation can be seen in the Fig. 2.5. All SU nodes are under the transmission range of the PU and SU node S tries to exploit the temporal opportunity to transmit to D. Assuming all SUs are allowed to transmit with constant and similar power $P$ and $SINR_{S\rightarrow D}$ as the received SINR value at D from S transmission. Let $R_{S\rightarrow D}$ be the fastest rate that can be used by S, s.t. $SINR_{S\rightarrow D} \geq Th_{R_{S\rightarrow D}}$. Upon sensing idle PU activity, S node can transmit to the D node with the rate $R_{S\rightarrow D}$ (shown with the bold line). When no multiple transmission rate and the assistance of relay node are not considered, this transmission scheme is optimal for one hop transmission between node S and D since the rate $R_{S\rightarrow D}$ is the fastest transmission rate that S can achieve to reach D.

![Diagram](image)

Fig. 2.5: **Observation**: SU may use a faster transmission rate with the assistance of a relay node
Now, if we take account of node A, B, and C which are closer to the node S and the possibility of employing multiple transmission rate. Under the same transmission power and set of selectable rate parameters, S can use node C as a relay and transmits with a faster rate $R_{S\rightarrow C}$, followed by C transmits to D with another faster rate $R_{C\rightarrow D}$ (both shown by the dashed line), s.t. $SINR_{S\rightarrow C} \geq Th_{R_{S\rightarrow C}}$, $SINR_{C\rightarrow D} \geq Th_{R_{C\rightarrow D}}$, and $R_{S\rightarrow C}, R_{C\rightarrow D} > R_{S\rightarrow D}$. This scenario is possible due to the closer node is more guaranteed to have higher received SINR, hence $SINR_{S\rightarrow C}, SINR_{C\rightarrow D} > SINR_{S\rightarrow D}$. The PU activity at relay node C is also tend to be the same because the relay nodes are located in, lesser than or at most, one hop distance from the source node. The question of this observation is whether an SU can exploit the temporal opportunity more efficiently by employing a faster rate with the assistance of a relay. To answer this question, we conduct an investigation on how the multi-rate and relay affect the performance of temporal spectrum sharing between primary and secondary users.

### 2.5 Investigation: Rate and Relay Impact

In this section, we conduct an investigation regarding the multi-rate and relay impact under temporal spectrum sharing. During our study, we investigate the impact of the rate and relay under two wireless LAN parameters, which are IEEE 802.11b and 802.11g. The main difference between the two models are the selectable transmission rate.

For both model, firstly, we conduct a numerical analysis on various combinations of transmission rate and number of relay performance under various fraction of primary users idle time. Secondly, we further validate the numerical analysis through simulation using QualNet simulator [31].
Table 2.1: General parameters: IEEE 802.11b model

<table>
<thead>
<tr>
<th>PHY</th>
<th>Channel 2.4 GHz</th>
<th>Radio type 802.11b Radio</th>
<th>$T_x$ power 15 dBm</th>
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</thead>
<tbody>
<tr>
<td>$T_x$ Range 1 Mbps</td>
<td>450 m</td>
<td>$T_x$ Range 2 Mbps</td>
<td>339 m</td>
</tr>
<tr>
<td>$T_x$ Range 5.5 Mbps</td>
<td>328 m</td>
<td>$T_x$ Range 11 Mbps</td>
<td>270 m</td>
</tr>
<tr>
<td>Carrier Sense Range</td>
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<table>
<thead>
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<th>RTS 20 Bytes</th>
<th>CTS 14 Bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACK 14 Bytes</td>
<td>MAC header 34 Bytes</td>
<td>DISF 50 µsec</td>
<td>SIFS 10 µsec</td>
</tr>
<tr>
<td>σ 20 µsec</td>
<td>$CW_{min}$ 32</td>
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<th>Static</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>SU traffic</td>
<td>CBR</td>
<td></td>
</tr>
<tr>
<td>SU packet size</td>
<td>1500 Bytes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulation duration</td>
<td>300 seconds</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.5.1 IEEE 802.11b model

In our model, multi-hop SU network may experience collision under two following factors: interruption from PU transmission and intra-flow contention between SUs. During low SU traffic, PU interruption dominates the collision probability while intra-flow contention is negligible. Let $P_{pc}$ denotes the collision probability because of PU interruption, given the PU mean idle duration as $\mu$ and successful transmission duration as $T_s$, $P_{pc}$ can be written as

$$P_{pc} = 1 - \int_{T_s}^{\infty} \frac{1}{\mu} e^{-\frac{t}{\mu}} dt = 1 - e^{-\frac{T_s}{\mu}}$$

(2.1)
We also determine that PU interruption is dominant during DATA transmission. Following the 802.11 scheme, a total of 4 DATA transmissions are allowed before the packet is dropped. Let $i$-th transmission denotes the initial and 3 retransmission of DATA, where $0 \leq i \leq 3$. Let $T_{si}$ denotes the successful transmission duration at $i$-th transmission. We define $T_{si} = T_c + \overline{BO}_i$, with $\overline{BO}_i = \frac{2^i.CW_{\text{min}}-1}{2}$, and $T_c = T_{\text{PHY}} + T_{\text{RTS}} + T_{\text{CTS}} + T_{\text{ACK}} + T_{\text{DATA}} + \text{DIFS} + 3\text{SIFS}$. Where $T_{\text{PHY}}, T_{\text{RTS}}, T_{\text{CTS}}, T_{\text{ACK}},$ and $T_{\text{DATA}}$ denote the time needed to transmit PHY header, RTS, CTS, ACK, and DATA packets, respectively. $T_{\text{DATA}}$ is a function of SU source data rate $R$, while the others are transmitted at 1 Mbps. $\overline{BO}_i$ is the expected backoff value at $i$-th transmission and $CW_{\text{min}}$ is the minimum contention window. We can substitute $T_{si}$ to (2.1) where we can derive $P_{pci}$ for each $i$ transmission as a function of $\overline{BO}_i$, with that, the probability of successful SU transmission during $\mu$ can be written as

$$P_{\text{suc}} = (1 - P_{pci0}) + P_{pci0}(1 - P_{pci1}) +$$
$$P_{pci0}.P_{pci1}(1 - P_{pci2}) + P_{pci0}.P_{pci1}.P_{pci2}(1 - P_{pci3})$$  \hspace{1cm} (2.2)
Fig. 2.7: Analysis and simulation result comparison for various SU source traffic rate and $\mu$

hence, the end-to-end throughput $S_{e2e}$ for low SU source traffic rate $S_{src}$ can be approximated with

$$S_{e2e} = S_{src} \cdot (P_{succ})^h$$  \hspace{1cm} (2.3)
where $h$ denotes the number of hops.

Analysis for busy $S_{src}$ is more difficult because we need to consider the collision caused by the intra-flow contention. First, we strictly define that if the total time needed to transmit successfully at $i$-th transmission is longer than inter-arrival time then intra-flow contention will occur [32]. Take $S_{src} = 800$ Kbps for example with the following parameters: SU packets inter-arrival time of 15 msec, expected busy PU duration of 14 msec, and SU packet size of 1500 Bytes. In such case, one transmission failure makes the next transmission duration longer than the inter-arrival time and only the first successful transmission can avoid intra-flow contention. Therefore, we can rewrite and approximate (2.3) for 800 Kbps as $S_{e2e}(800\text{Kbps}) = S_{src}(1 - P_{pc0})^h$.

