A Relay-Assisted Protocol for Spectrum Mobility and Handover in Cognitive LTE Networks

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***Abstract*—Most of the licensed and license-exempt bands are underused while usage in some unlicensed bands is increasing. This trend has driven unlicensed users, equipped with cognitive radios, to opportunistically and dynamically access the spectrum not used by licensed users. Relaying techniques are an important issue for coverage and capacity extension. In this paper, we describe a relay-assisted protocol for spectrum mobility and handover with minimum expected transmission times in cognitive long-term evolution networks, which allows unlicensed users access to not only the previous base stations but also the next base station, with the assistance of relay nodes. Performance analysis of the proposed handover protocol is investigated, and simulation results of the proposed handover protocol are presented, which illustrate a significant reduction in total transmission time and spectrum mobility ratio, and increases in throughput.**

***Index Terms*—Cognitive radio, cross-layer, green communication, handover, long-term evolution (LTE), relay, spectrum mobility.**

I. Introduction

The USE of emergency cognitive radio (CR) technology [1] in licensed, license-exempt, or light licensing bands was recently considered as a way to increase total spectrum efficiency. A Federal Communications Commission report [1] included a detailed discussion about whether cognitive access should be licensed, license-exempt, or subject to light licensing. IEEE 802.22 [2] standards were developed for wireless regional area networks for license-exempt band wireless access to TV white spaces (TVWS) in rural areas. CR access techniques allow unlicensed users to access the spectrum hole not used by licensed or license-exempt users to significantly improve spectrum utilization. In addition, the Cognitive Networking Alliance (CogNea) [3] is an open-industry association that promotes TVWS spectrum regulations worldwide and aims to establish a recognizable brand that indicates a device is CogNeA compliant and can interoperate with other CogNeA-certified devices from different manufacturers. Software defined radio (SDR) technology [4] was developed to implement the CR networks.

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This relaying technique is useful for increasing the robustness, capacity, and coverage of wireless systems without having to consume extra bandwidth, especially when supporting IP-based multimedia traffic for the Internet of things [5]–[7]. Dynamic relay station (RS) deployment is an efficient mechanism because there is no extra infrastructural cost, i.e., capital expenditures (CAPEX), needed and it provides a high degree of freedom. Extra operational expenditures (OPEX) are required due to the increased complexity of the proposed protocol. In this paper, we attempt to adopt a dynamic RS strategy with acceptable extra OPEX such that some secondary users (SUs) act as RSs.

The Third-Generation Partnership Project (3GPP) integrates second-generation (2G) and third-generation (3G) cellular systems to transition 3G long-term evolution (LTE) [8] toward 4G cellular systems. Logistically, orthogonal frequency division multiplexing (OFDM) transmission should be considered first with regard to the aforementioned requirements. LTE uses OFDM techniques for downlink (from the base station to terminal) and a precoded version of OFDM, called single-carrier frequency division multiple access, for uplink (from the terminal to base station). In this paper, an LTE network is called a cognitive LTE network if it adopts CR and OFDM techniques.

The main contribution of this paper is to further investigate the handover problem in CR networks. Here, we describe a relay-assisted protocol of spectrum mobility and handover in cognitive LTE networks. This paper aims to propose a relay-assisted handoff protocol with the minimum expected transmission time with the assistance of relay stations in cognitive LTE networks. Our simulation results demonstrate that the proposed scheme reduces the total transmission time (TTT) and end-to-end delay (EED) and improves overall throughput (TP).

The remainder of this paper is organized as follows. Section II discusses related studies. Section III overviews the system architecture and basic ideas of the proposed scheme. Section IV describes the relay-assisted protocol of spectrum mobility and handover in cognitive LTE networks. Performance analysis and simulation evaluations are presented in Sections V and VI, respectively. Finally, our conclusions are presented in Section VII.

II. Related Works

Haddad *et al.* [9] have recently demonstrated a hybrid approach for radio resource management in heterogeneous cognitive networks. To overcome the interference problem, Attar *et al.* [10] discussed an interference management technique using cognitive base-stations for universal mobile telecommunications system LTE. In addition, Lai *et al.* [11] reported an interesting application of cognitive techniques. They developed a detection scheme for cognitive injured body regions with multiple triaxial accelerometers for elderly falling. These aforementioned studies focus on important and interesting problems but are not applicable in mobility management.

Research demonstrating relay-assisted results are described in the following [12]–[16]. To avoid misuse of the spectrum holes of primary users (PUs), a physical layer is used to accurately sense PU spectrum holes. To this end, Jia *et al.* [12] developed a cooperative relay for CR networks. The main contribution of this paper was the development of a new relay-assisted MAC protocol for data transmission to improve system TP by exploiting the benefits of cooperative relay. Mao *et al.* [13] proposed relaying strategies, based on the cognitive relay channels, to select relays with high channel capacities to achieve high transmission rates. This paper attempted to exploit and identify dynamic relay nodes in cellular networks under the presentence of intercell interference. A reasonable criterion for choosing relay node candidates was also provided. Lee *et al.* [14] investigated the outage performance of cognitive relay networks where source nodes communicate with their destinations via multiple hops. In addition, Luo *et al.* [15] proposed optimal power allocation for cognitive relay networks. The power allocation of a cognitive relay network was modeled to minimize the system outage probability, which is subject to total and individual power constraints for cognitive relays and interference constraints for PU nodes.

Chen *et al.* [17] proposed a cross-layer protocol of spectrum mobility and handover in cognitive LTE networks. However, this paper did not utilize the assistance of dynamic relay nodes. In this paper, we further develop a relay-assisted protocol of spectrum mobility and handover in cognitive LTE networks. With the assistance of dynamic relay nodes, the proposed protocol can significantly reduce the TTT and EED and improve system TP, compared to existing protocols.

III. Preliminaries and Basic Ideas

A. System Architecture and Model

Fig. 1 illustrates the system architecture and model of the proposed protocol. The primary network uses a LTE system [8], [9] and the secondary network uses the CR-LTE system. CR-LTE is a LTE system that exploits CR and OFDM techniques. PUs in the primary network (LTE network) access LTE-based spectrum holes through the primary coordinator (eNB). The spectrum holes not used by PUs can be leased by SUs. SUs in the secondary network (CR-LTE network) access the leased spectrum holes through the secondary coordinator.

A system model of primary and secondary networks is shown in Fig. 2. The system model contains the LTE core systems, licensed users (also called PUs), unlicensed users (also called SUs), and some unlicensed users, which may all play the role of RNs. For a CR network (secondary network),

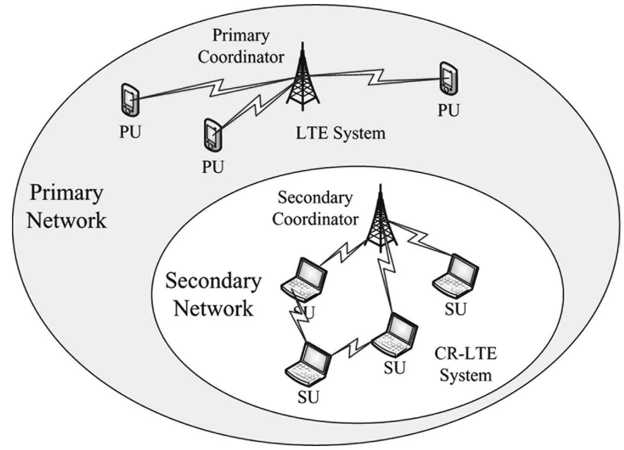


Fig. 1. Primary network (LTE network) and secondary network (CR-LTE network).

SUs and RNs are equipped with CRs to opportunistically access spectra not used by PUs. In this paper, a single-channel full duplex wireless communication system was modified to enable SUs to scan for PUs that are using a spectrum.

Fig. 2 illustrates a relay-assisted scenario in a CR-LTE network. A SU is moving from one cell into another along a straight path. Initially, the SU is far away from the overlapped area. If a PU appears in the primary network and attempts to access the spectrum occupied by the SU, the SU performs a spectrum mobility operation and jumps to a new spectrum hole. To continue moving, the SU moves to the overlapped area while the PU occupies the primary network. The SU continues to move in the overlapped area, between the serving eNB and new eNB, until another PU appears in the primary network and reclaims the spectrum hole used by the SU. To implement the aforementioned scheme, SUs and RNs are equipped with SDR devices that allow dynamic detection and allocation of spectrum holes.

B. Basic Idea and Challenges

Chen *et al.* [17] proposed a cross-layer protocol for spectrum mobility and handover in cognitive LTE networks. The idea is to periodically observe the ratio of the spectrum that is occupied to predict the probability of a PU reclaiming resources. With the spectrum occupied ratio, SUs can estimate the transmission time of any remaining SU data. Let T_E denote the expected transmission time, which is defined in [17]. Chen *et al.* [17] selects the spectrum hole with the minimum expected transmission time, T_E, as the next spectrum hole for a spectrum mobility operation.

The basic idea of this paper is to develop a new relay-assisted protocol for spectrum mobility and handover in cognitive LTE networks. With RNs, each SU has one or more connection paths to the eNB through dynamic RNs. The path with the minimum expected transmission time is selected from multiple paths through a RN if that RN has rich spectrum holes. It is possible that a spectrum hole may be occupied by many other SUs. Thus, there are fewer resources that allow the current SU to access the eNB. Under this condition, there are less resource blocks (RBs) and a higher spectrum

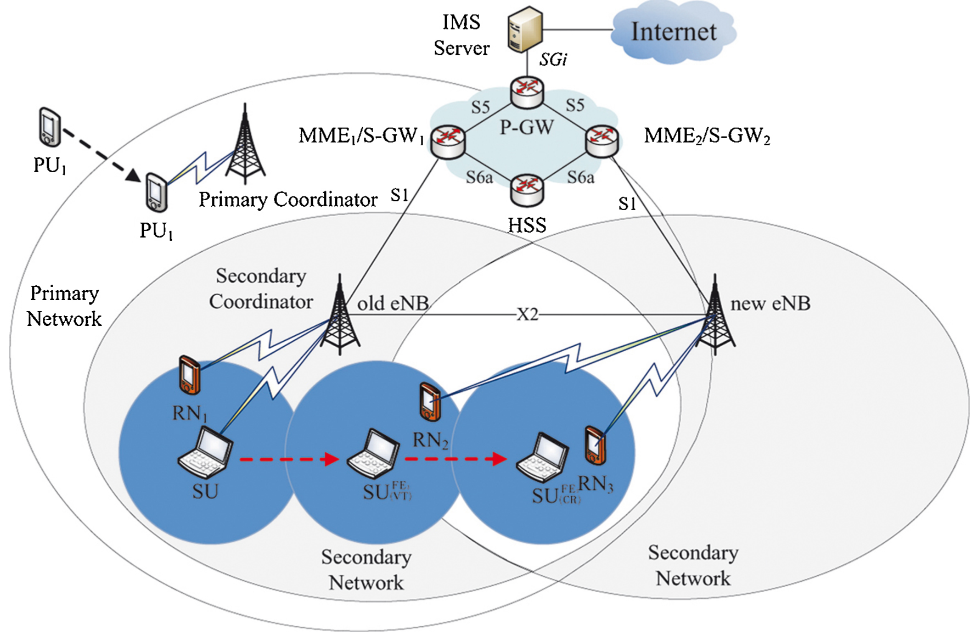


Fig. 2. System model of primary and secondary networks.

occupied rate. Some SUs can play the dynamic RNs if the SUs have the rich spectrum holes. Then, SI can perform the data transmission with the less-expected transmission time through the dynamic RNs. To reduce the transmission time of SUs, it is reasonable to perform data transmission with the assistance of dynamic RNs. Ad hoc communication between SUs and RNs can be established using IEEE 802.11n technology [18].

