A Cross-Layer Protocol of Spectrum Mobility and Handover in Cognitive LTE Networks

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Abstract

Cognitive radio technique is the next step toward efficient wireless bandwidth utilization. While some of the spectrum bands (unlicensed band) have been increasingly usage, most of the other spectrum resources (licensed band) are underutilized. This drives the challenges of open spectrum and dynamic spectrum access concepts, which allows unlicensed users (or called secondary users, SUs) equipped with cognitive radios to opportunistically access the spectrum not used by licensed users (or called primary users, PUs). Most existing results mainly focus on designing the lower layer cognitive radio problems. In the literature, this is the first result to investigate the higher layer solution for cognitive radio networks. In this paper, we present a cross-layer protocol of spectrum mobility (layer-2) and handover (layer-3) in cognitive LTE networks. With the consideration of the Poisson distribution model of spectrum resources, a cross-layer handoff protocol with the minimum expected transmission time is developed in cognitive LTE networks. Performance analysis of the proposed handoff protocol is investigated. Finally, simulation results illustrates the proposed handoff protocol significantly reduces the expected transmission time and the spectrum mobility ratio.

Keywords: *Cognitive radio, cross-layer, spectrum mobility, handover, LTE networks.*

1 Introduction

Over the past years, traditional approaches to spectrum management have been challenged by new insights into actual use of spectrum. Due to the wireless network bandwidth constraints can not fully take advantage of all of the radio spectrum resources for mobile devices and power supply can not continue to use, and the free and unutilized radio spectrum resources is very frequent to lead the low utilization of the radio spectrum. According to Federal Communications Commission (FCC), temporal and geographical variations in the utilization of the assigned spectrum range from 15% to 85% [11][17]. In order to improve the utilization of the overall radio spectrum, the cognitive radio (CR) network is a useful solution to this low utilization of the radio spectrum.

The cognitive radio (CR) concept is first presented by Joseph Mitola III *et al.* [21]. In CR networks, there are two types of users; one is licensed users (primary users or PUs), and the another is unlicensed users (secondary user or SUs). PUs can access the wireless network resources anytime and anywhere. SUs equipped with cognitive radios to opportunistically access the spectrum not used by PUs. When a PU reclaims the radio spectrum resources, the SU detects the reclamation and immediately moves away the current radio spectrum resources and switch to idle radio spectrum resources. To perform above operations of PUs and SUs in CR networks, the spectrum sensing, the spectrum management, the spectrum sharing, and the spectrum mobility are four important functions. Spectrum sensing is the first important issue to find an idle radio spectrum and detect the appearance of PUs. In the literatures [9][19][20][23][26], the spectrum sensing technology can effectively and rapidly sensing the spectrum holes.

With the development of wireless network technology, the wireless mobile access has been progressed by second-generation (2G) and third-generation (3G) cellular systems. In recent years, the Third Generation Partnership Project (3GPP) has proposed a 3G long term evolution (LTE) [1][6] toward 4G cellular systems. LTE is based on the universal terrestrial radio access (UTRA) and high speed down-link packet access (HSDPA) and further strengthen its communications capacity to upload in order to enhance its quality of service. LTE have to coexist with 2G/3G systems, WLAN, WiMAX, etc. The handover protocols are very important for the mobile networks [10][18][22].

Recently, Software Defined Radio (SDR) is a revolutionary technology [13][14][25] to implement the CR networks. The SDR is the first development to integrate different communication capabilities. To upgrade the inconvenience and inflexibility of hardware architecture, a SDR with the programmable and reconfigurable modules is integrated with different communication protocols. A mobile terminal (SU) with SDR device uses the sensing device in the physical layer to periodically sense the current signal strength and the idle spectrum resources. With the sensed information, the SU dynamically selects a suitable spectrum hole for the spectrum mobility.

Most existing results mainly focus on designing the lower layer cognitive radio problems. The main contribution of this paper is the first investigation of the higher layer cognitive radio problem. In this paper, we present a cross-layer protocol of spectrum mobility (layer-2) and handover (layer-3) in cognitive LTE networks. With the consideration of the Poisson distribution of spectrum resources, we develop a cross-layer handoff protocol with the minimum expected transmission time in cognitive LTE networks. Simulation results illustrates the proposed handoff protocol significantly reduces the expected transmission time and the spectrum mobility ratio.

The remainder of this paper is organized as follows. In section 2, related works are described. Section 3 overviews the system architecture, and the basic ideas of the proposed schemes. Section 4 describes the proposed hybrid spectrum mobility and handover protocol. Performance analysis and simulation result are presented in sections 5 and 6. Section 7 concludes this paper.

2 Related Works

In the literature [7][15][16][20][26], most existing results focus on designing the lower layer (layer-1 or layer-2) cognitive radio problems.

First, the spectrum sensing is the main layer-1 task of CR system to obtain the spectrum usage information and existence information of PUs. The traditional spectrum sensing is measured by the spectral content and the radio frequency energy. In the CR, the spectrum sensing is measured under more spectrum characteristics, such as the space, time, frequency and modulation code to determine which spectrum resource is occupied. Pawełczak *et al*. [20] proposed a spectrum sensing method based on the framework of opportunistic spectrum access networks (OSAN) to search for the available spectrum. In the OSAN framework, it divides these nodes into different clusters, each OSAN node sends the sensing information to the cluster header in the spectrum sensing cycle. Each cluster header keeps the spectrum information and the licensed user (LU) occupied channel information. The information is exchanged between cluster headers and then be forwarded to all OSAN nodes to make the accurate decision of the channel allocation. Yucek *et al*. [26] then proposed a partial match-filtering method to have a priory information about transmission properties of feasible PUs. To having the robust spectrum sensing results, the spectrum sensing algorithm finds the available spectrum for the data transmission by detecting the presence of PUs.

Second, the dynamic spectrum allocation (DSA) is the main layer-2 task of CR system to exploit the temporal and spatial traffic statistics to allocate the underutilized spectrum to SUs. Ohyun *et al*. [16] proposed a spectrum matching algorithms to efficiently allocate spectrum holes to SUs in the CR architecture. To minimize the probability of spectrum mobility, the spectrum matching algorithm is executed based on the different sizes of the underutilized spectrum holes and the different holding times, while the holding time is the predicted holding time for a specific spectrum hole. The spectrum matching algorithm selects and assigns a spectrum hole which is most closed to the real spectrum holding time. Akbar *et al*. [7] recently proposed a markov-based channel prediction algorithm (MCPA), where the channel occupancy of PUs is assumed by Poisson distribution. This algorithm utilizes the hidden markov model (MHH) to predict the appearance of spectrum holes in different spectrum bands. In addition, Hoyhtya *et al*. [15] proposed a simple classification and learning of predictive channel selection method. To choose a channel with the largest idle time, this predictive channel selection method is performed based on the statistics of spectrum sensing results and the channel history. The objective of the paper is to provide insights about the higher layer cognitive radio problem while most existing results mainly focus on designing the lower layer cognitive radio problems.

Efforts will be made in this work to develop a higher layer cognitive radio problem. In this paper, we present a cross-layer protocol of spectrum mobility (layer-2) and handover (layer-3) in cognitive LTE networks.

3 Preliminaries and Basic Ideas

This section describes the LTE systems architecture and the system model. We then explain the basic idea and the design challenges of our work.

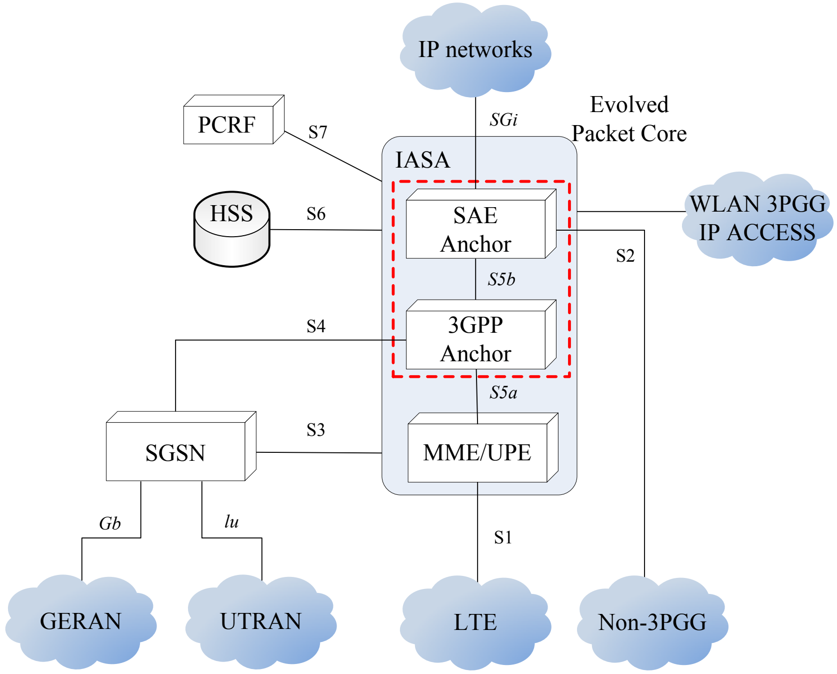


Figure 1: The 3GPP LTE systems architecture.

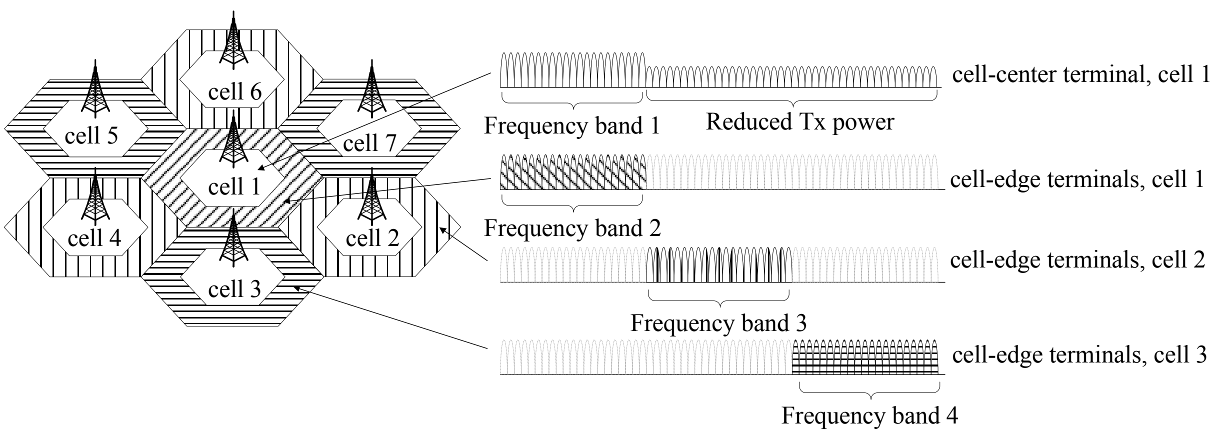


Figure 2: Example of inter-cell interference coordination.

3.1 Cognitive Radio LTE Systems Architecture and System Model

A LTE system/network is called as a cognitive radio LTE system/network, CR-LTE system/network, if the LTE system/network is adopted the cognitive radio technique. Existing heterogeneous system requires a wide range of agreements to integrate with different kinds of heterogeneous systems. To achieve all IP network architecture, the LTE systems can integrate with other wireless systems, for instance, GERAN, UTRAN, non-3GPP system, and WLAN system, as illustrated in Fig. 1. The core of LTE system includes System Architecture Evolution (SAE) anchor, 3GPP anchor, and Mobility Management Entity (MME)/User Plane Entity (UPE) to achieve the mobility management in the heterogeneous networks. The SAE anchor manages the mobility between 3PGG RATs (radio access technology) and non-3GPP RATs. The 3GPP anchor manages the mobility between GERAN/UTRAN and the LTE system.

The LTE system provides the frequency orthogonality for mobile users in the uplink and downlink communications. The performance of the LTE system, in terms of available data rates and

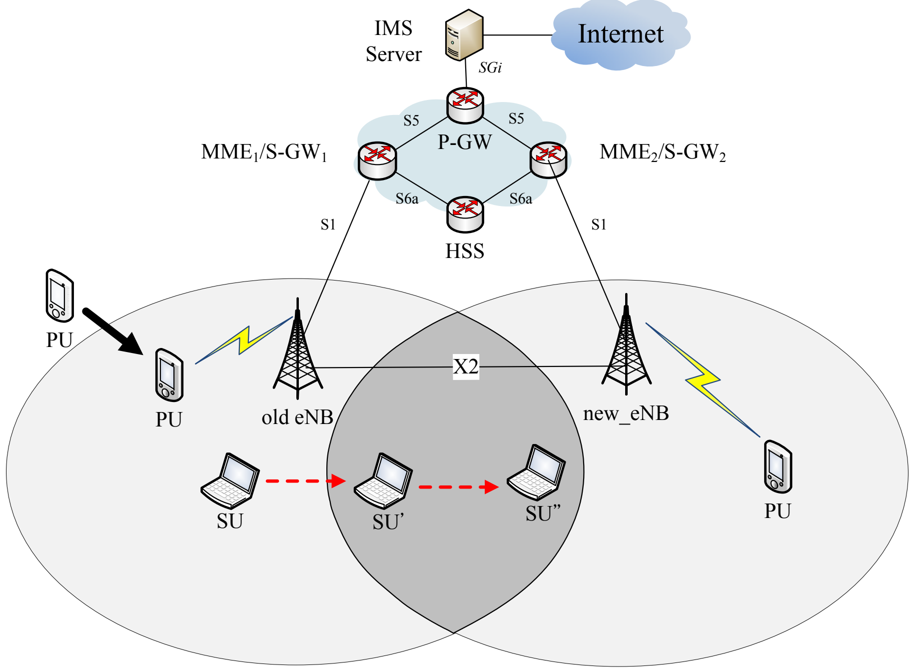


Figure 3: The system model.

spectrum efficiency, is limited by the inter-cell interference. The inter-cell interference coordination is a scheduling method to improve the date rate in the cell edge by taking the inter-cell interference into account. By restricting the transmission power of the spectrum, the interference appeared in the neighboring cells can be reduced to provide the higher data rates for user in the neighboring cell. Fig. 2 displays that different frequency reuse factor is used for distinct cells. One another interest characteristic of LTE systems is the spectrum agility. The LTE system supports more different bandwidth of channels. This characteristic of the LTE system is easily to adopt the CR concept to achieve the full frequency spectrum utilization.