We validate the analysis through simulation. Unless stated otherwise, general simulation parameters are being listed in Table 2.1. Fig. 2.6 illustrates the SU nodes topology for each data rate where source (node 1) and destination (node 7) is separated by distance of 900 m. All simulation results are obtained within the 95% confidence interval. In Fig. 2.7, we plot the end-to-end throughput ($S_{e2e}$) versus the PU mean idle duration ($\mu$) for two different SU source traffic rate($S_{src}$) 200 and 800 Kbps, where they represent low and busy traffic, respectively. The result shows some noticeable gap between analytical and simulation results, especially at the 800 Kbps traffic measurement. The main reason of this inaccuracy is that the numerical analysis does not properly address the intra-flow contention problem. Nevertheless, both analytical and simulation results show similar trends and agree that high $R$ is essential under limited $\mu$ duration. In low $S_{src}$, high $R$ is preferable even though high $R$ results in more $h$, while during busy $S_{src}$, balance between $R$ and $h$ is preferable as shown in the Fig. 2.7(b) where 5.5 Mbps gives better performance than the other two data rates.

In summary, analytical and simulation results give the following conclusions: higher data rate is essential when SU exploits temporal spectrum opportunity. Higher data
rate gives more guarantee for successful packet transmission during limited idle duration. Hence, it negates the packet drop caused by the PU interruption. As the SU source traffic rate is getting busier, intra-flow contention shows its effect. The contention is worsen as multi-hop nodes increase in numbers. In this case, it is preferable to balance the data rate and the number of hops.

2.5.2 IEEE 802.11g model

The evaluations are aimed to show the following: The possible gain of exploiting the use of faster rate with relay and the rate-relay diversity nature surfacing from the use of multi-rate and different number of relays. As an example case, secondary user is assumed to have similar characteristic with 802.11g radio and opportunistically exploit

<table>
<thead>
<tr>
<th>Table 2.2: General parameters: IEEE 802.11g model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PHY</strong></td>
</tr>
<tr>
<td>$T_x$ power</td>
</tr>
<tr>
<td>$T_x$ Range 6,9 Mbps</td>
</tr>
<tr>
<td>$T_x$ Range 12 Mbps</td>
</tr>
<tr>
<td>$T_x$ Range 18 Mbps</td>
</tr>
<tr>
<td>$T_x$ Range 24 Mbps</td>
</tr>
<tr>
<td>$T_x$ Range 36 Mbps</td>
</tr>
<tr>
<td>$T_x$ Range 48,54 Mbps</td>
</tr>
<tr>
<td>PHY header</td>
</tr>
<tr>
<td><strong>MAC</strong></td>
</tr>
<tr>
<td>RTS 20 Bytes</td>
</tr>
<tr>
<td>ACK 14 Bytes</td>
</tr>
<tr>
<td>DISF 28 $\mu$sec</td>
</tr>
<tr>
<td>$\sigma$ 9 $\mu$sec</td>
</tr>
<tr>
<td>Network</td>
</tr>
<tr>
<td>IP header</td>
</tr>
<tr>
<td><strong>Application</strong></td>
</tr>
<tr>
<td>SU traffic</td>
</tr>
<tr>
<td>SU payload size</td>
</tr>
<tr>
<td><strong>Simulation duration</strong></td>
</tr>
</tbody>
</table>
the primary channel in 2.4 GHz band. The general parameters for both evaluations can be found in Table 2.2. Under the stationary and ergodic system, SINR threshold for each $R_i$ can be translated into transmission ($T_x$) range shown by the Table 2.2.

For ease of analysis, no dynamic rate scheme is used in this evaluation. Instead, the communicating SU pair will select a constant rate with a static routing determines the relay hops. We run the simulation evaluation with QualNet network simulator.

Let $T_{intv}$ denotes the interval for the CBR SU traffic, we can approximate the number of queued packets $D_q$ during the whole busy and idle period as $D_q = \left\lfloor \frac{i_p + b_p}{T_{intv}} \right\rfloor$. The total transmission duration $T_D$ for an SU payload with the size of $L_s$ can be written as

$$T_D = \tau + T_s = DIFS + BO + T_s$$ (2.4)

Where $T_s = 3SIFS + T_{ov} + T_{pl} + T_{mac} + T_{ip}$ and $BO = \frac{CW_{\min} - 1}{2}$. Let $T_{ov}$ be the duration for PHY header, RTS, CTS, and ACK transmission with base rate $R_1$. $T_{pl}, T_{mac}, T_{ip}$ denote the duration for $L_s$ payload, MAC header, and IP header, respectively. All are transmitted with rate $R_i$. Let $h_i$ denotes the number of hops transmission needed from source to destination node for rate $R_i$ and with (2.4), we can approximate the number of transmitted packets during idle period $D_i$ as $D_i = \left\lfloor \frac{i_p}{T_D h_i} \right\rfloor$. The SU end-to-end throughput $C_s$ can be approximated as:

$$C_s = \begin{cases} 
\frac{D_i L_s}{b_p + i_p}, & \text{for } D_i \leq D_q \\
\frac{D_q L_s}{b_p + i_p}, & \text{for } D_i > D_q 
\end{cases}$$ (2.5)

To show the rate-relay diversity, we evaluate the performance of the following $R_i$ data

---

$^2$In this study, we differentiate the number of hops transmission and the number of the relay nodes terms. The number of hops transmission is equal to the number of the relay nodes added by one.
rate: 9, 36, and 54 Mbps. We set an ideal SU network topology as illustrated in Fig. 2.8 to guarantee that all data rate have a relay to assist the transmission. For the remaining of this paper, we refer to this topology as fully connected topology. According to the topology, the $h_i$ value for 9, 36, and 54 Mbps rate is 1, 2, and 8, respectively. SU source traffic rate is set to 5 Mbps which gives the $T_{intra}$ value of 2.4 msec. When PU is inactive, all of the selected rate should be able to accommodate this traffic rate but this is not true for the otherwise. The performance for each rate will differ under various PU temporal opportunity.

Fig. 2.9 shows the performance of SU in term of secondary end-to-end throughput $C_s$. The horizontal axis represents the fraction of PU idle time $\alpha$ which can be exploited by SU. The mean PU busy duration $b_p$ is set to 20 msec. Numerical and simulation results support our observation where the faster rate with a relay can be beneficial. In this case, the benefit can be seen by the $C_s$ gain. We can observe that the 36 Mbps rate with the assistance of a relay outperforms direct one hop transmission of 9 Mbps with no relay. 54 Mbps, though, gives no performance gain due to the cost of its relay outweigh its faster rate gain. This result shows the rate-relay diversity nature under temporal spectrum sharing, where not all faster rate are beneficial. Therefore, it needs a scheme to address this rate and relay diversity nature. The scheme is essential to prevent secondary user from choosing a transmission rate, which require far too many relays.
Fig. 2.9: **Rate-Relay diversity**: $C_s$ comparison for 9, 36, and 54 Mbps physical data rate
In this chapter, we devise an access method for secondary user to better exploit the temporal white space of primary user spectrum. Our access method relies on two factors: transmission rate and relay transmission. We use the observation from the section 2.4 to propose a new approach for efficient utilization of the primary user spectrum temporal white space. We refer to this approach as adaptive rate and relay approach. The summary of our proposed approach is that under the temporal spectrum sharing scenario, it is more beneficial for secondary user to utilize faster physical data rate even though it will leads to the need of a relay (or relays).