IV. Relay-Assisted Protocol of Spectrum Mobility and Handover

In the following section, two scenarios are considered: 1) scenario one (spectrum mobility): a SU is not located at the overlapped area; and 2) scenario two (handover): a SU approaches the overlapped border area or enters into the overlapped area. Four phases of the two scenarios are described in the following.

A. Relay Discovery Phase

The candidate dynamic RN is identified in this phase. Let SU_x denote the xth SU and RN_y denote the yth relay node. All RNs considered in this paper are assumed to be dynamic RNs, including static and unstable RNs. A dynamic RN is considered a static RN if it has low mobility. A dynamic RN is said to be an unstable RN if it has high mobility. The relay discovery procedure is given as follows.

1) Each SU_x senses all dynamic RNs in the sensing range. To maintain stable communication between SU_x and RNs, SU_x only keeps static RNs and removes unstable RNs.
2) Each SU_x removes RNs with long separations between the eNB and SU_x. All of the remaining RNs are inserted into the set of candidate RNs. The distance between the eNB and SU_x is estimated by the signal-to-noise ratio (SNR) between the eNB and SU_x, which is obtained by periodically sensing spectrum information with a SDR device.

Fig. 3 shows an example of scenario one, SU_1 senses four dynamic RNs, and all RNs are static (low mobility). The set of candidate RNs = $\{RN_1, RN_2\}$ because the distance between the eNB and SU_x of RN_3 and RN_4 is too long. Fig. 4 gives an example of scenario two, and the set of candidate RNs = $\{RN_2, RN_3\}$.

B. Environment Observation Phase

Let RN_z denote the zth dynamic RN that can access the current serving eNB and RN'_w denote the wth dynamic RN that can access the next eNB. SU_x collects spectrum information with an SDR device. The spectrum information includes SNR value from the current or next eNB, usage status of RBs, and spectrum holes used by SU_x and the neighbors of SU_x. The SNR and number of RBs are used to determine the transmission rate. Figs. 3 and 4 give examples of the spectrum bands of all possible RBs periodically sensed by SU_x, including the spectrum status of dynamic RN'_w, when determining the occupied frequency information of RBs in scenarios one and two. Let spectrum hole SH_i contain m_i RBs and λ_{mi} be the accumulated number of the m_ith RB that is occupied within a period of time.

The large value of λ_{m_i} implies that the m_ith RB is occupied by PUs more frequently. It also indicates that SU_x has a low opportunity to utilize the m_ith RB. The small value of λ_{mi} indicates that SU_x has a high opportunity to utilize the m_ith RB with a low probability of interruption by PUs. The SNR allows SU_x to define the relative location information and transmission quality. The environmental observation procedure is given as follows.

1) Each SU_x periodically senses all spectrum bands, RB_y, in the transmission coverage of the current serving eNB, where RB_y, $1 \leq y \leq N_{\max\text{imum\_number\_of\_RB}}$.

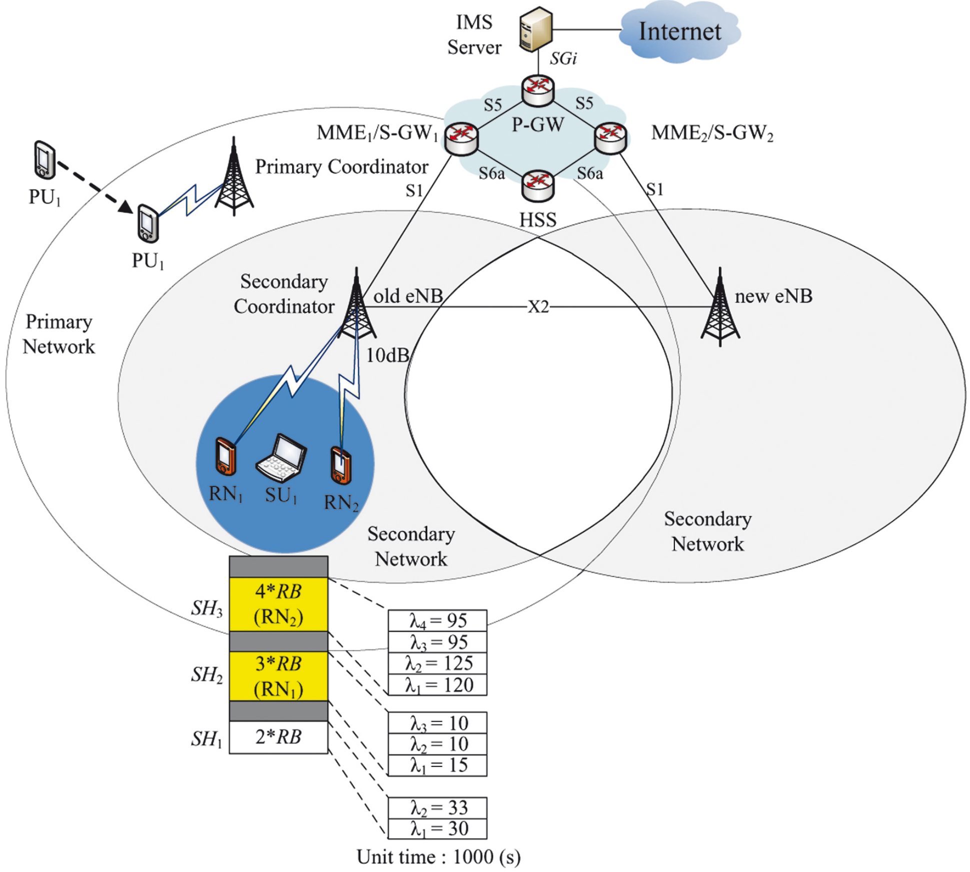


Fig. 3. Relay discovery and environment observation phase for scenario one (spectrum mobility).

The information of the occupied frequency, λ, is also observed and recorded for all RB_y within a period of time, where $1 \leq y \leq N_{\text{max imum\_number\_of\_RB}}$. Based on OFDMA technology, an adjacent, continuous, and idle RB_y can form a spectrum hole SH_j, where $1 \leq j \leq n$, and a sequence of spectrum holes $(\mathrm{SH}_1, \mathrm{SH}_2, \ldots, \mathrm{SH}_n)$ can be obtained.

2) If SU_x detects a spectrum hole, SH_i, being reclaimed by a PU, then SU_x broadcasts a request message to its neighbors from the set of candidate RNs and waits for a reply message to acquire spectrum hole information and received SNR from that neighbor. Otherwise, go to step 1.

3) SU_x performs the computation and analysis phase to perform a spectrum mobility operation or handover, either with or without the assistance of RNs depending on the value of $T_E(\mathrm{SH}_i)$, where $T_E(\mathrm{SH}_i)$ is calculated by the remaining service data size, d_t.

Fig. 3 shows scenario one, in which SU_1 determines the received SNR from the old eNB to be 10 dB. Then, SU_1 broadcasts a message to candidate relay nodes RN_1 and RN_2, and receives the SNR and spectrum information from those nodes. Fig. 3 also shows that SH_1, SH_2, and SH_3 of SH_1 are 2RB, 3RB, and 4RB, respectively. Fig. 4 shows scenario two, in which PU_1 moves into range of the old eNB and reclaims the spectrum hole used by SU_1. SU_1 enters the overlapping area of the old eNB and new eNB, and the SNR from the old eNB and new eNB are 10 dB and 15 dB, respectively. Then, SU_1 broadcasts a message to candidate relay nodes RN_2 and RN_3 to acquire the SNR and spectrum information from these nodes. Fig. 4 also illustrates that SH_1 and SH_3 of SU_1 to the old eNB are 2RB and 4RB, respectively. SH'_1, SH'_2, and RN_2 of SU_1 to the new eNB are 3RB, 4RB, and 5RB, respectively. SU_1 has two RBs, which occupy frequencies $\lambda_1 = 30/1000$ and $\lambda_2 = 33/1000$. Note that SH'_2 and SH'_3 are used by RN_2 and RN_3, respectively. This information is used to calculate the expected execution time, $T_E(\mathrm{SH}_i)$.

C. Computation and Analysis Phase

The phase is used to compute the expected execution time, $T_E(\mathrm{SH}_i)$, as follows.

1) To evaluate the expected transmission time, $T_E(\mathrm{SH}_i)$, for the remaining SU_x service data, the scenario one, SNR from the serving eNB is first calculated with the expressions $\mathrm{SNR} = \frac{P_{\text{signal}}}{P_{\text{noise}}}$ and $\mathrm{SNR}_{\text{dB}} = 10\log_{10}\left(\frac{P_{\text{signal}}}{P_{\text{noise}}}\right)$. In scenario two, the SNR from the next eNB is calculated with the expressions $\mathrm{SNR}^0 = \frac{P^0_{\text{signal}}}{P^0_{\text{noise}}}$ and $\mathrm{SNR}^0_{\text{dB}} = 10\log_{10}\left(\frac{P^0_{\text{signal}}}{P_{\text{noise}}}\right)^0$.

2) In scenario one, the SU_x estimates the maximum transmission rate for all spectrum holes, SH_i, based on SNR_{dB} to calculate the required transmission time, t_{req}, for the remaining service data size, d_t. Let R_i denote

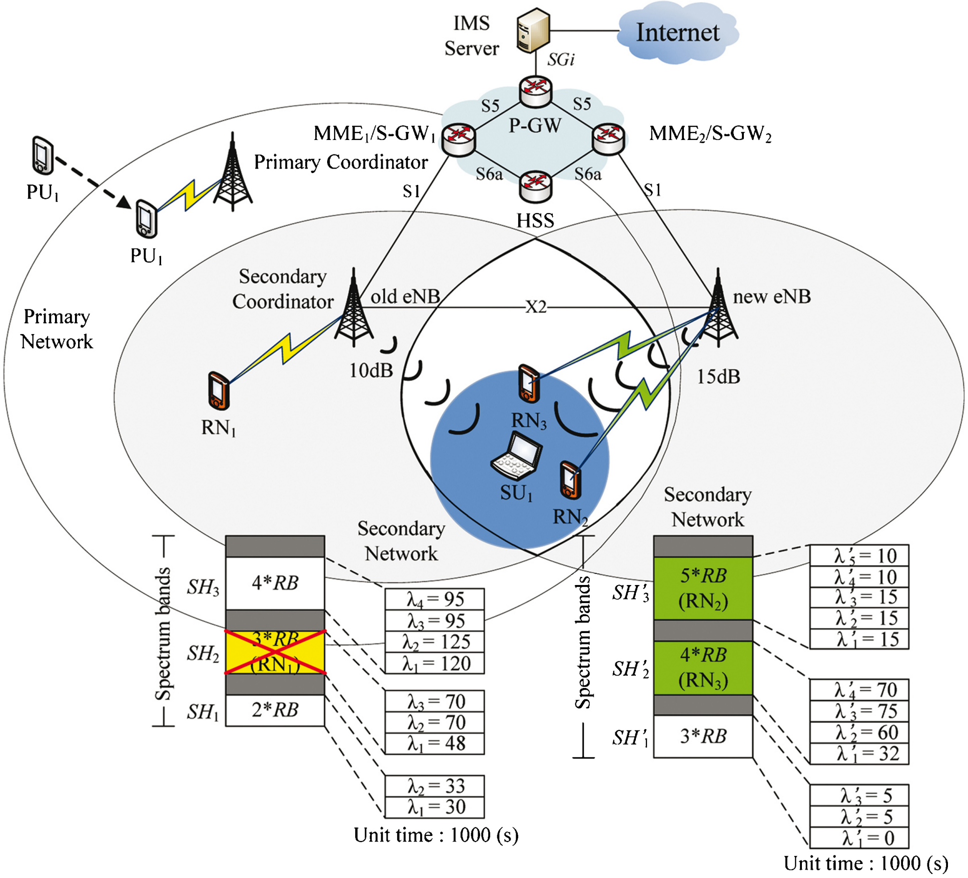


Fig. 4. Relay discovery and environment observation phase for scenario two (handover).

