A Spectrum-Aware Routing in DOFDM-based Cognitive Radio Ad-Hoc Networks

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Abstract—With the rapid requirement and development of the green ICT (Information and Communication Technology) technology, the demand for dynamically radio spectrum resources has significantly attentions. The low utilization of licensed spectrum leads to the scarcity of the spectrum resource. The emerging cognitive radio (CR) systems become increasingly important in the wireless green communication. In cognitive radio ad-hoc networks, unlicensed users (called secondary users, SUs) communicates with other CR users through an ad-hoc connection on licensed spectrum bands, but spectrum bands may be unexpectedly preempted by licensed users (called primary users, PUs) at any time. The design of routing protocol for cognitive radio ad-hoc network considers problems of the dynamic spectrum sensing, management, sharing, and mobility caused by reappearance of PUs. A cognitive ad hoc network is called as DOFDM-based cognitive radio ad-hoc network if the cognitive ad hoc network is adopted the discontinuous orthogonal frequency division multiplexing (DOFDM) technology. In this paper, we developed a spectrum-aware routing protocol for DOFDM-based cognitive radio ad-hoc networks by using the concept of the minimum expected total transmission time. With the expected total transmission time of all possible paths, a route with the smallest expected total transmission time is constructed. Finally, mathematical analysis and simulation result illustrate the proposed routing protocol can significantly reduce the total transmission time and improve the throughput.

Index Terms—*Cognitive radio; routing; DOFDM; cognitive ad-hoc networks; green communication.*

1 INTRODUCTION

With the rapid development of the green ICT technology, the demand for radio spectrum resources has significantly increased. A survey of the spectrum utilization made by the Federal Communications Commission (FCC) had indicated that the actual licensed spectrum was largely under-utilized [1]. The fixed spectrum assignment policy is usually adopted in the existing wireless networks to lead to the problem of the inefficient spectrum utilization. To solve the problem of the low spectrum utilization, it is necessary to design the efficient protocols with the ability of the dynamic sensing spectrum bands and accurately accessing the unused spectrum bands.

The cognitive radio (CR) [2] is the key enabling technology to efficiently utilize the unused spectrum bands for the next generation communication networks [3]. The cognitive access to the TV white spaces [4] which can intelligently detect the licence-exempt spectrum bands be occupied or not. When a spectrum band is not occupied, the unoccupied spectrum band is leased by the cognitive system. In cognitive radio networks, licensed users (called primary users, PUs) use traditional communication systems with static spectrum allocations, unlicensed users (called secondary users, SUs) equipped with cognitive devices and dynamically accesses spectrums. SUs must dynamically detect the presence and reappearance of PUs. SUs can utilize the unoccupied spectrum hole (SH), such that the spectrum hole unoccupied by PUs can utilized by SUs [5] to improve the spectrum utilization.

Discontinuous orthogonal frequency division multiplexing (DOFDM), known as non-contiguous orthogonal frequency division multiplexing (NC-OFDM), is recently and widely used in existing cognitive radio networks [6][7], due to its flexibility in dynamically allocating radio resources and its low interference between adjacent subcarriers [8]. A single radio can simultaneously access several discontinuous spectrum fragments, and aggregates these discontinuous spectrum fragments into one channel [6]. A DOFDM-based cognitive network can achieve the high data rates by collecting and combining a large number of narrow bandwidth subcarriers. In a cognitive radio ad-hoc network, any PU still has the highest priority to access the spectrum, and each SU has the ability to dynamically sense the spectrum holes to communicate with other SUs to form the cognitive ad-hoc network. If the leased channels by a SU are unexpectedly preempted by a PU, the SU must detect the presence of PU on the leased channels, and intelligently switch to another unoccupied channel. The available channels for SUs may be dynamically changed during the multi-hop data transmission. Consequently, the design difficulty of routing in cognitive radio ad-hoc networks is how to provide a efficient routing protocol under the dynamic environment, which is more difficult than designing the routing protocols in the traditional networks [9][10]. A cognitive radio ad-hoc network is called as the DOFDM-based cognitive radio ad-hoc network if the cognitive radio ad-hoc network is adopted the Discontinuous orthogonal frequency division multiplexing (DOFDM) technology [6][7].

In this paper, we developed a spectrum-aware routing protocol for DOFDM-based cognitive radio ad-hoc networks by using the concept of the minimum expected total transmission time. With the expected total transmission time of all possible paths, a route with the smallest expected total transmission time is constructed. Finally, mathematical analysis and simulation result illustrate the proposed routing protocol can significantly reduce the total transmission time and improve the throughput.

The rest of this paper is organized as follows. In section 2, related work and motivation are described. Section 3 describes the system model, problem formulation, and basic idea of our approach. Section 4 describes the proposed spectrum-aware routing protocol in DOFDM-based cognitive radio ad-hoc networks. Performance analysis and simulation results are presented in section 5 and 6. Section 7 concludes this paper.

2 RELATED WORK

This section firstly describes related works in subsection 2.1 and discusses the motivation of research in subsection 2.2.

2.1 Related Works

The emerging cognitive radio (CR) systems become increasingly important in the wireless communication, there are many results on the OFDM/DOFDM-based cognitive radio networks [11-18]. Most existing results [11-15] are developed in the infrastructure-based wireless networks. Although some studies have been addressed the routing protocols in cognitive radio networks [16-18], but less of works considered the routing problem in DOFDM-based cognitive radio ad-hoc network.

First, some related non-routing studies on the OFDM/DOFDM-based cognitive radio networks [11-15] are described. Ghosh *et al.* [11] proposed a priority-based spectrum allocation techniques for the DOFDM transmission by assigning one or more non-contiguous blocks of spectrum bands. Then, Chen *et al.* [12] proposed a cross-layer handover protocol to improve handover latency by intelligently selecting the spectrum bands with minimum expected transmission time. Xin *et al.* [13] proposed a control-free dynamic spectrum access protocol in cognitive radio networks. Huang *et al.* [14] investigates a cognitive MAC protocol with asynchronous-assembly line mode for improving spectrum utilization and network capacity. Gao *et al.* [15] recently developed a flexible carrier allocation strategy for multi-carrier cell architecture.

Regarding the routing protocols for cognitive radio networks, some results are discussed [16-18]. In general, the behavior of PU affects the transmission efficiency of cognitive-based routing protocol. Therefore, the design of cognitive-based routing protocols must take the behavior of PU into accounts.Jiang *et al.* [16] initially proposed a spectrum-aware, on-demand, cluster-based routing protocol by establishing a spectrum-cluster. Ju *et al.* [17] then proposed a spectrum-aware routing protocol for cognitive ad-hoc networks. This protocol divides into two functions; there are the intelligent multi-interface selection function (MISF) and the intelligent multi-path selection function (MPSF). In addition, Chiaraviglio *et al.* [18] recently proposed a cooperative green routing with energy-efficient consideration in order to reduce overall power consumption.

More recently, Shih *et al.* [19] introduced a concept of route robustness and the channel heterogeneity property to propose a jointly route selection and spectrum allocation algorithm for multi-hop cognitive radio networks. This paper considers the probability of reappearance of PUs during the route discovery to determine the best path with the maximum transmission rate satisfied the pre-specified robustness constraint P_m.

2.2 Motivation

Existing important routing protocol in cognitive radio ad-hoc networks [19] determines a robust route with the maximum robustness and transmission rate. Less work considers the route discovery based on the minimum expected total transmission time. The kernel estimation of the minimum expected total transmission time is to recursively calculate the probability of the reappearance of PUs for all possible occupied spectrum bands. With the consideration of the minimum expected total transmission time, a highly stable route can be constructed. In a cognitive ad-hoc radio network, each transmission link uses leased spectrum bands, which are used by a pair of SUs. The leased spectrum bands may be moved to other available spectrum bands if these leased spectrum bands must give back to PU if the PU reappears and reclaims these leased spectrum bands. This condition is called as the spectrum mobility. Therefore, the probability of spectrum mobility significantly affects the determination of a stable route. A stable route is called if the data transmission along a constructed route without the occurrence of the spectrum mobility. A low probability of spectrum mobility is, a highly stable route will be. It is important to design a stable route in a cognitive ad-hoc radio network with the low probability of spectrum mobility.

The objective of this work is to develop a stable routing protocol in DOFDM-based cognitive radio ad-hoc networks to achieve the purpose of the low transmission time. The low transmission time is achieved by determining a route with the high transmission rate and low probability of spectrum mobility. The probability of spectrum mobility is estimated by the arrival rate of PUs. In general, the higher arrival rate of PUs is, the low probability of un-occupied channels is. Thus, the low probability of un-occupied channels results in the performance degradation of a data transmission along a constructed route. The design of the routing protocols must consider the probability of un-occupied channels. Thus, this paper aims to design the routing protocol under the consideration of probabilities of spectrum mobility and un-occupied channels to calculate the expected total transmission time. To achieve the objective, a stable route with the minimum expected total transmission time is constructed from a source to a destination.

3 PRELIMINARIES

This section introduces the system model and the problem formulation, and then describes basic idea in subsections 3.1, 3.2 and 3.3.

3.1 System Model

The system model of the DOFDM-based cognitive radio ad-hoc network is defined as follows. In the DOFDM-based cognitive radio ad-hoc network, two types of users, primary users (PUs) and secondary users (SUs), are considered. A SU performs the spectrum sensing operation to detect the available spectrum bands for the data transmission. A SU obtains a list of the available spectrum bands and the SU selects an appropriate channel for the data transmission. The spectrum bands are borrowed temporarily by the SU. If the leased spectrum band was reclaimed by a PU, then the SU must perform the spectrum mobility by releasing the leased spectrum bands and switching to the other available spectrum bands [20].

Fig. 1(a) illustrates that spatial distribution of spectrum usage. The spectrum bands are composed of spectrum fragments, while the width of each pair of subcarriers is Δf. After carrying out the spectrum sensing operation, each SU knows which band is in used or not. Spectrum bands can be occupied by PUs or SUs, as shown in Fig. 1(a). The light gray zone indicates the spectrum bands occupied by a SU. For instance, frequency bands range from $f_c + f_{SU}^1$ to $f_c + f_{SU}^1 + W_{SU}^1$, where $f_c + f_{SU}^1$ is the initial frequency used by SU_1, and W_{SU}^1 is the bandwidth used by SU_1. The dark gray zones indicates the spectrum bands occupied by Pus. For instance, $f_c + f_{PU}^1$ to $f_c + f_{PU}^1 + W_{PU}^1$ and $f_c + f_{PU}^2$ to $f_c + f_{PU}^2 + W_{PU}^2$ are occupied by PU_1 and PU_2, respectively. In the DOFDM-based cognitive radio ad-hoc network, many discontinuous frequency bands are un-occupied. By the DOFDM technique, a SU can make use of some discontinuous frequency bands to communicate with a neighboring SU in a DOFDM-based cognitive radio ad-hoc network. A spectrum hole is composed by some adjacent tiles, where a tile is a time-frequency slot [21] or called as resource block (particularly used in the LTE networks) [22]. Fig. 1(b) provides an example of three spectrum holes SH_1, SH_2 and SH_3. The capacity of all spectrum holes is not necessary to be equal and the probability of the reappearance of PUs of each spectrum hole is not necessary to be equal.