In order to apply the proposed approach into a practical wireless ad hoc system, a distributed dynamic rate and relay adjustment scheme is needed. Referring to the proposed approach, at least, two issues are need to be addressed. The first one is on how we adjust the rate dynamically so that a faster rate beyond the optimal rate for one hop can be selected. The second one is on how to choose the relay nodes which can accommodate that faster rate. In this thesis, we devise a rate-relay adjustment scheme which address those two issues. The scheme is composed of rate adjustment, relay adjustment, and rate limit scheme. With the rate adjustment as the main component, we propose auto rate increase (ARI) and receiver-based auto rate increase (R-ARI) scheme. ARI and R-ARI are rate adjustment scheme that aim to exploit faster rate in a temporal spectrum sharing scenario. The further detail of this rate-relay adjustment schemes is being explained in the next section. We define all the necessary components
required to exploit the rate-relay diversity in temporal opportunistic spectrum access environment as one adaptive rate and relay approach.

3.1 Rate Adjustment

The first component is a rate adjustment scheme, which is also the main component of our adaptive rate and relay approach. During our study, we propose auto rate increase (ARI) and receiver-based auto rate increase (R-ARI) algorithms. Both algorithms aim to exploit the temporal opportunity of the primary users spectrum by dynamically adjust the transmission rate.

3.1.1 Auto Rate Increase (ARI)

ARI algorithm are built based on the Auto Rate Fallback (ARF) algorithm [28]. ARF is a popular dynamic rate algorithm for normal WLAN environment. ARF is known for its simplicity and it is widely implemented in the current WLAN devices. In this section, we briefly introduce ARF mechanism and explain the demerit of applying ARF into the temporal opportunistic spectrum access environment. In the end, we explain on how our proposed algorithm ARI is able to address the problem that ARF encounter under temporal opportunistic spectrum access environment.

Auto Rate Fallback (ARF)

The basic of the ARF algorithm is to decrement the data rate after a specific number of $f$ consecutive transmission failures and increment it after $s$ successful transmissions. Rate adjustment is decided at the source side by detecting whether it receives any response from the destination. In 802.11 DCF, if source does not receive CTS/ACK for longer than
a certain timeout then the transmission will be deemed as failure. The failure is caused by the high bit error rate (BER) in the signal received by the destination. By utilizing slower data rate, the BER can be decreased to the point that the destination is able to decode the transmission correctly. This is the main logic for ARF scheme to decrement the data rate whenever a transmission failure is detected.

Section 2.5 points out that by employing higher transmission rate under limited primary user idle duration, secondary user is able to exploit the temporal opportunity more efficiently. If the original ARF scheme were to work in the temporal opportunistic spectrum access model, ARF scheme treats all kind of failures by decrementing the data rate, this mechanism fails to efficiently exploit the temporal opportunity under opportunistic spectrum access model. ARI scheme addresses this issue and makes sure that the rate is adjusted correctly according to the environment.

**Auto Rate Increase (ARI)**

In order to solve the aforementioned problem, ARI scheme needs to distinguish between normal and PU failure. PU failure is defined as the transmission failure which is caused by the PU interruption, upon encountering such failure, SU tries to increment the data rate in the next retransmission in order to provide faster transmission during limited PU idle duration.

Next, normal and PU failure differentiation process is explained as follows. Considering the hardware constraint, SU can not performs simultaneous sensing and transmitting mechanism which makes it difficult to know whether the failure is caused by PU or normal failure. Let us refer to Fig. 3.1(a). From the source node point of view, the vulnerable periods of transmission failure are at `WAIT_FOR_CTS` and `WAIT_FOR_ACK` duration. `WAIT_FOR_CTS` and `WAIT_FOR_ACK` duration are the timers set by the source node.
after **RTS** and **DATA** transmission, respectively. When both of these timers expire and no **CTS** nor **ACK** is received then the transmission is marked as failure. Extensive simulation
from section 2.5 proves that PU interruption is dominant during \texttt{WAIT\_FOR\_ACK} duration. By combining MAC and PHY layer knowledge, SU marks the PU failure if the following are true: \texttt{WAIT\_FOR\_ACK} timer expires (\texttt{ACK} timeout), PHY state is on sensing, and for more reliability, PHY sensing detects PU signal. If one of these three conditions is not satisfied then SU treats the failure as normal failure. With these prerequisites, SU can distinguish normal and PU failure to adjust the data rate accordingly.

Summary of ARI scheme is as follows, let \( R = \{R_{\text{min}}, R_1, R_2, \ldots, R_{\text{max}}\} \) denotes the set of data rate defined by the PHY layer. \( R, R_{\text{min}}, R_{\text{max}} \) denote the selected data rate, lowest data rate, and highest data rate, respectively. \( R, R_{\text{min}}, R_{\text{max}} \in R \). For the initial transmission, SU sets \( R = R_{\text{min}} \) and as SU detects \( s \) numbers of successful transmissions and \( k \) numbers of PU failures, SU increments \( R \) until \( R = R_{\text{max}} \) and for \( f \) numbers of transmission failure \( R \) is decremented until \( R = R_{\text{min}} \). Fig. 3.1(b) describes the flowchart of ARI scheme.

3.1.2 Receiver based Auto Rate Increase (R-ARI)

We propose Receiver based Auto Rate Increase (R-ARI) as improvement to the ARI algorithm. The enhancement of R-ARI is based on the Receiver Based Auto Rate (RBAR) algorithm. In this section, we explain the unique feature of RBAR and how we implement that feature into R-ARI.

Receiver Based Auto Rate (RBAR)

Holland, et.al propose the Receiver Based Auto Rate (RBAR) algorithm with the following consideration. Rate adaptation is inseparable from the channel quality estimation, based on the channel quality, a wireless device select the most appropriate transmission rate to transmit a frame to the destination. In ARF, a sender node uses successful
and failure transmission as a mean to measure the channel quality then increment and decrement the transmission rate according to that result. Holland, et.al observe that if the channel estimation and rate selection are done by receiver, the result should be more reliable than the one done by the sender. RBAR algorithm is then proposed based on this observation.

RBAR algorithm uses the control frame RTS-CTS, commonly used in the IEEE 802.11 standard, to inform the result of the channel quality from the receiver to the sender. The sender node initiates the data transmission by sending RTS frame to the destination node. Upon receiving RTS frame, the destination estimates the channel quality and select the appropriate modulation scheme. The destination attaches the selected transmission rate result to the CTS frame and then send the CTS frame to the sender. Upon receiving CTS frame, the sender is able to infer the appropriate transmission rate

Fig. 3.2: RTS and CTS modification for RBAR
for data transmission. The RTS-CTS frames needs modification to accomodate RBAR algorithm. Fig. 3.2 shows the modification to the RTS and CTS frames, where they include additional transmission rate and data size information.

**Receiver based Auto Rate Increase (R-ARI)**

As an improvement to ARI scheme, R-ARI is proposed to exploit the rate-relay diversity in a temporal spectrum sharing scenario more efficiently. R-ARI aims to aggressively use a faster rate in order to better exploit the temporal opportunity of the primary system. The unique features of R-ARI are as follows. R-ARI possess two steps of rate adjustment algorithm and R-ARI takes account of the PU activity factor. The complete method of the R-ARI can be explained as follows.