the transmission rate of SH_i. If SH_i contains m_i RBs, R_i can be calculated with the Shannon theorem as $m_i \times \mathrm{RB} \times \log_2(1 + \mathrm{SNR_{dB}})$ [19]. The required transmission time is calculated with the expression $t_{\mathrm{req}} = \frac{d_t}{m_i \times \mathrm{RB} \times}$ $t_{\mathrm{req}} = \frac{d_t}{m_i \times \mathrm{RB} \times \log_2(1+\mathrm{SNR_{dB}})}$, where d_t represents the remaining service data size. In scenario two, SU_x determines the maximum transmission rate based on $\mathrm{SNR_{dB}}$ and $\mathrm{SNR}'_{\mathrm{dB}}$, where $\mathrm{SNR_{dB}}$ and $\mathrm{SNR}'_{\mathrm{dB}}$ are the SNR from the current and new eNBs. The required transmission time is calculated with the expression $t_{\mathrm{req}} = \frac{d_t}{m_i \times \mathrm{RB} \times \log_2(1+\mathrm{SNR_{dB}})}$ (through the current eNB) and t'_{req} (through the next eNB) for the remaining service data size, d_t. Let R'_i denote the transmission rate for SH'_i. If SH'_i contains m'_i RBs, then the required transmission time, t'_{reg}, is expressed as $\frac{d_t}{m'_i \times \mathrm{RB} \times \log_2(1+\mathrm{SNR}'_{\mathrm{dB}})}$.

3) To predict the availability of spectrum holes, SH_i, the uninterrupted probability of SH_i is calculated. Let $P_u(\mathrm{SH}_i, t_{\mathrm{req}})$ denote the probability that spectrum hole, SH_i, is unoccupied by PUs within the time period t_{req} or t'_{req}. A Poisson distribution [20] is used to predict the idle SH_i within a service required time, t_{req} or t'_{req}, which can be represented as $P(k, T) = \frac{(\lambda T)^k}{k!} e^{-(\lambda T)}$. Here, k is the number of events, T is the period time, and λ is the average expected occurrence. $P(k, T)$ represents the probability of k events occurring within the time period T. In general, when a PU is going to access a channel, the communication of a second user in the channel is interrupted by the PU. Based on the work by Akbar *et al.* [21], the probability of a channel being accessed by a PU can be predicted with the Poisson distribution. Here, the memoryless property can be described by $P_r(k > t + s | k > t) = P_r(k > s)$, where $P_r(k)$ is the probability of a PU accessing a channel, k and t are periods of time, and s is the initial time. To analyze the probability that SH_i will not be used within the service required time, t_{req} or t'_{req}, k is set to zero and T is set to t_{req}. Consequently, if SH_i contains m_i RBs, the probability of spectrum hole SH_i being uninterrupted by PUs within a time period t_{req} can be expressed as $P_u(m_i, t_{\mathrm{req}}) = \prod_{n=1}^{\mathrm{SH}_i} P_n(0, t_{\mathrm{req}}) = e - \sum_{n=1}^{m_i} \lambda_n t_{\mathrm{req}}$. In addition, when SU_x is in the overlapping area and evaluates $P'_u(\mathrm{SH}'_i, t'_{\mathrm{req}})$ for all dynamic RN'_w, if SH'_i contains m'_i RBs, the probability of spectrum hole SH'_i being uninterrupted by PUs within time period t'_{req} can be expressed as $P_u(\mathrm{SH}'_i, t'_{\mathrm{req}}) = \prod_{n=1}^{m'_i} P_n(0, t'_{\mathrm{req}}) = e^{-\sum_{n=1}^{m'_i} \lambda_n t_{\mathrm{req}}}$.

Fig. 5 provides an example of the computation and analysis phases of scenario one, where the $\mathrm{SNR_{dB}}$ of SU_1 is 10 dB. In addition, Fig. 5 shows that the transmission rates of SH_1, SH_2, and SH_3 are $2 \times 180\,(\mathrm{kHz}) \times \log_2(1 + 3.01) = 720\,\mathrm{kb/s}$, $3 \times 180\,(\mathrm{kHz}) \times \log_2(1 + 3.01) = 1080\,\mathrm{kb/s}$, and $4 \times 180\,(\mathrm{kHz}) \times \log_2(1 + 4.78) = 1440\,\mathrm{kb/s}$, respectively. The service required transmission time of SH_1, SH_2, and SH_3 are $10\,(\mathrm{Mb}) \div 720\,(\mathrm{kb/s}) =$

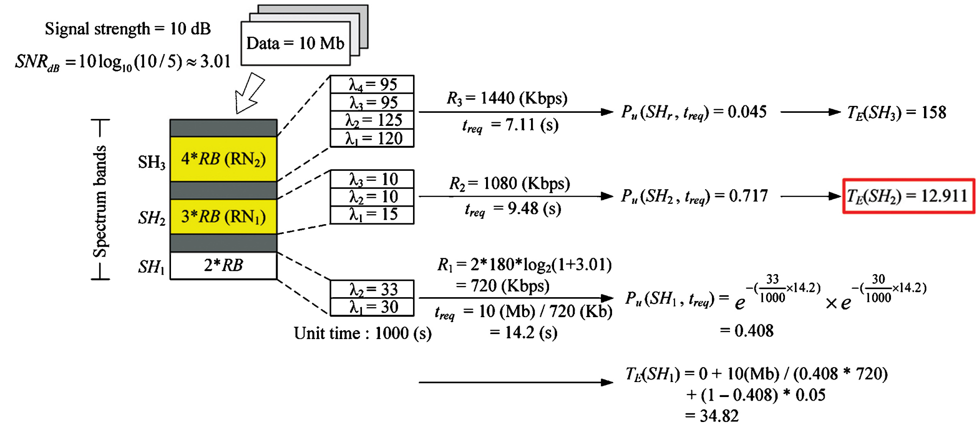


Fig. 5. Computation and analysis phase and evaluation and transmission phase in scenario one.

14.2 s, 10 (Mb) ÷ 1080 (kb/s) = 9.48 s, and SH_3 10 (Mb) ÷ 1440 (kb/s) = 7.11 s. The uninterrupted probabilities are $P_u(\mathrm{SH}_1, t_{\mathrm{req}}) = e^{-(\frac{30}{1000}\times 14.2)} \times e^{(\frac{33}{1000}\times 14.2)} = e^{-0.8946} \cong 0.408$, $P_u(\mathrm{SH}_2, t_{\mathrm{req}}) = e^{-(\frac{10}{1000}\times 9.48)} \times e^{-(\frac{10}{1000}\times 9.48)} \times e^{-(\frac{15}{1000}\times 9.48)} \cong 0.717$, and $P_u(\mathrm{SH}_3, t_{\mathrm{req}}) = e^{-(\frac{120}{1000}\times 7.111)} \times e^{-(\frac{125}{1000}\times 7.111)} \times e^{-(\frac{95}{1000}\times 7.111)} \times e^{-(\frac{125}{1000}\times 7.111)} \cong 0.045$. Fig. 6 gives an example of the computation and analysis phases of scenario two, where the $\mathrm{SNR}_{\mathrm{dB}}$ and $\mathrm{SNR}'_{\mathrm{dB}}$ are 10 dB and 15 dB, respectively. Fig. 6 shows that the transmission rates of SH_1 and SH'_1 are $2 \times 180\,(\mathrm{kHz}) \times \log_2(1+3.01) = 720$ kb/s and $3 \times 180\,(\mathrm{kHz}) \times \log_2(1+4.78) = 1188$ kb/s, respectively. The service required transmission time of SH_1 of the old eNB and SH'_1 of the new eNB are 10 (Mb) ÷ 720 (kb/s) = 14.2 s and SH'_1 10 (Mb) ÷ 1188 (kb/s) = 8.61 s, respectively. The uninterrupted probabilities are $P_u(\mathrm{SH}_1, t_{\mathrm{req}}) = e^{-(\frac{30}{1000}\times 14.2)} \times e^{-(\frac{33}{1000}\times 14.2)} = e^{-0.8946} \cong 0.408$, and $P'_u(\mathrm{SH}'_1, t'_{\mathrm{req}}) = e^{-(\frac{0}{1000}\times 8.61)} \times e^{-(\frac{5}{1000}\times 8.61)} \times e^{-(\frac{5}{1000}\times 8.61)} = 0.917$.

D. Evaluation and Transmission Phase

This phase calculates the expected execution time, $T_E(\mathrm{SH}_i)$, to determine whether to perform a spectrum mobility operation to the old eNB or handover to the new eNB. The transition is assisted by dynamic RNs if there is a poor network connection between SU_x and the old or new eNBs.

1) Two possible cases of SU_x are considered. First, SU_x performs a spectrum mobility operation to a new spectral band without the assistance of RN if no RNs are founded. Second, a spectrum mobility operation is performed with the assistance of relay node RN_z. The $T_E(\mathrm{SH}_i)$ is the expected transmission time of the SH_i through the old eNB. If SU_x is not located at the overlapped area, $T_E(\mathrm{SH}_i)$ is calculated as

$$T_E(\mathrm{SH}_i) = t_{\mathrm{RN}_z} + \frac{d_t}{P_u(m_i, t_{\mathrm{req}}) \times R_i} + (1 - P_u(m_i, t_{\mathrm{req}})) \times T_{\mathrm{L2H}} \tag{1}$$

where $t_{\mathrm{RN}_z} = \frac{d_t}{R_{\mathrm{WLAN}}}$ is the transmission time from SU_x to RN_z. This expression assumes that SU_x is assisted by RN_z, where RN_z currently occupies the spectrum hole, SH_z. In the first case, $t_{\mathrm{RN}_z} = \frac{d_t}{R_{\mathrm{WLAN}}} = 0$, T_{L2H} is the layer-2 switch time, and $(1 - P_u(m_i, t_{\mathrm{req}}))$ is the probability that SH_i (not by RN_z) or SH_z (by RN_z) is occupied during the time period t_{req}. If no PU appears, the transmission time is $\frac{d_t}{R_i}$. However, transmission can be interrupted by the appearance of other PUs. In this case, the expected transmission time should increase by $P_u(m_i, t_{\mathrm{req}}) \times R_i$. The usage of SH_i by SU_x may be interrupted again by the appearance of other PUs, in which case SU_x will have to perform another spectrum mobility operation. This condition is represented as $(1 - P_u(m_i, t_{\mathrm{req}})) \times T_{\mathrm{L2H}}$.