Fig. 2 illustrates the system model. The DOFDM-based cognitive radio network consists of the primary network and cognitive radio network. In the primary network, each PU has the high priority of spectrum band usage over all SUs, and PU activity can be only controlled by the base-station. The SUs cannot interfere with the PUs [23]. In the cognitive radio network, (also called the secondary network), each SU is not allowed to directly operate at the licensed band, the SU is equipped with a Software Defined Radio (SDR) with the ability of sensing the license spectrum. The SU communicates with neighboring SU through an ad-hoc communication on the licensed spectrum bands. For example as shown in Fig. 2, the PU_i can communicate with eNB_i by some spectrum holes, there are some unused spectrum holes which can be utilized by SU_i. For instance, source node SU_1 want to send data to destination SU_6, each SU_i performs the spectrum sensing operation to identify the available spectrum bands and find a route from SU_1 to SU_6.

In DOFDM-based technology, carrier aggregation is a useful technology to aggregate multiple component carriers into an overall wider bandwidth [24]. A single radio can simultaneously access several spectrum holes by aggregating them into one channel. Fig. 3 gives an example of spectrum aggregation using the DOFDM technology. It is observed that two non-continuous spectrum holes separated by a spectrum band occupied by a PU or a SU. These two non-continuous spectrum holes can be aggregated to be one large channel. When a SU need to perform the spectrum mobility, the large aggregated channel can be used [6]. Due to the hardware limitation of transceiver, the "span" of aggregated spectrum bands into one channel is limited [24]. Let S be the maximum span. That is to say, all of the aggregated spectrum bands must be within S. For instance as shown in . Fig. 3, let $S = 4$.

3.2 Problem Formulation

The protocol mainly calculates the expected total transmission time for a route searching. The expected transmission time is obtained from the data size and the transmission rate, which is expressed as $T_E = \frac{D_t}{R}$, where T_E is the expected transmission time, D_t is the data size and R is the expected transmission rate. However, in cognitive radio networks, the available spectrum bands is unstable and changeable over time. One spectrum band is in use now but may be unavailable at the next time. This is because that the spectrum mobility problem is occurred by a PU. It obviously increases the total transmission time by adding the extra time cost of spectrum mobility. The channel idle rate must be further considered of the estimation of the transmission time. Let P be the channel idle probability, the expected transmission time can be re-expressed as $T'_E = \frac{D_t}{P \times R}$. The number of available spectrum is highly influenced by the PU behavior. If a data transmission between SUs be interrupted by PU, the SU need to perform spectrum mobility to other channel to resume the transmission. Furthermore, if not available channel can be used, the SU must perform the route discovery again, which result in the performance degradation. The routing protocol must provide an accurate estimation of the route determination by considering the capacity of all channels and probability of the spectrum mobility.

3.3 Basic Idea

The basic idea of this work is to periodically observe the occupied frequency of spectrum bands caused by PUs to estimate the probability of channels occupied by the PUs. Then the expected total transmission time is calculated for each link based on the probability of spectrum mobility and capacity of all the available channels. A route is discovery based on the minimum expected total transmission time. Chen *et al.* calculated the expected transmission time in [12] for the handover problem. Based on the concept of the expected transmission time, this paper further calculates the expected total transmission time to determine a stable route. To make a clear difference of expected transmission time and expected total transmission time, some definitions are given below.

Definition 1. Expected transmission time. *Let* $T_E(SH_{n(i,j)})$ *denote as the expected transmission time of for link between* SU_i *and* SU_j*, where* $SH_{n(i,j)}$ *is the n-th spectrum hole,* SH_n*, of link between* SU_i *and* SU_j*.* $T_E(SH_{n(i,j)})$ *is calculated by the spectrum occupied ratio, the signal strength fluctuation, and the available bandwidth of the spectrum hole* SH_n*.*

Definition 2. Expected total transmission time. *Let* $T_{TE}(UCH_{(i,j)})$ *denote as the expected total transmission time for link between* SU_i *and* SU_j*. Basically, a* $T_{TE}(UCH_{(i,j)})$ *is adding the probability of the spectrum mobility into* $T_E(SH_{n(i,j)})$*. That is, the* $T_{TE}(UCH_{(i,j)})$ *is calculated by the spectrum occupied ratio, the signal strength fluctuation, the available bandwidth of the spectrum hole* SH_n*, and the probability of the spectrum mobility.*

The difference of $T_E(SH_{n(i,j)})$ [12] and $T_{TE}(UCH_{(i,j)})$ is explained as shown in Fig. 4. Fig. 4(a) initially provides a simple example of $T_E(SH_{n(i,j)})$ [12]. $T_E(SH_1)$, $T_E(SH_2)$ and $T_E(SH_3)$ are the expected transmission times by considering the spectrum occupied ratio, the signal strength fluctuation, and the available bandwidth of SH_1, SH_2 and SH_3, respectively. Fig. 4(b) shows how to obtain the $T_{TE}(UCH_{(i,j)})$. The estimation of $T_{TE}(UCH_{(i,j)})$ further adds the factor of the probability of the spectrum mobility into $T_E(SH_{n(i,j)})$. For instance, $T_{TE}(UCH_1)$ and $T_{TE}(UCH_2)$ are obtained by $T_E(UCH_1)$ and $T_E(UCH_2)$ by adding the probability of the spectrum mobility. In general, if a link used by a SU has a large value of $T_{TE}(UCH_{(i,j)})$, it implies that the SU has the high probability of reappearance of PU, so the high value the probability of the spectrum mobility will be. This effect of a data transmission along a constructed route is the extra time cost caused by the spectrum mobility. The smaller value of $T_{TE}(UCH_{(i,j)})$ implies the higher successful data transmission. Therefore, our idea is to select the route with the minimum value of $T_{TE}(UCH_{(i,j)})$.

Shih *et al.* [19] recently proposed an interested route selection algorithm to discover a robust route. In Shih *et al.* [19], P_{rr} is denoted the robustness of a route, and P_m is denoted as a robustness level. The higher the value of P_{rr} implies a more robust route is. A route is selected if the route is satisfied with the highest P_m. This robust approach only considers the individual channel. Let $L(SU_x,SU_y)$ denote as a link $SU_x \rightarrow SU_y$. Fig. 5(a) illustrates an example of constructing a route between SU_1 and SU_6. The route result of Shih *et al.* [19] is $SU_1 \rightarrow SU_3 \rightarrow SU_5 \rightarrow SU_6$, because that P_m= 0.8 of $L(SU_3,SU_5)$ is higher than P_m= 0.75 of $L(SU_2,SU_4)$. Our route result is $SU_1 \rightarrow SU_2 \rightarrow SU_4 \rightarrow SU_6$ as illustrated in Fig. 5(b), because although P_m= 0.75 of $L(SU_2,SU_4)$ is smaller than P_m= 0.8 of $L(SU_3,SU_5)$, but our approach further considers the factor of the spectrum mobility to determine the stable route, we observe that $L(SU_2,SU_4)$ has the secondary spectrum band with P_m = 0.7. If it needs to perform the spectrum mobility, $L(SU_2,SU_4)$ can easily switch to the secondary spectrum band with P_m = 0.7. Under the same situation, the result of Shih *et al.* [17], the selected route $SU_1 \rightarrow SU_3 \rightarrow SU_5 \rightarrow SU_6$, must re-performs the route discovery if it needs to perform the spectrum mobility at $L(SU_3,SU_5)$. This is because that no any suitable spectrum band possibly exists in

$L(SU_3,SU_5)$. Therefore, efforts will be made in this paper to develop a new routing protocol in DOFDM-based cognitive radio ad-hoc network to discover a route from source SU_{source} to destination $SU_{destination}$ with the consideration of the minimum value of $T_{TE}(UCH_{(i,j)})$ of all spectrum bands of all paths. All notations used in this paper are summarized in Table I.

4 SPECTRUM-AWARE ROUTING WITH MINIMUM EXPECTED TOTAL TRANSMISSION TIME

We initially give an overview of the spectrum aware routing protocol in DOFDM-based cognitive radio ad-hoc networks. The proposed scheme mainly evaluates the minimum expected total transmission time for all links along all possible paths from source SU_{source} to destination $SU_{destination}$. To achieve the purpose, three phase; $environment\ \ observation$ phase, $computation\ \ and\ \ analysis$ phase, and $route\ \ discovery$ phase; are performed of the protocol as follows.

- $Environment\ \ observation$ phase: Source SU_{source} aims to search for a path to the $SU_{destination}$. Each SU obtains the spectrum usage information (the available spectrum holes) through spectrum sensing operation. Each SU exchanges the spectrum usage information with the neighboring SUs to have the available aggregated channels.

- $Computation\ \ and\ \ analysis$ phase: Based on the information of the available aggregated channels, the SU selects the channels with the high bandwidth and the low spectrum occupation rate by PUs. This phase computes the expected transmission time and further calculates the expected total transmission time for all possible paths from source SU_{source} to destination $SU_{destination}$.

- $Route\ discovery$ phase: The $SU_{destination}$ determines a final route from the source SU_{source} with the minimum expected total transmission time.

4.1 Environment Observation Phase

The $environment\ \ observation$ phase aims to acquire a list of available aggregated channels between each pair of two neighboring SUs. Let SU_i denote the i-th SU and SU_j denote a neighboring SU of SU_i. Let $CH_{n(i)}$ denote the n-th channel of SU_i and $CH_{n(i,j)}$ denote the n-th common available channel between SU_i and SU_j. Let $Tile_{m(i)}$ denote the m-th tile of SU_i. The procedure is given as follows.

1. Each SU_i periodically senses all spectrum bands to obtain a list of $Tile_{m(i)}$, where SU_i is located in the transmission coverage of the serving base stations. It is observed that one SU_i may locate at the intersection area of two or more base stations.

2. Each SU_i obtains the information of the occupied frequency λ_m, where λ_m is the accumulated number that m-th tile be occupied within a period of time. The value of λ_m increases if m-th tile is occupied during the time period. If the value of λ_m is large, it implies that m-th tile is

frequently occupied by a PU. It also implies that any SU has the lower opportunity to use m-th tile. Otherwise, if the value of λ_m is small, SU has the high opportunity to use m-th tile without the interruption caused by PUs. The information of the occupied frequency λ_m is observed and recorded of all $Tile_{m(i)}$ within a period of time.

3. To obtain the available tiles, each SU_i exchanges the above information of spectrum bands in step 2 with the neighboring SU_j. Then SU_i and SU_j exchange $Tile_{m(i)}$ and $Tile_{m(j)}$ to each other to calculate the $Tile_{m(i,j)}$, where $Tile_{m(i,j)} = Tile_{m(i)} \cap Tile_{m(j)}$.

4. Due to the OFDMA property [24], some available continuous or dis-continuous tiles within maximum span S tiles can be aggregated into a single channel. The aggregation operation is performed to aggregate all common available $Tile_{m(i,j)}$ from step 3 into some available channels, where each channel contains l common available tiles, and $l \leq S$.