Firstly, R-ARI is able to select the optimal rate for a given relay/destination based on its SINR. The SINR estimation can be done through the RTS-CTS exchange and
overall, this process is similar to the RBAR algorithm explained previously. Referring to Fig. 3.3, S has the choice to utilize three transmission rates $R_{S\rightarrow D}$, $R_{S\rightarrow C}$, and $R_{S\rightarrow A}$, ordered from the slowest to fastest. Each circle indicates the transmission range of each transmission rate, e.g., $d(R_{S\rightarrow D})$ indicates the transmission range for data rate $R_{S\rightarrow D}$. Assumes S, using R-ARI, sends RTS to D. D, upon receiving the RTS, will calculate the received SINR from S and compare it with the SINR threshold for each applicable $R_i$. Knowing that $\text{SINR}_{S\rightarrow D} \geq Th_{R_{S\rightarrow D}}$, D attaches data rate $R_{S\rightarrow D}$ information unto CTS and then replies to S. Upon receiving CTS, S will use data rate $R_{S\rightarrow D}$ to transmit data packet to D. If S next hop changes into C, similar process will repeat and the selected transmission rate is $R_{S\rightarrow C}$. The RTS and CTS frames include additional transmission rate and data size information as explained in the Fig. 3.2.

After the next hop optimal rate selection, the rate adjustment process in R-ARI is still ongoing. The rate will be further incremented or decremented following successive numbers of $S_c$ success or $F_n$ failure transmission, respectively. This second stage scheme is similar to ARF method but with one key difference. The key difference is that R-ARI differentiates the failure transmission into normal and PU-induced failure. Upon encountering successive numbers of $F_{pu}$ PU-induced failure, R-ARI increments the data rate instead of decrements it. Fig. 3.4 illustrates on how SU detects PU-induced failure. Whenever an SU source does not receive any ACK after timer $T_w$ expired and SU senses any PU transmission, it will mark the failure as PU-induced failure. We also note that for RTS-CTS scheme, similar condition may happen, where SU source does not receive any CTS after sending RTS. R-ARI, however, does not count RTS-CTS failure as a PU-induced failure. The reason is that RTS-CTS is sent with base rate, therefore, it does not represent the actual data rate transmission.

The second stage of the rate adjustment in R-ARI tries to increase the rate for the next transmission beyond its optimal next hop rate. Combined with the relay selection
scheme, this scheme will indirectly forces the SU source to search for a different next hop to accommodate the faster transmission rate. In summary, R-ARI dictates two stages of rate adjustment. The first stage is to optimize data transmission rate based on the RTS-CTS exchange. The second stage is to search for possible relay which can accommodates faster rate. R-ARI also considers the SU transmission failure due to the
collision with PU event. Such events trigger the rate increment algorithm in R-ARI. Fig. 3.5 illustrates a simple flowchart of the R-ARI rate adjustment scheme seen from the SU source point of view.

### 3.2 Relay Adjustment

The next component is a mean to dynamically select a relay node. The ARI and R-ARI algorithm with its two step rate adjustment method has the capability to select a rate faster than the optimal rate for one hop communication. In order to accommodate this faster rate, an SU source needs to find a relay as the new next hop and build a route to the destination from the new relay. This issue can be resolved efficiently by utilizing a wireless ad-hoc routing protocol. Specifically, an ad-hoc routing protocol that consider a multi-rate capability can be utilized [33, 34, 35]. Due to the practicality and heuristic manner of our proposed rate adjustment, most multi-rate ad-hoc routing protocols will be suitable for the relay selection scheme. We also note that both of the rate adjustment and relay selection scheme are independent, with no explicit cross-layer protocol scheme.

Out of several multi-rate aware ad-hoc routing protocol choices, we decide to employ multi-rate greedy perimeter stateless routing (GPSR) from the work [35] based on the fact that the GPSR uses geographical information. This choice, by any means, does not imply that our approach only work under multi-rate GPSR. Instead, we point out that our approach is flexible under any multi-rate routing algorithm. The selection of the multi-rate GPSR is mainly based on the utilization of the geographical information to forward the packets. The utilization of the location information is also coincide with the last component of our approach, the rate limit metric. We also note the simplicity and the effectiveness of the GPSR algorithm compared to the other routing algorithm described in work [33, 34]. [33, 34] propose a routing algorithm that consider the use
of frequent control message exchange and a cross layer coordination that makes them more complex to implement than the multi-rate GPSR. In the next section, we explain the basic algorithm of the GPSR, then, we continue the explanation with its extension, the multi-rate GPSR algorithm.

### 3.2.1 Greedy Perimeter Stateless Routing (GPSR)

In this work, we employ the Greedy Perimeter Stateless Routing (GPSR) routing protocol [36] as the relay selection scheme to show the effectiveness of the rate-relay adjustment scheme. The routing proposes the aggressive use of geography in order for router or wireless nodes to utilize nearly stateless routing. Each node only need to know its neighbors’ positions. The position of a packet’s destination and the positions of the candidate next hops are sufficient to make correct forwarding decisions, without any other topological information.

Based on the geographic information, the GPSR uses two methods for packet forwarding. The first is greedy forwarding, the GPSR uses the greedy forwarding to forward a data packet to the closest relay node from the destination or to the destination itself, provided that the relay node (or destination) is in the range of the current transmission rate. The second method is perimeter forwarding, this forwarding activate whenever and wherever the greedy forwarding fails to forward the data packet. In this section, we will explain the brief detail of each forwarding.

As an important note, in this work, we only concern ourself, mainly, with the greedy forwarding method of the GPSR. Our main purpose is to evaluate the impact of an access scheme, which use the rate and relay diversity, to the temporal opportunistic spectrum access. We do not consider or evaluate the topological node effect with void region. When the routing algorithm encounter a void region, it necessitates the use of
the GPSR’ perimeter forwarding method. Further in this thesis, we consider the node topology is connected at least under the assumptions that we use the base transmission rate. In all scenarios, we consider the destination is reachable by one hop distance, at the least with the base transmission rate. Under these scenarios, the greedy forwarding with multi-rate method is sufficient to forward the packet.

**Greedy Forwarding Method**

As previously explained under GPSR, packets are marked by their originator with their destinations’ locations. As a result, a forwarding node can make a locally optimal, greedy choice in choosing a packet’s next hop. Specifically, if a node knows its a radio neighbors’ positions, the locally optimal choice of next hop is the neighbor geographically closest to the packet’s destination. Forwarding in this regime follows successively closer geographic hops, until the destination is reached.

An example of greedy next hop choice appears in Fig. 3.6. Here, S receives a packet destined for D. S’s radio range is denoted by the dotted circle about S, and the arc with radius equal to the distance between Y and D is shown as the dashed arc about D. S forwards the packet to Y, as the distance between Y and D is less than that between D and any of S’ other neighbors. This greedy forwarding process repeats until the packet reaches D.