2) If SU_x is in the overlapped area between the old eNB and the new eNB, the $T'_E(\mathrm{SH}'_j)$ of SU_x can be recalculated by considering the handover to the new eNB with the assistance of RNs using the following expression:

$$T'_E(\mathrm{SH}'_j) = t'_{\mathrm{RN}'_w} + \frac{d_t}{P'_u(m'_i, t_{\mathrm{req}}) \times R'_i} + (1 + P'_u(m'_i, t'_{\mathrm{req}})) \times T_{\mathrm{L2H}} + T_{\mathrm{L3H}} \tag{2}$$

where $t'_{\mathrm{RN}'w} = \frac{d_t}{R_{\mathrm{WLAN}}}$ denotes the transmission time from SU_x through RN'_w, and T_{L3H} is the layer-3 handover delay time [17], which includes the duplicate address detection and location update times. The SU_x may perform a layer-3 handover and use the occupied spectrum hole, SH'_j, of the selected RN'_w if there is a small number of free spectrum holes in the next eNB, i.e., in a poor network connection environment. However, if there is enough free spectrum holes, it may directly use spectrum hole SH'_j in the next eNB without the assistance of RN'_w. In this case, $\frac{d_t}{R_{\mathrm{WLAN}}} = 0$. Equation (2) can be used to calculate the expected execution of a SU_x, including layer-3 handover latency, with the assistance of dynamic relay nodes, which is especially useful for poor network environments.

3) SU_x performs a spectrum mobility operation if $(t_{\mathrm{RN}_z} + \frac{d_t}{P_u(m_i, t_{\mathrm{req}}) \times R_i} + (1 - P_u(m_i, t_{\mathrm{req}})) \times T_{\mathrm{L2H}}) - (t'_{\mathrm{RN}'_w} + \frac{d_t}{P'_u(m'_i, t'_{\mathrm{req}}) \times R'_i} + (1 - P'_u(m'_i, t'_{\mathrm{req}})) \times T_{\mathrm{L2H}} + T_{\mathrm{L3H}}) < T_{\mathrm{L3H}}$. Otherwise, SU_x performs a handover procedure.

Fig. 5 shows an example of the evaluation and transmission phase of scenario one, the expected transmission time of SH_1 is $T_E(\mathrm{SH}_1) = 0 + \frac{10\,(\mathrm{Mb})}{0.408 \times 720} + (1 - 0.408) \times 0.05\,(\mathrm{s}) = 34.82\,(\mathrm{s})$, and the expected transmission time of spectrum hole SH_2 is calculated as $T_E(\mathrm{SH}_2) = \frac{10\,(\mathrm{Mb})}{540\,(\mathrm{Mb/s})} + \frac{10\,(\mathrm{Mb})}{0.717 \times 1080} + (1 - 0.717) \times 0.05\,(\mathrm{s}) =$

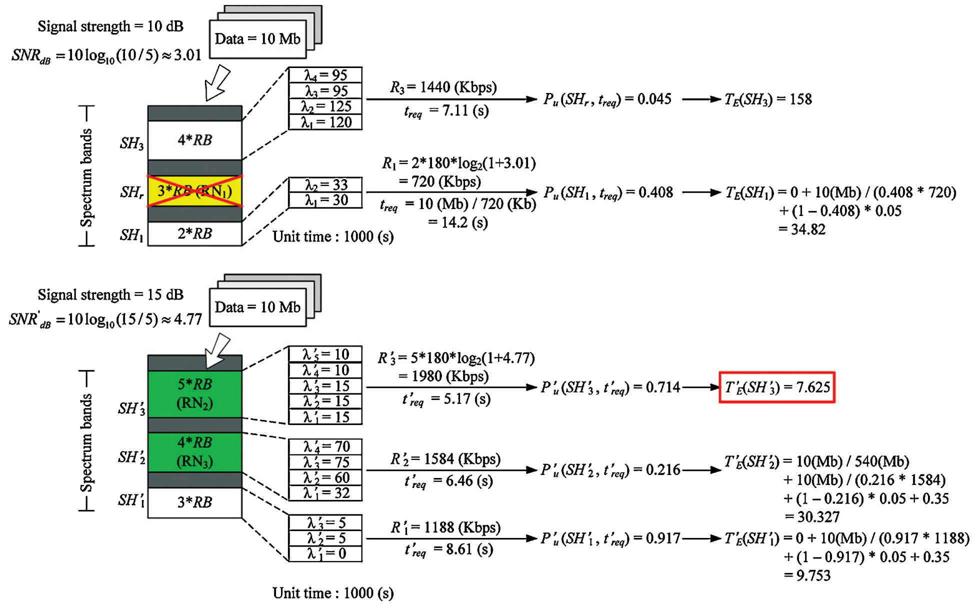


Fig. 6. Computation and analysis phase and evaluation and transmission phase in scenario two.

12.911. The expected transmission time of SH_3 is given in Fig. 5. SH_2 exhibits the minimum expected transmission time and is used by RN_1. Therefore, SU_1 performs a spectrum mobility operation through RN_1. When RN_1 receives data from the SU_1, and the data are relayed to the old eNB. Fig. 6 provides an example of the evaluation and transmission phases of scenario two, the expected transmission time of SH_1 in the old eNB is $T_E(\mathrm{SH}_1) = 0 + \frac{10\,(\mathrm{Mb})}{0.048\times 720} + (1-0.408)\times 0.05\,(\mathrm{s}) = 34.82\,(\mathrm{s})$ and the expected transmission time of spectrum hole SH'_2 in the new eNB are calculated as $T'_E(\mathrm{SH}'_2) = \frac{10\,(\mathrm{Mb})}{540\,(\mathrm{Mb/s})} + \frac{10\,(\mathrm{Mb})}{0.216\times 1584} + (1-0.216)\times 0.05\,(\mathrm{s}) + 0.35\,(\mathrm{s}) = 30.327.$ The expected transmission times of SH_3 (old eNB), SH'_1, and SH'_3 (new eNB) are given in Fig. 6. SH'_3 exhibits the minimum transmission time and is used by RN_3. Therefore, SU_1 performs a handover to the new eNB with the assistance of RN_3. Dynamic relay node RN_3 relays data to the new eNB when RN_3 receives data from SU_1.

V. Performance Analysis

In this section, we use an analytic model to analyze the TTT and TP for the proposed scheme. The Markov chain model is adopted and represented as a directed graph, as shown in Fig. 7. The SU_x uses SH_i over a given sequence of j spectrum holes (SH_1, SH_2, …, SH_i, …, SH_j) in the serving eNB, where $1 \le i \le j$. As previously discussed, two scenarios are considered for this analysis.

Without loss of generality, we can assume that SH_i has m RBs, where $1 \le m$. Let the data of the SU_x be divided into n packets. The Markov chain model is split into three parts, as shown in Fig. 7. In part I, an initial state of SH_i denotes SU_x transmitting data packets through SH_i. In part II, there are m RBs, where $1 \le m$. Therefore, there are m RB_i states, where $1 \le i \le m$. Each RB may be reclaimed by a PU, and therefore, m RBs are checked. If RB_i is reclaimed by a PU, the state changes to a relay-assisted or spectrum mobility operation to SH_i (part III); otherwise, the state increments to RB_{i+1}, where $1 \le i \le m$. If the RB_m state is reached and no blocks are reclaimed by a PU, the state is reinitialized to SH_i and no spectrum mobility operation is performed. In part III, relay-assisted or spectrum mobility operation to $SH_i{}'$ indicates that SU_x performs a spectrum mobility operation and changes the spectrum hole from SH_i to $SH_i{}'$ or performs data transmission with the assistance of a RN when SH_i is reclaimed by a PU. The state transition information is given below.

1) RB_i *to* RB_1: indicates that the previous packet was completely transmitted and next packet starts to be transmitted using SH_i.
2) RB_i *to* RB_{i+1}: there is a probability $e^{-\left(\frac{\lambda_i}{t_{\mathrm{unit}}}\times t_{\mathrm{req}}\right)}$ that RB_i is not reclaimed by a PU.
3) RB_i *to relay-assisted or spectrum mobility operation to* $SH_{i'}$: there is a $1-\prod_{k=1}^{i} e^{-\left(\frac{\lambda_i}{t_{\mathrm{unit}}}\times t_{\mathrm{req}}\right)}$ probability that RB_i is reclaimed by a PU and RB_i to RB_{i-1} are not reclaimed by a PU.
4) RB_m *to* SH_i: there is a probability $\prod_{k=1}^{m} e^{-\left(\frac{\lambda_i}{t_{\mathrm{unit}}}\times t_{\mathrm{req}}\right)}$ that RB_m is not reclaimed by a PU. This implies that all m RB_i are not reclaimed by a PU and SU_x can continue to use SH_i.
5) *Relay-assisted or spectrum mobility operation to* $SH_{i'}$ *to relay-assisted*: there is a probability $P_{\mathrm{relay}} \times (1 - \prod_{k=1}^{m} e^{-(\frac{\lambda_i}{t_{\mathrm{unit}}}\times t_{\mathrm{req}})})$ that SU_x transmits data through a RN.
6) *Relay-assisted or spectrum mobility operation to* $SH_{i'}$ *to spectrum mobility operation to* $SH_{i'}$: there is a probability $P_{\mathrm{spectrum\_mobility}} \times (1 - \prod_{k=1}^{m} e^{-(\frac{\lambda_i}{t_{\mathrm{unit}}}\times t_{\mathrm{req}})})$ that SU_x performs the spectrum mobility operation to change spectrum holes.

Let t_{unit} denote a period of time and λ_i be the number of RB_i reclaimed by a PU during t_{unit}. Let $t_{\mathrm{req}} = \frac{d_t}{m_i \times \mathrm{RB}_i \times \log_2(1+\mathrm{SNR_{dB}})}$ denote the required data transmission time between SU_x and the eNB through SH_i without considering λ_i P_{relay} is the probability of SU_x transmitting data through a RN when SH_i is reclaimed by PU, and P_{spectrum} is the probability of SU_x performing a spectrum mobility operation to a different spectrum hole. Note that $P_{\mathrm{spectrum\_mobility}} + P_{\mathrm{relay}} = 1$.

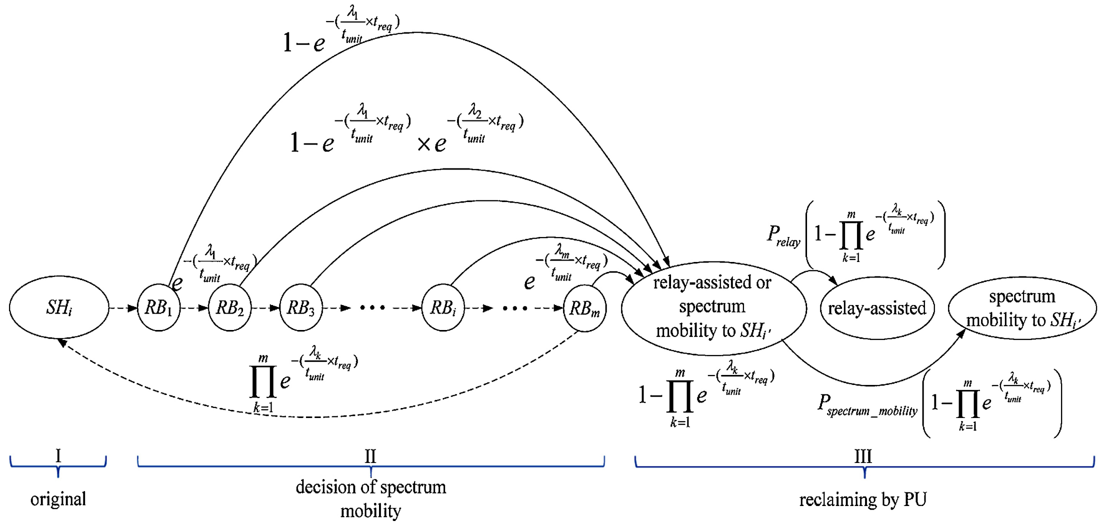


Fig. 7. Relationship between RBs in scenario one.