An example of the environment observation phase is given in Fig. 6 to illustrate the frequency distribution of unoccupied spectrum holes; SU_1 uses spectrum bands of eNB_1, SU_2 uses spectrum bands of eNB_1 or eNB_2, SU_3 uses spectrum bands of eNB_1 or eNB_3, SU_4 uses spectrum bands of eNB_1 or eNB_2, SU_5 uses spectrum bands of eNB_2 or eNB_3 and SU_6 uses spectrum bands of eNB_2. Fig. 7 illustrates the result of $Tile_{m(i,j)} = Tile_{m(i)} \cap Tile_{m(j)}$. After executing step 3, $L(SU_1,SU_2)$ uses spectrum bands of $eNB_1 = \{eNB_1\} \cap \{eNB_1, eNB_2\}$. Similarly, $L(SU_2,SU_4)$ utilizes spectrum bands of $\{eNB_1, eNB_2\} = \{eNB_1, eNB_2\} \cap \{eNB_1, eNB_2\}$. Therefore, $L(SU_1,SU_3)$ uses spectrum bands of eNB_1, $L(SU_3,SU_5)$ uses spectrum bands of eNB_3, and $L(SU_5,SU_6)$ uses spectrum bands of eNB_2. If the maximum span S is equal to 4, two channels of $L(SU_1,SU_2)$ are aggregated as shown in Fig. 8, where each channel has 3 tiles. All other links are performed the similar operations to acquire the available channels of all links.

4.2 Computation and Analysis Phase

The computation and analysis phase calculates the expected total transmission time, which is used for our route determination. The procedure is given as follows.

1. To evaluate the expected total transmission time $T_{TE}(UCH_{(i,j)})$ of $L(SU_i,SU_j)$, signal-to-noise ratio is calculated by $SNR_{dB} = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)$, P_{signal} is calculated by two-ray ground propagation model [26], $P_{signal} = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4} = \frac{kP_t}{d^4}$, where P_{signal} and P_{noise} are the power of the signal and the noise, P_t is the transmitting power, d is the distance between transmitter and receiver. In addition, G_t and G_r are antenna gains, h_t and h_r are the antenna heights of the transmitter and receiver, and k is a constant [26].

2. The SU_i and SU_j calculate the maximum available transmission rate based on the SNR_{dB} for all channels $CH_{n(i,j)}$ to estimate the required transmission time, t_{req}, for the data size D_t. Let $R_{n(i,j)}$ denote as the transmission rate of $CH_{n(i,j)}$. It is observed that $CH_{n(i,j)}$ contains $m_{n(i,j)}$ tiles, the bandwidth of $CH_{n(i,j)}$ is $m_{n(i,j)} \times Tile$. Following the Shannon equation [27], the

transmission rate is

$$R_{n(i,j)} = m_{n(i,j)} \times Tile \times \log_2(1 + SNR_{dB}), \tag{1}$$

and the required transmission time t_{req} is $t_{req} = \frac{D_t}{m_{n(i,j)} \times tile \times \log_2(1+SNR_{dB})}$.

3. To predict the availability of channel $CH_{n(i,j)}$, the unoccupied probability of $CH_{n(i,j)}$ is calculated. Let $P_u(CH_{n(i,j)}, t_{req})$ denote as the probability of channel $CH_{n(i,j)}$ unoccupied by PUs within the time period of t_{req}. To predict the idle $CH_{n(i,j)}$ within a service required time t_{req}, we use the Poisson distribution [28], the equation of Poisson distribution is $P(K,T) = \frac{(\lambda T)^k}{K!} e^{-(\lambda T)}$, where K is the number of events, T is the period time, and λ is the proportion of average event occurrence. Let $P(K,T)$ denote as the probability of K events occurred within the time period T. The next step is to analyze the probability of $CH_{n(i,j)}$ not be used within the service require time t_{req}, let K set as zero, and T set as t_{req}. Consequently, if $CH_{n(i,j)}$ contains $m_{n(i,j)}$ tile, the probability of channel $CH_{n(i,j)}$ unoccupied by PUs within the time period of t_{req} is

$$P_u(m_{n(i,j)}, t_{req}) = \prod_{x=1}^{m_{n(i,j)}} P_x(0, t_{req}) = e^{-\sum_{x=1}^{m_{n(i,j)}} \lambda_x t_{req}}. \tag{2}$$

4. Let $T_E(CH_{n(i,j)})$ denote the expected transmission time of all aggregated channels $CH_{n(i,j)}$ of $L(SU_i, SU_j)$, According to (1) and (2), the $T_E(CH_{n(i,j)})$ is computed as

$$T_E(CH_{n(i,j)}) = \frac{D_t}{P_u(m_{n(i,j)}, t_{req}) \times R_{n(i,j)}} + (1 - P_u(m_{n(i,j)}, t_{req})) \times T_{L2H}, \tag{3}$$

where T_{L2H} denotes the layer-2 switch time and $1 - P_u(m_{n(i,j)}, t_{req})$ is the probability of $CH_{n(i,j)}$ occupied within time period t_{req}. The usage of $CH_{n(i,j)}$ of SU_i and SU_j may be interrupted again by the appearance of other PUs, SU_i and SU_j may perform the spectrum mobility again. This condition is represented as $(1 - P_u(m_{n(i,j)}, t_{req})) \times T_{L2H}$.

5. After obtaining $T_E(CH_{n(i,j)})$ for all aggregated channels $CH_{n(i,j)}$ of $L(SU_i, SU_j)$, the expected total transmission time $T_{TE}(UCH_{(i,j)})$ of $L(SU_i, SU_j)$ is calculated. All aggregated channels $CH_{n(i,j)}$ are initially according to the value of $T_E(CH_{n(i,j)})$, sorted result is $UCH_{1(i,j)}$, $UCH_{2(i,j)}$, …, $UCH_{n-1(i,j)}$, and $UCH_{n(i,j)}$, such that $UCH_{1(i,j)}$ has the minimum expected transmission time and the $UCH_{n(i,j)}$ has the maximum expected transmission time. The total expected transmission time is consequently calculated as follows.

$$T_{TE}(UCH_{n(i,j)}) = \frac{D_t}{P_u(m_{n(i,j)}, t_{req}) \times R_{n(i,j)}} + (1 - P_u(m_{n(i,j)}, t_{req})) \times T_{RR}, \quad \text{and}$$

$$\begin{aligned} T_{TE}(UCH_{n-1(i,j)}) = {} & P_u(m_{n-1(i,j)}, t_{req}) \times \frac{D_t}{R_{n-1(i,j)}} \\ & + (1 - P_u(m_{n-1(i,j)}, t_{req})) \times (T_{L2H} + T_{TE}(UCH_{n(i,j)})), \end{aligned} \tag{4}$$

where the expected total transmission time $T_{TE}(UCH_{n(i,j)})$ is a recursive function from $T_{TE}(UCH_{1(i,j)})$ to $T_{TE}(UCH_{n(i,j)})$, where $T_{TE}(UCH_{1(i,j)})$ is the expected total transmission time of the first used channel and $T_{TE}(UCH_{n(i,j)})$ is the expected total transmission time of the last used channel, and T_{RR} is the extra time cost of the re-routing. The recursive function $T_{TE}(UCH_{n(i,j)})$ is used to calculate the total expected transmission time.

Fig. 9(a) shows an example of calculating the expected transmission time, CH_1 of $L(SU_2,SU_4)$ has three tiles, and their occupied frequencies are $\lambda_1 = 16$, $\lambda_2 = 10$ and $\lambda_3 = 12$. The transmission rate of CH_1 is $3 \times 180(K\text{Hz}) \times \log_2(1+3.01) \cong 1080\text{Kbps}$. The required transmission time is 10(Mb)/1080(Kbps) $\cong$ 14.22(s). The unoccupied probability of this channel is $\mathrm{e}^{-(\frac{16}{1000}*9.481)} \times \mathrm{e}^{-(\frac{10}{1000}*9.481)} \times \mathrm{e}^{-(\frac{12}{1000}*9.481)} \cong 0.6975$. $T_E(CH_{1(2,4)})$ is $\frac{10(\text{Mb})}{0.6975 \times 1080(\text{Kbps})} + (1-0.6975) \times 0.05(\text{s}) \cong 13.61(\text{s})$. Similarly, the expected transmission time of CH_2, $T_E(SH_{2(2,4)})$ is $\frac{10(\text{Mb})}{0.796 \times 1080(\text{Kbps})} + (1-0.796) \times 0.05(\text{s}) \cong 11.92$. The sorted result is CH_2, CH_1, CH_3, CH_4 because that $11.92(s) < 13.61(s) < 15.841(s) < 19.1488(s)$. Fig. 9(b) shows an example of the expected total transmission time of L (SU_2 , SU_4), $T_{TE}(CH_{(2,4)})$ is $0.7964 \times \frac{10(\text{Mb})}{1080(\text{Kbps})} + (1-0.7964) \times 0.05 + 10.702 = 9.7402(\text{s})$, where the extra time cost of the re-routing is $0.5(s)$. The expected total transmission time of $L(SU_2,SU_4)$ is the minimum expected total transmission time because that the sorted result is done. Therefore, the usage order of the channels are CH_2, CH_1, CH_3, and CH_4. That is, the route initially uses CH_2, CH_2 moves to CH_1 if the spectrum mobility is needed. Then, CH_1 moves to CH_3 if the spectrum mobility is needed again. Finally, CH_3 moves to CH_4 if the spectrum mobility is happened again.

4.3 Route Discovery Phase

This phase finally searches for a route with the minimum expected total transmission time. The basic idea is similar with existing on-demand routing protocols [29][30] by taking the minimum expected total transmission time into consideration. The procedure is given below.

1. If the SU_{source} has data to send, but does not have the route information to the destination. It broadcasts the Route Request (RREQ) packet included the spectrum information and accumulated its expected total transmission time, which the accumulated total transmission time is set to zero.

2. Assume an intermediate node SU_j has received an RREQ packet, it has to obtain the list of common available channels and calculates the expected total transmission time and cumulative the expected total transmission time of link between SU_{source} and SU_j, and then rebroadcasts RREQ packet.

3. Once the RREQ packet arrives at the $SU_{destination}$ by the flooding. The $SU_{destination}$ calculates the expected total transmission time and finds a path with the minimum accumulated total transmission time, then it generates a Route Reply (RREP) message along this path, which is sent in a unicast. Finally, the SU_{source} and the $SU_{destination}$ can start data transmission with each other.

Fig. 10 shows an example of expected total transmission time calculation results and routing process, the route $SU_1 \rightarrow SU_2 \rightarrow SU_4 \rightarrow SU_6$ is finally selected, since the route with the minimum accumulated total transmission time.

5 PERFORMANCE ANALYSIS

In this section, we propose an analytic model to analyze the total transmission time for our proposed scheme. The Markov chain model is adopted which is represented as a directed graph as shown in Fig. 11. Considered a pair of secondary users SU_i and SU_j, the SU_i and SU_j use i-th common available channel $\widehat{CH}_i$ from a given sequence of n common available channels $(\widehat{CH}_1, \widehat{CH}_2 \cdots, \widehat{CH}_i, \cdots \widehat{CH}_n)$ in the common base station, the sequence is according to the value of expected total transmission time to sort the sequential of channels. As shown in Fig. 11. The initial state of the Markov chain model is $\widehat{CH}_1$, which denotes the SU_i and the SU_j initially transmits the data through the initial channel $\widehat{CH}_1$. There are n common available channels on link ij. Thus, there are n channel states. If the $\widehat{CH}_1$ is reclaimed by a PU, that will transform the initial state to the next state $\widehat{CH}_2$. When all of the channels are reclaimed by PUs that wills transform the current state to the re-route state. The state transition information is given below.