The system model used in this paper is given in Fig. 3, the system model consists of the LTE core systems, licensed users (or called primary users, PUs), and unlicensed users (or called secondary users, SUs). For a CR network, it allows SUs equipped with cognitive radios to opportunistically access the spectrum not used by PUs. In this work, we consider the handover problem in a LTE-CR network. To our knowledge, this work is the first study to develop the handover protocol over CR networks. The main contribution of this work is to develop an efficient handover protocol in CR-LTE networks. Fig. 3 shows a handover scenario in a CR-LTE network. A SU is moving from one cell into the another cell. Two cases are considered. For the first case, the initial location of the SU is not in the overlapped area. If a PU is appeared and attempted to access and use the spectrum occupied by the SU, the SU performs the spectrum mobility processing to dynamically select a new spectrum hole, move to the new spectrum hole, and release the previously occupied spectrum for the PU.

The second case is when the SU continually moves to a overlapped area between two adjacent eNBs. Fig. 3 shows that the SU moves from location of SU' to that of SU". In our work, two possible events are happened; (1) one is the spectrum mobility, and (2) the another one is to handover to a new_eNB. We proposed a cross-layer protocol of spectrum mobility and handover in cognitive LTE Networks with the consideration of the minimum expected transmission time.

To implement the above purpose, a SU is equipped with the SDR (software-defined radio) device to detect and use these spectrum holes. The PU and SU architectures are given in Fig. 4. A PU

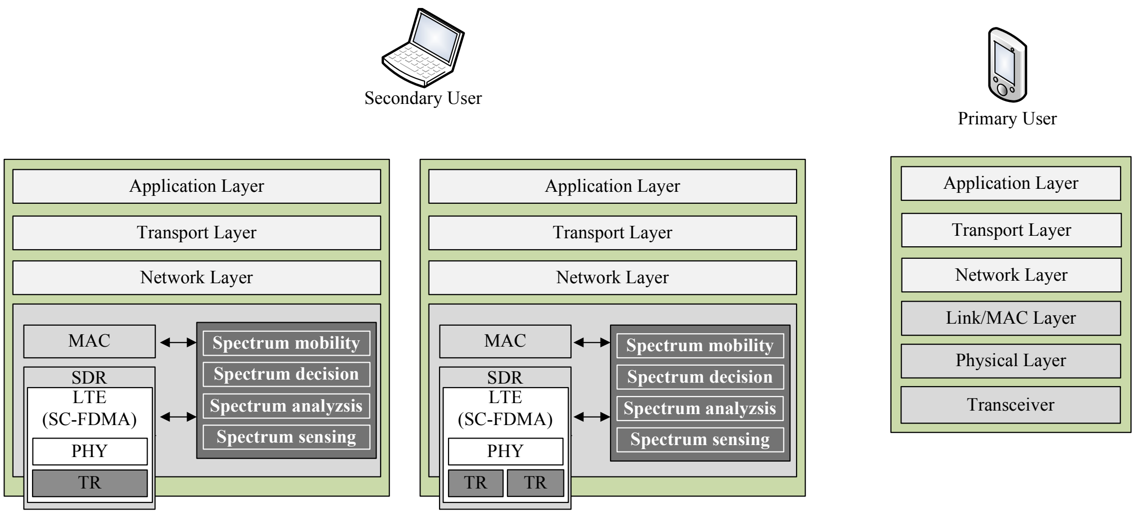


Figure 4: The PU and SU devices.

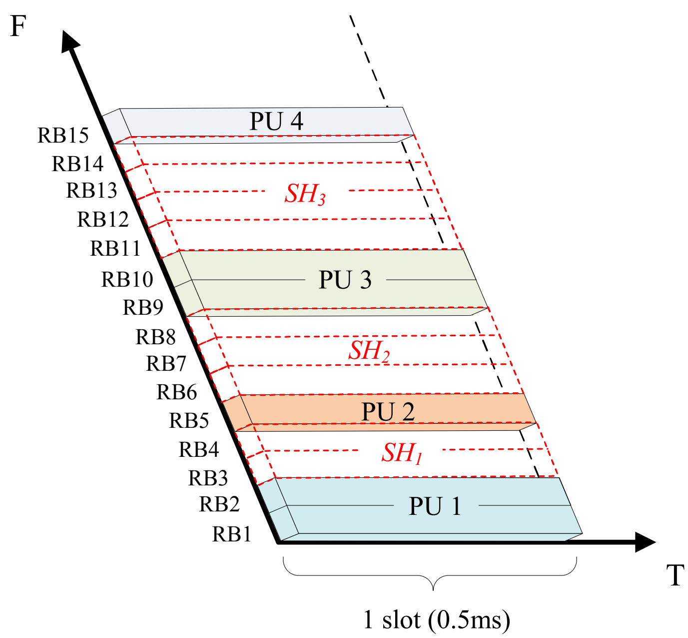


Figure 5: The sensed spectrum distribution.

device architecture is without any modification. In a SU device, components of layer-1 and layer-2 are modified to have the functions of spectrum sensing, spectrum analysis, spectrum decision, and spectrum mobility as shown in Fig. 4.

A SU with SDR device can be reconfigured for the different network protocols (802.11, 802.16, LTE, etc.) without addition devices and sense the different frequency band by one transceiver or two transceiver [12] to achieve the spectrum management, including the functionalities of spectrum sensing, spectrum analysis, spectrum decision, and spectrum mobility. For example, a SU performs the spectrum sensing in the CR-LTE system, and report the sensing result of the LTE spectrum bands given in Fig. 5. Obviously, the LTE spectrum is not fully utilized, and many underutilized spectrum holes can be used by SUs to improve the spectrum utilization. According to the LTE spectrum distribution, resource block (RB) is 180 KHz, where RB is the smallest unit of the LTE spectrum. The spectrum hole (SH) consists of one or more resource blocks (RB), this makes the SH with flexible size. For instance, $PU_1 = \{RB1, RB2\}$, $PU_2 = \{RB5\}$, $PU_3 = \{RB9, RB10\}$, and $PU_4 = \{RB15\}$.

3.2 Basic Idea and Challenges

The basic idea of this work is mainly to observe the spectrum occupied ratio to predict the probability of the resource reclaiming by PUs to perform the spectrum mobility on the serving eNB or the handover procedure to the new eNB. Our goal is to calculate the minimum expected transmission time when select a new spectrum, where the spectrum is in serving eNB or the next eNB. Some definitions are given below.

Let $T_E(SH_i)$ denote as the expected transmission time of spectrum hole i, denoted as SH_i, for data service of a SU. The large value of $T_E(SH_i)$ is, the higher expected transmission time will be. This also indicates that the SU has the higher probability of resource reclaimed by a PU. This may frequently cause the operations of spectrum mobility and handover. Conversely, the smaller value of $T_E(SH_i)$ is, the higher successful data transmission will be. This is because that there is no resource reclaimed by any PU. Therefore, the main contribution of this work is to propose a new scheme with the minimum $T_E(SH_i)$ in the CR-LTE systems.

The function of $T_E(SH_i)$ is determined by the spectrum occupied ratio, the signal strength fluctuation, and the available bandwidth of the spectrum hole. It is observed that the high spectrum occupied ratio implies that the opportunity of the spectrum utilization is low. In addition, if the signal strength is strong and the bandwidth is large, then the higher transmission rate is obtained. The transmission rate is normally computed by the signal strength and the bandwidth. That is, a $T_E(SH_i)$ with strong signal strength and bandwidth can reduce the data transmission time. Efforts will be made in this work to develop a new scheme with minimum expected transmission time, $T_E(SH_i)$.

The proposed scheme follows the standard model of the cognitive cycle. Three phases of the cognitive cycle of the proposed scheme are described below.

- *Environment observation* phase: each SU periodically monitors the spectrum utilization, receives signal power, and detects the appearance of any PU using the SDR device.
- *Computation and analysis* phase: each SU computes and analyzes the characteristics of spectrum hole; such as the transmission rate and the spectrum unoccupied rate, based on the observed information from *environment observation* phase.

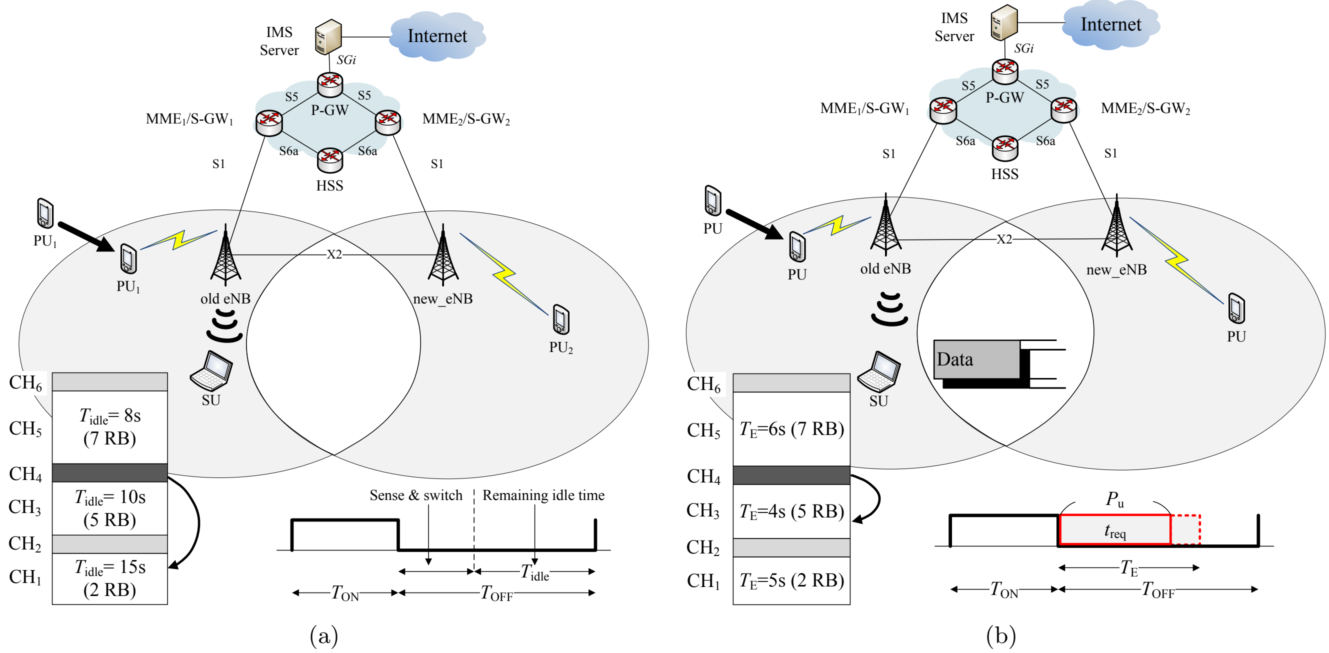


Figure 6: The difference of (a) the maximum idle time scheme, and (b) our proposed scheme.

- *Evaluation and transmission* phase: each SU evaluates all possible expected transmission times of the SU to determine to move to new spectrum on the serving eNB or handover to new eNB.

Our proposed protocol is a hybrid spectrum mobility and handover protocol in cognitive LTE networks. This is a first result to consider these two problems and provide a hybrid protocol. Most of existing protocols [15] only consider the spectrum mobility issue to switch a free spectrum when a PU reclaimed the resource occupied by a SU.

Hoyhtya *et al.* [15] recently proposed a predictive channel selection for cognitive radios. An example is shown in Fig. 6(a). Let T_{ON} denote a channel be occupied by PU, T_{OFF} denote a channel is idle, and T_{idle} denote a channel idle time. This predictive channel selection algorithm is to select the channel with the maximum idle time T_{idle}. For example as shown in Fig. 6(a), a SU performs the spectrum mobility from CH_4 to CH_1, where T_{idle} of CH_5, CH_3, and CH_1 are $8s$, $10s$, and $15s$.