With the Poisson distribution, the probability that SH_i is not reclaimed by PUs can be denoted as $P_u(\mathrm{SH}_i, t_{\mathrm{req}})$.

Lemma 1: If there are m RBs in SH_i, the probability that SH_i is not reclaimed by PUs is

$$P_u(\mathrm{SH}_i, t_{\mathrm{req}}) = \prod_{k=1}^{m} e^{-(\frac{\lambda_k}{t_{\mathrm{unit}}}\times t_{\mathrm{req}})}. \tag{3}$$

Proof: The required transmission time is $t_{\mathrm{req}} = \frac{d_t}{m_i\times \mathrm{RB}_i\times \log_2(1+\mathrm{SNR}_{\mathrm{dB}})}$, where d_t is the size of the remaining data and R_i is the transmission rate of SH_i. This can be expressed with the Poisson distribution as

$$f(n;\gamma) = \frac{\gamma^n \times e^{-\gamma}}{n!} \tag{4}$$

■

where n is the total number of event occurrences and γ is a positive real number that is equal to the expected occurrence during a given time interval. The probability of the ith RB, RB_i, not being reclaimed by PUs during a time interval is $\gamma_i = \frac{\lambda_i\times t_{\mathrm{req}}}{t_{\mathrm{unit}}}$. Therefore, the probability of $P_u(\mathrm{SH}_i, t_{\mathrm{req}})$ can be represented as $\prod_{k=1}^{m} e^{-(\frac{\lambda_k}{t_{\mathrm{unit}}}\times t_{\mathrm{req}})}$.

The TTT is represented as

$$T_{\mathrm{TTT}} = \frac{1}{j}\sum_{i=1}^{j}\sum_{k=0}^{n-1}(T_{\mathrm{old\_eNB}} + t_{\mathrm{non\text{-}reclamimed}}) \quad where\ 1 \le i \le j \tag{5}$$

$T_{\mathrm{old\_eNB}}$ is the expected time required for SU_x to perform a spectrum mobility operation and switch to the new spectrum hole, $\mathrm{SH}_{i'}$, or use a RN for packet transmission. $T_{\mathrm{non\_reclaimed}}$ is the expected transmission time for SU_x packet transmission using the original spectrum hole, SH_i. The expected transmission times, $T_{\mathrm{old\_eNB}}$ and $T_{\mathrm{non\_reclaimed}}$, are calculated in the following.

Lemma 2: If there is a SU_x data packet that needs to be transmitted through eNB by spectrum hole $\mathrm{SH}_{i'}$, the expected transmission time, $T_{\mathrm{old\_eNB}}$, can be expressed as

$$\begin{aligned} T_{\mathrm{old\_eNB}} = {} & P_{\mathrm{spectrum\_mobility}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \\ & \times (T_{\mathrm{L2H}} + \tfrac{d_t}{R_i\times n}) + P_{\mathrm{relay}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \\ & \times (\tfrac{d_t}{R_{\mathrm{WLN}}\times n} + \tfrac{d_t}{R_i\times n}). \end{aligned} \tag{6}$$

Proof: The transmission time of a data packet is $T_{\mathrm{L2H}} + \frac{d_t}{R_i\times n}$ assuming SU_x needs to perform a spectrum mobility operation. Here, T_{L2H} is the time required for a spectrum mobility operation, and $\frac{d_t}{R_i\times n}$ is transmission time between the SU_x and serving eNB. If SU_x uses a RN node for data transmission, the transmission time between SU_x and RN can be expressed as $\frac{d_t}{R_{\mathrm{WLN}}\times n}$. The probability of spectrum mobility is $P_{\mathrm{spectrum\_mobility}}(1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}}))$, and the probability of the relay-assisted approach is $P_{\mathrm{relay}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}}))$. The expected transmission time can be expressed as $P_{\mathrm{spectrum\_mobility}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times (T_{\mathrm{L2H}} + \frac{d_t}{R_i\times n}) + P_{\mathrm{relay}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times \left(\frac{d_t}{R_{\mathrm{WLN}}\times n} + \frac{d_t}{R_i\times n}\right)$. ■

Lemma 3: If there is a SU_x data packet that needs to be transmitted through the serving eNB by the original spectrum hole, SU_x, the expected transmission time, $T_{\mathrm{non\_reclaimed}}$, can be expressed as

$$T_{\mathrm{non\_reclaimed}} = P_u(\mathrm{SH}_i, t_{\mathrm{req}}) \times \left(\frac{d_t}{R_i \times n}\right). \tag{7}$$

Proof: The probability of a non-reclaimed case is $P_u(\mathrm{SH}_i, t_{\mathrm{req}})$, and the transmission time of a data packet is $\frac{d_t}{R_i\times n}$. The expected transmission time, $T_{\mathrm{non\_reclaimed}}$, is $P_u(\mathrm{SH}_i, t_{\mathrm{req}}) \times \left(\frac{d_t}{R_i\times n}\right)$. ■

Theorem 1: In general, if there are j spectrum holes from SH_1 to SH_j for $1 \le i \le j$, and n data packets transmitted from SU_x to the serving eNB, ranging from P_0 to P_{n-1}, the expected TTT, T_{TTT}, can be expressed as

$$\begin{aligned} T_{\mathrm{TTT}} = {} & \frac{1}{j}\sum_{i=1}^{j}((1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \\ & \times (P_{\mathrm{spectrum\_mobility}} \times n \times T_{\mathrm{L2H}} + P_{\mathrm{relay}} \times t_{\mathrm{RN}}) + t_{\mathrm{req}}) \end{aligned}$$

where $1 \le i \le j$, $t_{\mathrm{req}} = \frac{d_t}{R_i}$, and $t_{\mathrm{RN}} = \frac{d_t}{R_{\mathrm{WLAN}}}$.

Proof: Based on Lemmas 2 and 3, the transmission time of a packet is $T_{\text{old\_eNB}}+T_{\text{non\_reclaimed}}$. Based on (5), the expected TTT is $T_{\text{TTT}} = \frac{1}{j}\sum_{i=1}^{j}\sum_{k=1}^{n-1} T_{\text{one\_packet}}$, which can be rewritten as the following:

$$\begin{aligned}
T_{\text{TTT}} &= \frac{1}{j}\sum_{i=1}^{j}\sum_{k=0}^{n-1}\left(P_{\text{spectrum_mobility}}\times(1-P_u(\text{SH}_i,t_{\text{req}}))\times\left(T_{\text{L2H}}+\frac{d_t}{R_i\times n}\right)\right)\\
&\quad +P_{\text{relay}}\times(1-P_u(\text{SH}_i,t_{\text{req}}))\times(\tfrac{d_t}{R_{\text{WLAN}}\times n}+\tfrac{d_t}{R_i\times n})\\
&\quad +P_u\times\tfrac{d_t}{R_i\times n})\\
&= \frac{1}{j}\sum_{i=1}^{j}(P_{\text{spectrum_mobility}}\times(1-P_u(\text{SH}_i,t_{\text{req}}))\times(n\times T_{\text{L2H}}+t_{\text{req}})\\
&\quad +P_{\text{relay}}\times(1-P_u(\text{SH}_i,t_{\text{req}}))\times(t_{\text{RN}}+t_{\text{req}})\\
&\quad +P_u(\text{SH}_i,t_{\text{req}})\times t_{\text{req}})\\
&= \frac{1}{j}\sum_{i=1}^{j}(P_{\text{spectrum_mobility}}\times n\times T_{\text{L2H}}-P_{\text{spectrum_mobility}}\\
&\quad \times P_u(\text{SH}_i,t_{\text{req}})\times n\times T_{\text{L2H}}\\
&\quad +P_{\text{relay}}\times t_{\text{RN}}-P_{\text{relay}}\times P_u(\text{SH}_i,t_{\text{req}})\times t_{\text{RN}}+t_{\text{req}}\\
&= \frac{1}{j}\sum_{i=1}^{j}(P_{\text{spectrum_mobility}}((1-(P_u(\text{SH}_i,t_{\text{req}})))\\
&\quad \times(P_{\text{spectrum_mobility}}\times n\times T_{\text{L2H}}\\
&\quad +P_{\text{relay}}\times T_{\text{RN}})+t_{\text{req}})
\end{aligned}$$

where $1 \le i \le j$, $t_{\text{req}} = \frac{d_t}{R_i}$ and $t_{\text{RN}} = \frac{d_t}{R_{\text{WLAN}}}$. ■

In this section, we further consider scenario two, in which an SU_x performs a spectrum mobility operation or handover with or without the assistance of a RN when SU_x is close or located at the overlapped area. As shown in Fig. 8, the Markov chain model is split into three parts.

In part I, initial state of SH_i denotes that SU_x transmits the data packet through the current spectrum hole, SH_i. In part II, there are m RBs, where $1 \le m$, and m RB_i states, where $1 \le i \le m$. Each RB may be reclaimed by a PU. Therefore, m RBs are checked once. If RB_i is reclaimed by a PU, then the state changes to a relay-assisted or spectrum mobility operation to $\text{SH}_{i'}$ or relay-assisted or handover to $\text{SH}'_{i'}$ (part III). Otherwise, the state is incremented to RB_{i+1}, where $1 \le i \le m$. If no states are reclaimed by RB_m, the state is reinitialized to SH_i without performing a spectrum mobility operation or handover procedure. In part III, the handover to $\text{SH}_{i'}$ state indicates that the SU_x performs a handover procedure and changes the spectrum hole from SH_i to $\text{SH}'_{i'}$. Additional state transition information is given as follows.

1) RB_i *to relay-assisted or spectrum mobility operation to* $\text{SH}_{i'}$: there is a probability $P_{\text{new\_eNB}}(1-\prod_{k=1}^{i} e^{-(\frac{\lambda_k}{t_{\text{unit}}}\times t_{\text{req}})})$ that RB_i is reclaimed by a PU, a spectrum mobility operation is performed, and all states from RB_1 to RB_{i-1} are not reclaimed by PUs.
2) RB_i *to relay-assisted or handover to* $\text{SH}'_{i'}$: there is a probability $P_{\text{new\_eNB}}(1-\prod_{k=1}^{i} e^{-(\frac{\lambda_k}{t_{\text{unit}}}\times t_{\text{req}})})$ that RB_i is reclaimed by a PU, a handover procedure is performed, and all states from RB_1 to RB_{i-1} are not reclaimed by PUs.
3) *Relay-assisted or spectrum mobility operation to* $\text{SH}_{i'}$ *to relay-assisted*: there is a probability $P_{\text{old\_eNB}} \times P_{\text{old\_relay}} \times (1-\prod_{k=1}^{m} e^{-(\frac{\lambda_k}{t_{\text{unit}}}\times t_{\text{req}})})$ that SU_x transmits data through a relay node by accessing the current (old) eNB.
4) *Relay-assisted or spectrum mobility operation to* $\text{SH}_{i'}$ *to spectrum mobility operation to* $\text{SH}_{i'}$: there is a probability $P_{\text{new\_eNB}} \times P_{\text{spectrum\_mobility}} \times (1-\prod_{k=1}^{m} e^{-(\frac{\lambda_k}{t_{\text{unit}}}\times t_{\text{req}})})$ that SU_x performs a spectrum mobility operation to change spectrum holes.
5) *Relay-assisted or handover to* $\text{SH}'_{i'}$ *to relay-assisted*: there is a probability $P_{\text{new\_eNB}} \times P_{\text{new\_relay}} \times (1-\prod_{k=1}^{m} e^{-(\frac{\lambda_k}{t_{\text{unit}}}\times t_{\text{req}})})$ that SU_x transmits data through a relay node by accessing the next (new) eNB.
6) *Relay-assisted or handover to* $\text{SH}'_{i'}$ *to handover to* $\text{SH}'_{i'}$: there is a probability $P_{\text{new\_eNB}} \times P_{\text{handover}} \times (1-\prod_{k=1}^{m} e^{-(\frac{\lambda_k}{t_{\text{unit}}}\times t_{\text{req}})})$ that SU_x performs the handover procedure.

