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 used, 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.

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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 cannot fully take advantage of all of the radio spectrum resources for mobile devices and power supply cannot continue to use, and the free and unutilized radio spectrum resources are 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 Mitola and Maguire [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 has 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 illustrate that 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. Mishra 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 and Arslan [26] then proposed a partial match-filtering method to have a priory information about the 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. Jo and Cho [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 that is most closed to the real-spectrum holding time. Akbar and Tranter [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 (HMM) 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 into 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.

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 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

![Fig. 1. The 3GPP LTE systems architecture.](image_url)
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 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 transceivers [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 reports 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 selecting 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.
- **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.

![Fig. 5. The sensed spectrum distribution.](image-url)
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. 6a. 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

![Diagram](a)

**Fig. 6.** The difference of (a) the maximum idle time scheme and (b) our proposed scheme.

![Diagram](b)

**Fig. 7.** A SU is in the overlapped area.
channel selection algorithm is to select the channel with the maximum idle time $T_{idle}$. For example as shown in Fig. 6a, a SU performs the spectrum mobility from CH4 to CH1, where $T_{idle}$ of CH5, CH3, and CH1 are 8 s, 10 s, and 15 s.

It is observed that considering only a channel with the maximum idle time cannot 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. 6a is given in Fig. 6b. A SU performs the spectrum mobility from CH4 to CH3, where TE of CH5, CH3, and CH1 are 6 s, 4 s, and 5 s. Let $t_{req}$ denote the SU service required time, $T_{H_i}$ denote the ith channel hole, and $P_d(SH_i,t_{req})$ denote the probability of spectrum hole unoccupied by PUs. The $P_d(SH_i,t_{req})$ is the unoccupied probability of $SH_i$ within time period of $t_{req}$. The $T_{e}(SH_i)$ is calculated by $P_d(SH_i,t_{req})$, and the detailed algorithm is described in Section 4.

In addition, this proposed protocol further considers the handover procedure from the serving 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 handover (layer-3) with the consideration of the minimum $T_E$ 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 phases: (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 xth 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 $\lambda_{m_i}$ is the accumulated number that $m_i$th RB be occupied within a period of time. The value of $\lambda_{m_i}$ increases if $m_i$th RB is occupied and used once during the time period.

If the value of $\lambda_{m_i}$ is large, it implies that PUs frequently occupied $m_i$th RB. It also implies that SUs have the lower opportunity to use $m_i$th RB. Otherwise, if the value of $\lambda_{m_i}$ 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 location information and the transmission quality. The environment observation procedure is given as follows:

$S1$: Each $SU_x$ senses all spectrum bands, $RB_{p_i}$ in the transmission coverage of the current serving eNB, where $RB_{p_i}$, $1 \leq y \leq N_{\text{maximum number of RBs}}$. Let some adjacent idle $RB_{p_j}$ form a spectrum hole $SH_i$, where $1 \leq i \leq j$. Therefore, we can obtain a sequence of spectrum holes ($SH_1$, $SH_2$, ..., $SH_y$,...,$SH_j$). The information of the occupied frequency $\lambda_{m_i}$ is observed and recorded for all $RB_{p_i}$ within a period of time, where $1 \leq y \leq N_{\text{max imum number of RBs}}$. 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 $d_i$. 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 PU1 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, and 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 $RB$s, 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
4.2.1. Spectrum mobility: SU\textsubscript{x} is in the non-overlapped area

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

\textbf{S1:} To evaluate the expected transmission time \( T_{\text{req}}(SH_i) \) for the remaining service data of SU\textsubscript{x}, SNR = \frac{P_{\text{signal}}}{P_{\text{noise}}} \) is obtained from signals received from the serving eNB, where \( SNR_{\text{dB}} = 10\log_{10}\left(\frac{P_{\text{signal}}}{P_{\text{noise}}}\right) \).  

\textbf{S2:} The SU\textsubscript{x} determines the maximum transmission rate based on the received signal strength, SNR\textsubscript{db}, for all spectrum hole \( SH_i \) in serving eNB to estimate the required transmission time \( t_{\text{req}} \) 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 \( m_i \times RB \). 

\[ R_i = \frac{m_i \times RB \log_2(1 + SNR_{\text{dB}})}{C} \]

Following the equation proposed by Shannon [24], \( R_i = m_i \times RB \times \log_2(1 + SNR_{\text{dB}}) \) and the maximum transmission rate is \( C = B \times \log_2(1 + SNR_{\text{dB}}) \), where \( C \) is the maximum channel capacity, and \( B \) is the bandwidth. The required transmission time \( t_{\text{req}} \) is \( \frac{d_t}{m_i \times RB \times \log_2(1 + SNR_{\text{dB}})} \), where the remaining service data size is \( d_t \).