- $\widehat{CH}_i$ to $\widehat{CH}_{i+1}$: if the $\widehat{CH}_i$ is reclaimed by a PU that will transform the state from $\widehat{CH}_i$ to $\widehat{CH}_{i+1}$, the state transition probability is $1 - P_{\widehat{CH}_i}$, where $P_{\widehat{CH}_i}$ is probability of channel $\widehat{CH}_i$ unoccupied by PUs.

- $\widehat{CH}_{n-1}$ to $\widehat{CH}_n$: if $\widehat{CH}_{n-1}$ is reclaimed by a PU that will transform the state from $\widehat{CH}_{n-1}$ to $\widehat{CH}_n$, this will mean the SUs only have one channel can be used.

- $\widehat{CH}_n$ to re-route: if the last channel $\widehat{CH}_n$ is reclaimed by a PU that will transform the state from $\widehat{CH}_n$ to re-route, this will mean the forced termination of the SUs connection and reroute again.

Let t_{unit} denote a past period of time units and λ_m denote the accumulated number that m-th tile be occupied within a period of time. Let $t_{req} = \frac{d_t}{R_{n(i,j)}}$ denote the required transmission time between SU_i and SU_j without considering λ_m. Before calculation the expected total transmission time, we need to estimate the probability of each channel which is not reclaimed by PUs. With the Poisson distribution, the probability $\widehat{CH}_i$ which is not reclaimed by PUs in required transmission time t_{req} is denoted as $P_{\widehat{CH}_i}$.

Lemma 1 *Considered a channel $\widehat{CH}_i$, composition of m tiles, the probability of $\widehat{CH}_i$ which is not reclaimed by PUs is*

$$P_{\widehat{CH}_i} = \prod_{j=1}^{m} e^{-(\frac{\lambda_j}{t_{unit}} \times t_{req})} \tag{5}$$

Proof. Assumed the required transmission time is $t_{req} = \frac{d_t}{R_{n(i,j)}}$, where d_t is the data size and $R_{n(i,j)}$ is the transmission rate of $\widehat{CH}_i$ between SU_i and SU_j which is calculated by the Shannon theorem $C = B \times \log_2(1 + SNR_{dB})$, where C is the achievable channel capacity, B is the bandwidth, SNR is signal to noise ratio. According to the Poisson distribution $f(k;\lambda) = \frac{\lambda^k \times e^{-\lambda}}{k!}$, where k is the number of occurrences of an event, λ is positive real number, equal to the expected number of occurrences during the given interval. The probability of $\widehat{CH}_i$ which is not reclaimed by PUs can be represented by $\prod_{j=1}^{m} e^{-(\frac{\lambda_j}{t_{unit}} \times t_{req})}$. ∎

Lemma 2 *If there are* n *common available channels on link* ij $(\widehat{CH}_1, \widehat{CH}_2 \cdots \widehat{CH}_n), n > 1$, *the transmission time* T_{ET} *is*

$$T_{ET} = \sum_{x=1}^{n} \{\frac{D_t}{R_x} \times P_{\widehat{CH}_x} \times \prod_{y=1}^{x} [1 - P_{\widehat{CH}_{y-1}}]\} + \prod_{z=1}^{n-1} [1 - P_{\widehat{CH}_z}] \times \frac{D_t}{P_{\widehat{CH}_n} \times R_n} \tag{6}$$

Proof. Assumed the probability of $\widehat{CH}_i$ which is not reclaimed by PUs is $P_{\widehat{CH}_i}$, the probability of $\widehat{CH}_i$ reclaimed by PU in period of t_{req} is $1 - P_{\widehat{CH}_i}$. If the $\widehat{CH}_i$ reclaimed by PU, the secondary users can switch to $\widehat{CH}_{i+1}$, the probability of the SUs switch channel from $\widehat{CH}_i$ to $\widehat{CH}_{i+1}$ and $\widehat{CH}_{i+1}$ not reclaimed by PUs in period of t_{req} is $(1 - P_{\widehat{CH}_i}) \times P_{\widehat{CH}_{i+1}}$. Thus, the transmission time T_{ET} is calculated as following:

$$\begin{aligned}
T_{ET} = {} & P_{\widehat{CH}_1} \times \frac{D_t}{R_1} \\
& + (1 - P_{\widehat{CH}_1}) \times P_{\widehat{CH}_2} \times \frac{D_t}{R_2} \\
& \vdots \\
& + (1 - P_{\widehat{CH}_1}) \times \cdots \times (1 - P_{\widehat{CH}_{n-2}}) \times P_{\widehat{CH}_{n-1}} \times \frac{D_t}{R_{n-1}}, \\
& + (1 - P_{\widehat{CH}_1}) \times \cdots \times (1 - P_{\widehat{CH}_{n-1}}) \times \frac{D_t}{P_{\widehat{CH}_n} \times R_n}
\end{aligned}$$

where the R_n is the transmission rate of $\widehat{CH}_n$ and the $1 - P_{\widehat{CH}_0} = 1$. ∎

Theorem 1 *If there are* m *link in the path, the expected total transmission time* $\widehat{T_{TE}}$ *is*

$$\widehat{T_{TE}} = \sum_{x=1}^{m} T_{ET(x)} + T_{EH(x)} + T_{ERR(x)} \tag{6}$$

Proof. Based on Lemma 1 and Lemma2, the expected time cost of spectrum mobility is denote as T_{EH}, the T_{EH} is calculated as $\sum_{x=1}^{n-1} \prod_{y=1}^{x} [1 - P_{\widehat{CH}_y}] \times T_{L2H}$ and the expected time cost of re-route is denote as T_{ERR}, the T_{ERR} is calculated as $T_{ERR} = \prod_{z=1}^{n} [1 - P_{\widehat{CH}_z}] \times T_{RR}$, where T_{RR} is the re-route time. Thus, the expected total transmission time for a specific link is calculated as $T_{ET} + T_{EH} + T_{ERR}$. The expected total transmission time for a specific path can be represented by $\widehat{T_{TE}} = \sum_{x=1}^{m} T_{ET(x)} + T_{EH(x)} + T_{ERR(x)}$, where m denote as the number of link in the specific path. ■

6 SIMULATION RESULTS

Our paper presents a routing protocol with minimum expected transmission time in DOFDM-based cognitive radio networks. To evaluate the spectrum-aware routing protocol (denoted as proposed scheme) and Shih *et al.*'s robustness protocol (denoted as robustness scheme) [19], these two protocols are implemented using the Network Simulator-2 (NS2) [31] and ns-2 Cognitive Radio Network model [32]. In addition, the mathematical analysis result of our protocol is denoted as proposed scheme-A in the simulation. The network size is set to 1000×1000, where the number of SUs is assumed to be 20. The number of PUs is 15. In the simulation environment, the locations of SUs nad PUs are randomly deployed. The spectrum mobility delay time and spectrum sensing period are 0.01 and 0.04 seconds [12], respectively. The simulation time is 100 seconds in the simulation. The system parameters are given in Table II.

Before describing the performance metrics, the proportion of tile (PT) and the probability of PU occupancy (PPO) are defined. The PT is the proportion of the available channels to the total channels. The high value PT implies that SUs have many available tiles, where PT ranges from 0.1 to 0.9 in the simulation. The performance metrics to be observed are:

- The *total transmission time* (TTT) is the time interval of the data transmission between a pair of SU_{source} and $SU_{destination}$. The TTT is estimated from the first packet transmitted from SU_{source} until the final packet received by $SU_{destination}$.
- The *throughput* (TP) is total number of data packets which can be transmitted and received between a pair of SU node.
- The *end-to-end delay* (EED) is the average delay time of every packets of a data which can be transmitted from a SU node to other SU node.
- The *number of spectrum mobility* (NSM) is the total number of spectrum mobility during a data

transmission between a pair of a SU_{source} and a $SU_{destination}$.

- The $computation\ \ time$ (CT) is the computing time of the route discovery.

It is worth mentioning that an efficient routing protocol in a DOFDM–based cognitive radio network is achieved with a high throughput, low end-to-end delay, low total transmission time, low number of spectrum mobility.

6.1 Total Transmission Time (TTT)

The simulation results of the TTT under the different proportions of tiles and probability of PU occupancy are illustrated in Fig. 12. Fig. 12(a) provides the observed TTT under various proportions of tiles (ranging from 0 to 0.9). In general, the TTT of the proposed scheme was high as the proportion of tiles was low. The TTT of our proposed scheme is lower than that of the robustness scheme [19]. The difference of the TTT of the protocols is relatively small if the proportion of tiles is larger than 0.7. This is because that the channel capacity is relatively same if the proportion of tiles is high. It is observed that the curves of our proposed scheme and proposed scheme-A are very close in Fig. 12(a) and Fig. 12(b). Fig. 12(b) illustrates that the curve of the TTT of our scheme is lower than robustness scheme under various probability of PU occupancy (ranging from 0 to 0.9). The simulation shows that the TTT of the proposed scheme was low as the probability of PU occupancy was low.

6.2 Throughput (TP)

The throughput (TP) is obtained by calculating the average of all estimated throughput from SU_{source} to $SU_{destination}$. Fig. 13(a) and Fig. 13(b) provide the simulation results of throughput. It was observed that when the value of TP is high, then the routing performance increases. Fig. 13(a) shows the performance of the TP vs. the proportion of tiles (ranging from 0.1 to 0.9). In general, the TP increases as the proportion of tiles increases. This is because the high proportions of tiles lead to the high capacity of channels with the increased TP. Fig. 13(a) illustrates TP of our proposed scheme is better than that of the robustness scheme [19], because our proposed scheme takes the capacity of all channels into consideration. When the proportion of tiles is less than 0.5, the throughput significant increased. But if the proportion of tiles is large than 0.5, the throughput slightly increased. Fig. 13(b) shows the performance of the TP vs. the probability of PU occupancy (ranging from 0 to 0.9). The high probability of PU occupancy increases means the high probability of PU appearance. When the channel is always occupied by the PUs, the low throughput result will be.

6.3 End-to-End Delay (EED)

Fig. 14(a) and Fig. 14(b) provide the simulation results of EED of the proposed scheme and robustness scheme. The higherhe value of EED is, the lower the performance of CR-based ad-hoc routing protocol will be. Fig. 14(a) shows the performance of the EED vs. proportion of tiles (ranging from 0.1 to 0.9). We observed that the proportion of tiles is low, the less available tiles will be. The transmission rate of channels drops, the higher end-to-end delay result is obtained. Fig. 14(b) shows the performance of the EED vs. the probability of PU occupancy (ranging from 0 to 0.9). The EED increases as the probability of PU occupancy increases. This is because the high probability of PU occupancy increases leads to the high number of spectrum mobility to result in the performance degradation. When the probability of PU occupancy is less than 0.5, the EED slightly increases, because there are still many available channels can be selected. The EED of our scheme is less than that of robustness scheme because our scheme has the more accurately estimation of the total transmission time.