In the following section, we derive the expected TTT of scenario two. If an SU_x only transmits packets through the serving (old) eNB or next (new) eNB, we can write the following expressions:

$$P_{\text{old\_eNB}} + P_{\text{new\_eNB}} = 1 \tag{8}$$

$$P_{\text{old\_eNB}} + P_{\text{spectrum\_mobility}} = 1 \tag{9}$$

$$P_{\text{new\_eNB}} + P_{\text{handover}} = 1 \tag{10}$$

where $P_{\text{old\_eNB}}$ is the probability of accessing the old eNB and $P_{\text{new\_eNB}}$ is the probability of accessing the new eNB. The expected TTT can be expressed as

$$T_{\text{TTT}} = \frac{1}{j}\sum_{i=1}^{j}\sum_{k=0}^{n-1}[(T_{\text{old\_eNB}} + T_{\text{new\_eNB}}) + T_{\text{non\_claimed}}] \tag{11}$$

where $1 \le i \le j$ and $T_{\text{new\_eNB}}$ are the expected time required for SU_x to perform the handover and use the new spectrum hole, SH'_i, in the new eNB for data packet transmission. $T_{\text{non\_handover}}$ is the expected time required for SU_x data packet transmission using the original SH_i in the old eNB. In the following, the expected transmission times, $T_{\text{new\_eNB}}$ and $T_{\text{old\_eNB}}$, are calculated.

Lemma 4: If there is one packet transmitted to the new eNB, SU_x needs to perform the handover to the new eNB. The expected transmission time, $T_{\text{new\_eNB}}$, can be expressed as

$$\begin{aligned}
T_{\text{new_eNB}} &= P_{\text{new_eNB}} \times P_{\text{handover}} \times (1-P_u(\text{SH}_i,t_{\text{req}}))\\
&\quad \times\left(T_{\text{L2H}}+T_{\text{L3H}}+\tfrac{d_t}{R_i\times n}\right)\\
&\quad +P_{\text{new_eNB}}+P_{\text{new_relay}}\times(1-P_u(\text{SH}_i,t_{\text{req}}))\\
&\quad \times\left(T_{\text{L3H}}+\tfrac{d_t}{R_{\text{WLAN}}\times n}+\tfrac{d_t}{R_i\times n}\right).
\end{aligned}\tag{12}$$

Proof: The probability of a handover to $\text{SH}'_{i'}$ of SU_x is $P_{\text{new\_eNB}} \times P_{\text{handover}} \times (1-P_u(\text{SH}_i, t_{\text{req}}))$. The transmission time is $T_{\text{L2H}}+T_{\text{L3H}}+\frac{d_t}{R_i\times n}$, where T_{L2H} is the spectrum mobility time, T_{L3H} is the L3 handover time, and $\frac{d_t}{R_i\times n}$ is the time cost of one packet transmission. If SU_x uses a RN to access the new eNB for the data transmission, the transmission time between the SU_x and RN is $\frac{d_t}{R_{\text{WLAN}}\times n}$. The probability of a relay-assisted approach is $P_{\text{new\_eNB}} + P_{\text{new\_relay}} \times (1-P_u(\text{SH}_i, t_{\text{req}}))$, and the expected transmission time is $P_{\text{new\_eNB}} \times P_{\text{handover}} \times (1-P_u(\text{SH}_i, t_{\text{req}})) \times (T_{\text{L2H}} + T_{\text{L3H}} + \frac{d_t}{R_i\times n}) + P_{\text{new\_eNB}} + P_{\text{new\_relay}} \times (1-P_u(\text{SH}_i, t_{\text{req}})) \times (T_{\text{L3H}} + \frac{d_t}{R_{\text{WLAN}}\times n} + \frac{d_t}{R_i\times n})$. ■

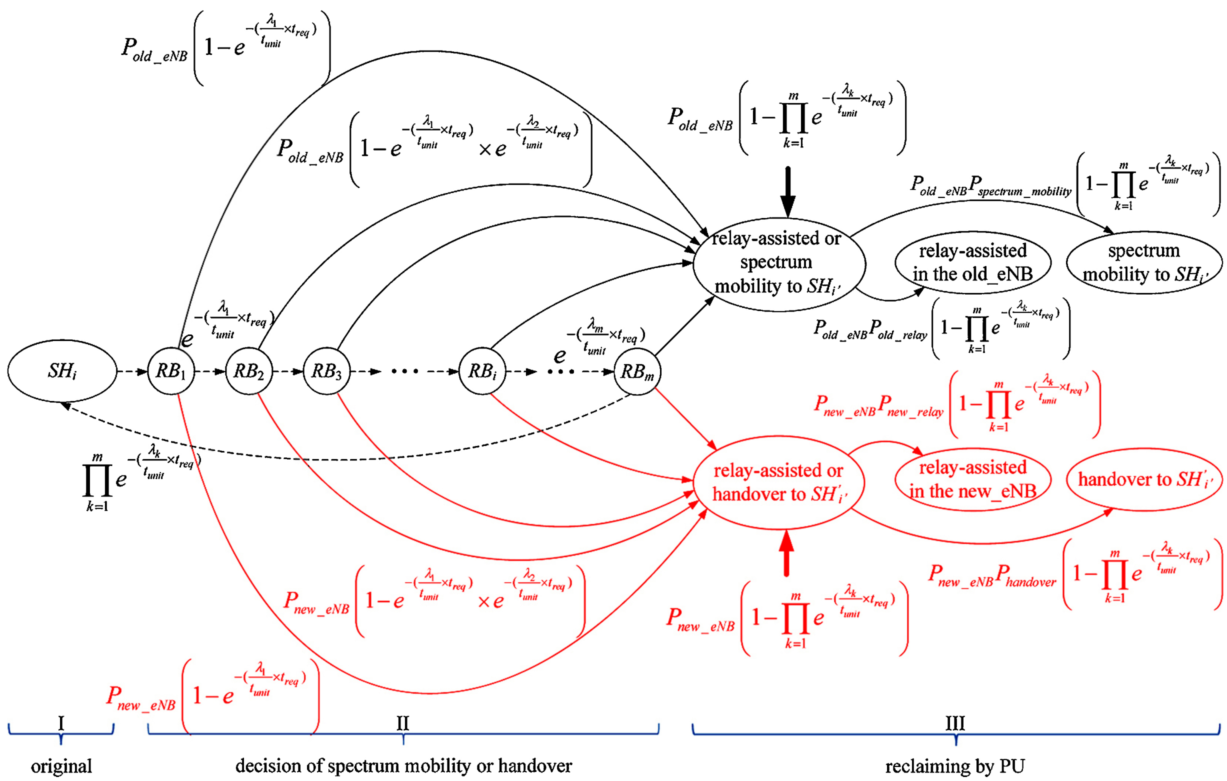


Fig. 8. Relationship between spectrum mobility and handover in scenario two.

Lemma 5: If there is one packet to be transmitted from SU_x to the serving eNB through a different spectrum hole, $SH_{i'}$, the expected transmission time, $T_{\mathrm{old\_eNB}}$, can be expressed as

$$T_{\mathrm{old\_eNB}} = P_{\mathrm{old\_eNB}} \times P_{\mathrm{spectrum\_mobility}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times \left(T_{\mathrm{L2H}} + \frac{d_t}{R_i \times N}\right) + P_{\mathrm{old\_eNB}} + P_{\mathrm{old\_relay}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times \left(\frac{d_t}{R_{\mathrm{WLAN}} \times n} + \frac{d_t}{R_i \times n}\right). \tag{13}$$

Proof: The transmission time of one packet is $T_{\mathrm{L2H}} + \frac{d_t}{R_i \times n}$ if SU_x needs to perform a spectrum mobility operation. Here, T_{L2H} is the time cost of the spectrum mobility operation and $\frac{d_t}{R_i \times n}$ is transmission time between SU_x and the serving eNB. If SU_x uses an RN for data transmission, the transmission time between SU_x and RN is $\frac{d_t}{R_{\mathrm{WLAN}} \times n}$. The probability of performing a spectrum mobility operation is $P_{\mathrm{old\_eNB}} \times P_{\mathrm{spectrum\_mobility}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}}))$, and the probability of the relay-assisted approach is $P_{\mathrm{old\_eNB}} + P_{\mathrm{old\_relay}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}}))$. The expected transmission time is $P_{\mathrm{old\_eNB}} \times P_{\mathrm{spectrum\_mobility}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times (T_{\mathrm{L2H}} + \frac{d_t}{R_i \times n}) + P_{\mathrm{old\_eNB}} + P_{\mathrm{old\_relay}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times (\frac{d_t}{R_{\mathrm{WLAN}} \times n} + \frac{d_t}{R_i \times n})$.

Theorem 2: If there are j spectrum holes from SH_1 to SH_j, for $1 \le i \le j$, and n data packets to be transmitted from SU_x to the serving (old) eNB or the next (new) eNB, ranging from P_0 to P_{n-1}, then the expected TTT, T_{TTT}, can be written as

$$\begin{aligned}
T_{\mathrm{TTT}} = \frac{1}{j} \sum_{i=1}^{j} \sum_{k=0}^{n-1} \Big\{ & P_{\mathrm{old_eNB}} \times P_{\mathrm{spectrum_mobility}} \\
& \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times \left(T_{\mathrm{L2H}} + \frac{d_t}{R_i \times n}\right) \\
& + P_{\mathrm{old_eNB}} + P_{\mathrm{old_relay}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \\
& \times \left(\frac{d_t}{R_{\mathrm{WLAN}} \times n} + \frac{d_t}{R_i \times n}\right) \\
& + P_{\mathrm{new_eNB}} + P_{\mathrm{handover}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \\
& \times \left(T_{\mathrm{L2H}} + T_{\mathrm{L3H}} + \frac{d_t}{R_i \times n}\right) \\
& + P_{\mathrm{new_eNB}} + P_{\mathrm{new_relay}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \\
& \times \left(T_{\mathrm{L3H}} + \frac{d_t}{R_{\mathrm{WLAN}} \times n} + \frac{d_t}{R_i \times n}\right) \\
& + P_u(\mathrm{SH}_i, t_{\mathrm{req}}) \times \frac{d_t}{R_i \times n} \Big\} \\
= \frac{1}{j} \sum_{i=1}^{j} \sum_{k=0}^{n-1} \Big\{ & T_{\mathrm{L2H}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \\
& \times (P_{\mathrm{old_eNB}} \times P_{\mathrm{spectrum\text{-}mobility}} + P_{\mathrm{new_eNB}} \\
& + P_{\mathrm{handover}}) + \frac{d_t}{R_{\mathrm{WLAN}} \times n} \\
& \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times (P_{\mathrm{old_eNB}} + P_{\mathrm{old_relay}} + P_{\mathrm{new_eNB}} \\
& + P_{\mathrm{new_relay}}) + P_{\mathrm{new_eNB}} \times (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times \frac{d_t}{R_i \times n} \Big\} \\
= \frac{1}{j} \sum_{i=1}^{j} \sum_{k=0}^{n-1} \Big\{ & (1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times [T_{\mathrm{L2H}} \ nonumber \\
& \times (P_{\mathrm{old_eNB}} \times P_{\mathrm{spectrum_mobility}} + P_{\mathrm{new_eNB}} \\
& + P_{\mathrm{handover}}) + \frac{d_t}{R_{\mathrm{WLAN}} \times n} \times (P_{\mathrm{old_eNB}} \\
& + P_{\mathrm{old_relay}} + P_{\mathrm{new_eNB}} + P_{\mathrm{new_relay}}) \\
& + T_{\mathrm{L3H}} \times P_{\mathrm{new_eNB}}] + \frac{d_t}{R_i \times n} \Big\}
\end{aligned}$$

$$= \frac{1}{j}\sum_{i=1}^{j}\{(1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times [n \times T_{\mathrm{L2H}} \times (P_{\mathrm{old\_eNB}} \times P_{\mathrm{spectrum\_mobility}} + P_{\mathrm{new\_eNB}}) + P_{\mathrm{handover}}) + t_{\mathrm{RN}} \times n \times (P_{\mathrm{old\_eNB}} + P_{\mathrm{old\_relay}} + P_{\mathrm{new\_eNB}} + P_{\mathrm{new\_relay}}) + n \times T_{\mathrm{L3H}} \times P_{\mathrm{new\_eNB}}] + t_{\mathrm{req}}\}$$

where $1 \le i \le j$, $t_{\mathrm{req}} = \frac{d_t}{R_i}$, and $t_{\mathrm{RN}} = \frac{d_t}{R_{\mathrm{WLAN}}}$. ■