\textbf{S3:} To predict the availability of spectrum hole \( SH_i \), the unoccupied probability of \( SH_i \) is calculated. Let \( P_{\text{u}}(SH_i, t_{\text{req}}) \) denote as the probability of spectrum hole \( SH_i \) unoccupied by PUs within the time period of \( t_{\text{req}} \). To predict the idle \( SH_i \) within a service required time \( t_{\text{req}} \), we use the Poisson distribution [8], \( P(k, T) = \frac{\lambda^k}{k!} e^{-\lambda T} \), where \( k \) is the number of events, \( T \) is the period time, and \( \lambda \) 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

\[ P(k, T) = \frac{\lambda^k}{k!} e^{-\lambda T} \]
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 $P_u(m_i, t_{req}) = \prod_{n=1}^{m_i} P_n(0, t_{req}) = e^{- \sum_{n=1}^{m_i} t_{req}}$.

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)/1810 (Kbps) = 5.6 s. The unoccupied probability of $SH_1$ is $e^{- \left( \frac{30}{180} \right)} \times e^{- \left( \frac{33}{180} \right)} = e^{-0.3582} \approx 0.7$. 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 of $SH_i$ and $SH'_i$ 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, $SNR = \frac{P_{s,nal}}{P_{n,noise}}$ and $SNR' = \frac{P_{s,nal}}{P_{n,noise}}$, where $SNR_{dB} = 10 \log_{10} \left( \frac{P_{s,nal}}{P_{n,noise}} \right)$ and $SNR'_{dB} = 10 \log_{10} \left( \frac{P_{s,nal}}{P_{n,noise}} \right)$.

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

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 $P_u(m_i, t_{req}) = \prod_{n=1}^{m_i} P_n(0, t_{req}) = e^{- \sum_{n=1}^{m_i} t_{req}}$.

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 $P_u(m'_i, t'_{req}) = \prod_{n=1}^{m'_i} P_n(0, t'_{req}) = e^{- \sum_{n=1}^{m'_i} t'_{req}}$.

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 $2 \times 180$ (kHz) $\times \log_2(1 + 15.8)$ = 1466 Kbps and $2 \times 180$ (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)/1245 (Kbps) = 8 s and $SH'_1$ 10 (Mb)/1466 (Kbps) = 6.8 s. The unoccupied probability $P_u(SH_1, t_{req})$ is $e^{- \left( \frac{40}{180} \right)} \times e^{- \left( \frac{35}{180} \right)} = e^{-0.504} \approx 0.6$, and $P_u(SH'_1, t_{req})$ is $e^{- \left( \frac{30}{180} \right)} \times e^{- \left( \frac{48}{180} \right)} = 0.6$. These calculated results are useful in the evaluation and transmission phase.

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

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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

$$T_e(SH_i) = \frac{d_t}{P_u(m_i, t_{req})} + \left(1 - P_u(m_i, t_{req})\right) \times T_{12H},$$

(1)

where $T_{12H}$ 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 $\frac{d_t}{P_u(m_i, t_{req})} + \left(1 - P_u(m_i, t_{req})\right) / C_0$ to increase the transmission time. The usage of $SH_i$ of $SU_x$ may be interrupted again by the appearance of other PUs, the $SU_x$ may perform the spectrum mobility again. This condition is represented as $\left(1 - P_u(m_i, t_{req})\right) / C_0$.

S2: If the $SU_x$ is in the overlapped area between the old eNB and the new eNB, the $SU_x$ must additionally calculates $T_e(SH'_i)$ for the new eNB for the final evaluation. Similarly, the $T_e(SH'_i)$ is

$$T_e(SH'_i) = T_{13H} + \frac{d_t}{P_u'(m'_i, t'_{req})} \left(1 - P_u'(m'_i, t'_{req})\right) \times T_{12H},$$

(2)

where $T_{13H}$ 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 $T_e(SH_i)$, $T_e(SH'_i)$ additionally plus the time cost of $T_{13H}$.