It is observed that considering only a channel with the maximum idle time can not be optimal for the data transmission time. Because the channel size in LET system may be different, a channel with the maximum idle time may be with the minimum channel size. If the selected channel has a maximum idle time and minimum size, the data transmission time will be longer. It significantly reduces the data transmission time if the factor of the channel size is considered for designing a new predictive channel selection. In our proposed scheme, a channel with the maximum channel size and the maximum idle time is considered. Similar example of Fig. 6(a) is given in Fig. 6(b). A SU performs the spectrum mobility from CH_4 to CH_3, where T_E of CH_5, CH_3, and CH_1 are $6s$, $4s$, and $5s$. Let t_{req} denote the SU service required time, SH_i denote the i-th spectrum hole, and $P_u(SH_i, t_{req})$ denote the probability of spectrum hole unoccupied by PUs. The $P_u(SH_i, t_{req})$ is the unoccupied probability of SH_i within time period of t_{req}. The $T_E(SH_i)$ is calculated by $P_u(SH_i, t_{req})$, the detailed algorithm is described in Section 4.

In addition, this proposed protocol further considers the handover procedure from the serving

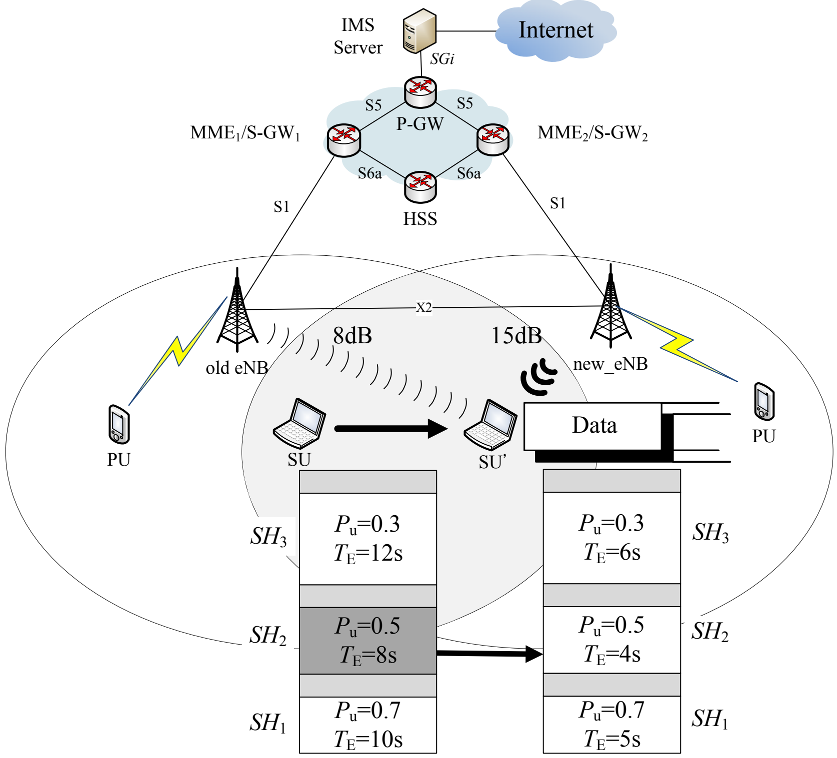


Figure 7: A SU is in the overlapped area.

eNB to the next eNB with the consideration of the minimum T_E. The main work of this paper is to develop a hybrid spectrum mobility (layer-2) and handover (layer-3) with the consideration of the minimum T_E in cognitive LTE networks. Fig. 7 illustrates that when a SU in the overlapped area between old_eNB and new_eNB. Two possible results are generated. One is that SU still performs the spectrum mobility to move to SH_2 in original old_eNB, because that the minimum T_E in old_eNB is lower than the minimum T_E of new_eNB plus the handover delay time. Conversely, the SU is handover to SH_1 of new_eNB.

4 Cross-layer protocol of spectrum mobility and handover

This section presents the hybrid spectrum mobility and handover protocol in CR-LTE systems. The proposed scheme evaluates and selects the minimum expected transmission time to make the decision to perform the layer-two spectrum mobility procedure on the old eNB or layer-three handover procedure to the new eNB. The protocol is split into three phase; (1) *environment observation* phase, (2) *computation and analysis* phase, and (3) *evaluation an transmission* phase. The detailed operations are described as follows.

4.1 *Environment observation* phase

Let SU_x denote the x-th SU, the SU_x collects the spectrum information through the SDR device. To acquire the spectrum distribution and utilization, this phase uses the SDR device to observe the signal power from the eNB and usage status of resource blocks (RBs). Fig. 7 also shows that SU_x periodically senses the spectrum bands of each resource block in order to acquire the information of occupied frequency information of each resource block (RB), while spectrum hole SH_i contains m_i

resource blocks. Let λ_{m_i} is the accumulated number that m_i-th RB be occupied within a period of time. The value of λ_{m_i} increases if m_i-th RB is occupied and used once during the time period.

If the value of λ_{m_i} is large, it implies that PUs frequently occupied m_i-th RB. It also implies that SUs has the lower opportunity to use m_i-th RB. Otherwise, if the value of λ_{m_i} is small, SU has higher opportunity to use m_i-th RB without the interruption caused by PUs. In addition, the signal strength is considered to help SU_x to know the the location information and the transmission quality. The environment observation procedure is given as follows.

S1: Each SU_x senses all spectrum bands, RB_y, in the transmission coverage of the current serving eNB, where $RB_y, 1 \leq y \leq N_{\max imun\_number\_of\_RB}$. Let some adjacent idle RB_y form a spectrum hole SH_i, where $1 \leq i \leq j$. Therefore, we can obtain a sequence of spectrum holes $(SH_1,\ SH_2, \cdots, SH_i, \cdots, SH_j)$. The information of the occupied frequency λ_{m_i} is observed and recorded for all RB_y within a period of time, where $1 \leq y \leq N_{\max imun\_number\_of\_RB}$. In addition, the signal strength for SU_x from current serving eNB is also periodically estimated.

S2: If the SU_x detects a resource, SH_i, reclaiming by PU, then performs S3 step; otherwise, go to S1 step.

S3: The SU_x goes to the next phase to make the decision of performing the spectrum mobility or handover, depending on the value of $T_E(SH_i)$, where $T_E(SH_i)$ is calculated by the remaining service data size d_t. The function of $T_E(SH_i)$ is given in the next phase.

For example as shown in Fig. 8, a SU periodically observes the frequency bands by the SDR device. When a PU_1 moves to the location of PU_1', PU_1' reclaims the spectrum resource of SU_1. At the moment, SU_1 still does not enter the overlapped area of old eNB and the new eNB, the received signal strength of SU_1 from old eNB is 15 dB. Fig. 8 shows that SH_1, SH_2, and SH_3 are $2RB$, $3RB$, and $4RB$, respectively. The detected SH_2 has three RBs, and their occupied frequencies are $\lambda_1 = 48$, $\lambda_2 = 70$, and $\lambda_3 = 70$. The information will be used to calculate the expected execution time $T_E(SH_i)$.

4.2 *Computation and analysis* phase

The main task of the computation and analysis phase is to compute the necessary information used to calculate the expected execution time $T_E(SH_i)$ based on the related location of SU. Two cases are considered; (1) spectrum mobility: SU_x is in the non-overlapped area and (2) spectrum mobility or handover: SU_x is in the overlapped area, if a SU_x detects the appearance of PU_y.

4.2.1 Spectrum mobility: SU_x is in the non-overlapped area

When a SU_x is located in the non-overlapped case, SU_x has only one serving eNB. According to SU_x received signal from the serving eNB, if the received signal strength is greater than the a threshold value, SU_x can perform the successful data transmission through the serving eNB. Otherwise, SU_x executes the unsuccessful data transmission through the serving eNB. In the following, the required transmission time t_{req} and the unoccupied probability of SH_i are obtained as follows.

S1: To evaluate the expected transmission time $T_E(SH_i)$ for the remaining service data of SU_x, $SNR = \frac{P_{signal}}{P_{noise}}$ is obtained from signals received from the serving eNB, where $SNR_{dB} = 10\log_{10}(\frac{P_{signal}}{P_{noise}})$.

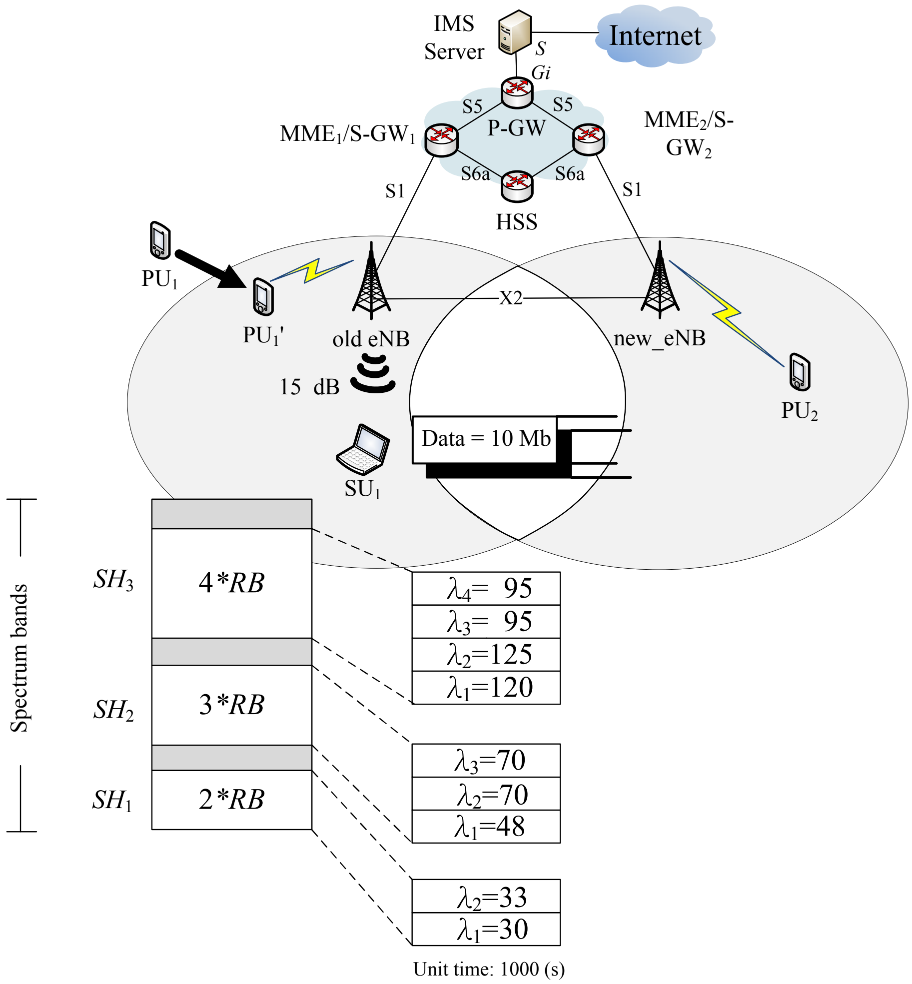


Figure 8: Example of environment observation.

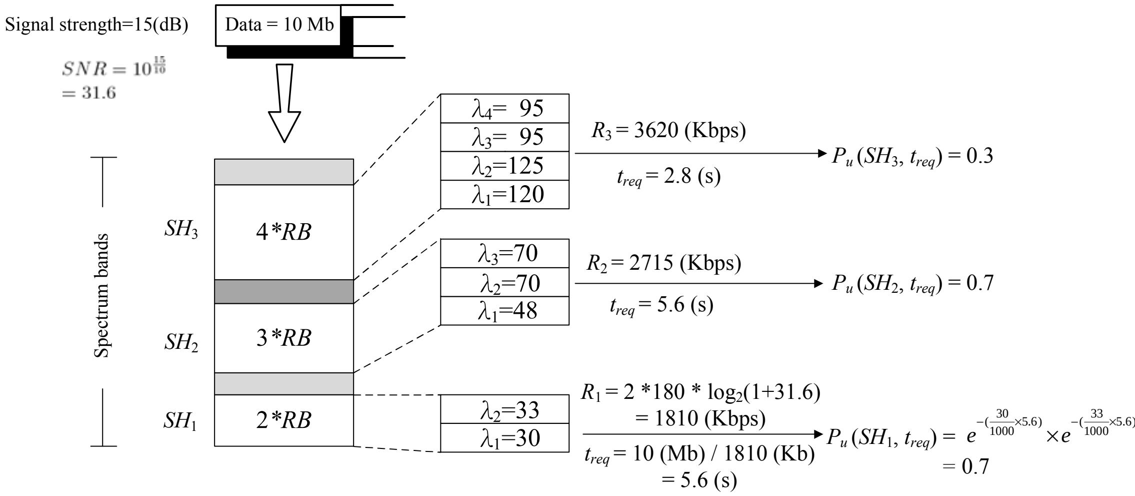


Figure 9: Example of computation and analysis in the non-overlapped area.