The TP of the proposed protocol is also analyzed. In general, the TP is equal to the data size divided by the TTT and expressed as

$$\mathrm{TP} = \frac{d_t}{T_{\mathrm{TTT}}}. \quad (14)$$

Theorem 3: Assuming an SU_x data size of d_t and a TTT of T_{TTT}, where T_{TTT} is derived from Theorem 1 for scenario one (SU_x is in the nonoverlapped area) and Theorem 2 for scenario two (SU_x is close to or in the overlapped area), the respective TPs, TP_1 and TP_2, are derived as follows:

$$\mathrm{TP}_1 = \frac{d_t \times j}{\sum_{i=1}^{j}((1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times (P_{\mathrm{spectrum\_mobility}} \times n \times T_{\mathrm{L2H}} + P_{\mathrm{relay}} \times t_{\mathrm{RN}}) + t_{\mathrm{req}})}. \quad (15)$$

Proof: Based on Theorem 1, TP TP_1 is expressed as

$$\mathrm{TP}_1 = \frac{d_t}{\frac{1}{j}\sum_{j=1}^{i}((1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times (P_{\mathrm{spectrum\_mobility}} \times n \times T_{\mathrm{L2H}} + P_{\mathrm{relay}} \times t_{\mathrm{RN}}) + t_{\mathrm{req}})}$$
$$= \frac{d_t \times j}{\sum_{j=1}^{i}((1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \times (P_{\mathrm{spectrum\_mobility}} \times n \times T_{\mathrm{L2H}} + P_{\mathrm{relay}} \times t_{\mathrm{RN}}) + t_{\mathrm{req}})}.$$

The derivation of TP_2 is similar to that of TP_1 and is omitted for simplicity. ■

Finally, the number of spectrum mobility (NSM) operations and handovers were also analyzed.

Lemma 6: If there is one SU_x packet to be transmitted to the serving eNB through SH_i, the probability that SH_i is reclaimed by PUs is

$$\frac{1}{j}\sum_{i=1}^{j}\left(1 - \prod_{k=1}^{m} e^{-\left(\frac{\lambda_k}{t_{\mathrm{unit}}} \times t_{\mathrm{req}}\right)}\right). \quad (16)$$

Proof: Based on Lemma 1, the probability that SH_i is not reclaimed by PUs is $P_u(\mathrm{SH}_i, t_{\mathrm{req}}) = \prod_{k=1}^{m} e^{-\left(\frac{\lambda_k}{t_{\mathrm{unit}}} \times t_{\mathrm{req}}\right)}$. Then, the probability that SH_i is reclaimed by PUs can be expressed as

$$\begin{aligned} &= \frac{1}{j}\sum_{i=1}^{j}(1 - P_u(\mathrm{SH}_i, t_{\mathrm{req}})) \\ &= \frac{1}{j}\sum_{i=1}^{j}\left(1 - \prod_{k=1}^{m} e^{-\left(\frac{\lambda_k}{t_{\mathrm{unit}}} \times t_{\mathrm{req}}\right)}\right). \end{aligned} \quad (17)$$

■

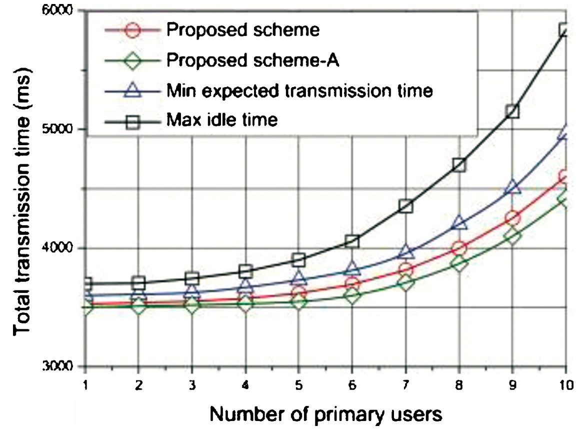


Fig. 9. TTT versus number of PUs in scenario one.

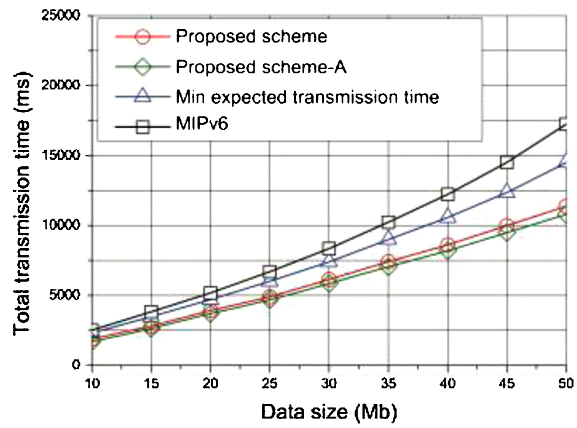


Fig. 10. TTT versus data size in scenario two.

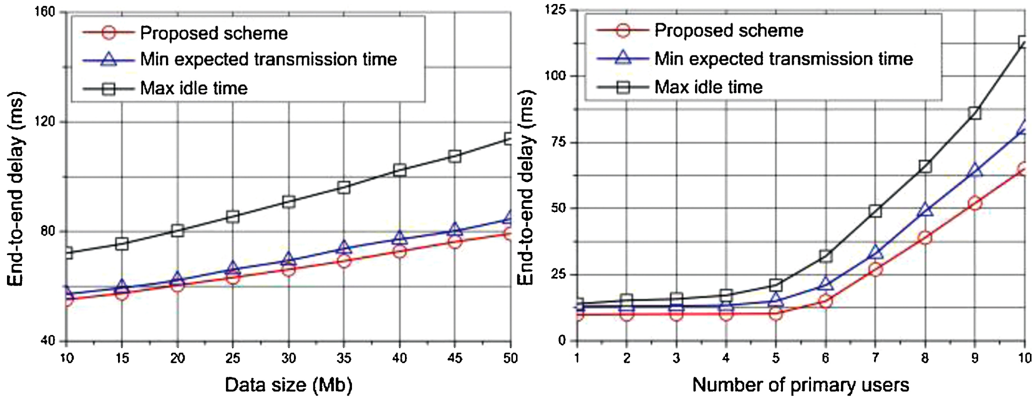
Theorem 4: Assuming that the SU_x data size is d_t and can be divided into n packets, the expected NSM operations or handovers can be expressed as

$$\mathrm{OH} = \frac{1}{j}\sum_{i=1}^{j} n \times \left(1 - \prod_{k=1}^{m} e^{-\left(\frac{\lambda_k}{t_{\mathrm{unit}}} \times t_{\mathrm{req}}\right)}\right). \quad (18)$$

Proof: The probability of spectrum mobility operations or handovers during a single packet transmission is $1 - \prod_{k=1}^{m} e^{-\left(\frac{\lambda_k}{t_{\mathrm{unit}}} \times t_{\mathrm{req}}\right)}$, and the expected NSM operations or handovers for one packet is $\frac{1}{j}\sum_{i=1}^{j}\left(1 - \prod_{k=1}^{m} e^{-\left(\frac{\lambda_k}{t_{\mathrm{unit}}} \times t_{\mathrm{req}}\right)}\right)$. Consequently, the expected NSM operations or handovers for a data size of d_t is $\frac{1}{j}\sum_{i=1}^{j} n \times \left(1 - \prod_{k=1}^{m} e^{-\left(\frac{\lambda_k}{t_{\mathrm{unit}}} \times t_{\mathrm{req}}\right)}\right)$. ■

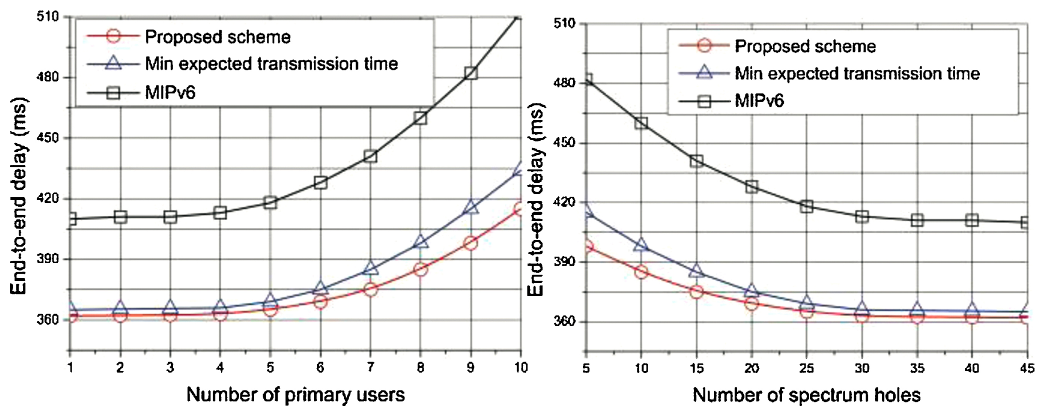
VI. Simulation Results

This paper presents a relay-assisted, cross-layer protocol of spectrum mobility and handover in cognitive LTE systems. To evaluate our proposed protocol, two simulation scenarios are implemented using the network simulator-2 (NS-2) [22], NS-2 CR network model [23], and 3GPP module [24]. The simulation is performed under two scenarios. The proposed scheme is compared to the layer-2 scheme. In simulation scenario one, our proposed scheme compares the spectrum



(a) (b)

Fig. 11. (a) EED versus data size in scenario one. (b) EED versus number of PUs in scenario one.