S3: The $SU_x$ performs the spectrum mobility if

$$\frac{d_t}{P_u(m_i, t_{req})} + \left(1 - P_u(m_i, t_{req})\right) \times T_{12H} = \frac{d_t}{P_u'(m'_i, t'_{req})} \left(1 - P_u'(m'_i, t'_{req})\right) \times T_{12H}.$$
Otherwise, the SU\textsubscript{x} performs the handover procedure.

Fig. 11 shows an example of evaluation and transmission phase, the expected transmission time of SH\textsubscript{1} in old_eNB is

\[
T_{E}(SH_{1}) = \frac{10(\text{Mb})}{0.6} + (1 - 0.6) \times 0.05(s) = 13.407(s),
\]

and the expected transmission time of spectrum hole SH\textsubscript{1} in new_eNB is calculated as

\[
T_{E}(SH_{1}) = 0.35(s) + \frac{10(\text{Mb})}{0.6} + (1 - 0.6) \times 0.05 = 11.739.
\]

The other expected transmission time of SH\textsubscript{2} and SH\textsubscript{3} (old_eNB) and SH\textsubscript{0}\textsubscript{2} and SH\textsubscript{0}\textsubscript{3} (new_eNB) is shown in Fig. 11. The minimum expected transmission time is SH\textsubscript{0}\textsubscript{2}. Consequently, SU\textsubscript{1} performs the handover to SH\textsubscript{0}\textsubscript{2} of the new_eNB for the data transmission.

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\textsubscript{x}, the SU\textsubscript{x} uses ith spectrum hole SH\textsubscript{i} from a given sequence of j spectrum holes (SH\textsubscript{1}, SH\textsubscript{2}, ..., SH\textsubscript{i}, ..., SH\textsubscript{j}) in the serving eNB, where 1 ≤ i ≤ j. Two cases are considered for our analysis. First case is that a SU\textsubscript{x} performs the spectrum mobility if the SU\textsubscript{x} is in the non-overlapped area. Another case is that a SU\textsubscript{x} performs the spectrum mobility or the handover if the SU\textsubscript{x} is in the overlapped area.

Without loss of generality, assumed that let ith spectrum hole SH\textsubscript{i} has m resource blocks, where 1 ≤ m. Let the data of the SU\textsubscript{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\textsubscript{i}” denotes SU\textsubscript{x} transmits the next data packet through the current spectrum hole SH\textsubscript{i}. In the part II, there are m resource blocks, where 1 ≤ m. Therefore, there are m RB\textsubscript{i} states, where 1 ≤ i ≤ m. Each resource block may be reclaimed by a PU. Therefore, m resource blocks are checked once. If RB\textsubscript{i} is reclaimed by a PU, then go to state of “spectrum mobility to SH\textsubscript{i}” (part III); otherwise, go to the next state of RB\textsubscript{i+1}, where 1 ≤ i < m. Until reaching to state of “RB\textsubscript{m}”, if there is still no reclaimed by a PU, then go to the initial state of “SH\textsubscript{i}” without performing the spectrum mobility. In the part III, state of “spectrum mobility to SH\textsubscript{i}” state denotes the SU\textsubscript{x} performs spectrum mobility and change the spectrum hole from SH\textsubscript{i} to SH\textsubscript{i}, which SH\textsubscript{i} is reclaimed by a PU.

The state transition information is given below:

- SH\textsubscript{i} to RB\textsubscript{i}: indicates that the previous packet was completely transmitted completely and the next packet starts to be transmitted.

![Diagram](https://example.com/diagram.png)

Fig. 11. Example of computation and analysis phase and the evaluation and transmission phase.

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Let $t_{\text{unit}}$ denote as a past period of time units. Let $\lambda_i$ denote as the reclaimed number by a PU of $RB_i$ within $t_{\text{unit}}$. Let $t_{\text{req}} = \frac{d_i}{R_i}$ be the required data transmission time between SU$_x$ and eNB through SH$_i$, without considering $k_i$. According to the Poisson distribution

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

where $n$ is the total number of event occurrences and let $\gamma$ be a positive real number which is equal to the expected occurrence number during a given time interval. The probability of $i$th resource block $RB_i$ not being reclaimed by PUs within the time interval is $\lambda_i = \frac{d_i}{R_i \times t_{\text{unit}}}$. The probability of $P_{\text{u}}(SH_i, t_{\text{req}})$ is represented by $\prod_{k=1}^{m} e^{-\left(\frac{k_i}{t_{\text{unit}}} \times t_{\text{req}}\right)}$. □

The total transmission time is

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

where $1 \leq i \leq j$ and $T_{\text{old, eNB}}$ is the expected time cost of SU$_x$ performing 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 $T_{\text{old, eNB}}$ and $T_{\text{non-spectrum mobility}}$ are calculated as follows.