S2: The SU_x determines the maximum transmission rate based on the received signal strength, SNR_{dB}, for all spectrum hole SH_i in serving eNB to estimate the required transmission time t_{req} for the remaining service data size d_t. Let R_i denote as the transmission rate for SH_i. It is observed that SH_i contains m_i resource blocks RBs, so the bandwidth of SH_i is $m_i \times RB$. Following the equation proposed by [24], R_i is $m_i \times RB \times \log_2(1 + SNR_{dB})$ and the maximum transmission rate is $C = B \times \log_2(1 + SNR_{dB})$, where C is the maximum channel capacity, and B is the bandwidth. The required transmission time t_{req} is $\frac{d_t}{m_i \times RB \times \log_2(1+SNR_{dB})}$, where the remaining service data size is d_t.

S3: To predict the availability of spectrum hole SH_i, the unoccupied probability of SH_i is calculated. Let $P_u(SH_i, t_{req})$ denote as the probability of spectrum hole SH_i unoccupied by PUs within the time period of t_{req}. To predict the idle SH_i within a service required time t_{req}, we use the Poisson distribution [8], the formal 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 happened. Let $P(k,T)$ denote as the probability of k events occurred within the time period T. To analyze the probability that the SH_i not be used within the service require time t_{req}, let k set as zero, and T set as t_{req}. Consequently, if SH_i contains m_i RB, the probability of spectrum hole SH_i unoccupied by PUs within the time period of t_{req} is $P_u(m_i, t_{req}) = \prod_{n=1}^{m_i} P_n(0, t_{req}) = e^{-\sum_{n=1}^{m_i} \lambda_n t_{req}}$.

Fig. 9 shows an example that SH_1 has two RBs, and their occupied frequencies are $\lambda_1 = 30$ and $\lambda_2 = 33$. The transmission rate of SH_1 is $2 \times 180(KHz) \times \log_2(1 + 31.6) = 1810$ Kbps. The required transmission time is $10(Mb) \div 1810(Kbps) = 5.6$ s. The unoccupied probability of SH_1 is $e^{-(\frac{30}{1000}\times 5.6)} \times e^{-(\frac{33}{1000}\times 5.6)} = e^{-0.3582} \cong 0.7$. The unoccupied probability of SH_2 and SH_3 are 0.7 and 0.3, as shown in Fig. 9.

4.2.2 Spectrum mobility or handover: SU_x is in the overlapped area

In the overlapped area, SU_x is between the old eNB and the new eNB. Before executing the evaluation and transmission phase, the required transmission times t_{req} and t'_{req}, and the unoccupied probability

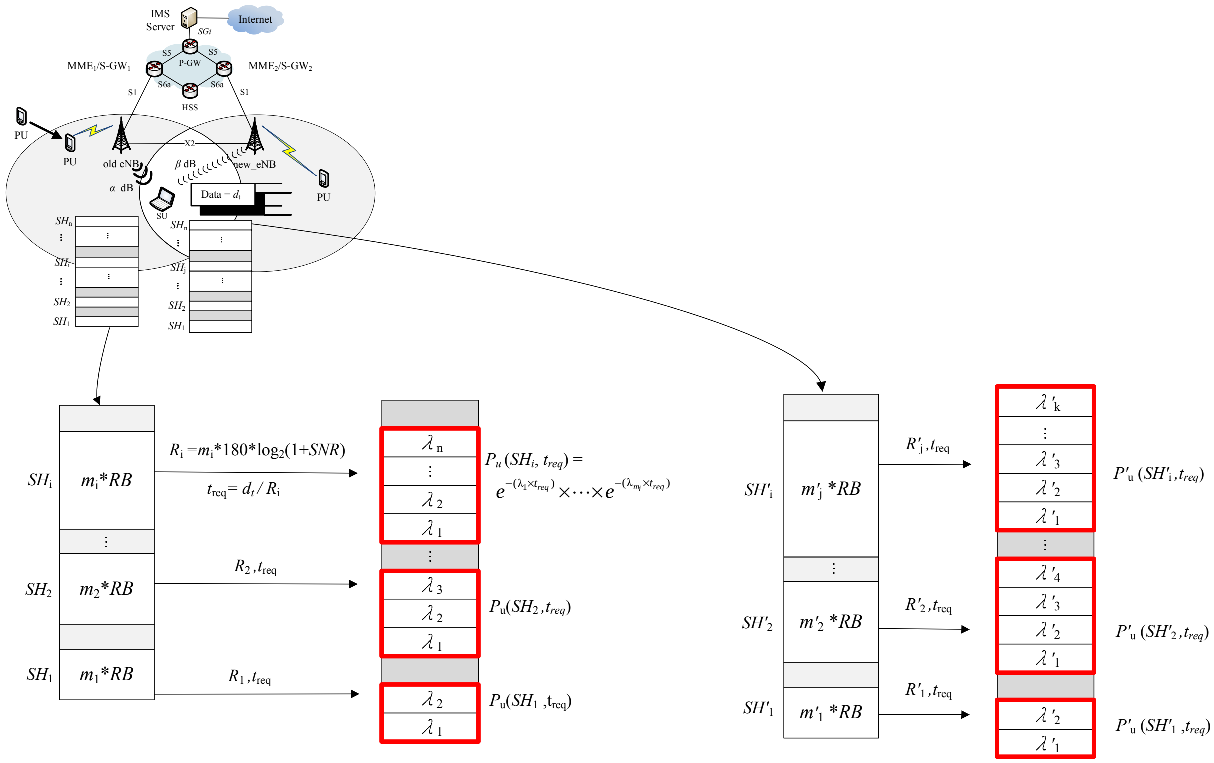


Figure 10: The analysis of the spectrum holes in the overlapped area.

of SH_i and SH'_j of SU_x for the old eNB and the new eNB are estimated, respectively. An example is given in Fig. 10.

S1: The SU_x received two signals from the old eNB and the new eNB, $SNR = \frac{P_{signal}}{P_{noise}}$ and $SNR' = \frac{P'_{signal}}{P'_{noise}}$ are obtained, where $SNR_{dB} = 10\log_{10}(\frac{P_{signal}}{P_{noise}})$ and $SNR'_{dB} = 10\log_{10}(\frac{P'_{signal}}{P'_{noise}})$.

S2: The SU_x determines the maximum transmission rate based on SNR_{dB} and SNR'_{dB}, where SNR_{dB} is from all SH_i in old eNB and SNR'_{dB} is from all SH'_j in new eNB to estimate the required transmission time t_{req} and t'_{req} for the remaining service data size d_t. Let R_i denote the transmission rate for SH_i. The SH_i contains m_i resource blocks RBs, the bandwidth of SH_i is $m_i \times RB$. Following the equation proposed by [24], the required transmission time t_{req} is $\frac{d_t}{m_i \times RB \times \log_2(1+SNR_{dB})}$, where the remaining service data size is d_t. Let R'_j denote as the transmission rate for SH'_j and SH'_j contains m'_j resource blocks RBs, the bandwidth of SH'_j is $m'_j \times RB$. The required transmission time t'_{req} is $\frac{d_t}{m'_j \times RB \times \log_2(1+SNR'_{dB})}$.

S3: If the SH_i contains m_i RB, the probability of spectrum hole SH_i unoccupied by PUs within time period of t_{req} is $P_u(m_i, t_{req}) = \prod_{n=1}^{m_i} P_n(0, t_{req}) = e^{-\sum_{n=1}^{m_i} \lambda_n t_{req}}$. If the SH'_j contains m'_j RB, the probability of spectrum hole SH'_j unoccupied by PUs within time period of t'_{req} is $P_u(SH'_j, t'_{req}) = \prod_{n=1}^{m'_j} P_n(0, t'_{req}) = e^{-\sum_{n=1}^{m'_j} \lambda_{m'_j} t'_{req}}$.

An example is given in Fig. 11 to illustrate the case when SU_x is in the overlapped area. The SNR_{dB} and SNR'_{dB} is 10 dB and 12 dB from the old eNB and the new eNB, respectively. The transmission rates of SH_1 and SH'_1 are 2×180 (KHz) $\times \log_2(1 + 15.8) = 1466$ Kbps and 2×180

(KHz) $\times \log_2(1+10) = 1245$ Kbps, respectively. The service required transmission time in SH_1 of old_eNB and SH'_1 of new_eNB are 10 (Mb) $\div$ 1245 (Kbps) $=$ 8 s and SH'_1 10 (Mb) $\div$ 1466 (Kbps) $= 6.8$ s. The unoccupied probability $P_u(SH_1, t_{req})$ is $e^{-(\frac{30}{1000}\times 8)} \times e^{-(\frac{33}{1000}\times 8)} = e^{-0.504} \cong 0.6$, and $P_u(SH'_1, t_{req})$ is $e^{-(\frac{35}{1000}\times 6.8)} \times e^{-(\frac{40}{1000}\times 6.8)} = 0.6$. These calculated results are useful in the evaluation and transmission phase.

4.3 *Evaluation and transmission* phase

This phase aims to calculate the expected execution time $T_E(SH_i)$ to make the decision to execute the spectrum mobility on old eNB or handover to new eNB. The detailed procedure is given below.

S1: As recalled, $T_E(SH_i)$ denotes the expected transmission time of the SH_i in old eNB. If SU_x is in the non-overlapped or overlapped areas, for each spectrum hole SH_i of the old_eNB, $T_E(SH_i)$ is

$$T_E(SH_i) = \frac{d_t}{P_u(m_i, t_{req}) \times R_i} + (1 - P_u(m_i, t_{req})) \times T_{L2H}, \tag{1}$$

where T_{L2H} denotes the layer-2 switch time and $1 - P_u(m_i, t_{req})$ is the probability of SH_i be occupied within time period t_{req}. If no PU appears, the transmission time is $\frac{d_t}{R_i}$. However, this time will be interrupted caused by the appearance of PU. Therefore, the expected transmission time is added by $P_u(m_i, t_{req}) \times R_i$ to increase the transmission time. The usage of SH_i of SU_x may be interrupted again by the appearance of of other PUs, the SU_x may perform the spectrum mobility again. This condition is represented as $(1 - P_u(m_i, t_{req})) \times T_{L2H}$.

S2: If the SU_x is in the overlapped area between the old eNB and the new eNB, the SU_x must additionally calculates $T'_E(SH'_j)$ for the new eNB for the final evaluation. Similarly, the $T'_E(SH'_j)$ is

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

where T_{L3H} is denoted as the layer-3 handover delay time, which includes the DAD time and location update time [4]. In the overlapped area, SU_x has two ways to go. One way is that SU_x still performs the spectrum mobility to select new spectrum bands from the old eNB. Another way is to perform the layer-3 handover to new eNB and select the new spectrum bands in the new eNB. Compared to $T_E(SH_i)$, $T'_E(SH'_j)$ additionally plus the time cost of T_{L3H}.

S3: The SU_x performs the the spectrum mobility if $\frac{d_t}{P_u(m_i, t_{req}) \times R_i} + (1 - P_u(m_i, t_{req})) \times T_{L2H} - \frac{d_t}{P'_u(m'_i, t'_{req}) \times R'_i} + (1 - P'_u(m'_i, t'_{req})) \times T_{L2H} > T_{L3H}$. Otherwise, the SU_x performs the handover procedure.

Fig. 11 shows an example of evaluation and transmission phase, the expected transmission time of SH_1 in old_eNB is $T_E(SH_1) = \frac{10 \text{ (Mb)}}{0.6 \times 1245} + (1 - 0.6) \times 0.05(\text{s}) = 13.407(\text{s})$, and the expected transmission time of spectrum hole SH'_1 in new_eNB is calculated as $T'_E(SH'_1) = 0.35(s) + \frac{10(Mb)}{0.6 \times 1466} + (1 - 0.6) \times 0.05 = 11.739$. The other expected transmission time of SH_2 and SH_3 (old_eNB) and SH'_2 and SH'_3 (new_eNB) are shown in Fig. 11. The minimum expected transmission time is SH'_2. Consequently, SU_1 performs the handover to SH'_2 of the new_eNB for the data transmission.

