



Analytical modeling for spectrum handoff decision in cognitive radio networks



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ABSTRACT

Cognitive Radio (CR) is an emerging technology used to significantly improve the efficiency of spectrum utilization. Although some spectrum bands in the primary user's licensed spectrum are intensively used, most of the spectrum bands remain underutilized. The introduction of open spectrum and dynamic spectrum access lets the secondary (unlicensed) users, supported by cognitive radios; opportunistically utilize the unused spectrum bands. However, if a primary user returns to a band occupied by a secondary user, the occupied spectrum band is vacated immediately by handing off the secondary user's call to another idle spectrum band. Multiple spectrum handoffs can severely degrade quality of service (QoS) for the interrupted users. To avoid multiple handoffs, when a licensed primary user appears at the engaged licensed band utilized by a secondary user, an effective spectrum handoff procedure should be initiated to maintain a required level of QoS for secondary users. In other words, it enables the channel clearing while searching for target vacant channel(s) for completing unfinished transmission. This paper proposes prioritized proactive spectrum handoff decision schemes to reduce the handoff delay and the total service time. The proposed schemes have been modeled using a preemptive resume priority (PRP) M/G/1 queue to give a high priority to interrupted users to resume their transmission ahead of any other uninterrupted secondary user. The performance of proposed handoff schemes has been evaluated and compared against the existing spectrum handoff schemes. Experimental results show that the schemes developed here outperform the existing schemes in terms of average handoff delay and total service time under various traffic arrival rates as well as service rates.

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1. Introduction

The term Cognitive Radio (CR), first introduced by Mitola [1,2], is a new technology to improve the usage of scarce frequency spectrum by letting secondary users (SUs) temporarily utilize primary users' (PUs) unused licensed spectrum bands [3–7].

Spectrum handoff plays a critical role in cognitive radio networks as it provides a reliable transmission for interrupted secondary users when the primary users return to their spectrum and helps secondary users to resume their unfinished transmission either at the same channel or at another vacant channel. This can guarantee smooth and fast switching which leads to minimized performance degradation during a spectrum handoff [8].

In a cognitive radio network (CRN) context, a handoff means the transition of a spectrum from a low priority user (secondary user) to the spectrum's owner (primary user). However, in cognitive radio networks the term “handoff” does not

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necessary indicate spectrum switching. Hence, two types of spectrum handoffs are identified in CRNs, namely: switching spectrum handoff; and non-switching spectrum handoff, as illustrated in Fig. 1.

Spectrum handoff (mobility) has this far received less attention from the research community in comparison to the functionalities of cognitive radio networks such as spectrum sensing, spectrum management, and spectrum sharing [5]. In general, spectrum handoff techniques can be classified, from the point of view of decision timing, into two major groups: a proactive-decision spectrum handoff; and a reactive-decision spectrum handoff [9,10].

1. In a proactive-decision spectrum handoff, secondary users prepare target channels for a spectrum handoff prior to the start of their transmission. It does this by periodically monitoring all channels to collect information regarding channel statistics and to decide the candidate set of target channels for future spectrum handoffs according to long-term observation results [11–15].
2. For a reactive-decision spectrum handoff [4,16–18], the interrupted secondary user will search for the target channel in an on-demand fashion (mostly instantaneous wideband sensing) after the spectrum handoff request is made [19,20]. Following this search, the interrupted transmission can be resumed on one of the target channels.

Proactive-decision handoff schemes do not consume time on sensing, as instantaneous wideband sensing is not performed in this type. This therefore results in reducing handoff delay and the total service time [21]. However, the problem here is that the pre-selected target channel(s) may no longer be available when the interruption event occurs. Conversely, although a reactive-decision handoff scheme consumes time on sensing for free channels, sensed results are considered to be more reliable and accurate.

Multiple spectrum handoffs can severely degrade QoS for interrupted users by increasing the handoff delay and the total service time. Giving priority to handoff (interrupted) users over new (uninterrupted) users can show significant performance gains. In some traditional wireless systems [22–26] on-going (handoff) calls are assigned or given priority over originating (new) calls, since it is much less desirable and less tolerable to force the termination of calls in progress than to block calls which are yet to be connected. In this paper we borrow liberally from traditional wireless systems to argue that there should be a high priority level assigned to handoff (interrupted) users over new (uninterrupted) users.

This work proposes and implements a queuing network models to investigate the effects of repeated spectrum handoff delays on the total service time in cognitive radio networks. The main contribution of this work is to develop a prioritized handoff model to effectively manage the spectrum usage by primary users, secondary users and interrupted secondary users. This work is an extension of our previous works [15,17]. The implemented schemes are validated against a simulation and compared with existing handoff schemes through extensive simulation experiments. To the authors' knowledge, existing work does not give priority to interrupted secondary users over uninterrupted ones with respect to transmission resumption in the new channel. Nevertheless, existing work gives such priority in cases where interrupted users choose to wait (stay) at the operating channel to resume their unfinished transmission. This means, interrupted users who decide to change their operating channel will have to wait in a queue until all other primary and secondary users receive their services. Certainly this waiting time will incur extra delay to interrupted users and will increase their handoff delay and total service time. However, by giving higher priority to interrupted secondary users in order to utilize the idle channels, the handoff delay and the total service time can be reduced. This, in turn, will improve the quality of service (QoS) of the interrupted secondary users.

The rest of this paper is organized as follows: Section 2 presents a literature review regarding spectrum handoffs in cognitive radio networks, Section 3 describes a system model and gives some illustrative examples for spectrum handoffs with different handoff schemes. Section 4 derives the closed form of the total service time and the handoff delay for the proposed schemes. Section 5 presents simulation setup, performance calculations and compares simulation and numerical results for various spectrum handoff schemes implemented. Conclusions follow in Section 6.

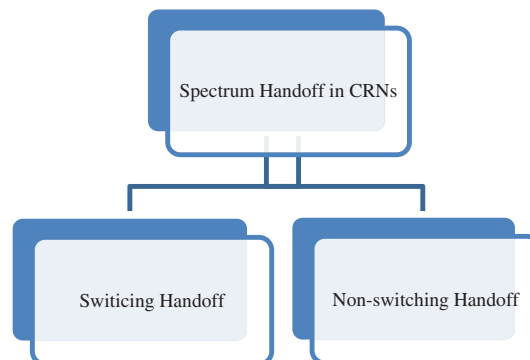


Fig. 1. Handoff process in CRNs.

2. Related work

In cognitive radio networks, the spectrum mobility functionality aims to help the secondary users select the best channel(s) to send and receive their data in case of spectrum handoff. Yet, there has been limited attention given to the performance analysis of spectrum mobility in CR networks using analytical models. This is in light of the importance of analytical modeling for performance analysis and its ability to provide a useful interpretation of the process of spectrum mobility.

There have been several earlier studies conducted into spectrum handoff in cognitive radio networks. In [14,27,28] a preemptive resume priority (PRP) M/G/1 queuing model is proposed to evaluate the total service time of SU transmissions for proactive-decision spectrum mobility. In [28–30], the interrupted communication of secondary users on a particular channel is resumed on the same channel when the channel becomes idle. Conversely, although interrupted secondary users in [9,14,27,31,32] can change their operating channel after an interruption event occurs; no priority is considered for interrupted users over existing secondary users to resume unfinished transmission in the new target channel. In this case, the most common disadvantage is the delay resulting from repeated spectrum handoffs. What is more, the interrupted secondary users are subjected to joining the tail of the secondary users' queue of the new channel which will increase the handoff delay and the total service time even more. Our previous work [17] presented a reactive spectrum handoff decision scheme in which an interrupted secondary user had a higher priority over existing uninterrupted users to utilize the idle channel. The interrupted users were allowed to switch to another communication channel but the presented work was not supported by any results. Although, our work [15] in proactive spectrum handoffs adopted a prioritized schemes which give higher priority for interrupted users to engage idle channels over other uninterrupted secondary users, the work is not extended using analytical models.