---

**Fig. 12.** Relation between resource blocks in the scenario one.
Lemma 2. If there is one packet to be transmitted from a SU to the serving eNB through the different spectrum hole $SH_i$. The expected transmission time, $T_{old,eNB}$, is

$$T_{old,eNB} = (1 - P_u(SH_i, t_{req})) \times \left( \frac{d_i}{R_i \times N} \right). \tag{6}$$

Proof. The transmission time of one packet is $T_{old,eNB} = \frac{d_i}{R_i \times N}$ if the SU needs to perform the spectrum mobility, where $T_{old,eNB}$ is the time cost of spectrum mobility and $\frac{d_i}{R_i \times N}$ is the transmission time between the SU and the serving eNB. The probability of spectrum mobility is $1 - P_u(SH_i, t_{req})$. Therefore, the expected transmission time is $(1 - P_u(SH_i, t_{req})) \times \left( \frac{d_i}{R_i \times N} \right)$. \qed

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

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

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

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 to the serving eNB. The expected total transmission time, $T_{TTT}$, is

$$T_{TTT} = \frac{1}{j} \sum_{i=1}^{j} \left( (1 - P_u(SH_i, t_{req})) \times T_{old,eNB} + t_{req} \right), \quad \text{where} \quad 1 \leq i \leq j, \quad t_{req} = \frac{d_i}{R_i}. \tag{8}$$

Proof. Based on Lemmas 2 and 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 $T_{TTT} = \frac{1}{j} \sum_{i=1}^{j} \sum_{k=0}^{N-1} T_{one, packet}$. Then, we have the following result.

$$T_{TTT} = \frac{1}{j} \sum_{i=1}^{j} \sum_{k=0}^{N-1} \left[ (1 - P_u(SH_i, t_{req})) \times \left( \frac{d_i}{R_i \times N} \right) + P_u(SH_i, t_{req}) \times \frac{d_i}{R_i \times N} \right]$$

$$= \frac{1}{j} \sum_{i=1}^{j} \left( T_{old,eNB} + t_{req} - P_u(SH_i, t_{req}) \times T_{old,eNB} \right)$$

$$= \frac{1}{j} \sum_{i=1}^{j} ((1 - P_u(SH_i, t_{req})) \times T_{old,eNB} + t_{req}), \quad \text{where} \quad 1 \leq i \leq j, \quad t_{req} = \frac{d_i}{R_i}. \quad \blacktriangleleft$$

In the following, we further consider the case of a SU performing the spectrum mobility or the handover if the SU 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 “$SH_1$” denotes $SU_i$ transmits the next data packet through 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 $SH_j$”, or state of “handoff to $SH_j$” (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 or the handoff procedure. In part III, state of “handoff to $SH_j$” state denotes the SU performs the handoff procedure and changes the spectrum hole from $SH_i$ to $SH_j$. The additional state transition information is given below:

- $RB_i$ to “spectrum mobility to $SH_j$”: $RB_i$ has the probability of $P_{old,NB}(1 - \prod_{k=1}^{i} \exp \left( - \frac{d_k}{t_{req}} \right))$ if the $RB_i$ is reclaimed by a PU and performs the spectrum mobility and $RB_i$ to $RB_{i+1}$ are not reclaimed by the PU.
- $RB_i$ to “handoff to $SH_j$”: $RB_i$ has the probability of $P_{new,NB}(1 - \prod_{k=1}^{i} \exp \left( - \frac{d_k}{t_{req}} \right))$ if the $RB_i$ is reclaimed by a PU and performs the handoff procedure and $RB_i$ 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 $SU_i$ only transmits packet through the serving (old) eNB or the next (new) eNB. We have

$$P_{old,eNB} + P_{new,eNB} = 1,$$ \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
where $1 \leq i \leq j$ and $T_{\text{new}_eNB}$ is the expected time cost of a SU$_x$ performing the handover and using the new spectrum hole $SH_i$ in the new eNB for one packet transmission, and $T_{\text{non-handoff}}$ is the expected time cost of a SU$_x$ using the original $SH_i$ in the old eNB for one packet transmission, where $T_{\text{non-handoff}} = T_{\text{non-spectrum mobility}}$.