6.4 Number of Spectrum Mobility (NSM)

The simulation results of the NSM under various proportions of tiles and the probability of PU occupancy are illustrated in Fig. 15. Fig. 15(a) gives the observed NSM under various proportions of tiles (ranging from 0.1 to 0.9). In general, the NSM decreases as the TTT decreases. Fig. 15(a) illustrates that the curve of the NSM of our scheme is lower than the robustness scheme under various proportions of tiles. In general, the NSM decreases as the probability of PU occupancy decreases. Fig. 15(b) shows the performance of the number of spectrum mobility vs. the probability of PU occupancy (ranging from 0 to 0.9), the curve of the NSM of our scheme is lower than the robustness scheme, because our scheme carefully considers the probability of spectrum mobility of all channels.

6.5 Computation Time (CT)

Fig. 16(a) and Fig. 16(b) finally provide the simulation results of CT under various proportions of tiles and the probability of PU occupancy. Fig. 16(a) illustrates the observed CT under various proportions of tiles (ranging from 0.1 to 0.9). We observed that the CT of the proposed scheme was high as the proportion of tiles was low. The CT of our proposed scheme was slightly higher than that of the robustness scheme (only few tens of milliseconds), but the TTT of our proposed scheme is significantly better than that of the robustness scheme (several seconds). In general, the CT decreases as the NSM decreases. Fig. 16(b) shows the performance of the CT vs. the probability of PU occupancy (ranging from 0 to 0.9). The CT increases as the probability of PU occupancy increases. This is because the high probability of PU occupancy increases leads the result of the high number of re-route, although our protocol has slightly high computation time to determine the state route.

7 CONCLUSIONS

This paper presented a routing a spectrum-aware routing protocol with minimum expected total transmission time in DOFDM-based cognitive radio networks. With the consideration of the probability of spectrum mobility and capacity of channels, a stable routing protocol is developed. The simulation results illustrate that the proposed routing protocol significantly increases the throughput and reduces the end-to-end delay time. Future work is to develop routing protocols in cognitive sensor network, and further design green and power-saving routing protocols for the cognitive networks.

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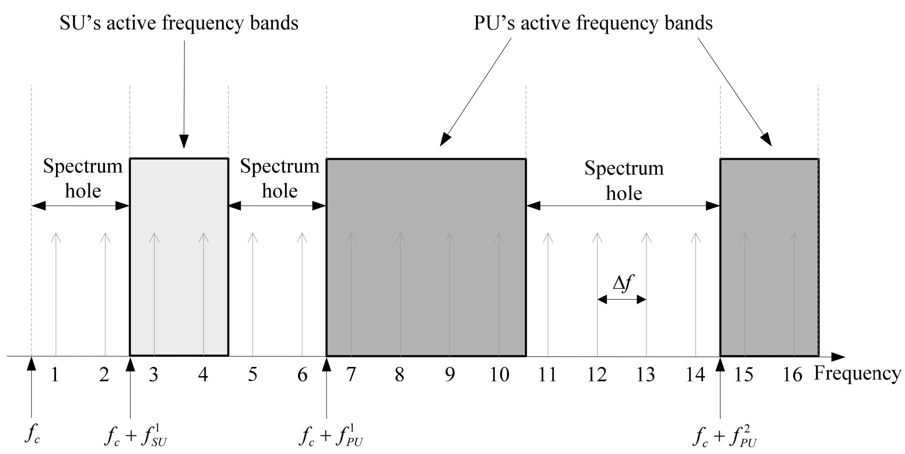
Table I: Definition of notation.

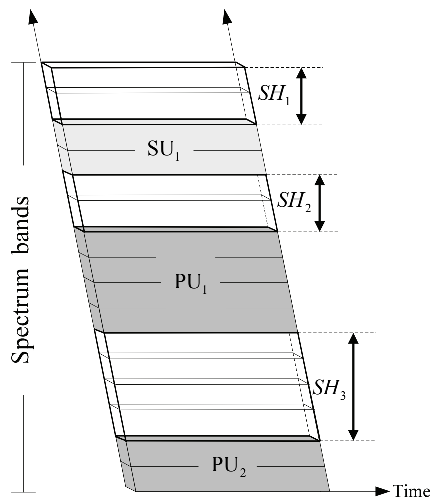
PU_i	The i-th primary user
SU_i	The i-th secondary user
SU_{source}	The source secondary user
$SU_{destination}$	The destination secondary user
T_E	The expected transmission time
T_{TE}	The expected total transmission time
D_t	Data size
R	Transmission rate
$CH_{n(i,j)}$	The n-th channel between SU_i and SU_j
UCH_1	The channel with minimum T_E
$Tile_{m(i,j)}$	The m-th common tile between SU_i and SU_j
λ_m	Primary users occupied frequency for m-th tile
t_{req}	Required transmission time
$m_{n(i,j)}$	Number of tiles in $CH_{n(i,j)}$
T_{L2H}	Layer two switch time
T_{RR}	Re-route time
d	Distance between transmitter and receiver
P_t	Transmission power
G_t/G_r	Antenna gains at the transmitter and receiver
h_t/h_r	Antenna heights
P_{signal}	Signal power
P_{noise}	Noise
K	Number of events
T	Period time
λ	Proportion of average event happened
S	Max span of one aggregated channel

Table II: Simulation parameters.

Parameter	Value
Network size	1000×1000 m
Number of Secondary users	20
Number of primary users	15
Spectrum switching delay	10 ms
Spectrum sensing period	40 ms
Simulation time	100 s
Number of simulation runs	500



(a)



(b)

Figure 1: (a) The distribution of spectrum usage. (b) The distribution of spectrum holes in cognitive radio networks.

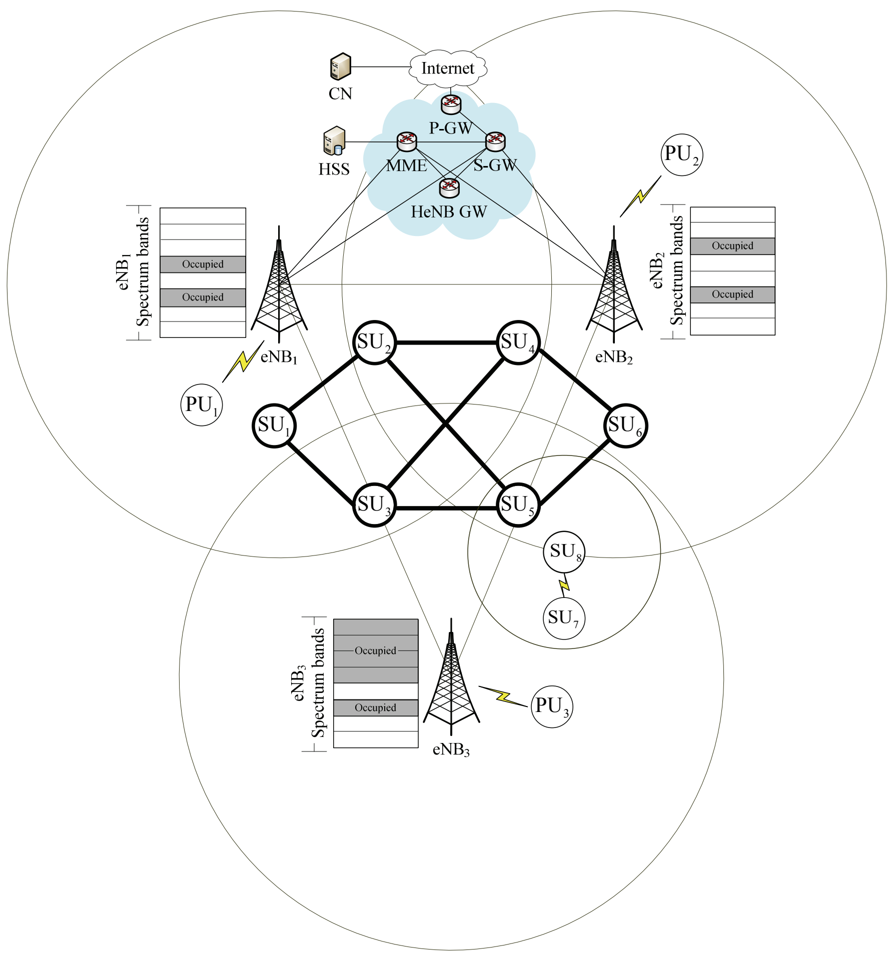


Figure 2: System model.

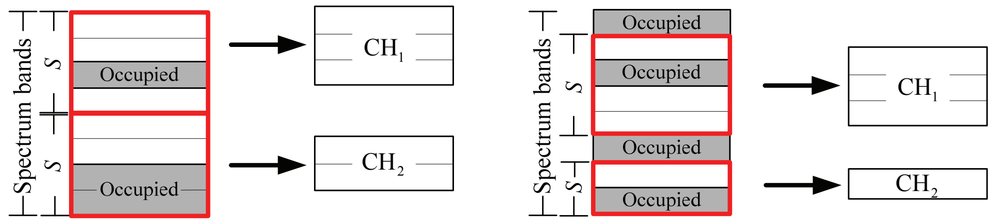


Figure 3: Example of the spectrum aggregation.

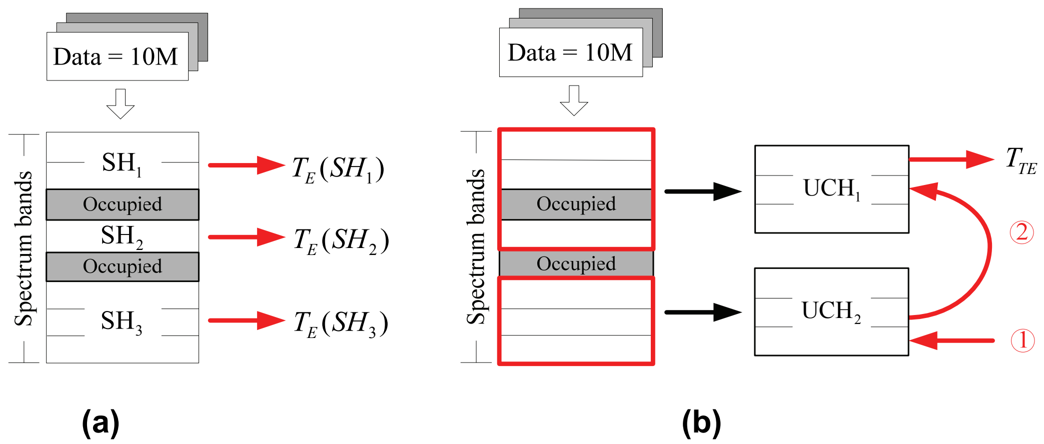
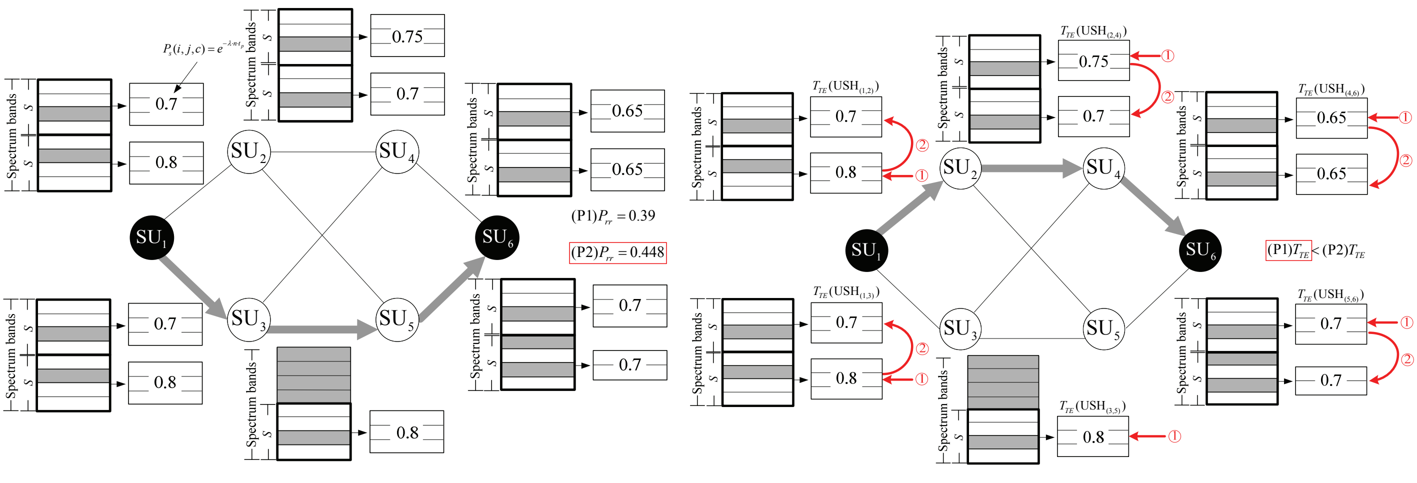