3. Spectrum handoffs

3.1. System model

In this paper, we adopted a cognitive radio network with a time-slotted system as shown in Fig. 2. Each user divides its data into equal-sized time slots. Each time-slot is divided into two parts, the first part is for spectrum sensing and the second is for data transmission. When a secondary user starts transmitting in a channel, this channel must be sensed (monitored) periodically in every time slot. If a SU senses, during the first part of the slot, that the present channel is idle, transmission will be commenced in the second part of the slot. However, in general, if the current channel is busy, a spectrum handoff procedure must be performed to help the interrupted user to resume unfinished transmission in an appropriate channel.

The proposed system model suggests that primary users and secondary users will compete for utilizing spectrum channels using access points (APs) for both uplink and downlink transmissions as illustrated in Fig. 3. The model consists of two independent wireless channels as shown in Fig. 4. Each wireless channel is comprised of three priority queues. Low-priority queue (mainly for secondary users' transmissions), high-priority queue (for primary users' transmissions), and handoff (HD) queue (for interrupted users' transmissions).

The queues are implemented with infinite length for simplicity. In addition, a Preemptive Resume Priority (PRP) M/G/1 queuing model is proposed to manage the spectrum handoff procedure.

PU will preempt the transmission of secondary users at the moment of their arrival if they find their channels are being used by secondary users. The preemption priority queue characterizes the inherent traffic structure in CRNs as it gives a right to spectrum owners (PUs) to interrupt secondary users' transmissions at the time of their arrival. Based on this model, we proposed prioritized proactive spectrum handoff decision schemes. This scheme gives higher priority to interrupted secondary users to utilize idle channels over existing uninterrupted SUs which improves the handoff delay and the total service times.

Some preliminary properties for the PRP M/G/1 queuing network model are listed below:

- The low-priority (secondary) users and the high-priority (primary) users will arrive at their default channel, say k , according to Poisson processes with mean rates of $\lambda_s^{(k)}$ and $\lambda_p^{(k)}$, respectively. If the channel is busy, then arrived users will wait in their corresponding queues until it becomes idle. In addition, their service times are generally distributed with mean rates of $E[X_s^{(k)}]$ and $E[X_p^{(k)}]$, respectively. Primary users have higher priority over secondary users to utilize the two wireless channels. Therefore, primary users will interrupt (preempt) secondary user's transmission when they arrive and find their default channels being used by secondary users. Within the primary users' class, PUs will compete to utilize the default

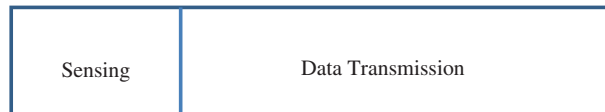


Fig. 2. Time slot structure of the secondary networks.

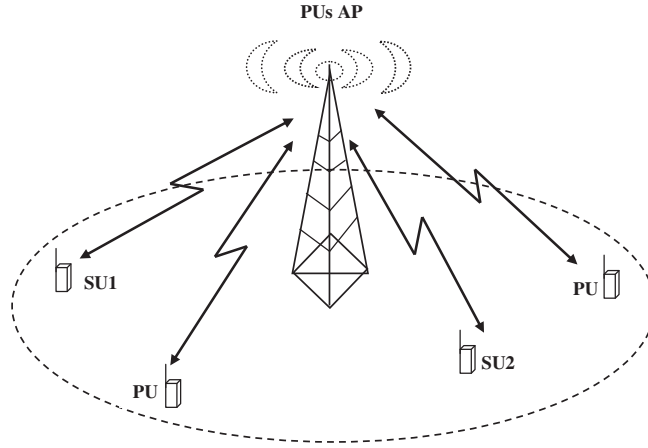


Fig. 3. Proposed CR network scenario.

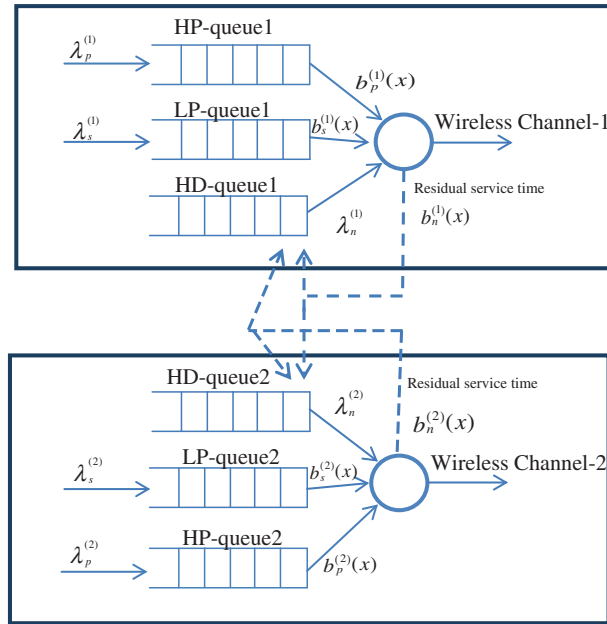


Fig. 4. Proposed preemptive resume priority (PRP) M/G/1 queuing network model with two wireless channels where n denotes n th interruption.

frequency channels on the basis of the first-come-first-served (FCFS) scheduling algorithm at each channel. Handoff secondary users will be served after all primary users, and before any other uninterrupted secondary users already waiting in the low-priority queue of the channel.

- Interrupted users will arrive at their target channel, say k , according to Poisson process with mean rate of $\lambda_i^{(k)}$ and an effective transmission time with mean $E[X_i^{(k)}]$.
- Interrupted users will stay or change their operating channel depending on the adopted spectrum handoff scheme.
- Interrupted secondary users will be put into the handoff-priority queue in the target channel and will be served on a FCFS basis, and before any uninterrupted secondary users.

3.2. Examples for various spectrum handoff decision schemes

To investigate the performance of the proposed proactive spectrum handoff decision schemes, we presented other various existing schemes and compare them.

In this section, the effect of multiple spectrum handoffs in Total Service Time (TST) and Handoff Delay (HD) will be explained through the timeline illustrated in the next figures. TST is defined as the period from the moment of launching

transmission up to the point of completing the transmission [14,27,28]. Whereas the HD is defined as the period from the point of pausing transmission until the moment of starting the transmission [9]. In the case of an interruption, the spectrum handoff procedure will be initiated immediately. However, the interrupted user will choose the target channel according to one of the following handoff schemes to resume unfinished transmission:

3.2.1. Non-switching-handoff (also known as non-handoff scheme) spectrum decision scheme

In this type of scheme, the interrupted secondary user will stop transmitting, stay in the original channel at the interrupted secondary user's queue, and wait until the primary user finishes transmitting all of its data [9,27]. This technique is like the non-hopping approach of IEEE 802.22 [16,18].

Fig. 5 illustrates spectrum handoffs which are described in details as follows:

- Initially, a secondary user SU1 starts to transmit its data on its default channel CH_n to SU2.
- Next, when a primary user arrives at the same channel, because it is its default channel, it will interrupt the transmission of SU1, and then the non-switching-handoff procedure will be initiated. SU1 will stay at the same channel and join the head-of-line (HOL) of SUs' queue to resume unfinished transmission after the primary user finishes its transmission. However, some other primary users may arrive during the period of waiting time of SU1. Upon completion of the primary users' transmission, SU1 will immediately resume its unfinished transmission. Hence, handoff delay here is the waiting time for interrupted users which is exactly equal to the busy period (Y_0) resulting from the primary users in the same channel.
- After each interruption, the same handoff procedure will be repeated until SU1 finishes its data transmission.

3.2.2. Switching-handoff (also known as handoff scheme) spectrum decision scheme

In this type of scheme, whenever the secondary user faces interruption, it will have to change its operating channel until it has finished transmitting all its data [9,27]. Clearly, successive channel switching would increase total service time and the average handoff delay for the interrupted users and this could degrade the quality of service (QoS) of secondary users. The switching-handoff procedure describing this process is shown in Fig. 6:

- In the beginning, SU1 initiates data transmission in its default channel CH_1 to SU2.
- When the first interruption occurs, the switching-handoff procedure will be initiated to change the operating channel to CH_2 . Since, CH_2 is idle, SU1 will resume transmission immediately. In this case, the handoff delay is just the channel switching delay (T_{sw}).
- In the second interruption, the target channel CH_1 is busy. As discussed earlier, by applying our prioritized principle, SU1 can only get service if all the other primary users in the primary users' queue of CH_1 and any other previously interrupted users have been served. However, the old switching-handoff scheme [14,27] does not differentiate between interrupted and uninterrupted secondary users as it serves them in a FCFS fashion which increases the handoff delay and the total service time of the interrupted users. In both models, the handoff delay is the sum of switching delay (T_{sw}) and waiting delay (W_s).
- This procedure will be continued until SU1 finishes sending its data. Here the operating channel will be changed continuously between CH_1 and CH_2 which significantly increases the handoff delay and the total service time of the interrupted secondary users; especially at high PUs arrival rates. This effect can be minimized by giving higher priority to the interrupted users to finish their transmission before any of the other uninterrupted secondary users in the new channel. By introducing this prioritized principle, perhaps unsurprisingly, the QoS of the interrupted users can be improved.