A simple beaconing algorithm provides all nodes with their neighbors’ geographical location information. Periodically, each node broadcast a beacon, containing its identifier (IP address) and positions. The position is represented as two four bytes floating point quantities, for x and y coordinate values. Each node, then, save the node id and location information into a table and use this table to forward packet according to the greedy forwarding mechanism.
Greedy forwarding’s greatest advantage is its reliance only on the knowledge of the forwarding node’s immediate neighbors. The routing decision only depends on the node location and the state of the node is almost negligible, hence, we can consider the routing algorithm is stateless.

**Perimeter Forwarding Method**

There are topologies in which the only route to a destination requires a packet move temporarily farther in geometric distance from the destination. These topologies render the advantage of the greedy forwarding. Fig. 3.7 shows the simple illustration of such topology. Here, S is closer to D than its neighbors W and Y. Optimally, we can select the route S-Y-Z-D and S-W-V-D to forward the packets, but the nature of greedy forwarding algorithm does not allow a route such as that. We need some other mechanism to forward a packet in these situations.

The GPSR uses the perimeter forwarding on the top of the greedy forwarding to avoid
this void region. Upon receiving a greedy-mode packet for forwarding, a node searches its neighbor table for the neighbor geographically closest to the packet’s destination. If this neighbor is closer to the destination, the node forward to that the packet to that neighbor. When no neighbor is closer, the node marks the packet into perimeter mode. GPSR forwards the perimeter-mode packets using a simple planar graph traversal. Because we do not actually use the perimeter forwarding in our research, we do not explain the detail of the perimeter forwarding algorithm in this thesis. Interested readers can refer to the reference in [36] for more detail of the perimeter forwarding.
3.2.2 Multi-rate GPSR

GPSR can be easily extended to consider the multi-rate transmission capability [35]. By utilizing multi-rate GPSR and the algorithm mentioned in the section 3.1, the next hop of an SU source may dynamically change over the time along with the rate adjustment. By possessing the knowledge of each physical data rate transmission range, GPSR is able to decide the next hop for each transmission rate.

After the periodical beacon exchange process, each node in GPSR maintains a set of neighboring list $H$ and their respective position information. Let $d(S, D)$ denotes the euclidean distance between SU source node $S$ to destination node $D$ and $d(R_i)$ as the transmission range for rate $R_i$. Denotes $n_j$ as the source node $S$ neighbor node with $0 < j \leq H, \forall n_j \in H$ and $H$ is the number of the neighbor nodes. Then, the euclidean distance between source $S$ to neighboring node $n_j$ and neighboring node $n_j$ to destination $D$ can be denoted as $d(S, n_j)$ and $d(n_j, D)$, respectively. The packet advancement for node $n_j$ can be calculated as $a_j = d(S, D) - d(n_j, D)$. With that, the relay selection in GPSR follows the pseudo code shown by Fig. 3.8.

Every SU source node with a packet to send will run the code to select next hop node. From the code, we can observe that the selected next hop node has two constraints. First, it is in the range of currently selected data rate $R_i$ (Line 6). Second, it has the largest packet advancement value $a_j$ (Line 7 and 8). If a destination node $D$ is in the range of transmission rate $R_i$ and $D \in H$, the code will always return $D$ as next hop then. Note that the notation source node $S$ in the above code refers to any node that has a packet to send. After the selected relay node receives the packet from the source node, the relay node needs to forward it to the destination node (or another relay node). The relay node, then, shall acts as source node $S$ and run the code to select the suitable next hop.
As explained before, we do not consider the use of the perimeter forwarding to avoid the void region. This is because in our study, we consider the topology is always connected, at the least, under the use of a base transmission rate. Using this assumption, we can avoid the void region with the use of the greedy forwarding and multi-rate adjustment method. Fig. 3.9 depicts the simple example on how the node avoid the void region by switching to the slower rate. The S node switches to use a slower transmission rate and wider transmission range to find the destination node. Normal greedy forwarding is sufficient to forward the packets under this scenario.

### 3.3 Rate Limit

The last component is a rate limit scheme. The rate limit scheme is a mean to limit the fastest selectable rate. The importance of this scheme relates to the nature of the rate-relay diversity. Consider the use of both ARI or R-ARI paired with the GPSR as the rate-relay adjustment algorithm. Under the rate increment algorithm of ARI and
R-ARI, it is possible that a rate which requires too many relay nodes is selected. Even though the selected rate is inarguably fast, the use of over too many relays may cause a significant performance degradation. Previously in the section 2.5 a numerical and simulation evaluation are conducted to show the rate-relay diversity, where the best rate to use is not always the fastest rate. The results also validate the importance of this rate limit scheme.

Let $S_{org}$ denotes the SU source origin node where the packet is first generated and let $d(S_{org}, D)$ denotes the euclidean distance between SU source origin and destination node. The expected number of hops transmission for rate $R_i$ from source origin to destination node can be written as:

$$\bar{h}_i = \left\lfloor \frac{d(S_{org}, D)}{d(R_i)} \right\rfloor$$
With that, the gain for rate $R_i$ can be calculated as:

$$G_i = \frac{R_i}{h_i + (h_i - 1)\beta}$$

where $\beta$ is a weight factor value. We define the limit for a selectable rate with rate $R_l$, where $R_l \in \mathbb{R}$ and $R_l \leq R_k$. $R_l$ is equal to the rate $R_i$ which has the highest $G_i$.

In summary, the rate increase defined by R-ARI is limited to the fastest rate $R_l$. By limiting the selectable rate to $R_l$, an SU can reduce the possibility of choosing a rate which requires too many relays. This rate limit scheme requires the location of source and destination (gateway) node to be known. The information can be obtained from a location devices such as Global Positioning System (GPS). The selection of the GPSR routing protocol as our relay adjustment mechanism is also helpful to distribute this geographical information to all surrounding node.
In this chapter, we evaluate the feasibility and the performance of the adaptive rate and relay approach. The performance evaluations are all done by simulation evaluation under QualNet simulator. We conduct two stages evaluation. The first one is the initial evaluation that aims to compare the performance of the ARI and ARF. The simulation parameter configuration follows IEEE 802.11b with limited selectable rates and secondary users node topology environment. The second stage is the general evaluation. In this stage, we evaluate a more general secondary users node topology and the simulation parameters follow IEEE 802.11g with more transmission rate selection.

4.1 ARI versus ARF

In our initial evaluation, we evaluate ARI algorithm by comparing it with the original ARF with QualNet simulator. In this initial evaluation, ARI is not yet paired with the multi-rate GPSR and the rate limit scheme. In other word, the adaptive rate and relay approach is not yet realized in this evaluation. Therefore, the feasibility of ARI algorithm is limited to a fix topology and few selectable transmission rates. The results mainly show the benefit of ARI in compare with traditional ARF algorithm under temporal spectrum sharing environment.
4.1.1 Simulation Configuration

General simulation parameters are similar to the parameters in the Table 2.1 with one exception, because the rate will be dynamically adjusted over times, we use AODV dynamic routing instead of static routing. Parameter \( f \) and \( s \) follow the ARF scheme which are 10 and 2, respectively. Set of data rate \( R = \{1, 2, 5.5, 11\} \) follows 802.11b specification where 1 and 11 Mbps correspond to \( R_{\text{min}} \) and \( R_{\text{max}} \), respectively.