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, a SU$_x$ needs to perform the handover to the new eNB. The expectation transmission time, $T_{\text{new}_eNB}$, is

$$T_{\text{new}_eNB} = P_{\text{new}_eNB} \times (1 - P_{\text{a}}(SH_i, t_{\text{req}})) \times \left(T_{\text{L2H}} + T_{\text{L3H}} + \frac{d_l}{R_i \times N}\right).$$  

**Proof.** The probability of the handover of SU$_x$ is $P_{\text{new}_eNB} \times (1 - P_{\text{a}}(SH_i, t_{\text{req}}))$. The transmission time is $T_{\text{L2H}} + T_{\text{L3H}} + \frac{d_l}{R_i \times N}$, where $T_{\text{L2H}}$ is the spectrum mobility time, $T_{\text{L3H}}$ is the L3 handover time, and $\frac{d_l}{R_i \times N}$ is the time cost of one packet transmission. Therefore, the expected transmission time of $T_{\text{new}_eNB}$ is $P_{\text{new}_eNB} \times (1 - P_{\text{a}}(SH_i, t_{\text{req}})) \times \left(T_{\text{L2H}} + T_{\text{L3H}} + \frac{d_l}{R_i \times N}\right)$. \hfill $\Box$

**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, $T_{\text{old}_eNB}$, is

$$T_{\text{old}_eNB} = P_{\text{old}_eNB} \times (1 - P_{\text{a}}(SH_i, t_{\text{req}})) \times \left(T_{\text{L2H}} + \frac{d_l}{R_i \times N}\right).$$

**Proof.** The probability of the spectrum mobility of SU$_x$ is $P_{\text{old}_eNB} \times (1 - P_{\text{a}}(SH_i, t_{\text{req}}))$, and the expected transmission time of $T_{\text{old}_eNB}$ is $P_{\text{old}_eNB} \times (1 - P_{\text{a}}(SH_i, t_{\text{req}})) \times \left(T_{\text{L2H}} + \frac{d_l}{R_i \times N}\right)$. \hfill $\Box$
Based on Lemmas 3–5, we have the following result.

**Theorem 2.** If there are \( j (1 \leq i \leq j) \) spectrum holes, from \( SH_i \) 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 \( 1 \leq i \leq j \) and \( t_{req} = \frac{d_i}{R_i} \).

**Proof.** Based on Eq. (10) and Lemmas 3–5, it can be derived the final result as follows:

\[
T_{TTT} = \frac{1}{j} \sum_{i=1}^{j} \left[ \left( P_{old,eNB} \times (1 - P_u(SH_i, t_{req})) \times \left( T_{L2H} + \frac{d_i}{R_i \times N} \right) \right) \\
+ \left( P_{new,eNB} \times (1 - P_u(SH_i, t_{req})) \times \left( T_{L2H} + T_{L3H} + \frac{d_i}{R_i \times N} \right) \right) \\
+ \left( P_u(SH_i, t_{req}) \times \frac{d_i}{R_i \times N} \right) \right]
\]

\[
= \frac{1}{j} \sum_{i=1}^{j} [(P_{old,eNB} \times (1 - P_u(SH_i, t_{req})) \times (T_{L2H} + t_{req})) \\
+ (P_{new,eNB} \times (1 - P_u(SH_i, t_{req})) \times (T_{L2H} + T_{L3H} + t_{req})) \\
+ P_u(SH_i, t_{req}) \times t_{req}] \\
= \frac{1}{j} \sum_{i=1}^{j} [T_{L2H} + t_{req} - P_u(SH_i, t_{req}) \times T_{L2H} \\
+ P_{new,eNB} \times (1 - P_u(SH_i, t_{req})) \times T_{L3H} \\
+ P_u(SH_i, t_{req}) \times t_{req}] \\
= \frac{1}{j} \sum_{i=1}^{j} [(1 - P_u(SH_i, t_{req})) \times T_{L2H} + P_{new,eNB} \times (1 - P_u(SH_i, t_{req})) \times T_{L3H} + t_{req}] \\
= \frac{1}{j} \sum_{i=1}^{j} [(1 - P_u(SH_i, t_{req})) \times (T_{L2H} + P_{new,eNB} \times T_{L3H}) + t_{req}], \text{ where } 1 \leq i \leq j \text{ and } t_{req} = \frac{d_i}{R_i}. \quad \square
\]