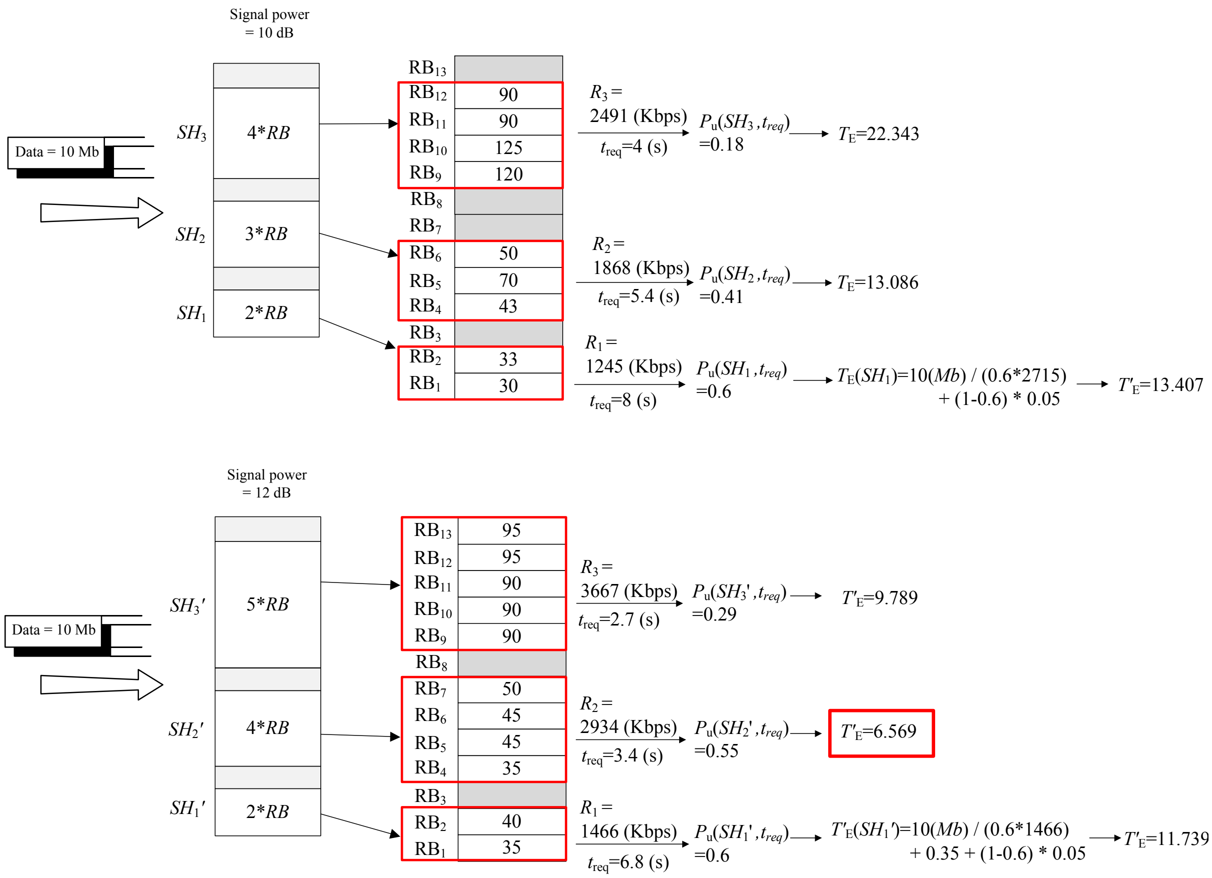


Figure 11: Example of computation and analysis phase the evaluation and transmission phase.

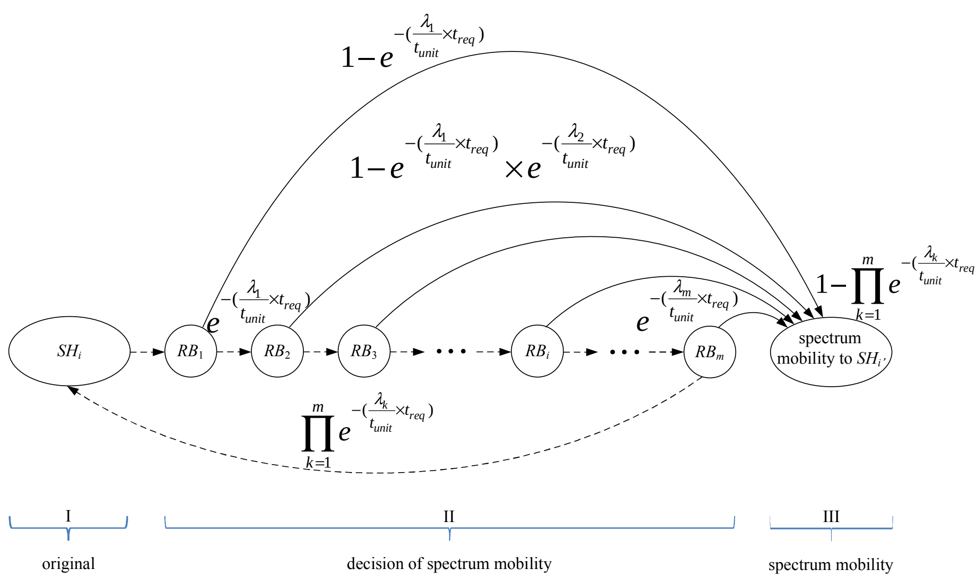


Figure 12: Relation between resource blocks in the scenario one.

5 Performance analysis

In this section, we propose an analytic model to analyze the total transmission time and the throughput for our proposed scheme. The Markov chain model is adopted. The Markov chain is represented as a directed graph as shown in Fig. 12. Considered a secondary user SU_x, the SU_x uses i-th spectrum hole SH_i from a given sequence of j spectrum holes $(SH_1,\ SH_2, \cdots, SH_i, \cdots, SH_j)$ in the serving eNB, where $1 \leq i \leq j$. Two cases are considered for our analysis. First case is that a SU_x performs the spectrum mobility if the SU_x is in the non-overlapped area. Another case is that a SU_x performs the spectrum mobility or the handover if the SU_x is in the overlapped area.

Without loss of generality, assumed that let i-th spectrum hole SH_i has m resource blocks, where $1 \leq m$. Let the data of the SU_x be divided into n packets. As shown in Fig. 12, the Markov chain model is split into three parts. In the part I, initial state of "SH_i" denotes SU_x transmits the next data packet through the current spectrum hole SH_i. In the part II, there are m resource blocks, where $1 \leq m$. Therefore, there are m RB_i states, where $1 \leq i \leq m$. Each resource block may be reclaimed by a PU. Therefore, m resource blocks are checked once. If RB_i is reclaimed by a PU, then go to state of "spectrum mobility to $SH_{i'}$" (part III); otherwise, go to the next state of RB_{i+1}, where $1 \leq i < m$. Until reaching to state of "RB_m", if there is still no reclaimed by a PU, then go to the initial state of "SH_i" without performing the spectrum mobility. In the part III, state of "spectrum mobility to $SH_{i'}$" state denotes the SU_x performs spectrum mobility and change the spectrum hole from SH_i to $SH_{i'}$, which SH_i is reclaimed by a PU.

The state transition information is given below.

- SH_i to RB_1: indicates that the previous packet was completely transmitted completely and the next packet starts to be transmitted.
- RB_i to RB_{i+1}: RB_i has the probability of $e^{-(\frac{\lambda_i}{t_{unit}} \times t_{req})}$ if RB_i is not reclaimed by a PU.
- RB_i to "spectrum mobility to $SH_{i'}$": RB_i has the probability of $1 - \prod_{k=1}^{i} e^{-(\frac{\lambda_k}{t_{unit}} \times t_{req})}$ if the RB_i is reclaimed by a PU and RB_1 to RB_{i-1} are not reclaimed by the PU.
- RB_m to SH_i: RB_m has the probability of $\prod_{k=1}^{m} e^{-(\frac{\lambda_k}{t_{unit}} \times t_{req})}$ if RB_m is not reclaimed by a PU. This implies that all m RB_i are not reclaimed by a PU and the SU_x can continually uses the SH_i.

Let t_{unit} denote as a past period of time units. Let λ_i denote as the reclaimed number by a PU of RB_i within t_{unit}. Let $t_{req} = \frac{d_t}{m_i \times RB_i \times \log_2(1+SNR_{dB})}$ be the required data transmission time between SU_x and eNB through SH_i without considering λ_i.

Before calculating the expected total transmission time, we need to estimate the probability of each spectrum hole which is not reclaimed by PUs. With the Poisson distribution, the probability of SH_i which is not reclaimed by PUs denoted as $P_u(SH_i, t_{req})$.

Lemma 1 *Considered a SH_i, if there are m resource blocks of SH_i, the probability of SH_i which is not reclaimed by PUs is*

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

Proof. Assumed the required transmission time is $t_{req} = \frac{d_t}{m_i \times RB_i \times \log_2(1+SNR_{dB})}$, where d_t is the data size of the data packet and R_i is the transmission rate of SH_i. According to the Poisson distribution

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

where n is the total number of event occurrences and let γ be a positive real number which is equal to the expected occurrence number during a given time interval. The probability of of i-th resource block RB_i not be reclaimed by PUs within the time interval is $\gamma_i = \frac{\lambda_i \times t_{req}}{t_{unit}}$. The probability of $P_u(SH_i, t_{req})$ is represented by $\prod_{k=1}^{m} e^{-(\frac{\lambda_k}{t_{unit}} \times t_{req})}$. ■

The total transmission time is

$$T_{TTT} = \frac{1}{j} \sum_{i=1}^{j} \sum_{k=0}^{N-1} (T_{\text{old\_eNB}} + T_{\text{non-spectrum mobility}}), \tag{5}$$

where $1 \leq i \leq j$ and T_{old_eNB} is the expected time cost of SU_x performming the spectrum mobility and using the new spectrum hole $SH_{i'}$ for one packet transmission. $T_{\text{non-spectrum mobility}}$ is the expectation time of SU_x still using the original SH_i for one packet transmission. In the following, the expected transmission time T_{old_eNB} and $T_{\text{non-spectrum mobility}}$ are calculated as follows.

Lemma 2 *If there is one packet to be transmitted from a SU_x to the serving eNB through the different spectrum hole $SH_{i'}$. The expected transmission time, T_{old_eNB}, is*

$$T_{old\_eNB} = (1 - P_u(SH_i, t_{req})) \times (T_{L2H} + \frac{d_t}{R_i \times N}). \tag{6}$$

Proof. The transmission time of one packet is $T_{L2H} + \frac{d_t}{R_i \times N}$ if the SU_x needs to perform the spectrum mobility, where T_{L2H} is the time cost of spectrum mobility and $\frac{d_t}{R_i \times N}$ is transmission time between the SU_x and the serving eNB. The probability of spectrum mobility is $1 - P_u(SH_i, t_{req})$. Therefore, the expected transmission time is $(1 - P_u(SH_i, t_{req})) \times (T_{L2H} + \frac{d_t}{R_i \times N})$. ■

Lemma 3 *If there is one packet to be transmitted from a SU_x to the serving eNB through original spectrum hole SH_i. The expected transmission time, $T_{\textit{non-spectrum mobility}}$, is*

$$T_{\textit{non-spectrum mobility}} = P_u(SH_i, t_{req}) \times (\frac{d_t}{R_i \times N}). \tag{7}$$

Proof. The probability of non-spectrum mobility is $P_u(SH_i, t_{req})$ and the transmission time of one packet is $\frac{d_t}{R_i \times N}$. Therefore, the expectation time $T_{\text{non-spectrum mobility}}$ is $P_u(SH_i, t_{req}) \times \frac{d_t}{R_i \times N}$. ■

Consequently, the expected total transmission time T_{TTT} is estimated below.

Theorem 1 *If there are j $(1 \leq i \leq j)$ spectrum holes, from SH_1 to SH_j, and N data packets, ranging from P_0 to P_{N-1}, to be transmitted from a SU_x to the serving eNB. The expected total transmission time, T_{TTT}, is*

$$T_{TTT} = \frac{1}{j} \sum_{i=1}^{j} ((1 - P_u(SH_i, t_{req})) \times T_{L2H} + t_{req}), \;\; \textit{where } 1 \leq i \leq j, t_{req} = \frac{d_t}{R_i}. \tag{8}$$

Proof. Based on Lemma 2 and Lemma 3, the transmission time of one packet is calculated as $T_{old\_eNB} + T_{non-spectrum\ mobility}$. Using Eq. 5, the expected total transmission time is $T_{TTT} = \frac{1}{j}\sum_{i=1}^{j}\sum_{k=1}^{N-1} T_{one\_packet}$. Then, we have the following result.

$$\begin{aligned} T_{TTT} &= \frac{1}{j}\sum_{i=1}^{j}\sum_{k=0}^{N-1}[(1-P_u(SH_i,t_{req}))\times(T_{L2H}+\frac{d_t}{R_i\times N})+P_u(SH_i,t_{req})\times\frac{d_t}{R_i\times N}] \\ &= \frac{1}{j}\sum_{i=1}^{j}(T_{L2H}+t_{req}-P_u(SH_i,t_{req})\times T_{L2H}) \\ &= \frac{1}{j}\sum_{i=1}^{j}((1-P_u(SH_i,t_{req}))\times T_{L2H}+t_{req}),\ \text{where } 1\le i\le j, t_{req}=\frac{d_t}{R_i}. \end{aligned}$$

■

In the following, we further consider the case of a SU_x performing the spectrum mobility or the handover if the SU_x is in the overlapped area. Similarly, as shown in Fig. 13, the Markov chain model is split into three parts. In the part I, initial state of "SH_i" denotes SU_x transmits the next data packet through current spectrum hole SH_i. In the part II, there are m resource blocks, where $1 \le m$. Therefore, there are m RB_i states, where $1 \le i \le m$. Each resource block may be reclaimed by a PU. Therefore, m resource blocks are checked once. If RB_i is reclaimed by a PU, then go to state of "spectrum mobility to $SH_{i'}$" or state of "handoff to $SH'_{i'}$" (part III); otherwise, go to the next state of RB_{i+1}, where $1 \le i < m$. Until reaching to state of "RB_m", if there is still no reclaimed by a PU, then go to the initial state of "SH_i" without performing the spectrum mobility or the handoff procedure. In the part III, state of "handoff to $SH_{i'}$" state denotes the SU_x performs the handoff procedure and change the spectrum hole from SH_i to $SH'_{i'}$. The additional state transition information is given below.