3.2.3. Random-handoff spectrum decision scheme

In this scheme, the spectrum handoff procedure will uniformly select a target channel for the spectrum handoff from available channels [14]. Since, in this work two wireless channels are assumed, there is equal opportunity (50%) to choose either to stay at the same transmission channel or to change to the other channel. However, the handoff delay and the total

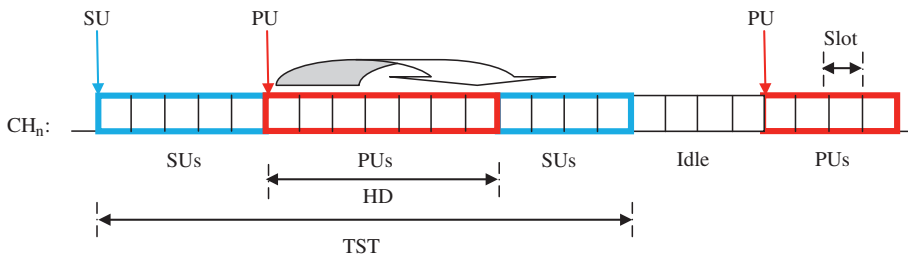


Fig. 5. Non-switching handoff process.

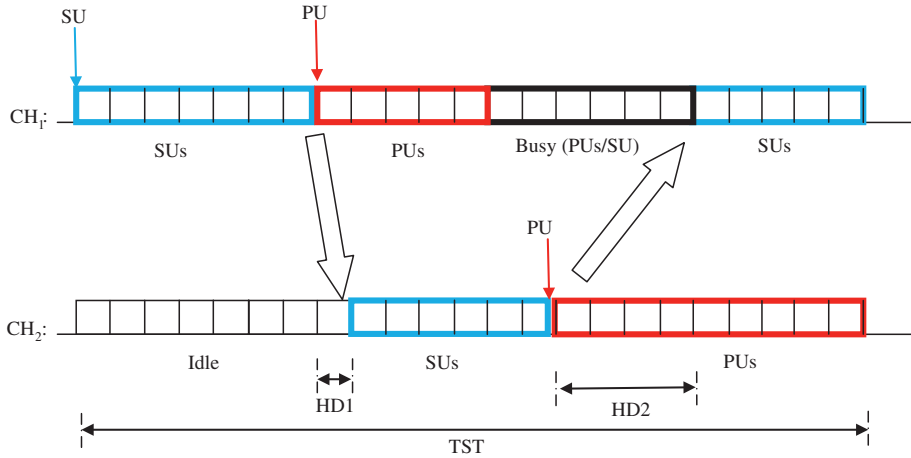


Fig. 6. Switching-handoff process.

service time can be calculated in the same way as in previous handoff schemes. In fact, our prioritized principle will give higher priority to interrupted SUs to resume transmission as explained in the switching-handoff procedure.

3.2.4. Reactive-handoff spectrum decision scheme

In [16,18], the spectrum sensing delay refers to the time it takes such that the interrupted secondary user finds an idle channel for transmission after an interruption event occurs. It is clear that sensing delay plays a major role in this type of handoff scheme since it increases the handoff delay and the total service time.

In this type of scheme, the interrupted users will perform wideband sensing for some time, say T_{se} , to search for candidate idle channels. If they find more than one idle channel, then the handoff procedure will randomly select one out of those channels to resume transmission. In the case where there are no idle channels, interrupted SUs will have to wait at the head-of-line of SUs' queue of their operating channel until the channel becomes idle [16,18]. Indeed, sensing delay is directly proportional to the number of candidate wireless channels to be sensed, i.e., if it takes c time units to sense one wireless channel, we need nc time units for sensing n channels. However, when a secondary user senses a small number of candidate channels, this can lead to minimize the total service time. On the other hand, it is more difficult to find a free channel when sensing a fewer number of channels and consequently the handoff delay as well as the total service time could be increased [33,34]. Perhaps it is worth also considering the handshaking time (T_{ha}). That is the time to accomplish consent on the target channel between communicating SUs. In essence these delays should be added to the previous delays mentioned in order to evaluate the total service time.

In general, the sum of sensing time (T_{se}), handshaking time (T_{ha}) and switching time (T_{sw}) is known as the total processing time. Since the interrupted secondary users may stay or change their operating channel depending on other channels conditions, two types of processing time can be defined. The first type is $T_{pr-stay}$, which is associated with the stay case, and the second is $T_{pr-change}$, which is associated with the change case:

$$T_{pr-stay} = T_{se} + T_{ha} \quad (3.1)$$

$$T_{pr-change} = T_{se} + T_{ha} + T_{sw} \quad (3.2)$$

Eq. (3.2) implies switching time as the interrupted secondary users changes their operating channels. If switching time is assumed to be zero, then the total processing time (T_{pr}) is:

$$T_{pr} = T_{pr-stay} = T_{pr-change} \quad (3.3)$$

In this reactive model of the spectrum handoff decision, the prioritized principle is not applicable because the interrupted user will only change its operating channel to an idle target channel. For the other types of spectrum handoff schemes, the handshaking time does not exist because the target channel for spectrum handoff is already determined before the communication starts between the intended secondary users.

4. Spectrum handoff analytical modeling

We apply the preemptive resume priority (PRP) M/G/1 queuing network model shown in Fig. 4 to derive the closed form expression for the total service time for the newly implemented (switching-handoff and random-handoff) schemes. In these models, the effective transmission time is an important parameter. It is defined as the time from starting transmitting or resuming communication until the time an interruption event occurs. In addition, let $\lambda_s^{(k)}$ and $\lambda_p^{(k)}$ be the initial arrival rates of the secondary users' and the primary users' connections to their default wireless channel k , respectively. Both arrival rates

are modeled by the Poisson processes. Also, let $b_s^{(k)}(x)$ and $b_p^{(k)}(x)$ be their service time distributions with means $E[X_s^{(k)}]$ and $E[X_p^{(k)}]$, respectively. In this work, we take into consideration the effect of the traffic load of the interrupted secondary users coming from other wireless channels on each channel, i.e. a secondary user with i interruptions ($i \geq 0$) will arrive to target channel k with rate $\lambda_i^{(k)}$ and effective transmission time $b_i^{(k)}(x)$ with mean $E[X_i^{(k)}]$ to resume its unfinished transmission. Note that, SU's parameters with zero interruptions ($i = 0$) are denoted with $\lambda_s^{(k)}, E[X_s^{(k)}]$, etc.

The detection of newly arrived primary users is assumed to be perfect, which means no false alarms. In addition there is an infinitesimal delay for the SU to terminate transmission so that the existence of the secondary users is absolutely transparent to the primary users.