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

\[
TP = \frac{d_i}{T_{TTT}}.
\]

**Theorem 3.** Assumed that the data size of a SU\(_x\) is \( d_i \) and the total transmission time of \( d_i \) is \( T_{TTT} \), where \( T_{TTT} \) is derived 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:

\[
TP_1 = \frac{d_i \times j}{\sum_{i=1}^{j} [(1 - P_u(SH_i)) \times T_{L2H} + t_{req}]},
\]

\[
TP_2 = \frac{d_i \times j}{\sum_{i=1}^{j} [(1 - P_u(SH_i, t_{req})) \times (T_{L2H} + P_{new,eNB} \times T_{L3H}) + t_{req}]},
\]

where \( 1 \leq i \leq j \), \( t_{req} = \frac{d_i}{R_i} \).

**Proof.** Based on Theorem 1, the throughput, \( TP_1 \), is

\[
TP_1 = \frac{d_i \times j}{\sum_{i=1}^{j} [(1 - P_u(SH_i)) \times T_{L2H} + t_{req}]},
\]

Based on Theorem 2, the throughput, \( TP_2 \), is
\[
TP_2 = \frac{d_t}{\sum_{i=1}^{j} \left( (1 - P_u(SH_i, t_{req})) \times (T_{LH} + t_{req}) \right)}.
\]

\[
= \frac{d_t \times j}{\sum_{i=1}^{j} \left( (1 - P_i(SH_i, t_{req})) \times (T_{LH} + P_{new\_eNB} \times T_{LH}) + t_{req} \right)}.
\]

6. Simulation results

Our paper presents a cross-layer protocol of spectrum mobility and handover in cognitive LTE systems. To fairly evaluate the proposed protocol, two simulation scenarios are implemented as shown in Fig. 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 record 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 as follows:

- 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 can 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 TE 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.

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

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS transmission range</td>
<td>50 km</td>
</tr>
<tr>
<td>Network size</td>
<td>500 × 500 km</td>
</tr>
<tr>
<td>Secondary users speed</td>
<td>0–100 km/h</td>
</tr>
<tr>
<td>Number secondary user</td>
<td>0–20</td>
</tr>
<tr>
<td>Spectrum sensing period</td>
<td>40 ms</td>
</tr>
<tr>
<td>Spectrum switching delay</td>
<td>10 ms</td>
</tr>
<tr>
<td>Handover delay</td>
<td>200–350 ms</td>
</tr>
<tr>
<td>Packet size</td>
<td>1500 bytes</td>
</tr>
<tr>
<td>Simulation time</td>
<td>100–1000 s</td>
</tr>
</tbody>
</table>

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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 Figs. 15 and 16. Fig. 15 shows the 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. 15a. Fig. 15a 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. 15b. Fig. 15b 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.

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 Figs. 18 and 19. Fig. 18 shows the 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. Fig. 18a illustrates that the curve of 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. Fig. 18b 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 collecting the
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. Fig. 21a shows the 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. Fig. 21a 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. 21b. Fig. 21b 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 that the fixed spectrum resource scheme is used in MIPv6 protocol. It is verified 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. Fig. 23a shows the observed NSM under various data size, where the $P_u$ is fixed at 0.5. In general, the NSM drops as
Fig. 21. Throughput (a) vs. time, and (b) vs. number of primary user, for the simulation scenario 1.

Fig. 22. Throughput vs. data size for the simulation scenario 2.

Fig. 23. Number of spectrum mobility (a) vs. data size, and (b) vs. number of primary users, for the simulation scenario 1.
the data size decreases. Fig. 23a 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. Fig. 23b 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. Fig. 24a shows the observed NSM under various number of spectrum holes, where the \( P_u \) is fixed at 0.5. In general, the NSM drops as the number of spectrum holes increases. Fig. 24a 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. Fig. 24b 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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References


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