- RB_i to "spectrum mobility to $SH_{i'}$": RB_i has the probability of $P_{old_nNB}(1-\prod_{k=1}^{i} e^{-(\frac{\lambda_k}{t_{unit}}\times t_{req})})$ if the RB_i is reclaimed by a PU and perform the spectrum mobility and RB_1 to RB_{i-1} are not reclaimed by the PU.
- RB_i to "handoff to $SH'_{i'}$": RB_i has the probability of $P_{new_nNB}(1-\prod_{k=1}^{i} e^{-(\frac{\lambda_k}{t_{unit}}\times t_{req})})$ if the RB_i is reclaimed by a PU and perform the handoff procedure and RB_1 to RB_{i-1} are not reclaimed by the PU.

In the following, we derive the expected total transmission time of the second case. If a SU_x only transmits packet through the serving (old) eNB or the next (new) eNB. We have

$$P_{old\_eNB} + P_{new\_nNB} = 1, \tag{9}$$

where P_{old_eNB} is the probability of using the old eNB spectrum hole and P_{new_eNB} is the probability of using the new eNB. Similarly, the expected total transmission time is

$$T_{TTT} = \frac{1}{j}\sum_{i=1}^{j}\sum_{k=0}^{N-1}[(T_{old\_eNB}+T_{new\_eNB})+T_{non-handoff}], \tag{10}$$

where $1 \le i \le j$ and T_{new_eNB} is the expected time cost of a SU_x performming the handover and using the new spectrum hole $SH'_{i'}$ in the new eNB for one packet transmission, and $T_{non-handoff}$ is

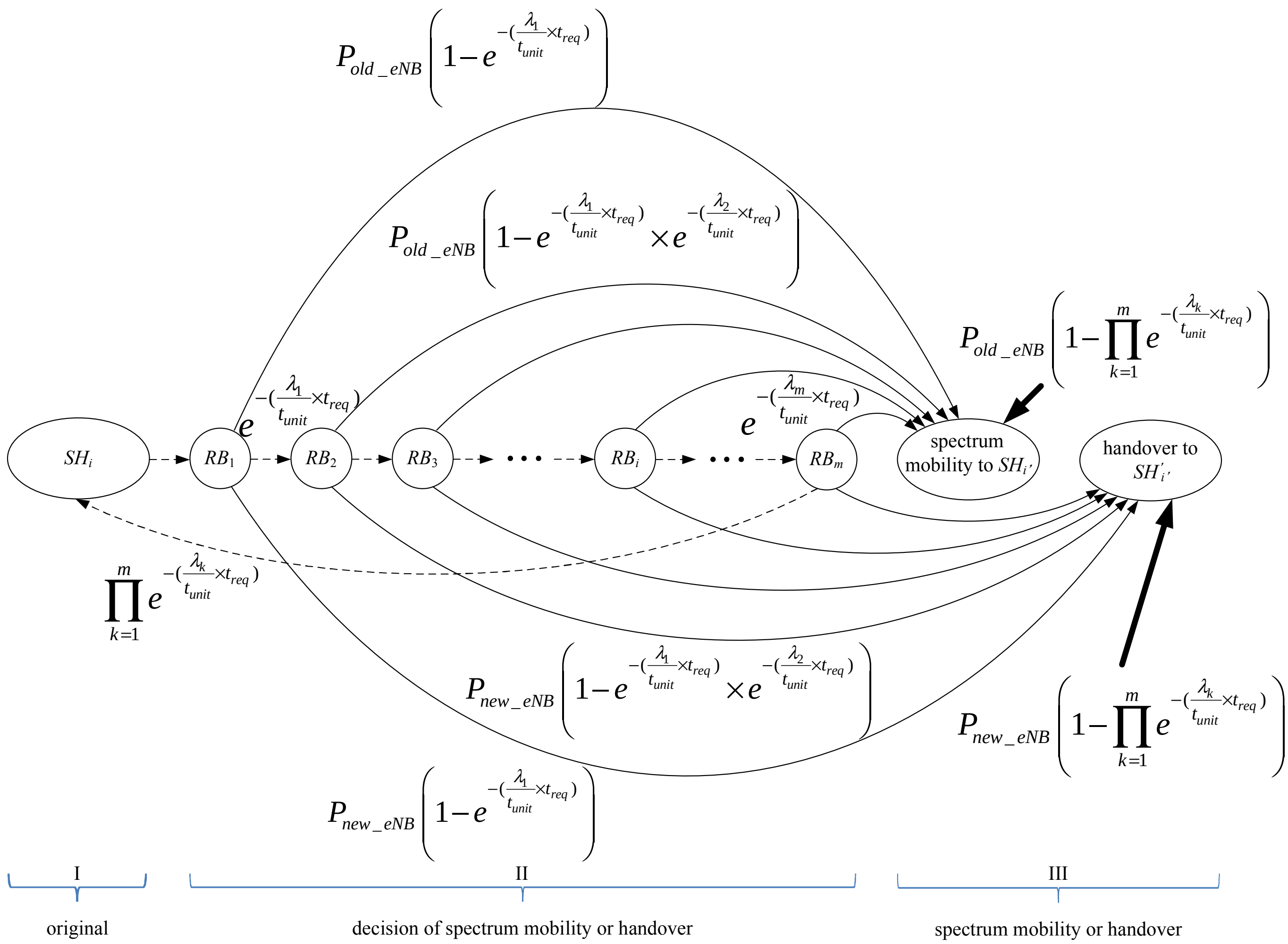


Figure 13: Relation spectrum mobility and handover in the scenario two.

the expected time cost of a SU_x using the original SH_i in the old eNB for one packet transmission, where $T_{non-handoff} = T_{non-spectrum\ mobility}$.

In the following, the expected transmission times T_{new_eNB} and T_{old_eNB} are calculated.

Lemma 4 *If there is one packet transmitted to the new eNB, a SU_x needs to perform the handover to the new eNB. The expectation transmission time, T_{new_eNB}, is*

$$T_{new\_eNB} = P_{new\_eNB} \times (1 - P_u(SH_i, t_{req})) \times (T_{L2H} + T_{L3H} + \frac{d_t}{R_i \times N}). \tag{11}$$

Proof. The probability of the handover of SU_x is $P_{new\_eNB} \times (1 - P_u(SH_i, t_{req}))$. The transmission time is $T_{L2H} + T_{L3H} + \frac{d_t}{R_i \times N}$, 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. Therefore, the expected transmission time of T_{new_eNB} is $P_{new\_eNB} \times (1 - P_u(SH_i, t_{req})) \times (T_{L2H} + T_{L3H} + \frac{d_t}{R_i \times N})$. ■

Lemma 5 *If there is one packet transmitted to the old eNB, a SU_x performs the spectrum mobility to the old eNB. The expectation transmission time, T_{old_eNB}, is*

$$T_{old\_eNB} = P_{old\_eNB} \times (1 - P_u(SH_i, t_{req})) \times (T_{L2H} + \frac{d_t}{R_i \times N}). \tag{12}$$

Proof. The probability of the spectrum mobility of SU_x is $P_{old\_eNB} \times (1 - P_u(SH_i, t_{req}))$, the expected transmission time of T_{old_eNB} is $P_{old\_eNB} \times (1 - P_u(SH_i, t_{req})) \times (T_{L2H} + \frac{d_t}{R_i \times N})$ ■

Based on Lemma 3, 4, and 5, we have the following result.

Theorem 2 *If there are j $(1 \leq i \leq j)$ spectrum holes, from SH_1 to SH_j, and N data packets, ranging from P_0 to P_{N-1}, to be transmitted from a SU_x to the serving (old) eNB or the next (new) eNB. The expected total transmission time, T_{TTT}, is*

$$T_{TTT} = \frac{1}{j} \sum_{i=1}^{j} [(1 - P_u(SH_i, t_{req})) \times (T_{L2H} + P_{new\_eNB} \times T_{L3H}) + t_{req}],$$

where $1 \leq i \leq j, t_{req} = \frac{d_t}{R_i}$.

Proof. Based on Eq. 10 and lemmas 3, 4, and 5, it can be derived the final result as follows.

$$\begin{aligned}
T_{TTT} &= \frac{1}{j}\sum_{i=1}^{j}\sum_{k=0}^{N-1}[(P_{old_eNB} \times (1 - P_u(SH_i, t_{req})) \times (T_{L2H} + \frac{d_t}{R_i \times N})) \\
&\quad +(P_{new_eNB} \times (1 - P_u(SH_i, t_{req})) \times (T_{L2H} + T_{L3H} + \frac{d_t}{R_i \times N})) \\
&\quad +(P_u(SH_i, t_{req}) \times \frac{d_t}{R_i \times N})] \\
&= \frac{1}{j}\sum_{i=1}^{j}[(P_{old_eNB} \times (1 - P_u(SH_i, t_{req})) \times (T_{L2H} + t_{req})) \\
&\quad +(P_{new_eNB} \times (1 - P_u(SH_i, t_{req})) \times (T_{L2H} + TL3H + t_{req}) \\
&\quad +P_u(SH_i, t_{req}) \times t_{req}] \\
&= \frac{1}{j}\sum_{i=1}^{j}[T_{L2H} + t_{req} - P_u(SH_i, t_{req}) \times T_{L2H} \\
&\quad +P_{new_eNB} \times (1 - P_u(SH_i, t_{req})) \times T_{L3H} \\
&\quad +P_u(SH_i, t_{req}) \times t_{req}] \\
&= \frac{1}{j}\sum_{i=1}^{j}[(1 - P_u(SH_i, t_{req})) \times T_{L2H} + P_{new_eNB} \times (1 - P_u(SH_i, t_{req})) \times T_{L3H} \\
&\quad +t_{req}] \\
&= \frac{1}{j}\sum_{i=1}^{j}[(1 - P_u(SH_i, t_{req})) \times (T_{L2H} + P_{new_eNB} \times T_{L3H}) + t_{req}], \text{ where } 1 \le i \le j \text{ and } t_{req} = \frac{d_t}{R_i}.
\end{aligned}$$

■

The analysis of throughput is given as follow. The throughput is equal to the data size divided by the total transmission time. The throughput (TP) is expressed as,

$$TP = \frac{d_t}{T_{TTT}}. \tag{13}$$

Theorem 3 *Assumed that the data size of a SU_x is d_t and the total transmission time of d_t is T_{TTT}, where T_{TTT} is derived from from Theorem 1 for the case of the SU_x is in the non-overlapped area and Theorem 2 for the case of the SU_x is in the overlapped area, the throughput TP_1 (the SU_x is in the non-overlapped area) and TP_2 (the SU_x is in the overlapped area), are derived as follows.*

$$TP_1 = \frac{d_t \times j}{\sum_{i=1}^{j}((1 - P_u(SH_i)) \times T_{L2H} + t_{req})}, \tag{14}$$

$$TP_2 = \frac{d_t \times j}{\sum_{i=1}^{j}((1 - P_i(SH_i, t_{req})) \times (T_{L2H} + P_{new\_eNB} \times T_{L3H}) + t_{req})}, \tag{15}$$

where $1 \le i \le j, t_{req} = \frac{d_t}{R_i}$.

Proof. Based on theorem 1, the throughput, TP_1, is

$$TP_1 = \frac{d_t \times j}{\sum_{i=1}^{j}((1 - P_u(SH_i)) \times T_{L2H} + t_{req})}.$$

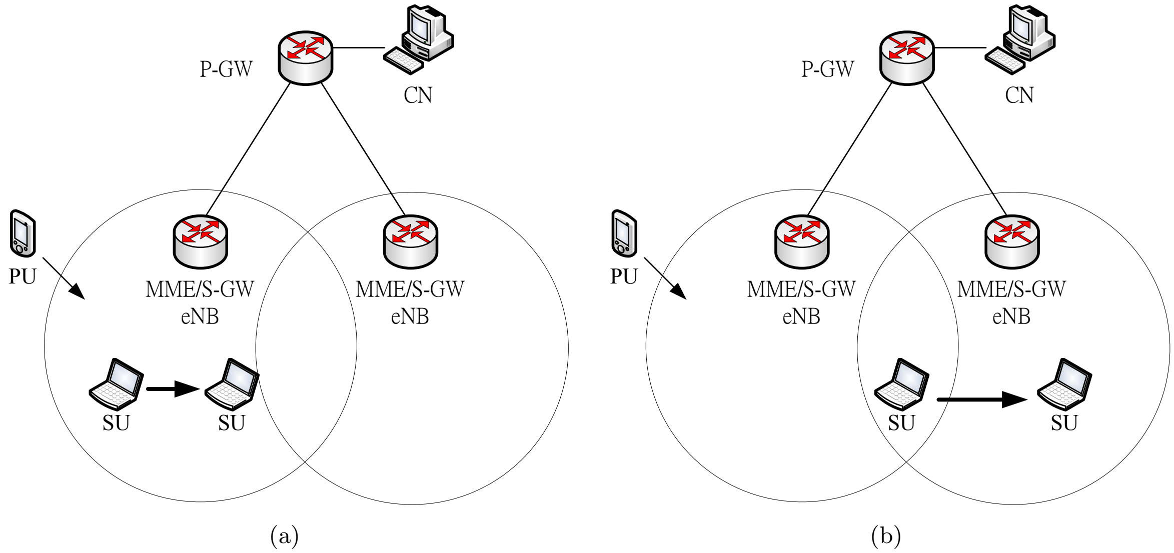


Figure 14: (a) The simulation scenario 1 and (b) the simulation scenario 2.