Intuitively, the best \( k \) value is not larger than the number of maximum long retransmission limit (number of ACK timeout encountered before the packet is dropped) specified by 802.11 DCF which is 4. Although not shown in this thesis, simulation has been done to determine the best \( k \) value. The results show that, although slightly, \( k = 2 \) seems to give the best performance overall. Hence, for the rest of this section, we use \( k = 2 \) for ARI scheme.

4.1.2 Secondary Throughput

Fig. 4.1(a) shows the result of ARF and ARI performance comparison in 7 SU nodes topology as depicted in 11 Mbps nodes topology from Fig. 2.6. In this topology, all data rates are guaranteed to have the network connected. The result shows that ARI scheme outperforms ARF scheme in both low (200 Kbps) and busy (800 Kbps) SU source traffic during limited PU mean idle duration (\( \mu \)). ARI scheme performance increase is due to the more frequent selection of high data rate as opposed to ARF scheme where it always decrements the data rate for transmission failure. Fig. 4.1(b) shows the result for 4 nodes, please refer to 5.5 Mbps SU topology in Fig. 2.6 for the illustration. The 4 nodes topology restricts the use of 11 Mbps as data rate selection. This topology will further proves whether ARI scheme is able to distinguish between normal and PU failure, failure to do so causes ARI scheme to choose the highest data
rate available (11 Mbps) and leads to significant performance degradation. The result shows the otherwise, ARI scheme can adapts well with the change of topology and still outperforms ARF under OSA model. Both results from Fig. 4.1 show that ARI scheme performs better than the original ARF scheme under OSA model by choosing the highest possible data rate available depending on the various situation, e.g., busy SU source traffic rate or topology.

Table 4.1 summarizes ARI performance increases and decreases compared to the ARF, represented by the (+) and (-) signs, respectively. We can clearly see that, in general, ARI outperforms ARF scheme under relatively short PU mean idle duration. Slight performance decreases of ARI can be spotted in low SU source traffic and relatively long PU mean idle duration. The decreases are around 0-3% and insignificant compared to the increases in performance which are up to 56%.

<table>
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<tr>
<th>µ (msec)</th>
<th>200 Kbps, 7 nodes</th>
<th>800 Kbps, 7 nodes</th>
<th>200 Kbps, 4 nodes</th>
<th>800 Kbps, 4 nodes</th>
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<tr>
<td>5</td>
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<td>+28.45%</td>
<td>+54.09%</td>
<td>+16.67%</td>
</tr>
<tr>
<td>10</td>
<td>+22.24%</td>
<td>+34.6%</td>
<td>+56.51%</td>
<td>+39.62%</td>
</tr>
<tr>
<td>15</td>
<td>+7.21%</td>
<td>+29.08%</td>
<td>+17.15%</td>
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</tr>
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<td>20</td>
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<td>+19.67%</td>
<td>-0.81%</td>
<td>+23.03%</td>
</tr>
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<td>-3.45%</td>
<td>+13.67%</td>
</tr>
<tr>
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<td>+21.28%</td>
<td>-1.03%</td>
<td>+18.07%</td>
</tr>
<tr>
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</tr>
<tr>
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<tr>
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<tr>
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<td>+12.86%</td>
<td>-0.58%</td>
<td>+16.48%</td>
</tr>
</tbody>
</table>
4.2 Adaptive Rate and Relay Approach

In this section, the performance of the adaptive rate and relay approach is evaluated under QualNet simulator. In this evaluation, the rate adjustment algorithms are properly paired with the multi-rate GPSR and rate limit scheme, enabling us to evaluate the algorithm on more general topology and able to accommodate more selectable transmis-
sion rates. The results show that with a proper rate and relay adjustment scheme, a rate and relay diversity nature in temporal spectrum sharing can be efficiently exploited.

### 4.2.1 Simulation Configuration

The $b_p$ value is set to 20 msec, the value satisfies the requirement of hard protection scheme, where $T_s << b_p$. Under hard protection scheme, $T_{MAX}$ is set equal to the packet transmission duration for a payload size of maximum transmission unit (MTU) with basic rate $R_1$. Hence, as long as the payload size $\leq$ MTU and selected $R_i \geq R_1$, SU is free to transmit with $\eta = 1$.

We take two performance metrics into consideration. The first metric is the secondary user end to end throughput $C_s$. Another important metric is the percentage of primary and secondary user transmission collision $P_{coll}$. From the viewpoint of a primary user, $P_{coll}$ can be calculated with:

$$P_{coll} = \lim_{T \to \infty} \frac{\text{numb. of collisions in } [0,T]}{\text{numb. of busy periods in } [0,T]}$$

We evaluate the performance under both primary protection constrains. The following $\eta$ values are set: 1 (hard protection), 0.5, and 0.2. The parameter for $S_c, F_n, F_{pu}$, and $\beta$ is set to 10, 2, 2, and 0.75, respectively. Unless stated otherwise, the SU traffic source rate is set to 5 Mbps and the other general parameters still follow Table 2.2.

For a comparative means, four rate-relay adjustment schemes are compared. The key difference between each scheme is the rate adjustment scheme component. We evaluate the following rate adjustment schemes: ARF, RBAR, ARI, and R-ARI. ARF is a sender based rate algorithm that aims to increment the rate following consecutive $S_c$ successful transmission and decrement the data rate following $F_n$ failures. RBAR scheme is a receiver based rate algorithm which main logic is to select the optimal data rate based
on the received SINR obtained from the receiver side. ARI scheme is a sender based rate algorithm where it is almost similar to the R-ARI scheme with one different. As sender based rate algorithm, ARI lacks the next hop optimal rate selection feature in R-ARI. In this evaluation, RBAR represents a direct source and destination node communication utilizing the optimal transmission rate. The detail for ARF, RBAR, and ARI can be found in work [28], [29], and [37], respectively. GPSR routing protocol is used as the relay selection scheme. ARF, ARI, and R-ARI corporate the rate limit scheme due to their rate increment algorithm. On the other hand, RBAR does not need to use the rate limit scheme because it will not increases the rate aggressively. Table 4.2 sums the differences between each rate-relay adjustment scheme. From here on, we refer to each scheme by their rate adjustment scheme name, respectively.

### 4.2.2 Temporal Impact

In this section, the temporal opportunity impact is evaluated. We vary the fraction of time $\alpha$ which SU can exploit. The SU topology is set to fully connected topology as in Fig 2.8 where a one flow traffic from S to D is defined. Due to the use of the rate limit scheme, the rate increment is limited to a certain value and prevents the possibility of an SU to choose a rate that needs too many relay nodes. Based on the SU node topology and configuration, the $R_t$ value selected in this evaluation is 36 Mbps. The results are averaged values from 10 seeds evaluation.
Fig. 4.2: Temporal impact: $C_s$ and $P_{coll}$ versus $\alpha$ for $\eta=1$

Fig. 4.2(a) to 4.2(b) depict the performance comparison under interference threshold of 1. Meaning that the system does not restrict the collision between primary and secondary transmission at all. This can be seen by examining Fig 4.2(b) the collision between primary and secondary transmission is quite high, around 80 %.
Based on the results, we can see that the proposed scheme, R-ARI, outperforms the other schemes in most cases. The gain comes from both $C_s$ and $P_{coll}$ metrics. $P_{coll}$ gain comes in the form of lower $P_{coll}$ value, where it means the primary system is less intruded. Both gains are more visible when we compare the performance of R-ARI with RBAR (one hop communication). In most cases, R-ARI returns higher $C_s$ and lower $P_{coll}$ than RBAR. Interestingly, RBAR gives the lowest performance out of all schemes. The reason for this result is because RBAR, although transmits using optimal data rate, does not try to exploit the assistance of relay. The other schemes, on the other hands, try to increase the data rate sporadically beyond the optimal rate of a direct transmission, implicitly, forcing the use of relay nodes. The result also supports the benefit of utilizing a faster rate even though the assistance of a relay (or relays) is needed.