The primary and secondary users' utilization factors are defined as:

$$\rho_p^{(k)} = \sum \lambda_p^{(k)} E[X_p^{(k)}] \quad (4.1)$$

$$\rho_i^{(k)} = \sum \lambda_i^{(k)} E[X_i^{(k)}] \quad (4.2)$$

Respectively, and the aggregate system utilization is given by:

$$\rho^{(k)} = \rho_p^{(k)} + \sum_{i=0}^{\infty} \rho_i^{(k)} \quad (4.3)$$

For simplicity, we suppose that all the channels are identical and have the same traffic parameters. So, dropping the notation (k) in all system parameters yields:

$$\rho = \rho_p + \sum_{i=0}^{\infty} \rho_i \quad (4.4)$$

The necessary and sufficient conditions for system stability are:

$$\rho < 1, \sum_{i=0}^{\infty} \rho_i < 1 \quad \text{and} \quad \left(\rho_p + \sum_{i=0}^{\infty} \rho_i \right) < 1$$

Let us assume that $E[X_s]$ is the average service time, $E[D]$ is the average handoff delay, and $E[N]$ is the average number of interruptions for a secondary user's connection during a period of $E[X_s]$. The total estimated service time of the secondary users is defined [14,27] as:

$$E[T] = E[X_s] + E[N]E[D] \quad (4.5)$$

The second term in (4.5) refers to the average cumulative handoff delay ($E[D_{cum}]$), i.e.,

$$E[D_{cum}] = E[N]E[D] \quad (4.6)$$

Thus,

$$E[T] = E[X_s] + E[D_{cum}] \quad (4.7)$$

where $E[N]$ can be expressed as:

$$E[N] = \lambda_p E[X_s] \quad (4.8)$$

4.1. New switching-handoff model

Let Q_p be the mean number of primary users in the high priority queue and Q_i be the mean number of secondary users in the interrupted SUs' priority queue with i interruptions ($i \geq 1$). Then the waiting time (W_s) that interrupted secondary users have to wait before receiving the service can be expressed as follows:

$$W_s = R_s + \sum_{i=1}^{\infty} Q_i E[X_i] + Q_p E[X_p] + \lambda_p W_s E[X_p] \quad (4.9)$$

The first term in Eq. (4.9) (R_s) represents the residual service time of the user (primary or secondary) in service upon a secondary user's arrival whereas, the second term represents the service time obtained due to existing interrupted secondary users with i interruptions in the interrupted users queue. The third term describes service time resulting from primary users in the high-priority queue. Finally, the last term represents the time that a secondary user has to wait due to the primary users' arrival before commencing its service. The next steps will derive the first two parts of Eq. (4.9) one by one.

The first term R_s can be derived as follows:

$$R_s = \frac{1}{2} \lambda_p E[(X_p)^2] + \frac{1}{2} \sum_{i=0}^{\infty} \lambda_i E[(X_i)^2] \quad (4.10)$$

where the first term of Eq. (4.10) represents the residual service time for the primary user and the second term represents the residual service time for the secondary users with i interruptions.

From [14,27], $E[(X_i)^2]$ and λ_i (both based on exponential distribution) can be expressed as:

$$E[(X_i)^2] = \frac{2}{(\lambda_p + \mu_s)^2} \quad (4.11)$$

$$\lambda_i = \lambda_s \left(\frac{\lambda_p}{\lambda_p + \mu_s} \right)^i \quad (4.12)$$

Substituting Eqs. (4.11) and (4.12) into Eq. (4.10) yields:

$$R_s = \frac{1}{2} \lambda_p E[(X_p)^2] + \frac{\lambda_s}{(\lambda_p + \mu_s)^2} \sum_{i=0}^{\infty} \left(\frac{\lambda_p}{\lambda_p + \mu_s} \right)^i \quad (4.13)$$

We assume the service time of the secondary users and the primary users follow the exponential distribution, i.e., $b_s^{(k)}(x) = \mu_s e^{-\mu_s x}$ and $b_p^{(k)}(x) = \mu_p e^{-\mu_p x}$ with mean $\mu_s = 1/E[X_s]$ and $\mu_p = 1/E[X_p]$, respectively. As a consequence the remaining service time of the interrupted secondary user's connection also follows the identical exponential distribution.

For simplicity we assume that:

$$\frac{\lambda_p}{\lambda_p + \mu_s} = C \quad (4.14)$$

Then, substituting the expression (4.14) into Eq. (4.12) yields

$$\lambda_i = \lambda_s C^i \quad (4.15)$$

Thus, R_s can be rewritten as:

$$R_s = \frac{1}{2} \lambda_p E[(X_p)^2] + \frac{\lambda_s}{(\lambda_p + \mu_s)^2} \sum_{i=0}^{\infty} C^i \quad (4.16)$$

Using the well-known series:

$$\sum_{i=0}^{\infty} C^i = C^0 + C^1 + C^2 + C^3 + \dots = \frac{1}{1-C} \quad (4.17)$$

Again, we can rewrite R_s as follows:

$$R_s = \frac{1}{2} \lambda_p E[(X_p)^2] + \frac{\lambda_s}{(\lambda_p + \mu_s)^2} \cdot \frac{1}{1-C} \quad (4.18)$$

After some simplifications we get:

$$R_s = \frac{1}{2} \lambda_p E[(X_p)^2] + \frac{\lambda_s}{\mu_s(\lambda_p + \mu_s)} \quad (4.19)$$

and using $\rho_s = \lambda_s/\mu_s$, we have:

$$R_s = \frac{1}{2} \lambda_p E[(X_p)^2] + \frac{\rho_s}{(\lambda_p + \mu_s)} \quad (4.20)$$

According to Little's law, Q_i in the second term of (4.9) can be expressed as:

$$\sum_{i=1}^{\infty} Q_i E[X_i] = \sum_{i=1}^{\infty} W_s \lambda_i E[X_i] \quad (4.21)$$

where

$$Q_i = W_s \lambda_i \quad \text{where } i \geq 1 \quad (4.22)$$

and W_s is the mean waiting times of secondary users.

By substituting Eq. (4.12) into (4.21) we get:

$$\sum_{i=1}^{\infty} Q_i E[X_i] = W_s \lambda_s \sum_{i=1}^{\infty} \left(\frac{\lambda_p}{\lambda_p + \mu_s} \right)^i E[X_i] \quad (4.23)$$

According to [14,27], $E[X_i]$ is determined as:

$$E[X_i] = \frac{1}{(\lambda_p + \mu_s)} \quad (4.24)$$

Thus,

$$\sum_{i=1}^{\infty} Q_i E[X_i] = \frac{W_s \lambda_s}{(\lambda_p + \mu_s)} \sum_{i=1}^{\infty} \left(\frac{\lambda_p}{\lambda_p + \mu_s} \right)^i \quad (4.25)$$

Since $C = \lambda_p / (\lambda_p + \mu_s)$

$$\sum_{i=1}^{\infty} Q_i E[X_i] = \frac{W_s \lambda_s}{(\lambda_p + \mu_s)} \sum_{i=1}^{\infty} C^i \quad (4.26)$$

Using the series:

$$\sum_{i=1}^{\infty} C^i = C^1 + C^2 + C^3 + \dots = \frac{C}{1-C} \quad (4.27)$$

Therefore,

$$\sum_{i=1}^{\infty} Q_i E[X_i] = \frac{W_s \lambda_s}{(\lambda_p + \mu_s)} \cdot \frac{C}{1-C} \quad (4.28)$$

After some manipulations we can derive the following formula:

$$\sum_{i=1}^{\infty} Q_i E[X_i] = \frac{W_s \rho_s \lambda_p}{(\lambda_p + \mu_s)} \quad (4.29)$$

By substituting the value of Q_p obtained from [14,27] in (4.9), the third term of (4.9) can be rewritten as:

$$Q_p E[X_p] = \frac{\lambda_p^2 E[(X_p)^2]}{2(1-\rho_p)} E[X_p] \quad (4.30)$$

By substituting (4.20), (4.29), and (4.30) into (4.9) we can get:

$$W_s = \frac{1}{2} \lambda_p E[(X_p)^2] + \frac{\rho_s}{(\lambda_p + \mu_s)} + \frac{\lambda_p^2 E[(X_p)^2]}{2(1-\rho_p)} E[X_p] + \frac{W_s \rho_s \lambda_p}{(\lambda_p + \mu_s)} + \lambda_p W_s E[X_p] \quad (4.31)$$

where $\lambda_p E[X_p] = \rho_p$, after some simplifications (4.31) can be rewritten as:

$$W_s = \frac{\frac{1}{2} \lambda_p E[(X_p)^2] + \frac{\rho_s}{(\lambda_p + \mu_s)} + \frac{\lambda_p^2 E[(X_p)^2]}{2(1-\rho_p)} E[X_p]}{(1 - \rho_s \left(\frac{\lambda_p}{\lambda_p + \mu_s} \right) - \rho_p)} \quad (4.32)$$