Table 1: Simulation parameters

Parameter	Value
BS transmission range	50 km
Network size	500×500 km
Secondary users speed	0-100 km/hr
Number secondary user	0-20
Spectrum sensing period	40 ms
Spectrum switching delay	10 ms
Handover delay	200 - 350 ms
Packet size	1500 bytes
Simulation time	100-1000 s

Based on theorem 2, the throughput, TP_2, is

$$\begin{aligned} TP_2 &= \frac{d_t}{\frac{1}{j}\sum_{i=1}^{j}((1-P_u(SH_i,t_{req}))\times T_{L2H}+t_{req})}. \\ &= \frac{d_t\times j}{\sum_{i=1}^{j}((1-P_i(SH_i,t_{req}))\times(T_{L2H}+P_{new\_eNB}\times T_{L3H})+t_{req})}. \end{aligned}$$

■

6 Simulation results

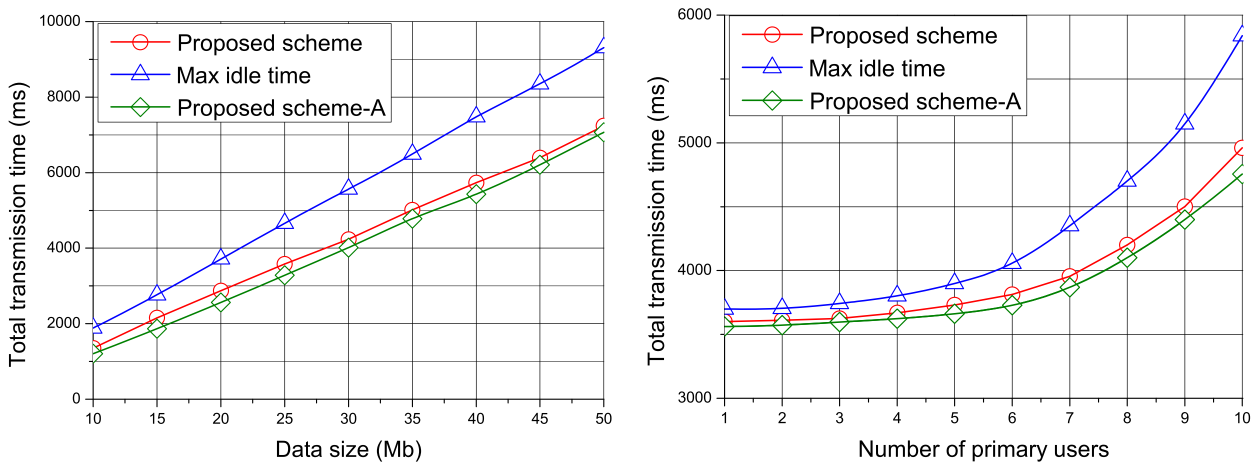
Our paper presents a cross-layer protocol of spectrum mobility and handover in cognitive LTE systems. To fair evaluate the proposed protocol, two simulation scenarios are implemented as shown in Figure 14 using the Network Simulator-2 (NS-2) [5], ns-2 Cognitive Radio Network model [2], and 3GPP module [3]. For the simulation scenario 1, the SU is located within the non-overlapped area. It is observed that only the spectrum mobility is executed. The proposed scheme is mainly compared with the predictive channel selection scheme proposed by Hoyhtya *et al.*[15], which is denoted as the maximum idle time scheme. This scheme is to periodically recorded the channel idle time, the channel idle time is acquired at the next time period such that the channel with the maximum idle time is chosen. For the simulation scenario 2, the SU moves across the overlapped area with the constant speed such that the SU may execute the spectrum mobility or handover procedures. The proposed scheme is mainly compared with mobile IPv6, MIPv6, protocol [4]. The system parameters are given in Table 1. It is noted that proposed scheme-A is denoted as the analyzed result of our proposed scheme derived from the performance analysis in Section 5, respectively. The performance metrics to be observed are:

- The *total transmission time* (TTT) is the time interval of the data transmission between a pair of a SU and a corresponding node, CN, through the old eNB or new eNB. The TTT is estimated from the first packet transmitted from CN until the final packet received by SU through the old eNB or new eNB.
- The *end-to-end delay* (EED) is the average delay time of every packets of a data which be transmitted from a SU to a CN by the old eNB or new eNB. If data sizes are same, the EED is large that represents the T_E of spectrum hole which be selected by SU is higher.
- The *throughput* (TP) is total number of data packets which can be transmitted and received between a pair of SU and CN per unit time.
- The *number of spectrum mobility* (NSM) is the total number of spectrum mobility during a data transmission between a pair of SU and CN.

It is worth mentioning that an efficient handoff protocol in cognitive LTE networks is achieved with a low TTT, low EED, high TP, and low NSM. In the following, we illustrate our simulation results for *total transmission time* (TTT), *end-to-end delay* (EED), *throughput* (TP), and *number of spectrum mobility* (NSM) from several aspects.

6.1 Total transmission time (TTT)

The simulation results of the TTT under various data sizes, number of PUs, and spectrum hole unoccupied ratio, P_u, for the simulation scenario 1 are shown in Fig. 15 and Fig. 16. Figure 15 shows that observed TTT under various data sizes and number of PUs. We observed that the TTT of the proposed scheme was low as the data size was low, which was nearly equal to the proposed scheme-A, as illustrated in Fig. 15(a). Fig. 15(a) illustrates that the curve of the TTT of our scheme is lower than that of maximum idle time scheme under various data sizes. We observed that the TTT of the proposed scheme was low if the number of PUs was low, which was nearly equal to the proposed scheme-A, as shown in Fig. 15(b). Fig. 15(b) illustrates that the curve of the TTT of our scheme is lower than that of maximum idle time scheme, under various number of PUs. This is because that our scheme adopts the minimum expected transmission time. Fig. 16 illustrates the impact of TTT with various spectrum hole unoccupied ratio, P_u, (ranging from 0.1 to 0.9) and spectrum hole size. In general, the TTT decreases as P_u increases. The large value of P_u indicates that SUs have the more opportunities to stably utilize the spectrum holes without any interruption. It is observed that the TTT with the spectrum hole = 5RB < that of the spectrum hole = 3RB < that of the spectrum hole = 1RB, due to the large spectrum hole with the high transmission rate.



(a)

(b)

Figure 15: Total transmission time (a) vs. data size and (b) vs. number of primary user, for the simulation scenario 1.

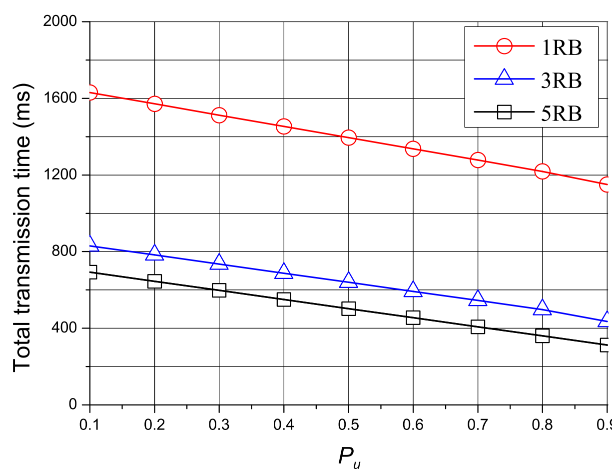


Figure 16: Total transmission time vs. P_u for the simulation scenario 1.

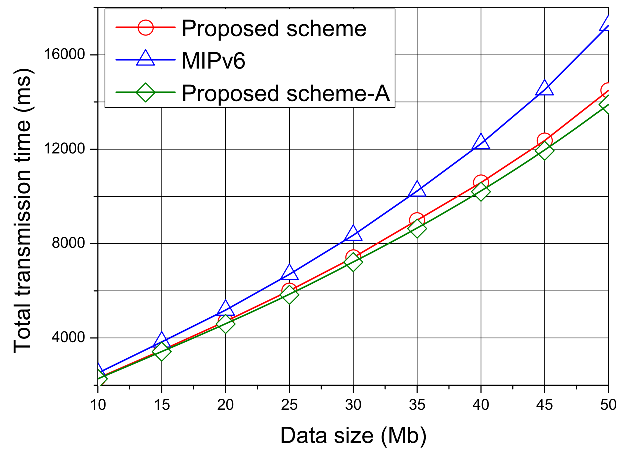
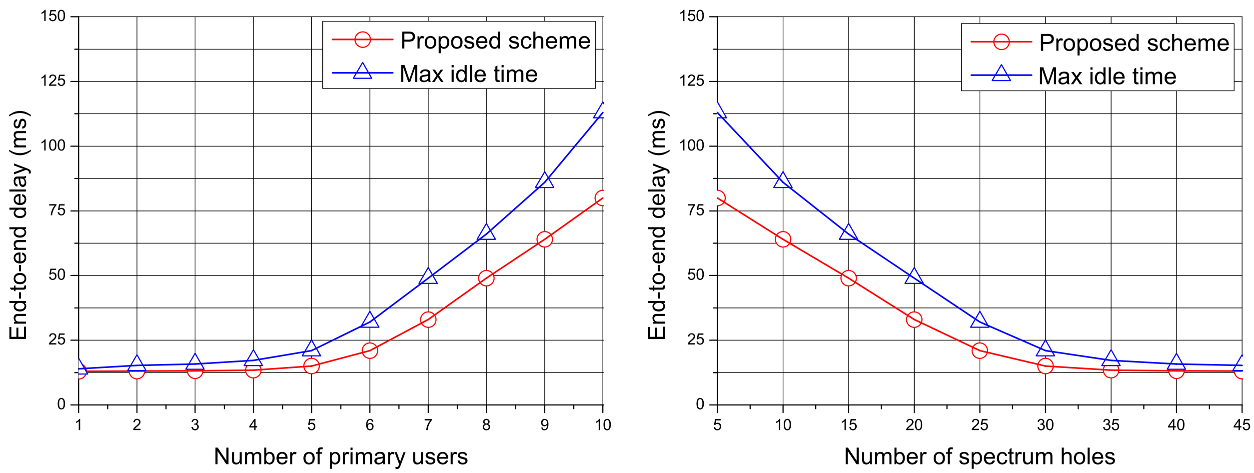


Figure 17: Total transmission time vs. data size for the simulation scenario 2.



(a) (b)

Figure 18: End-to-end delay (a) vs. number of primary user and (b) vs. number of spectrum hole for the simulation scenario 1.

Fig. 17 illustrates the simulation result of TTT under various date sizes (ranging from 10 Mb to 50 Mb) for the simulation scenario 2. Fig. 17 shows that the TTT of the proposed scheme drops as the data size decreases, which was nearly equal to the proposed scheme-A. With the same data size, the MIPv6 protocol needs more transmission time than our scheme because that the fixed spectrum resource scheme is used in MIPv6 protocol. Our proposed scheme adopts the dynamic spectrum resource scheme by dynamically collecting the spectrum hole information such that our scheme can significantly improve the MIPv6 protocol. This information is useful for the layer-3 handoff procedure by selecting the large size of spectrum hole and the low P_u. Fig. 17 verifies that the TTT of our proposed scheme is less than the MIPv6 protocol.

6.2 End-to-end delay (EED)

The simulation results of the EED under various number of PUs, number of spectrum holes, and data sizes for the simulation scenario 1 are shown in Fig. 18 and Fig. 19. Figure 18 shows that observed EDD under number of PUs, number of spectrum holes, where the P_u is fixed at 0.5. In general, the EDD increases as the number of PUs increases. Figure 18(a) illustrates that the curve of

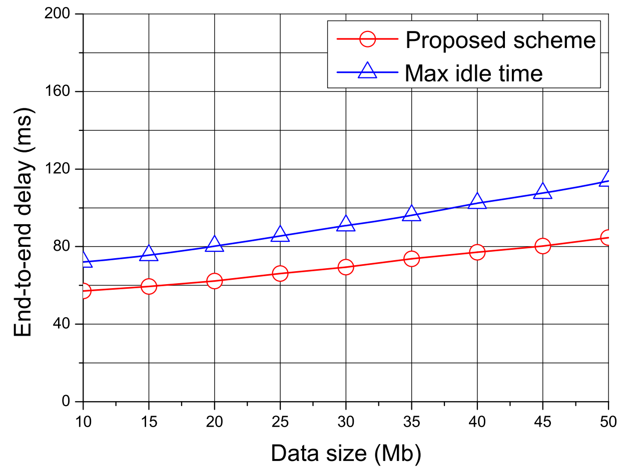
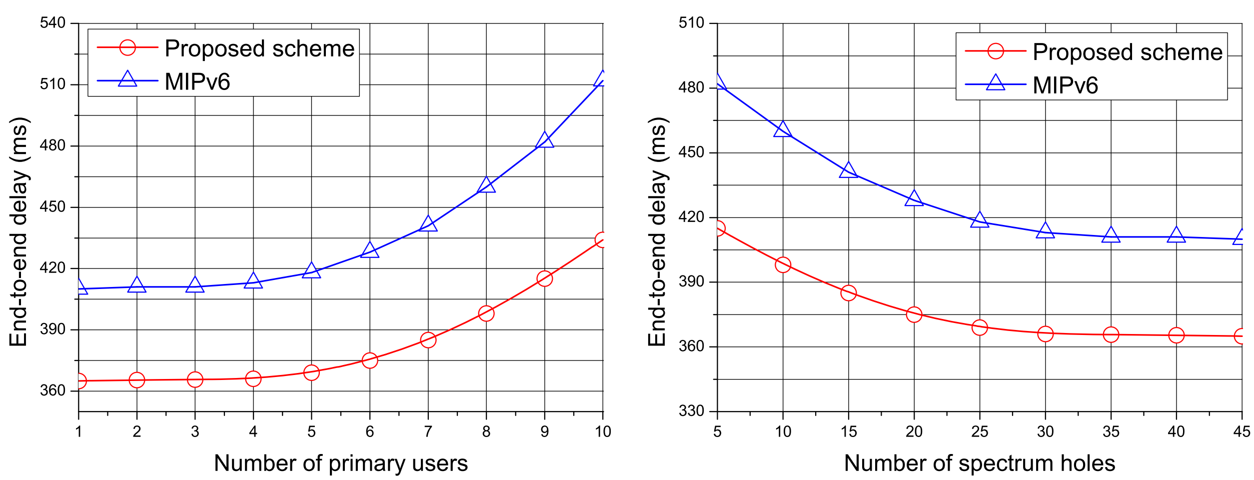


Figure 19: End-to-end delay vs. data size for the simulation scenario 1.