Figure 4: (a) The minimum expected transmission time. (b) Our proposed approach.



(a) (b)

Figure 5: (a) The robustness-based routing protocol. (b) The routing protocol with minimum expected total transmission time.

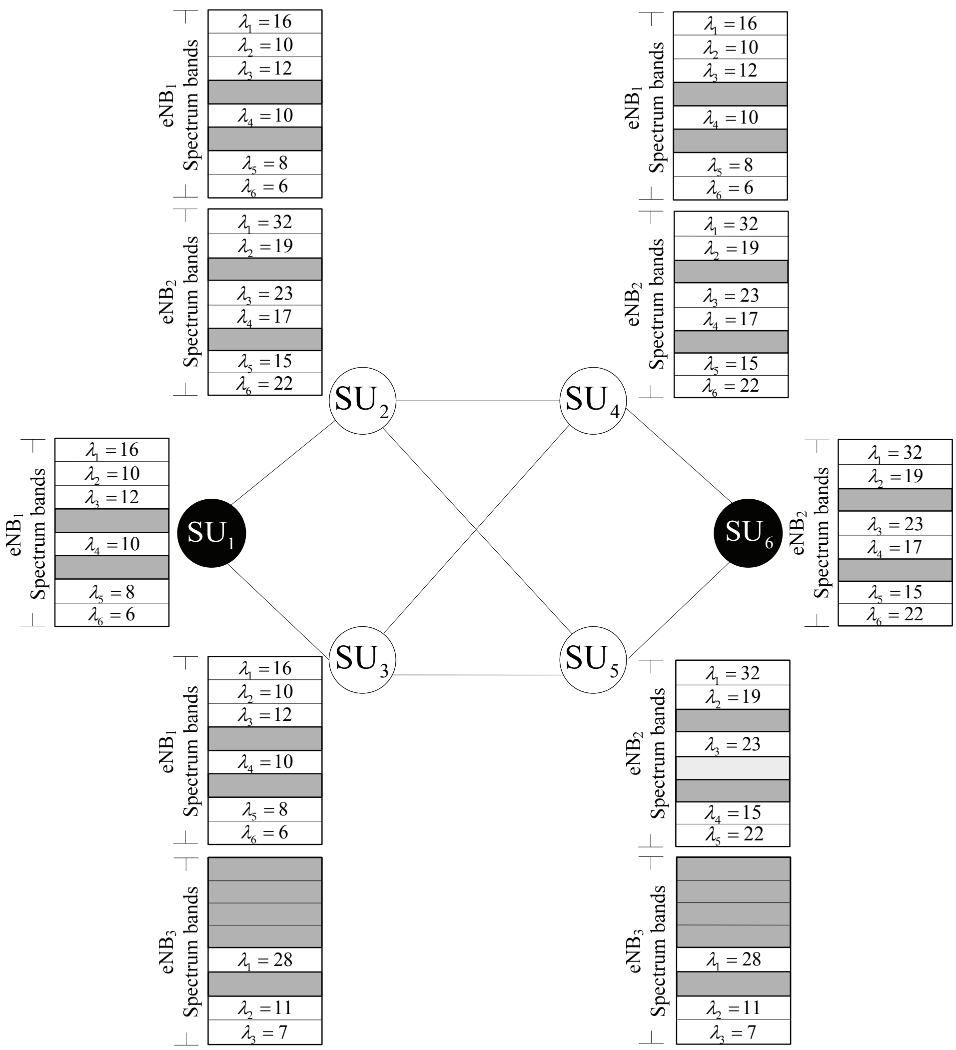


Figure 6: Frequency distribution of unoccupied spectrum holes.

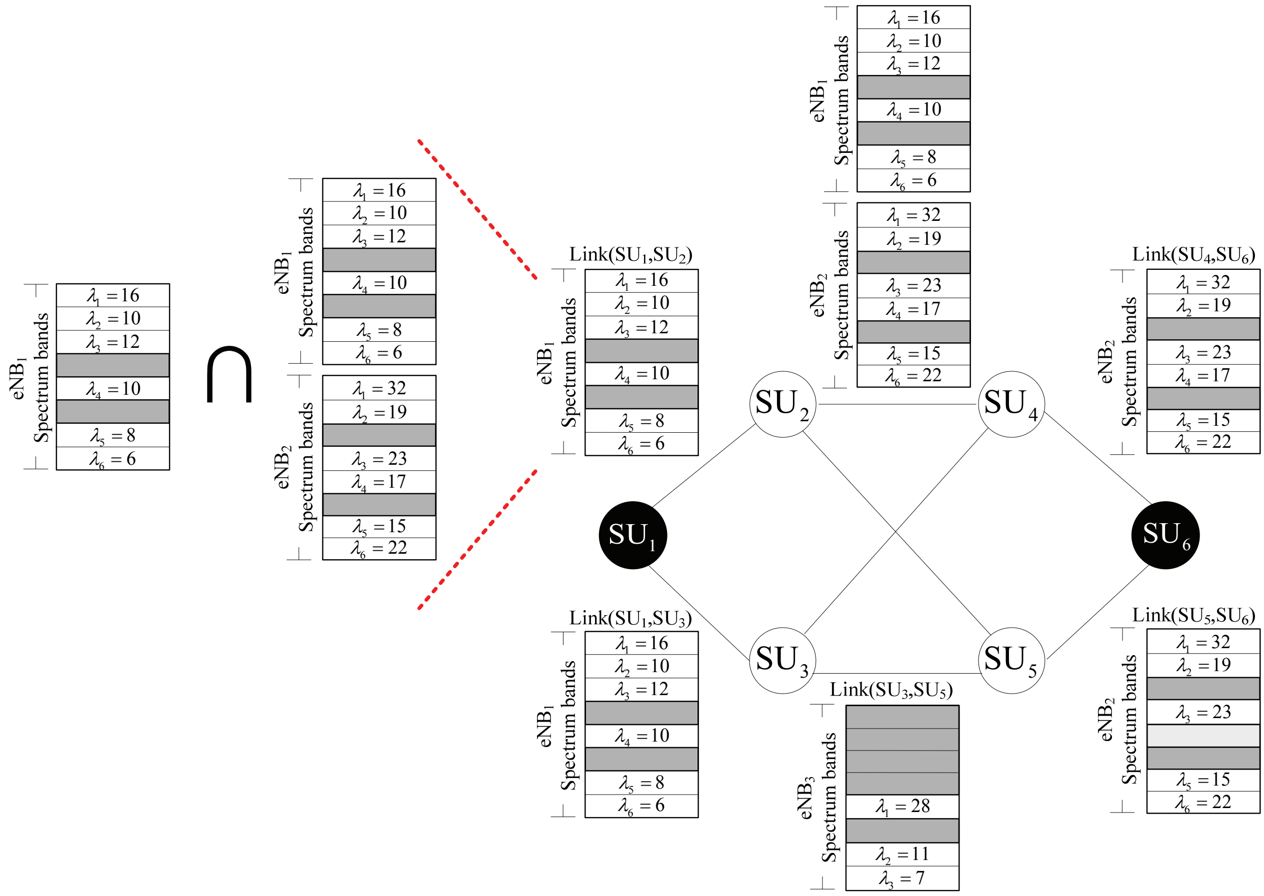


Figure 7: Example of the available tiles.