The handoff delay in this case is the sum of waiting delay and channel switching delay:

$$E[D] = W_s + T_{sw} \quad (4.33)$$

or

$$E[D] = \frac{\frac{1}{2} \lambda_p E[(X_p)^2] + \frac{\rho_s}{(\lambda_p + \mu_s)} + \frac{\lambda_p^2 E[(X_p)^2]}{2(1-\rho_p)} E[X_p]}{(1 - \rho_s \left(\frac{\lambda_p}{\lambda_p + \mu_s} \right) - \rho_p)} + T_{sw} \quad (4.34)$$

Also, put Eq. (4.34) into Eq. (4.6) cumulative handoff delay can be estimated as:

$$E[D_{cum}] = E[N] \left(\frac{\frac{1}{2} \lambda_p E[(X_p)^2] + \frac{\rho_s}{(\lambda_p + \mu_s)} + \frac{\lambda_p^2 E[(X_p)^2]}{2(1-\rho_p)} E[X_p]}{(1 - \rho_s \left(\frac{\lambda_p}{\lambda_p + \mu_s} \right) - \rho_p)} + T_{sw} \right) \quad (4.35)$$

In general, the total service time is expressed as:

$$E[T] = E[X_s] + E[N](W_s + T_{sw}) \quad (4.36)$$

Finally, the total service time can be found by substituting Eq. (4.34) into Eq. (4.36) as:

$$E[T] = E[X_s] + E[N] \left(\frac{\frac{1}{2} \lambda_p E[(X_p)^2] + \frac{\rho_s}{(\lambda_p + \mu_s)} + \frac{\lambda_p^2 E[(X_p)^2]}{2(1-\rho_p)} E[X_p]}{(1 - \rho_s \left(\frac{\lambda_p}{\lambda_p + \mu_s} \right) - \rho_p)} + T_{sw} \right) \quad (4.37)$$

4.2. Random handoff model

Considering the switching-handoff scheme and the non-switching-handoff scheme, [14] determines the total service time for random handoff as follows:

$$E[T] = E[X_s] + \frac{E[N]}{2} Y_p + \frac{E[N]}{2} (W_s + T_{sw}) \quad (4.38)$$

where Y_0 is the primary users' busy period in each wireless communication channel.

In this type of spectrum handoff, a target channel for resuming interrupted transmission will be selected uniformly among available channels. In reality, this formula can be applied to compute the total service time of our new model by substituting the value of W_s derived in Eq. (4.32) into Eq. (4.38).

5. Simulation and numerical results

In this section we present the simulation results that have been achieved using the discrete event simulator (MATLAB) tool to analyze the cumulative handoff delay. Table 5.1 summarizes various implemented handoff models with corresponding features. A summary of simulation parameters are shown in Table 5.2.

The presented simulation results cover a high range of channel utilization (up to ~90%) according to the simulation parameters shown in Table 5.2.

5.1. Simulation setup

In order to evaluate the performance of the proposed handoff schemes, we performed an extensive number of simulation experiments for different PUs arrival rates and PUs and SUs service rates. We consider a cognitive radio system with two wireless channels and each of these wireless channels is assumed to be collision-free. We neglect the effect of T_{sw} and T_{ha} . A 95% confidence interval is used to evaluate the accuracy of the achieved results. In addition we assume secondary users have the ability to perfectly sense the available spectrum bands which means that the detection of PUs is perfect.

5.2. Performance calculations

In general, for simulation experiments the average total service time $E[T]$ can be calculated for each wireless channel using the following formula:

$$E[T] = E[X_s] + E[N] * \frac{(\sum \text{Handoff Delays})}{\text{Number of Interruptions}} + T_{sw} + T_{pr} \quad (5.1)$$

The average handoff delay $E[D]$ is just:

$$E[D] = \frac{(\sum \text{Handoff Delays})}{\text{Number of Interruptions}} + T_{sw} + T_{pr} \quad (5.2)$$

and the average number of interruptions $E[N]$ can be defined as:

$$E[N] = \frac{\text{Number of Interruptions}}{\text{Number of SUs Arrivals}} \quad (5.3)$$

It is worth noting that here the term T_{pr} in Eqs. (5.1) and (5.2) is a general term and should be defined carefully and separately for each of the spectrum handoff schemes. For example, in proactive handoff schemes sensing delay should be equal zero. Alternatively, the switching delay in a non-switching handoff scheme does not exist at all.

In order to achieve credible simulation results, the average statistics of the two channels have been taken in order to draw the figures.

Table 5.1
Implemented handoff models.

Model-name	Symbol	Decision's behavior
Non-switching-handoff	NSWH	Proactive
Old Switching-handoff	SWH-OLD	
New Switching-handoff	SWH-NEW	
Old Random-handoff	RAH-OLD	Reactive
New Random-handoff	RAH-NEW	
Reactive-handoff	REH	

Table 5.2
Simulation parameters.

Parameter	Symbol	Value(s)
PU arrival rate	λ_p	0.05–0.30
SU arrival rate	λ_s	0.15
PU service time	μ_p^{-1}	0.60
SU service time	μ_s^{-1}	0.40

5.3. Numerical results

Numerical results presented in Figs. 7–14 show comparisons between analytical and simulation results. In general, from the graphs it is clear that the analytical and simulation results are approximately the same in the case of NSWH, SWH-OLD, RAH-NEW, and REH schemes. On the other hand, the remaining schemes (SWH-NEW and RAH-OLD) give very close results especially at low PUs arrival rates of about (0.05–0.20) and (0.05–0.15), respectively. Above these ranges the difference between the two curves increases as the PUs arrival rate increases.

Fig. 15 compares the performance of reactive-handoff decision schemes (REH) for a range of sensing delay values (T_{se}). The graph shows that as the sensing time increases, the cumulative handoff delay increases.

Figs. 16 and 17 show that the switching-handoff (SWH-NEW) and random-handoff (RAH-NEW) models implemented with the prioritized criteria outperform their old corresponding schemes (SWH-OLD and RAH-OLD) for every PUs arrival rate. For example, when a PUs arrival rate is 0.3, the SWH-NEW scheme can significantly improve the cumulative handoff delay by 65% (Fig. 16) and the RAH-NEW scheme considerably by 60% (Fig. 17). This is the case as the interrupted users

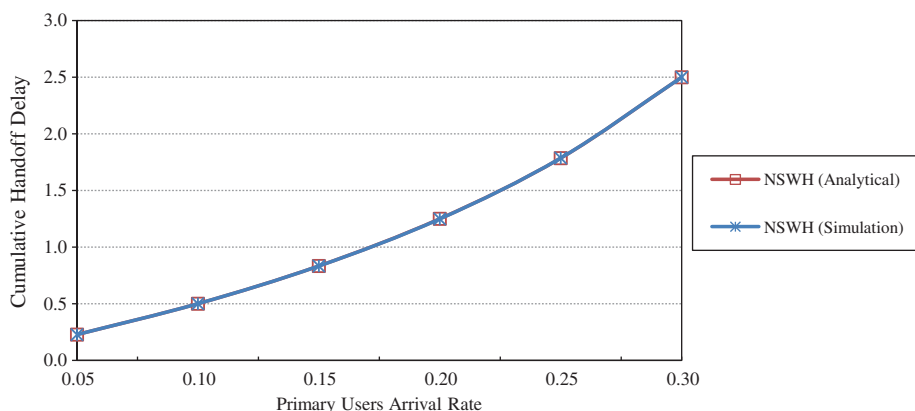


Fig. 7. Non-switching handoff scheme.

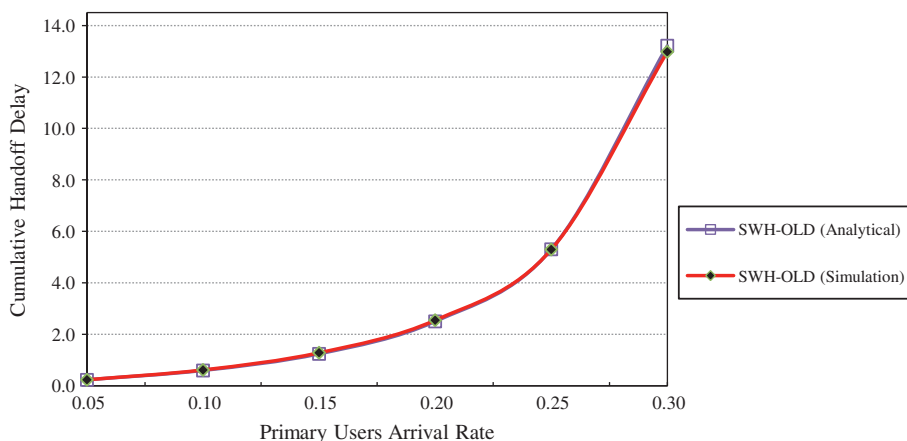


Fig. 8. Old switching-handoff scheme.