(a) (b)

Figure 20: End-to-end delay (a) vs. number of primary user, and (b) vs. number of spectrum hole, for the simulation scenario 2.

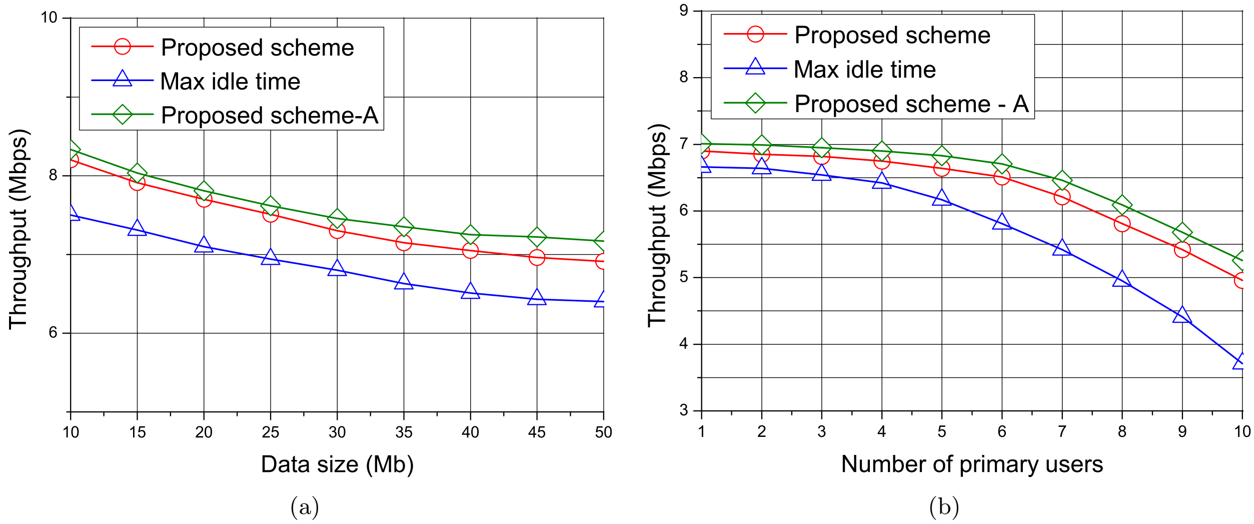


Figure 21: Throughput (a) vs. time, and (b) vs. number of primary user, for the simulation scenario 1.

the EED of our scheme is lower than that of maximum idle time scheme. In general, the EED drops as the number of spectrum holes increases. Figure 18(b) illustrates that the curve of the EDD of our scheme is lower than that of maximum idle time scheme. Finally, Fig. 19 illustrates that the curve of the EED of our scheme is lower than that of maximum idle time scheme under various data sizes (ranging from 10 Mb to 50 Mb). This is because that our scheme adopts the minimum expected transmission time by utilizing the sensed spectrum information.

Fig. 20 illustrates the simulation results of EED under various number of PUs and number of spectrum holes for the simulation scenario 2. In general, the EED increases as the number of PUs increases and the number of spectrum holes decreases. Fig. 20 displays that the MIPv6 protocol needs more EED than our scheme because that the fixed spectrum resource scheme is used in MIPv6 protocol. Our proposed scheme adopts the dynamic spectrum resource scheme by dynamically collect the spectrum hole information. This information is useful for our layer-3 handoff procedure by selecting the large size of spectrum hole. Fig. 20 verifies that the EDD of our proposed scheme is less than that of MIPv6 protocol.

6.3 Throughput (TP)

The simulation results of the TP under various data sizes and number of PUs for the simulation scenario 1 are shown in Fig. 21. Figure 21(a) shows that observed TP under various data size, where the P_u is fixed at 0.5. The TP of the proposed scheme drops as the data size increases, which was nearly equal to the proposed scheme-A. Figure 21(a) illustrates that the curve of the TP of our scheme is higher than that of maximum idle time scheme under various data sizes. The TP of the proposed scheme drops as the number of PUs increases, which was nearly equal to the proposed scheme-A, as shown in Fig. 21(b). Fig. 21(b) illustrates that the curve of the TP of our scheme is higher than that of maximum idle time scheme under various number of PUs. This is because that our scheme adopts the minimum expected transmission time.

Fig. 22 illustrates the simulation results of TP under various data sizes for the simulation scenario 2. The TP of the proposed scheme drops as the data size increases, which was nearly equal to the proposed scheme-A. Fig. 22 displays that the MIPv6 protocol has lower TP than our scheme because

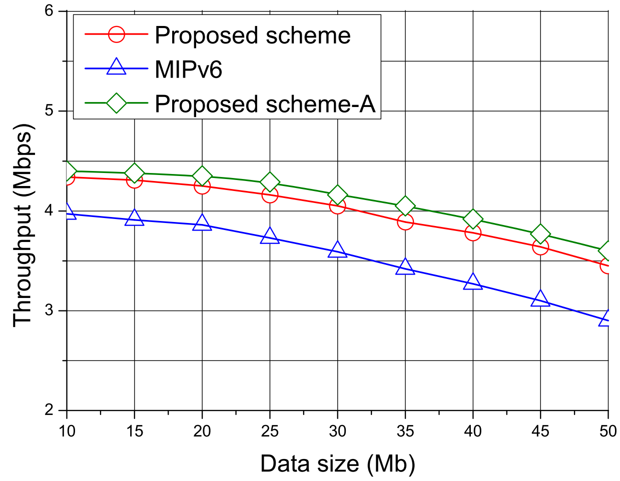
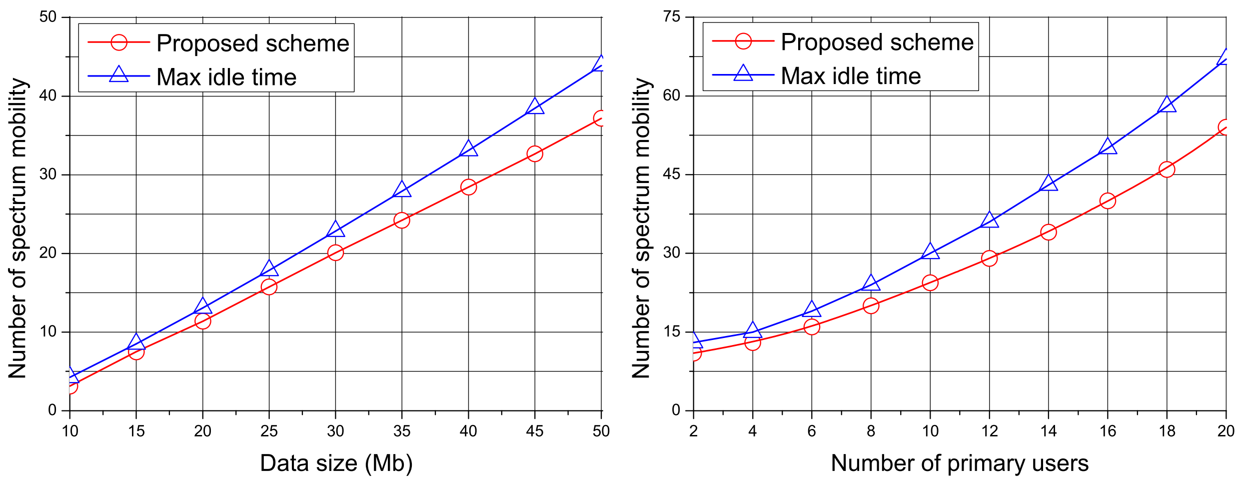


Figure 22: Throughput vs. data size for the simulation scenario 2.



(a)

(b)

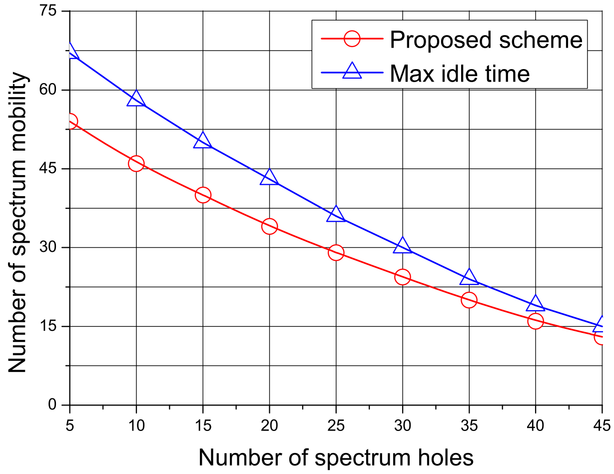
Figure 23: Number of spectrum mobility (a) vs. data size, and (b) vs. number of primary users, for the simulation scenario 1.

that the fixed spectrum resource scheme is used in MIPv6 protocol. It is verifies that the TP of our proposed scheme is higher than that of MIPv6 protocol.

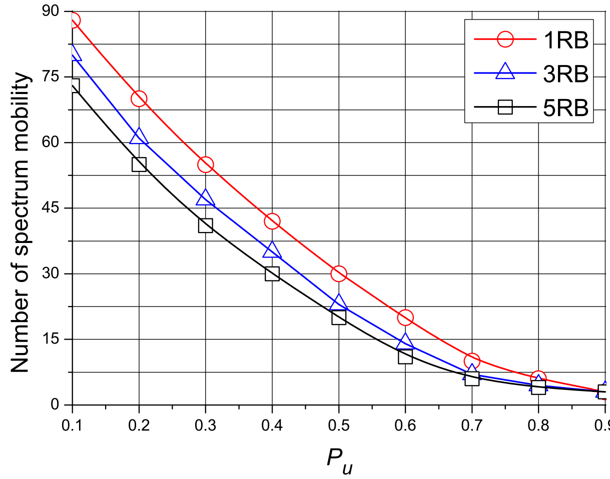
6.4 Number of spectrum mobility (NSM)

The simulation results of the NSM under various data sizes and number of PUs for the simulation scenario 1 are shown in Fig. 23. Figure 23(a) shows that observed NSM under various data size, where the P_u is fixed at 0.5. In general, the NSM drops as the data size decreases. Figure 23(a) illustrates that the curve of the NSM of our scheme is lower than that of maximum idle time scheme under various data sizes. In general, the NSM drops as the number of PUs decreases. Figure 23(b) illustrates that the curve of the NSM of our scheme is lower than that of maximum idle time scheme under various number of PUs.

In addition, Fig. 24 illustrates the simulation results of the NSM under various number of spectrum holes and P_u for the simulation scenario 1. Figure 24(a) shows that observed NSM under various number of spectrum holes, where the P_u is fixed at 0.5. In general, the NSM drops as the



(a)



(b)

Figure 24: Number of spectrum mobility (a) vs. number of spectrum hole, (b) vs. spectrum hole unoccupied ratio P_u, for the simulation scenario 1.

number of spectrum holes increases. Figure 24(a) illustrates that the curve of the NSM of our scheme is lower than that of maximum idle time scheme under various number of spectrum holes. In general, the NSM drops as P_u increases. Figure 24(b) illustrates that the curve of NSM with the spectrum hole = 5RB < that of the spectrum hole = 3RB < that of the spectrum hole = 1RB. It is observed that the large spectrum hole leads to the less number of spectrum mobility under various P_u.

7 Conclusions

In this paper, we present a cross-layer protocol of spectrum mobility (layer-2) and handover (layer-3) in cognitive LTE networks. With the consideration of the Poisson distribution model of spectrum resources, a cross-layer handoff protocol with the minimum expected transmission time is developed in cognitive LTE networks. Performance analysis of the proposed protocol is investigated in this work. Simulation results also illustrates the proposed handoff protocol significantly reduces the expected transmission time and the spectrum mobility ratio. Future work will be done to further develop a relay-based protocol of spectrum mobility and handover in the cognitive LTE networks.

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