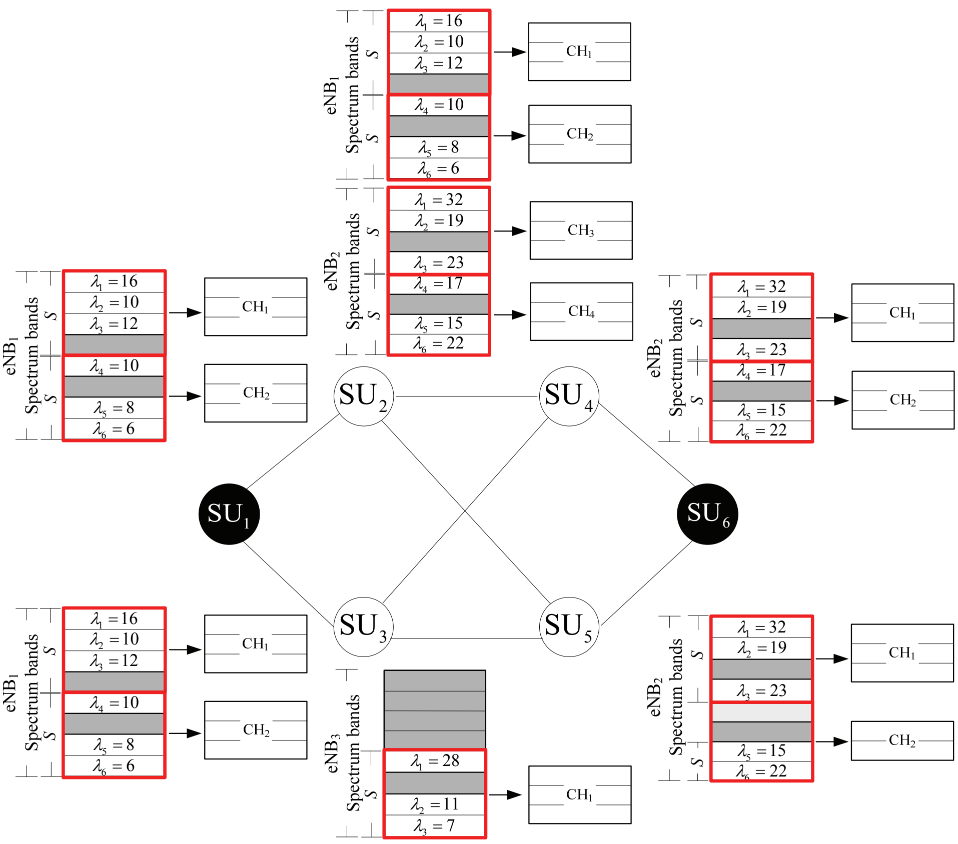
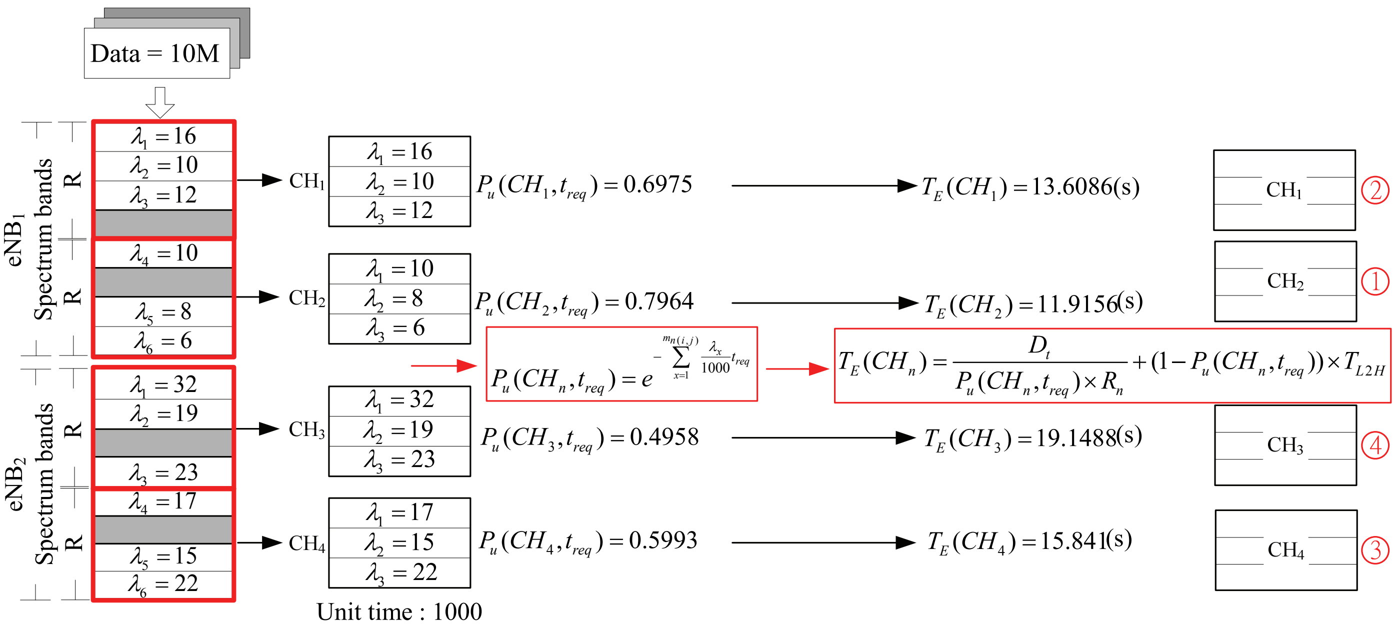
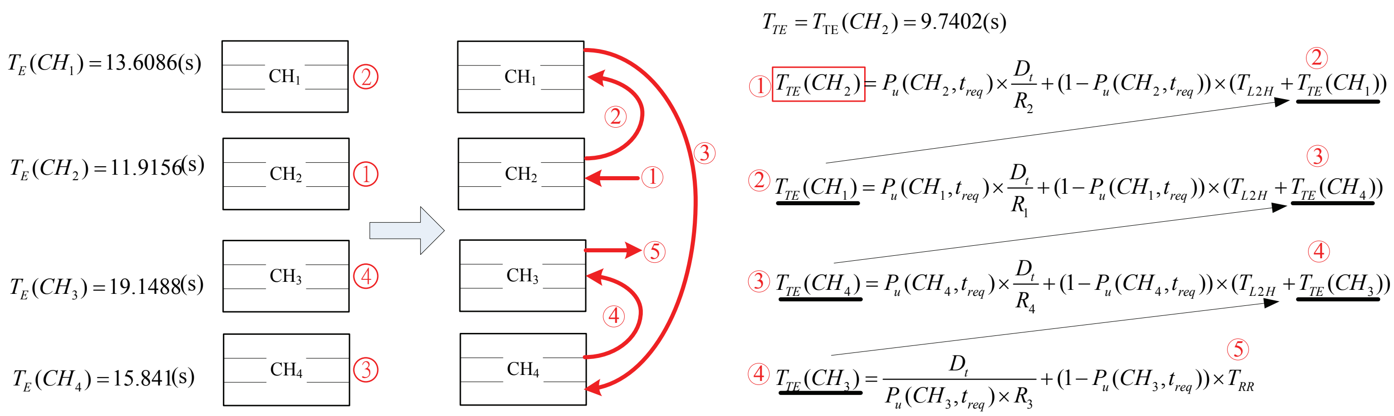


Figure 8: Example of the aggregation operation.



(a)



(b)

Figure 9: (a) Example of expected transmission time. (b) Example of expected total transmission time.

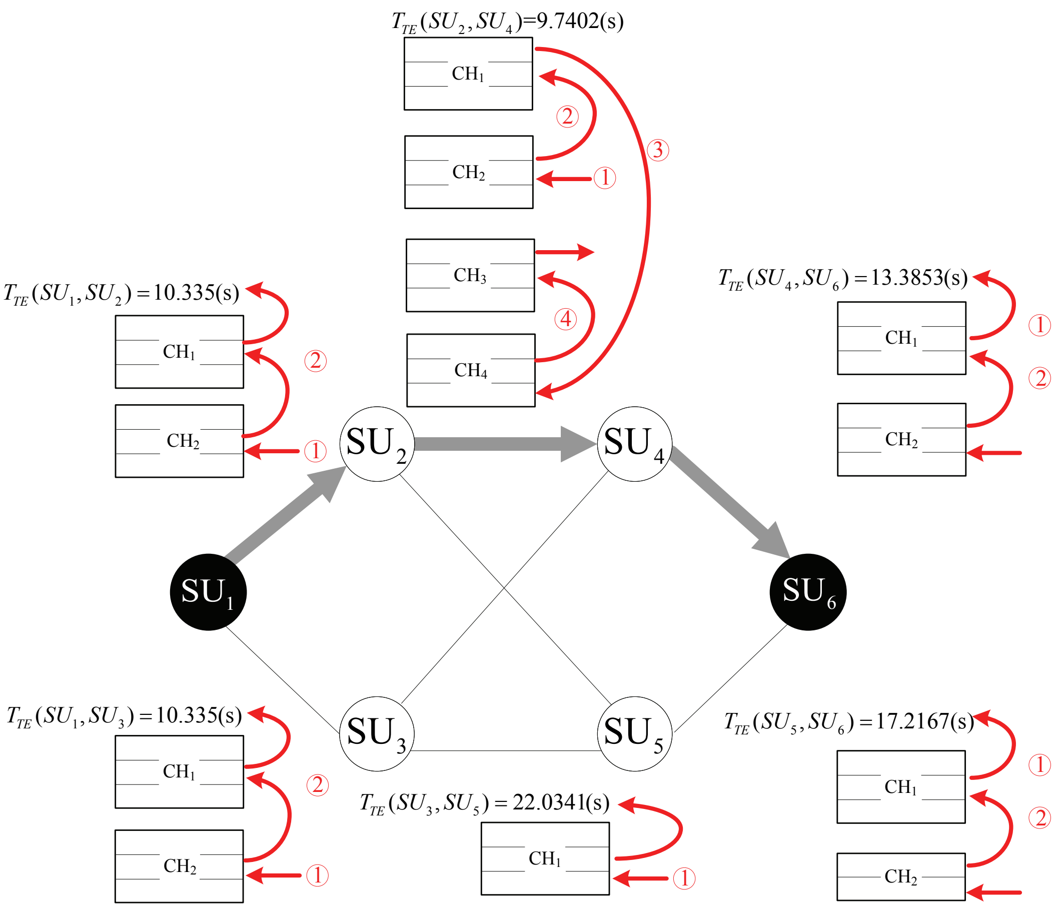


Figure 10: Example of the route discovery.

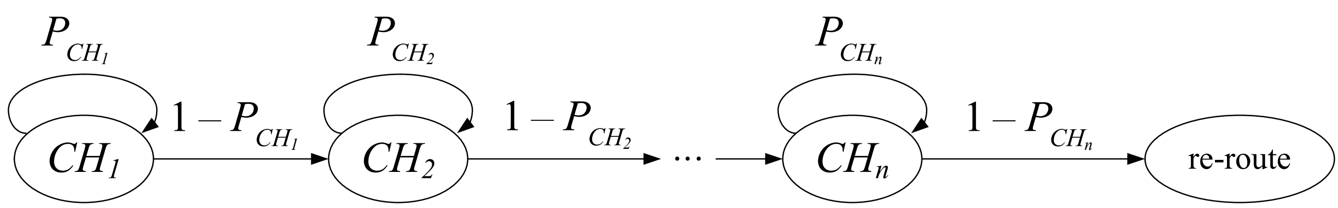


Figure 11: A state transition diagram for a link with spectrum handoff.

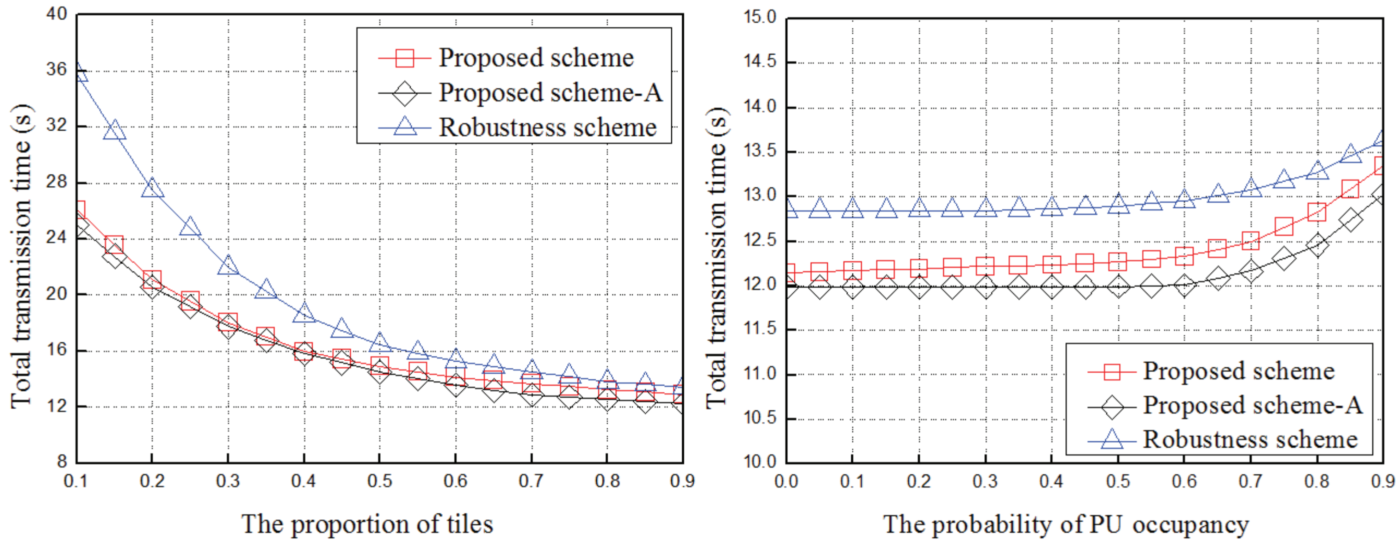


Figure 12: (a) Total transmission time vs. the proportion of tiles. (b) Total transmission time vs. the probability of PU occupancy.