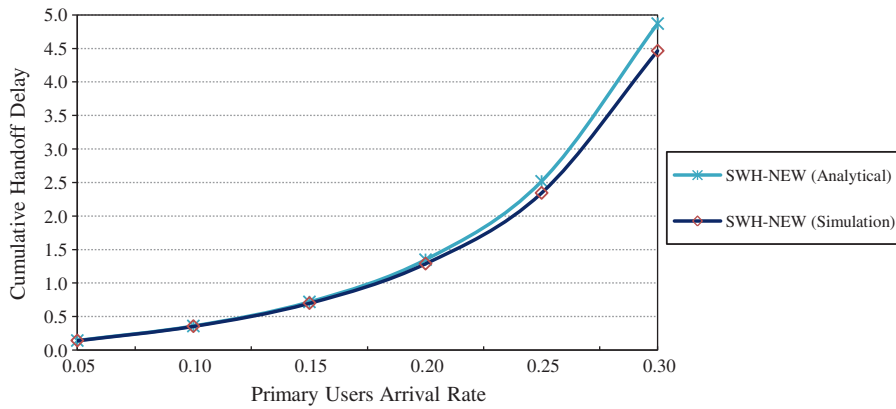


Fig. 9. New switching-handoff scheme.

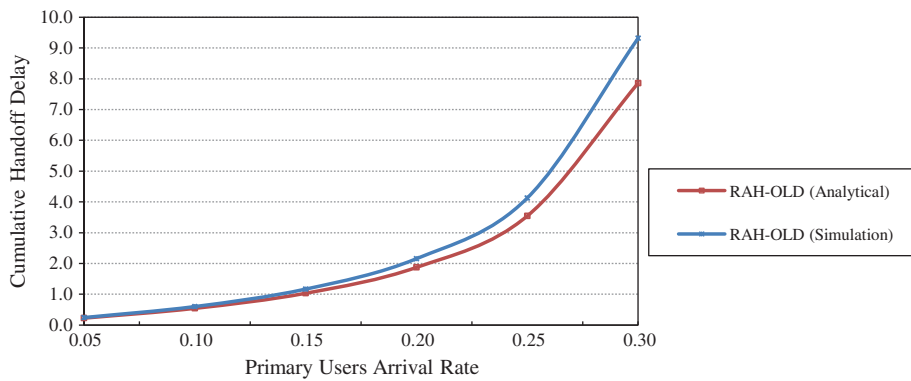


Fig. 10. Old random-handoff scheme.

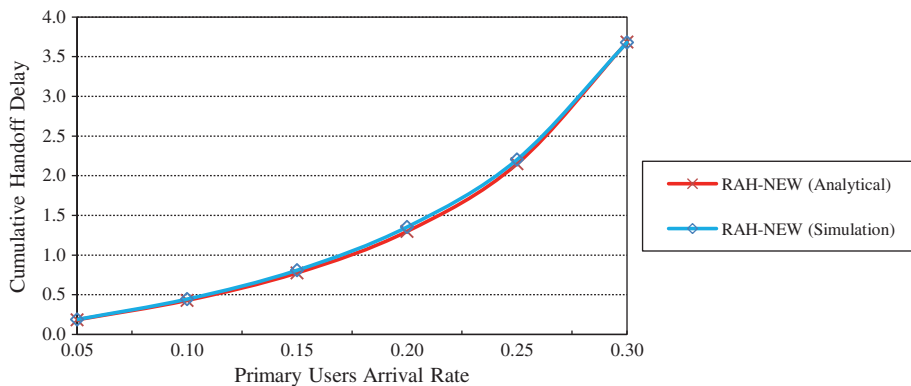


Fig. 11. New random-handoff scheme.

in the new models precede any uninterrupted users in receiving service. This will decrease the cumulative handoff delay for the interrupted secondary users.

Fig. 18 compares the performance of reactive-decision schemes (REH) for a range of sensing delay values (T_{se}) with SWH-NEW and RAH-NEW. As can be seen, when $T_{se} = 0$ (not realistic), the reactive scheme achieves the shortest cumulative handoff delay for all the PUs arrival rates. However, in general, as the sensing delay increases, the reactive model performs poorly compared with other proactive models. For example, when $T_{se} = 2.0$ for the majority PUs arrival rates (0.05–0.27), the REH scheme shows the worst performance in terms of cumulative handoff delay.

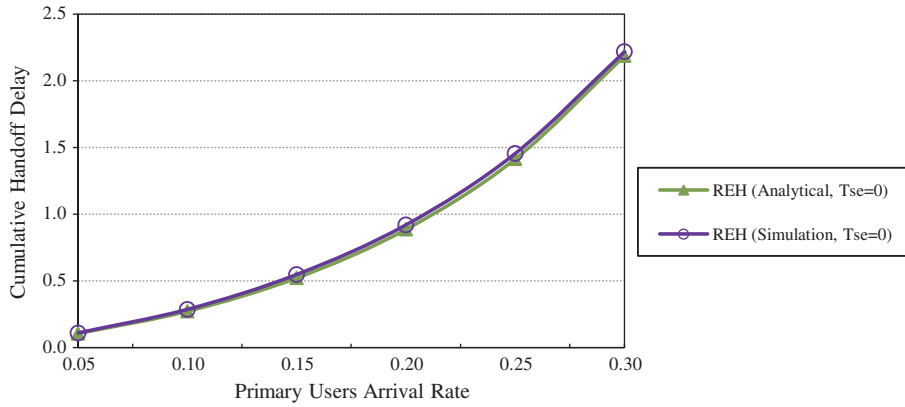


Fig. 12. Reactive-handoff scheme ($T_{se} = 0$).

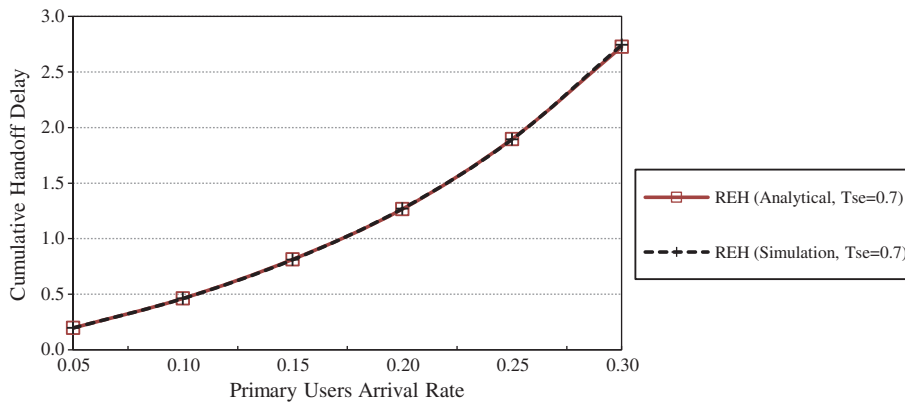


Fig. 13. Reactive-handoff scheme ($T_{se} = 0.7$).

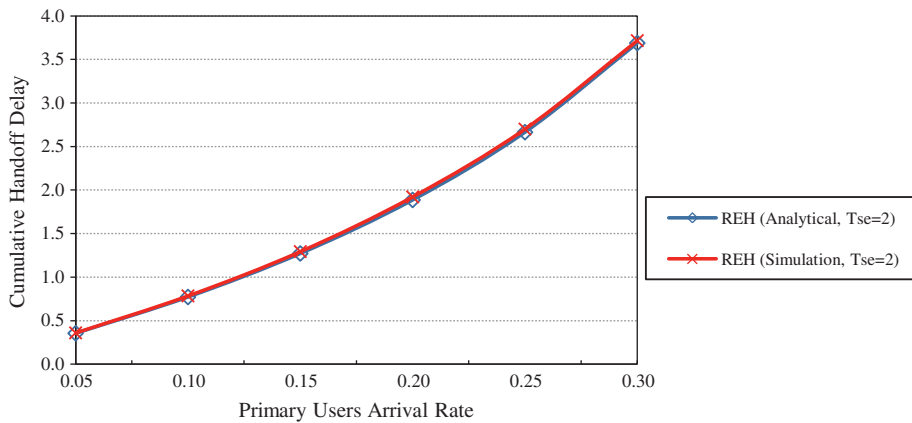


Fig. 14. Reactive-handoff scheme ($T_{se} = 2$).