Next, we focus on the performance of ARF, ARI, and R-ARI. Notice the performance of ARI and R-ARI outperforms ARF in both $C_s$ gain and lower $P_{coll}$ value. Recall the unique feature of ARI scheme, where it differentiates the normal and PU-induced failure. R-ARI and ARI exploit this feature to gain better performance than ARF. For $\eta = 1$, the probability of PU-SU collision is relatively high, ARI and R-ARI scheme exploit this event to gain faster rate. In contrast with ARI and R-ARI, ARF decreases the rate during PU collision. This feature is the main reason on the performance gain for ARI and R-ARI scheme over ARF. In summary, the PU-SU collision can act as an advantage for ARI and R-ARI scheme where under normal circumstances, this event is usually regarded as a meaningless disadvantage. Overall, R-ARI gives the best performance. R-ARI has an advantage over ARI by the ability to select the optimal data rate for a given next hop instantaneously and by determining the transmission rate at the receiver side.

Next, we evaluate the secondary throughput ($C_s$) and $P_{coll}$ under interference threshold $\eta=0.5$ as shown as Fig 4.3. The results show the degradation of $C_s$ and reduction of the
collision percentage $P_{coll}$. Interference threshold $\eta=0.5$ shows the interference threshold mechanism limit the interference between primary and secondary user at most 50%. As for the comparison of each rate adjustment scheme, the trend still shows that R-ARI outperforms other scheme in both $C_s$ and $P_{coll}$. As the $\eta$ getting stricter, the performance
difference between R-ARI, ARI, and ARF is getting smaller. Stricter $\eta$ means lesser PU-induced failure events to trigger the secondary user node to aggressively switch to higher transmission rate. In this case, the performance of R-ARI and ARI are almost similar to the ARF scheme. Again, RBAR gives the lowest performance among other scheme by not utilizing faster rate beyond the one hop transmission and the assistance of a relay node.

Lastly, we evaluate the secondary throughput ($C_s$) and $P_{coll}$ under interference threshold $\eta=0.2$. Fig 4.4 shows strict $\eta$ value resulting in low primary and secondary collision percentage $P_{coll}$ and further degrade the secondary throughput $C_s$. Stricter $\eta$ makes the secondary user to transmit more conservative in order to keep the interference between primary and secondary transmission low. The performance gain of ARI and R-ARI almost diminish to none for $\eta = 0.2$. PU collisions are rarely happen, which the performance of R-ARI, ARI, and ARF is indistinguishable. The rate increase event for all three schemes is limited to the $S_c$ numbers of successful transmission.

Overall, the results are able to show us the following observations. Compared to the one hop communication, taking advantage of faster transmission rate with the assistance of a relay node can results in the performance gain for primary and secondary system. The benefits can be found in term of lower $P_{coll}$ and higher $C_s$ value. The benefits are also shown to exist for various temporal and primary protection ($\eta$) constraints.

### 4.2.3 Node Density Impact

The next evaluation is aimed at more general SU network topology. This time, a random SU topology is evaluated. 50 SU nodes are uniformly distributed in $d$ m x $d$ m area as shown in Fig. 4.5. In this section, the node density impact is evaluated. In order to emphasize the node density impact, we vary the terrain side length $d$. Source and
destination node are randomly selected and the distance between them is kept around 400 m. To avoid the edge effect, the random source node is chosen in the middle area of the topology (marked with the red rectangle). The results are averaged from ten evaluations where the source-destination pair is randomly changed each time.
Fig. 4.5: Random Topology: SU nodes are uniformly distributed in $d \times d$ area.

Fig. 4.6 to 4.8 show the results for various terrain side length $d$ under $\alpha = 50\%$. The smaller the $d$ value is, the denser a node topology becomes. The results show that for dense SU node topology ($d = 500 - 800$ m), RBAR is outperformed by the other three schemes in most cases. The performance gain can be seen in both $C_s$ and $P_{coll}$. The similar reasoning stated in section 4.2.2 contributes to these performance gain. Again, we can observe that R-ARI has the best performance of all. Dense SU node topology guarantee an SU to find a suitable relay to support faster transmission rate.

As the SU node density getting sparser, the other three schemes result in significant performance degradation. The performance of ARF, ARI, and R-ARI are degraded to below RBAR. The reason for this degradation is that those schemes can not find suitable relay node. Recall the rate-relay diversity nature, not all faster rate can outperform one hop optimal transmission rate. The gain of utilizing a faster rate must outweigh the
overhead of using a relay node. In sparse topology \((d = 900 \text{ m})\), the chance for finding a suitable relay is considerably slimmer. Instead, it is possible that the selected relay is a relay in which the overhead for using the relay is higher than the gain of using a faster rate. RBAR performance is rather stable for every \(d\) value. This is because RBAR relies on the one hop communication and does not utilize any relay. The drawback is RBAR can not exploit the relay assistance. Whereas in a dense topology, the use of faster rate and relay is proved to provide a performance gain. Based from this evaluation, we can infer a caveat where the proposed rate-relay adjustment scheme is best used in a dense SU network topology where the probability of finding a suitable relay is considerably high.

4.2.4 Mobility Impact

In this section, we evaluate the performance of the proposed scheme under mobility scenario. We use the same random topology shown in Fig. 4.5 with \(d\) value of 500 m. Under this scenario, all SU nodes are mobile, except for the source and destination nodes. In other words, the possible relay nodes are all mobile. The SU nodes movement follows random way-point mobility model. The speed values are randomly selected in range of \([0,40]\) m/s. The results can be observed in Fig. 4.9 to 4.11.

The results show that using the proposed rate-relay adjustment scheme still yields in the performance gain of \(C_s\) compared with the one hop direct transmission, even under mobile scenario. The toll of nodes mobility is shown in term of increased \(P_{\text{coll}}\) ratio compared with the one hop transmission. While the \(P_{\text{coll}}\) is higher, we can say the benefit of utilizing relay nodes is still quite strong compared to the one hop transmission due to the performance gain in \(C_s\). The increase in \(P_{\text{coll}}\) is still tolerable within the interference threshold of the primary system \((\eta)\).
Fig. 4.6: **Node density impact**: $C_s$ and $P_{coll}$ versus $d$ m of terrain side length for $\eta=1$
Density impact: $\alpha = 50\%$, $\eta = 0.5$

Scheme I (ARF)
Scheme II (RBAR)
Scheme III (ARI)
Scheme IV (R-ARI)