(a) (b)

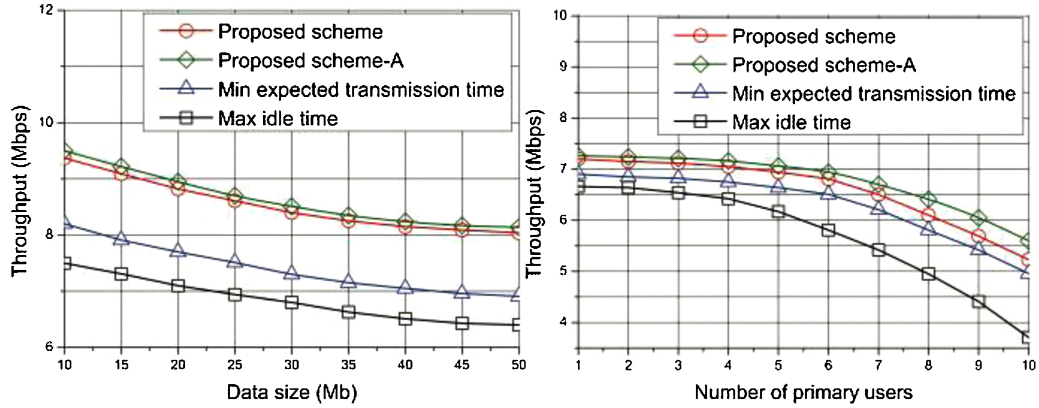
Fig. 12. (a) EED versus number of PUs in scenario two. (b) EED versus number of spectrum hole in scenario two.

mobility result of [17] by adopting the minimum expected transmission time, T_E, without RN assistance. The *max idle time* utilizes the predictive channel selection scheme that is based on the concept of the maximum idle time proposed by Hoyhtya *et al.* [25]. Proposed scheme A is represented as the analysis results of our proposed scheme, which is derived from the performance analysis described in Section V. That is, proposed scheme A represents the theoretical results and proposed scheme represents the numerical results. In simulation scenario two, our proposed scheme is compared to the results of the mobile IPv6 protocol, also known as MIPv6, [26] and handover results [17] that adopted the minimum expected transmission time without RN assistance. The system parameters are given in Table I, and we consider the expected transmission time, T_E, as a simulation parameter. If T_E is large, then the expected transmission time of the spectrum hole will be high. This implies that the SU experiences a higher risk of PUs reclaiming resources and also results in frequent spectrum mobility operations and handovers. Small values of T_E imply a high service data transmission success rate and a reduced probably of resources being reclaimed by PUs. The performance metrics measured are described as follows.

1) The TTT is the data transmission time interval between an SU and corresponding node, CN, through the old eNB or the new eNB. The TTT is estimated from the first packet transmitted from CN to the final packet received by SU through the old eNB or the new eNB.
2) The EED is the average delay time for every packet of data that can be transmitted from an SU to CN by the old eNB or the new eNB. For the same data size, large values of EED correspond to higher T_E values.
3) The TP is the total number of data packets that can be transmitted and received between an SU–CN pair per unit time.
4) The NSM is the total NSM operations during data transmission between an SU–CN pair.

A. Total Transmission Time

The simulation results of TTT, for various data sizes and numbers of PUs, using simulation scenario one are shown in Fig. 9. Fig. 9 shows the observed TTT under different numbers of PUs, where P_u is fixed at 0.5. Fig. 9 shows that the TTT curve of our proposed protocol is lower than that of the minimum expected transmission time and maximum idle time schemes for different numbers of PUs. We also observed that the TTT of the proposed scheme was low if the number of PUs was low, which was also observed in proposed scheme A. Finally, Fig. 9 shows that the TTT curve in our proposed scheme is lower than that of the minimum expected transmission time and maximum idle time schemes



(a) (b)

Fig. 13. (a) TP versus data size in scenario one. (b) TP versus number of PUs in scenario one.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
BS transmission range	50 km
Network size	300 km × 300 km
SUs sensing range	1 km
SUs speed	0–50 km/h
No. of SUs	0–20
Spectrum sensing period	40 ms
Spectrum switching delay	10 ms
Transfer delay	10 ms
Handover delay	200–350 ms
Packet size	1500
Simulation time	Bytes 100–1000 s

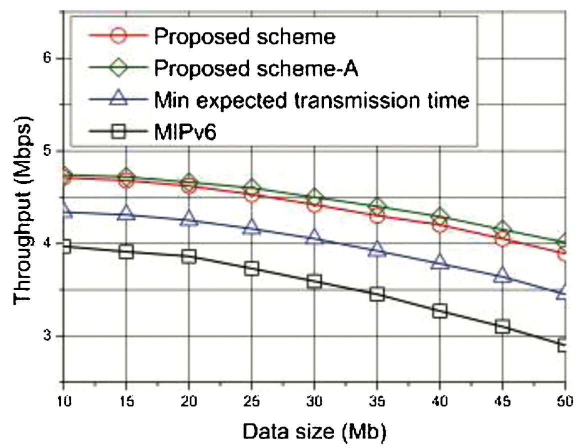


Fig. 14. TP versus data size in scenario two.

for different numbers of PUs. This is because our scheme adopts the minimum expected transmission time scheme with RN assistance.

The TTT simulation results for various data sizes and numbers of PUs for simulation scenario two are shown in Fig. 10. Fig. 10 shows the observed TTT for various data sizes, where P_u is fixed at 0.5. We observed that the TTT curve for our proposed scheme was low for small data sizes, which was also observed in proposed scheme A, as illustrated in Fig. 10. Fig. 10 also shows that the TTT curve for our scheme is lower than that of the minimum expected transmission time and MIPv6 schemes for various data sizes.

B. End-to-End Delay

The EED simulation results for various data sizes and numbers of PUs for simulation scenario one are shown in Fig. 11. Fig. 11(a) shows the observed EDD under various data sizes (ranging from 10 to 50 Mb), where P_u is fixed at 0.5. In general, the EDD increases as the number of PUs increases. Fig. 11(a) illustrates that the EED curve for our scheme is lower than that of the minimum expected transmission time and maximum idle time schemes. In general, the EED drops as the number of spectrum holes increases. Fig. 11(b) shows the observed EDD under various data sizes, where P_u is fixed at 0.5. Fig. 11(b) illustrates that the EED curve for our scheme is lower than that of the minimum expected transmission time and maximum idle time schemes. This is because our scheme adopts the minimum expected transmission time scheme with RN assistance. Fig. 12 illustrates the EED simulation results for various numbers of PUs and spectrum holes for simulation scenario two. In general, the EED increases as the number of PUs increases and spectrum holes decreases. Fig. 12(a) shows that our scheme has less EDD than that of the minimum expected transmission time and MIPv6 protocols because that our scheme utilizes RN assistance. Our proposed scheme adopts the dynamic spectrum resource scheme by dynamically collecting spectrum hole information from dynamic RNs, especially in poor network environments. This information is useful for our layer-3 handoff procedure because it selects large size spectrum holes. Fig. 12(b) confirms that the EDD of our proposed scheme is less than that of the minimum expected transmission time and MIPv6 protocols for various numbers of spectrum holes.

C. Throughput

The TP simulation results for various data sizes and number of PUs for simulation scenario one are shown in Fig. 13. Fig. 13(a) shows the observed TP under various data sizes, where P_u is fixed at 0.5. The TP of the proposed scheme drops as the data size increases, which was also observed in proposed scheme A. Fig. 13(a) illustrates that the TP curve for our scheme is higher than that of the minimum expected

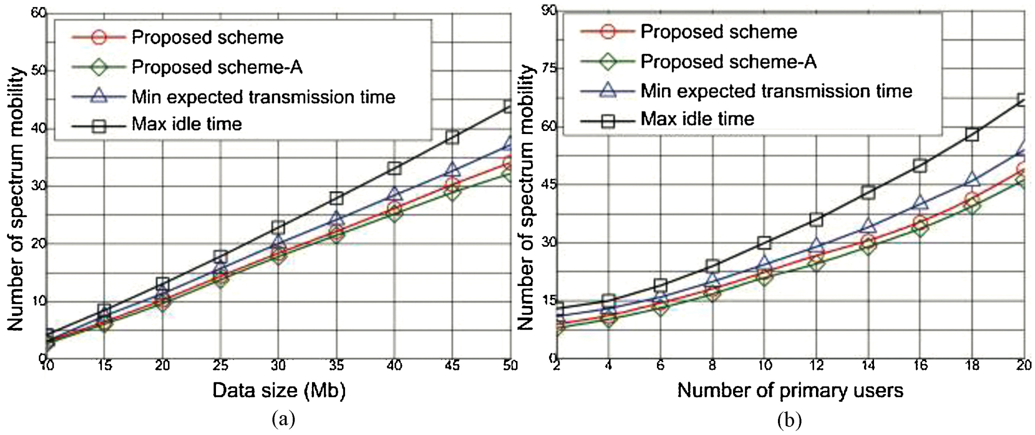


Fig. 15. (a) Number of spectrum mobility versus data size in scenario one. (b) Number of spectrum mobility versus number of PUs in scenario one.

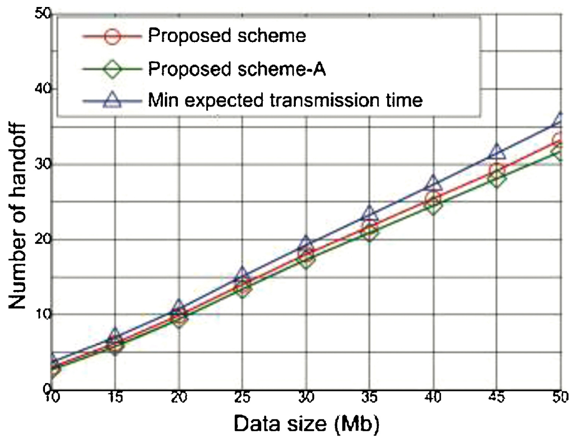


Fig. 16. Number of handoff versus data size in scenario two.

transmission time and maximum idle time schemes under various data sizes. The TP of the proposed scheme drops as the number of PUs increases, which was also observed in proposed scheme A, as shown in Fig. 13(b). Fig. 13(b) illustrates that the TP curve for our scheme is higher than that of the minimum expected transmission time and that maximum idle time schemes under various number of PUs. This is because our scheme adopts the minimum expected transmission time with RN assistance. Fig. 14 shows the simulated TP results of various data sizes for the simulation scenario two. The TP of the proposed scheme drops as the data size increases, which was also observed in proposed scheme A. Fig. 14 shows that the MIPv6 protocol has the lowest TP value because the fixed spectrum resource scheme is used in the MIPv6 protocol. It also shows that our scheme has a better TP value than the minimum expected transmission time scheme because our scheme utilizes RN assistance.

D. Number of Spectrum Mobility

The simulation results of the NSM under various data sizes and number of PUs for simulation scenario one are shown in Fig. 15. Fig. 15(a) shows the NSM for various data sizes, where P_u is fixed at 0.5. In general, the NSM drops as the data size decreases. Fig. 15(a) shows that the NSM curve for our scheme is lower than that of the minimum expected transmission time and maximum idle time schemes for various data sizes. In general, the NSM drops as the number of PUs decreases. Fig. 15(b) shows that the NSM curve for our scheme is lower than that of the minimum expected transmission time and maximum idle time schemes under various numbers of PUs. In addition, Fig. 16 shows the NSM simulation results under various data sizes for simulation scenario two. In general, the NSM drops as the data size decreases. Fig. 16 illustrates that the NSM curve for our scheme is lower than that of the minimum expected transmission time scheme.

VII. Conclusion

This paper described a relay-assisted protocol for spectrum mobility and handover with a minimum expected transmission time in cognitive LTE networks. A performance improvement was demonstrated in the relay-assisted cross-layer handoff protocol with dynamic relay nodes. We presented an in-depth performance analysis of the relay-assisted spectrum mobility and handover protocol to better characterize this performance enhancement. Our simulation results illustrated that the proposed cross-layer protocol, with the assistance of RNs, can significantly reduce the expected transmission time and spectrum mobility ratio, especially in poor network environments.

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