Finally, Fig. 19 compares NSWH, SWH-NEW, RAH-NEW, and RE ($T_{se} = 0.7$). The results show that for the PUs arrival rate of 0.05–0.20, SWH-NEW performs the best. However, for the remaining range, NSWH provides the best performance. It is perhaps unsurprising that for lower PUs rates, the target channel is more likely to be in an idle state, the waiting delay will be decreased which, in turn, reduces the cumulative handoff delay. This could be arguably the reason why SWH-NEW performs better than the other schemes. However, for higher PUs arrival rates, the opposite is true and NSWH shows a better performance.

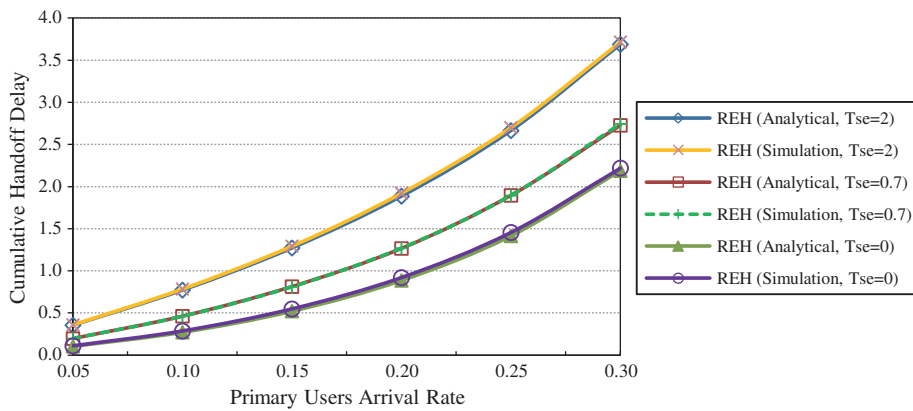


Fig. 15. Comparison of reactive-handoff scheme with different values of sensing time.

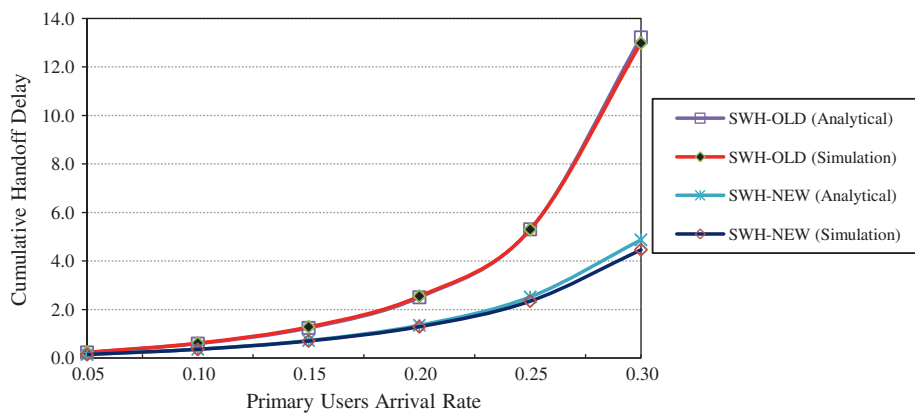


Fig. 16. Comparison between old and new switching-handoff schemes.

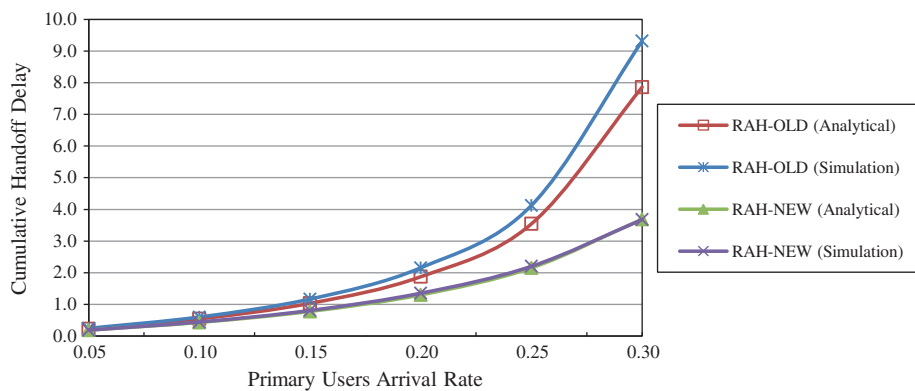


Fig. 17. Comparison between old and new random-handoff schemes.

Fig. 20 shows the effects of the secondary users' service rate μ_s on the cumulative handoff delay ($E[D_{cum}]$) when considering the SWH-NEW scheme. From the graph it is clear that $E[D_{cum}]$ increases as μ_s decreases. This can be interpreted as; when the rate μ_s decreases the average service time $E[X_s]$ increases, thus, $\mu_s = 1/E[X_s]$, therefore, the secondary user in service will be interrupted with a high probability which leads to an increase in the cumulative delay.

Fig. 21 shows the effects of the primary users' service rate μ_p on the cumulative handoff delay in the case of the SWH-NEW scheme. Again, from the graph it is clear that $E[D_{cum}]$ increases as μ_p decreases. This can be understood as; when

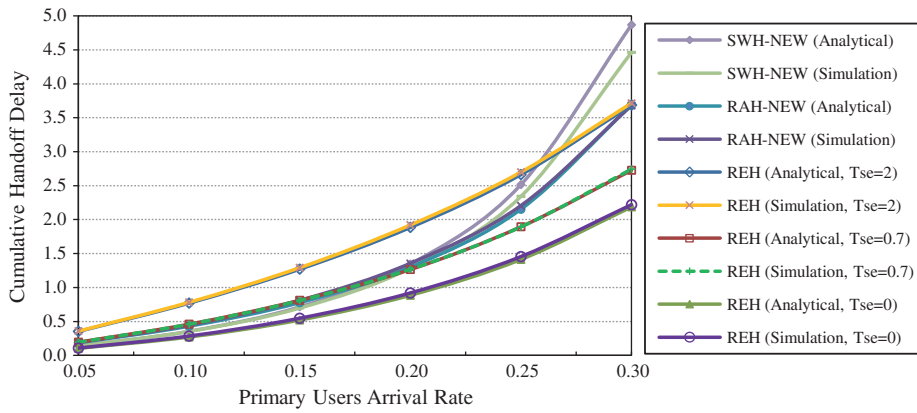


Fig. 18. Comparison of reactive scheme for different values of sensing delay with new proactive schemes.

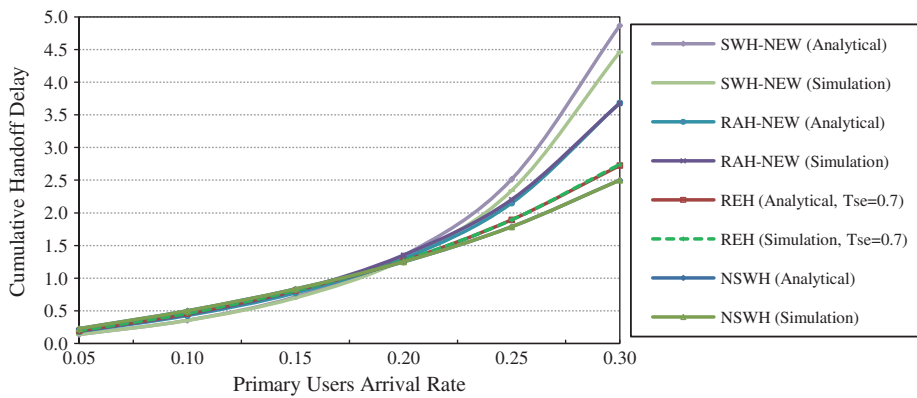


Fig. 19. Performance of various handoff schemes.