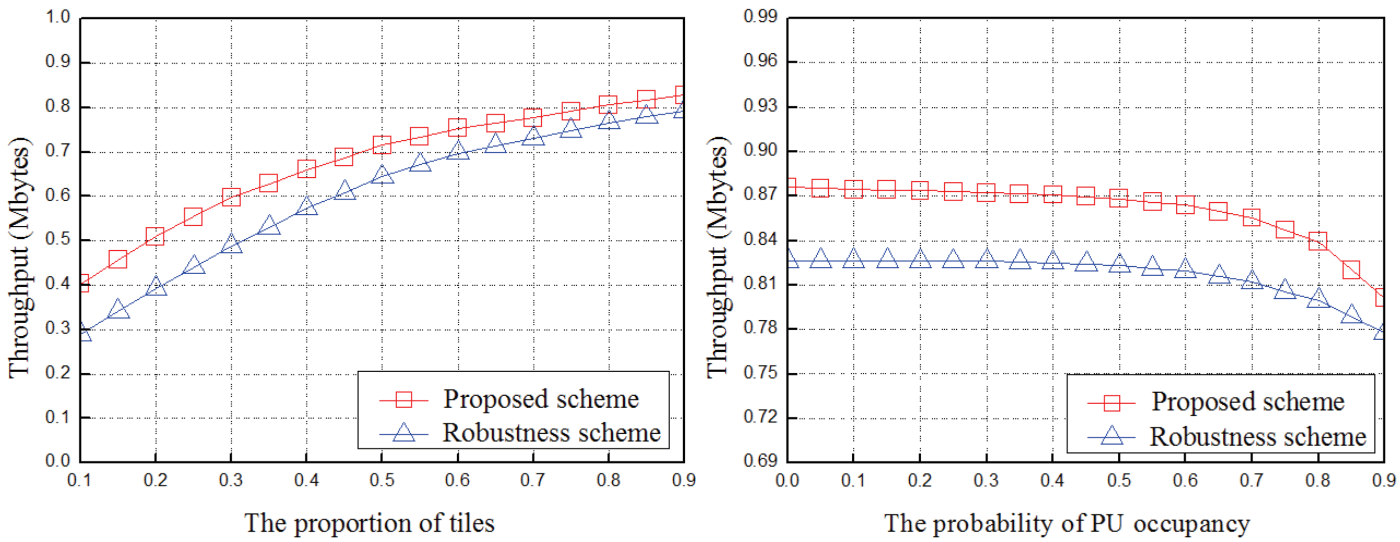


Figure 13: (a) Throughput vs. the proportion of tiles. (b) Throughput vs. the probability of PU occupancy.

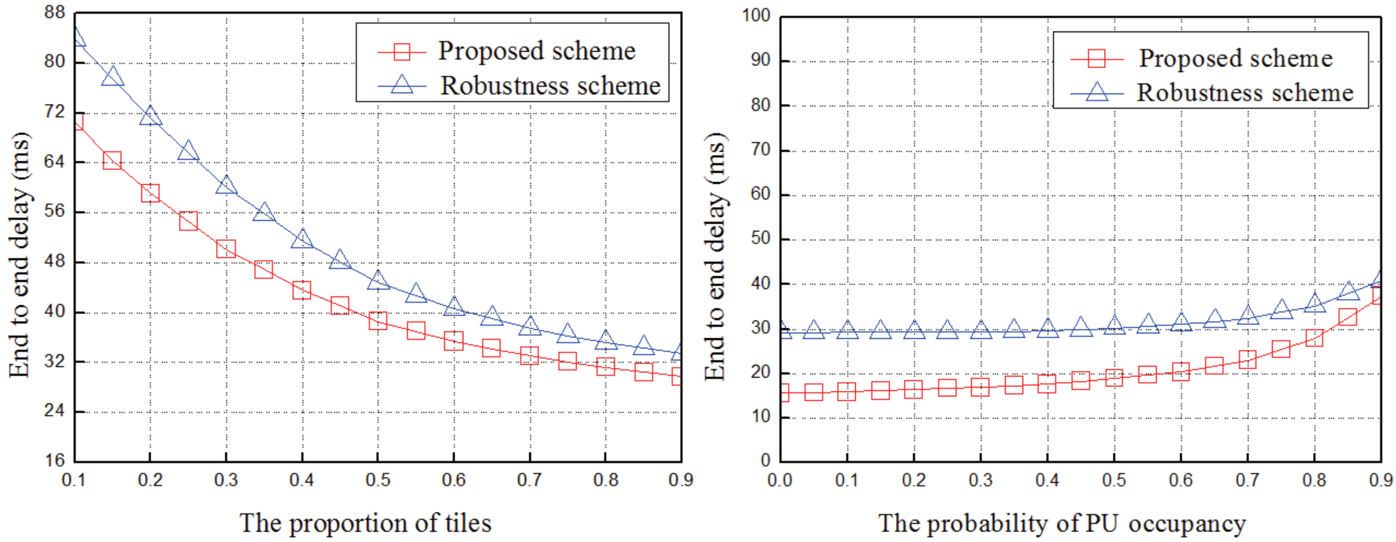


Figure 14: (a) End to end delay vs. the proportion of tiles. (b) End to end delay vs. the probability of PU occupancy.

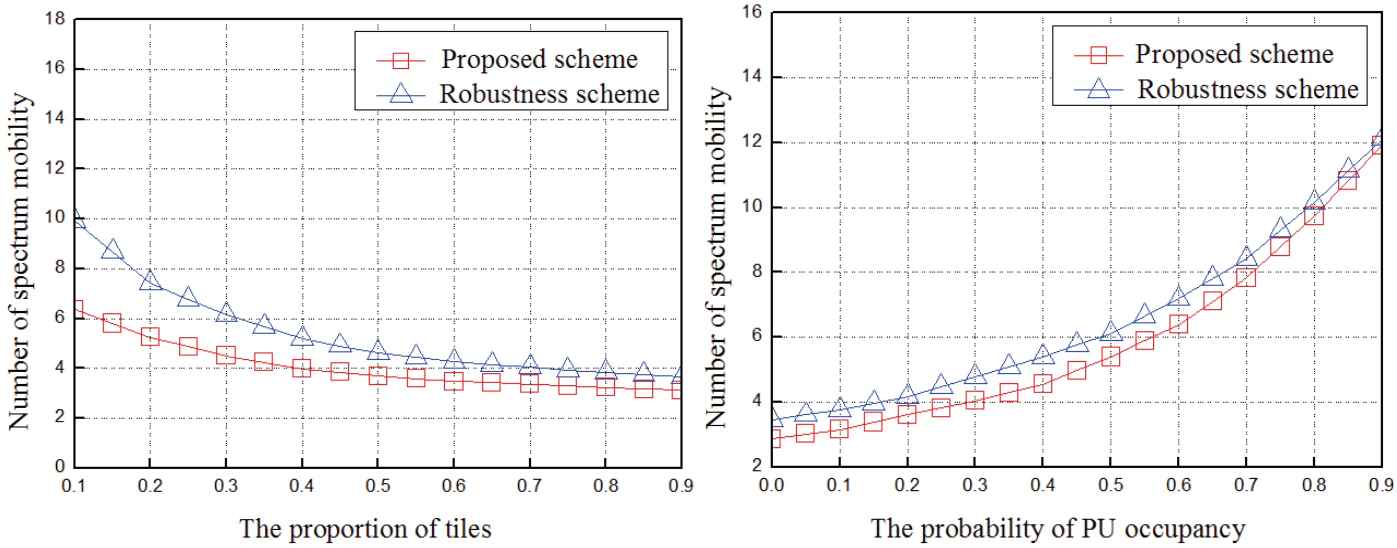


Figure 15: (a) Number of spectrum mobility vs. the proportion of tiles. (b) Number of spectrum mobility vs. the probability of PU occupancy.

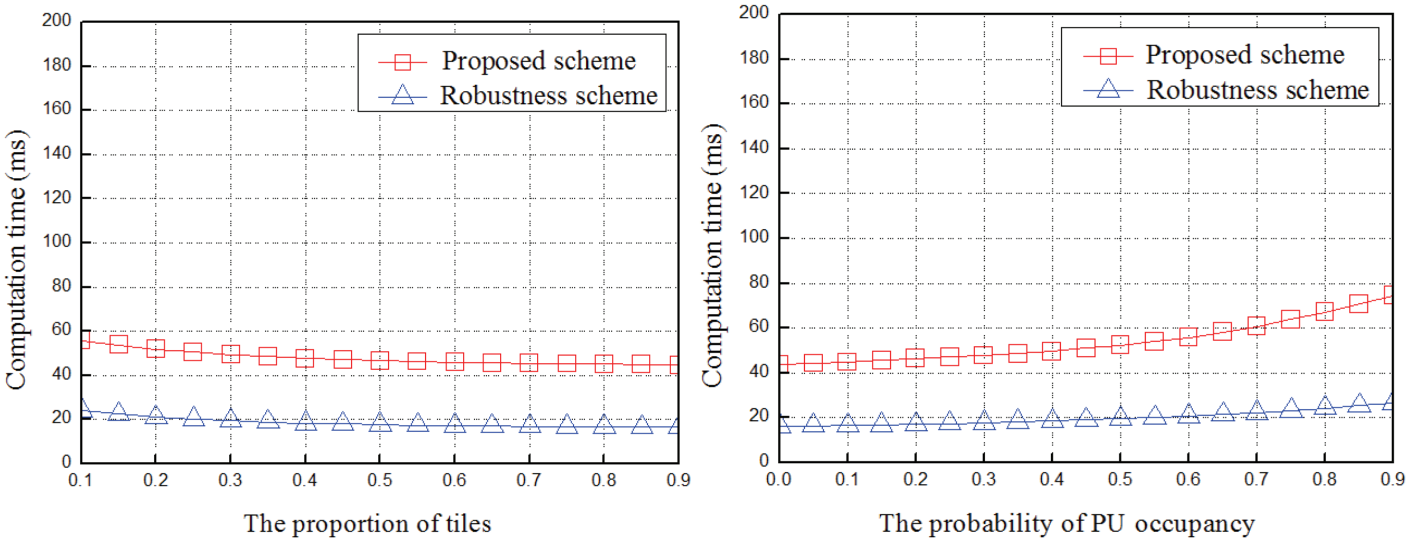


Figure 16: (a) Computation time vs. the proportion of tiles. (b) Computation time vs. the probability of PU occupancy.