Fig. 4.7: **Node density impact:** $C_s$ and $P_{\text{coll}}$ versus $d$ m of terrain side length for $\eta=0.5$
Node density impact: $C_s$ and $P_{coll}$ versus $d$ m of terrain side length for $\eta=0.2$
If we try to compare the result in this section with the one in static scenario, such as shown in Fig. 4.2 to 4.4 under mobile scenario, we can see the gain of $C_s$ is slightly degraded and the $P_{coll}$ value is obviously higher. The reason of this performance degradation is mainly come from the relay node mobility. Due to the mobility, the chance of retransmission and packets drop are considerably higher where they result in lower $C_s$ and higher $P_{coll}$. 
Fig. 4.9: **Mobility impact:** $C_s$ and $P_{coll}$ versus $\alpha$ under node mobility speed range of [0,40] m/s for $\eta=1$
Fig. 4.10: Mobility impact: \( C_s \) and \( P_{\text{coll}} \) versus \( \alpha \) under node mobility speed range of \([0,40]\) m/s for \( \eta = 0.5 \)
Fig. 4.11: **Mobility impact:** $C_s$ and $P_{coll}$ versus $\alpha$ under node mobility speed range of $[0,40]$ m/s for $\eta=0.2$
In this thesis, we study the temporal aspect of an opportunistic spectrum access scheme. We propose an argument that the use of faster rate with the assistance of a relay (or relays) can be beneficial for the secondary users to exploit the temporal white space of the primary user more efficiently. To support our proposed argument, we investigate the impact of utilizing multiple transmission rates and relays under fast varying time domain opportunistic spectrum access. From the investigation, we find that the utilization of faster rate along with the relay assistance is actually lead to better temporal spectrum sharing performance compared with the direct transmission with the one hop optimal transmission rate. One caveat is that, for a system with diverse transmission rate selection, such as IEEE 802.11g or IEEE 802.11n system, not all the fast transmission rates results in the performance gain in the temporal spectrum sharing environment. The balance between a fast transmission rate and the number of the relay transmission need to be considered to improve the temporal spectrum sharing performance. As result, we observe that the proper exploitation of the rate and relay diversity nature has the potential to improve the efficiency of temporal spectrum sharing between the primary and secondary users.

In light of the multi-rate and multi-relay impact to the temporal opportunistic spectrum access investigation, we devise an approach to put the exploitation of this rate and relay diversity into practical wireless networks system. We propose an adaptive rate and relay approach for the temporal opportunistic spectrum access environment. The adaptive
rate and relay approach are composed of three components. As the main component, we propose Auto Rate Increase (ARI) and Receiver based Auto Rate Increase (R-ARI) as the rate adjustment algorithms. Secondly, we utilize the multi-rate GPSR routing algorithm as the mean to dynamically select the relay assistance. Lastly, we propose a rate limit formula as a metric to balance the transmission rate and the number of relays. We propose the novel rate adaptation algorithms ARI and R-ARI to address the weakness of the conventional WLAN rate adaptation algorithm. The current dynamic rate algorithms are designed for normal wireless networks environment without ever considering the existence of primary and secondary users. Our proposed rate adaptation algorithms consider, in addition to the channel condition, the effect of primary and secondary transmission collision and adjust the transmission rate so that the secondary users are able to efficiently exploit the temporal opportunity.

We evaluate the performance of our proposed approach through QualNet network simulator. The initial evaluation is aimed to compare the Auto Rate Increase (ARI) and Auto Rate Fallback (ARF) rate adaptation algorithm. The simulation parameters in this initial evaluation are modeled after the IEEE 802.11b model. The selectable rates are limited to 1, 2, 5.5, and 11 Mbps. We evaluate the algorithms under the connected network topology. The connected topology means for every transmission rate, a node is guaranteed to find the relay node to assist its transmission. The results show that the performance of ARI clearly outperforms ARF by wide margin. At most, we can expect around 56% improvement of the secondary throughput. Although the results show the superiority of Auto Rate Increase, the evaluation environment cannot be considered as practical wireless networks with few selectable transmission rate and fully connected topology. As mentioned previously, we propose the adaptive rate and relay approach to exploit the rate and relay diversity nature and implement it into practical wireless. The next performance evaluation is to evaluate the feasibility of this adaptive rate and
relay approach for various conditions and topologies. The simulation parameters are modeled from IEEE 802.11g with various selectable transmission rates from 6 to 54 Mbps. The performance metrics are the secondary users’ throughput and the primary-secondary transmission collision probability. We evaluate the performance for various primary protection thresholds, fractions of idle time, node density, and mobility factors. We also evaluate the performance under the connected and random node topology. The results show the proposed ARI and R-ARI algorithms outperform the conventional rate adaptation algorithms although the advantage of the proposed approaches diminishes under strict primary protection threshold.

In conclusion, the performance evaluations through QualNet network simulator validate the feasibility of our adaptive rate and relay approach and show that our proposed rate adjustment algorithms are able to outperform the traditional dynamic rate adjustment algorithm and the optimal one hop transmission scheme under the temporal spectrum sharing environment. The performance gains are shown in the improvement of the secondary users’ throughput and lower primary and secondary transmission collisions probability. However, we also note that the adaptive rate and relay approach comes with some caveats. The first caveat is that the adaptive rate and relay approach is suitable for the temporal spectrum sharing environment with a hard protection requirement, where the primary system is able to tolerate the secondary system interruption. The reason is that the proposed rate adaptation ARI and R-ARI utilize the primary and secondary collision events to improve the performance of the secondary system. The second caveat is that the adaptive rate and relay approach is best used under high node density topology. This is because the nature of the approach that prefer to use relay assistance to transmit with faster transmission rate. The performance evaluation results show that under low or sparse node density topology, the performance of the ARI and R-ARI degrades below the optimal one hop transmission scheme R-BAR. The
future research direction in this work may involve studying the impact of the rate-relay diversity for the spatial and spectral opportunities.
References


[24] D. Shiung, C.-S. Tsai, and J.-J. Huang, “Joint power and rate adaptation in a
cognitive radio network: The rate-distance approach,” in *Proceedings IEEE VTC
Fall 2011*, pp. 1 –5, sept. 2011.


[26] E. Jung and X. Liu, “Opportunistic spectrum access in heterogeneous user envi-

[27] K. W. Sung, S.-L. Kim, and J. Zander, “Temporal spectrum sharing based on
primary user activity prediction,” *IEEE Transactions on Wireless Communications*,
vol. 9, pp. 3848 –3855, december 2010.

for the unlicensed band,” *Bell Labs Technical Journal*, vol. 2, no. 3, pp. 118–133,
1997.


of unlicensed and licensed spectrum users,” in *Dynamic Spectrum Access Networks

[31] “Qualnet simulator version 4.5.”

2007.
[33] Y. Seok, J. Park, and Y. Choi, “Multi-rate aware routing protocol for mobile ad

[34] J.-L. Hsu and I. Rubin, “Cross-layer multi-rate routing strategies in wireless multi-
GLOBECOM ’07. IEEE*, pp. 609 –613, nov. 2007. 39

adaption for manet throughput improvement,” *IEEE Transaction on Vehicular


access in multi-hop ad hoc networks,” in *Proceedings IEEE PIMRC 2011*, pp. 561
–565, sept. 2011. 53

[38] S. Geirhofer, L. Tong, and B. Sadler, “Cognitive radios for dynamic spectrum access
- dynamic spectrum access in the time domain: Modeling and exploiting white

random node locations,” *Mobile Computing, IEEE Transactions on*, vol. 9, pp. 540
–552, april 2010.

[40] A. T. Hoang, D. Wong, and Y.-C. Liang, “Design and analysis for an 802.11-based