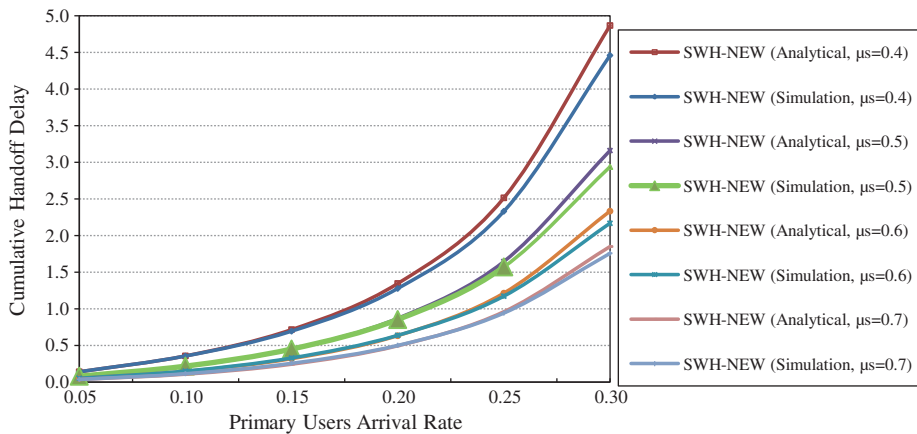


Fig. 20. Effect of SUs service rate on the cumulative handoff delay.

the rate μ_p decreases the average service time $E[X_p]$ increases, since, $\mu_p = 1/E[X_p]$, therefore, the interrupted secondary users in their associated queues will wait for long periods before the channel becomes idle which leads to an increase in the cumulative delay.

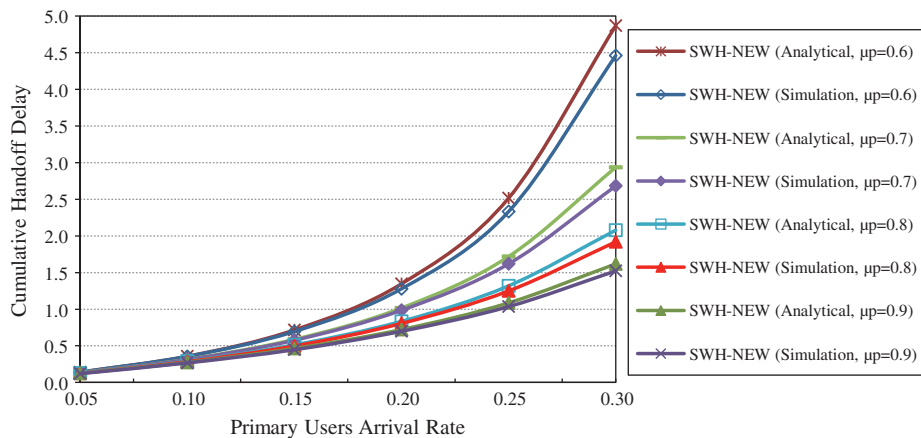


Fig. 21. Effect of PUs service rate on the cumulative handoff delay.

6. Conclusion

In this paper, we presented a prioritized proactive decision handoff schemes in cognitive radio networks. Existing work does not consider any preferences for interrupted secondary users to resume their unfinished transmission on the target channel under the case of a handoff process. The proposed prioritized schemes provide the interrupted secondary users with higher priority to utilize unused licensed channels. Results confirm that our proposed prioritized schemes reduce the cumulative handoff delay and hence the total service time of the interrupted secondary users.

Acknowledgments

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References

- [1] J. Mitola III, G.Q. Maguire Jr., Cognitive radio: making software radios more personal, *Personal Communications, IEEE* 6 (1999) 13–18.
- [2] J. Mitola, Cognitive radio: An integrated agent architecture for software defined radio, Doctor of Technology, Royal Inst. Technol. (KTH), Stockholm, Sweden, 2000, pp. 271–350.
- [3] S. Haykin, Cognitive radio: brain-empowered wireless communications, *IEEE Journal on Selected Areas in Communications* 23 (2005) 201–220.
- [4] C.W. Wang, L.C. Wang, F. Adachi, Performance gains for spectrum utilization in cognitive radio networks with, spectrum handoff, *International Symposium on Wireless Personal Multimedia Communications (WPMC)* (2009).
- [5] I.F. Akyildiz, W.Y. Lee, M.C. Vuran, S. Mohanty, NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey, *Computer Networks* 50 (2006) 2127–2159.
- [6] R.W. Thomas, L.A. DaSilva, A.B. MacKenzie, Cognitive Networks (2005) 352–360.
- [7] L.C. Wang, C.W. Wang, Y.C. Lu, C.M. Liu, A concurrent transmission MAC protocol for enhancing throughput and avoiding spectrum sensing in cognitive radio, in: *IEEE Wireless Communications and Networking Conference (WCNC 2007)*, (2007), pp. 121–126.
- [8] I.F. Akyildiz, W.Y. Lee, M.C. Vuran, S. Mohanty, A survey on spectrum management in cognitive radio networks, *Communications Magazine, IEEE* 46 (2008) 40–48.
- [9] W. Li-Chun, W. Chung-Wei, Spectrum handoff for cognitive radio networks: reactive-sensing or proactive-sensins?, in: *IEEE International Performance, Computing and Communications Conference*, 2008, IPCCC 2008. 2008, pp. 343–348.
- [10] L.C. Wang, C.W. Wang, K.T. Feng, A queueing-theoretical framework for QoS-enhanced spectrum management in cognitive radio networks, *Wireless Communications, IEEE* 18 (2011) 18–26.
- [11] Q. Shi, D. Taubenheim, S. Kyperountas, P. Gorday, N. Correal, Link maintenance protocol for cognitive radio system with OFDM PHY, in: *Proceedings of the IEEE International Symposium on New frontiers in Dynamic Spectrum Access Networks*, Dublin, Ireland, 2007, pp. 440–443.
- [12] S. Srinivasa, S.A. Jafar, The throughput potential of cognitive radio: a theoretical perspective, *IEEE Communications Magazine*. pp. 73–79 (2007).
- [13] H. Su, X. Zhang, Channel-hopping based single transceiver MAC for cognitive radio networks, in: *Proceedings of the 42nd Annual Conference on Information Sciences and Systems (CISS '08)*, (2008), pp. 197–202.
- [14] W. Chung-Wang, W. Li-Chung, Modeling and analysis for proactive-decision spectrum handoff in cognitive radio networks, in: *IEEE International Conference on Communications*, 2009, ICC '09, 2009, pp. 1–6.
- [15] S. Zahed, I. Awan, M. Geyong, Prioritized proactive scheme for spectrum handoff decision in cognitive radio networks, in: *Presented at the 7th International Conference on Broadband and Wireless Computing, Communication and Applications (BWCCA 2012)*, University of Victoria, Victoria, Canada, 2012.
- [16] W. Chung-Wei, W. Li-Chun, F. Adachi, Modeling and analysis for reactive-decision spectrum handoff in cognitive radio networks, in: *Global Telecommunications Conference (GLOBECOM 2010)*, 2010 IEEE, 2010, pp. 1–6.
- [17] S. Zahed, I. Awan, M. Geyong, Performance evaluation of secondary users in cognitive radio networks, in: *27th UKPEW*, Bradford, UK, 2011, pp. 340–343.
- [18] C.-W. Wang, L.-C. Wang, Analysis of reactive spectrum handoff in cognitive radio networks, *IEEE Journal on Selected Areas in Communications* 30 (2012) 2016–2028.
- [19] J. Tian, G. Bi, A new link maintenance and compensation model for cognitive UWB radio systems, in: *International Conference on ITS Telecommunications Proceedings*, 2006, 254–257.

- [20] D. Willkomm, J. Gross, A. Wolisz, Reliable link maintenance in cognitive radio systems, in: Proc. of the IEEE Symposium on New Frontiers in Dynamic System Access Networks (DySPAN 2005), 2005, pp. 371–378.
- [21] Q. Zhao, L. Tong, A. Swami, Y. Chen, Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework, *IEEE Journal on Selected Areas in Communications* 25 (2007) 589–600.
- [22] C.T. Chou, K.G. Shin, Analysis of combined adaptive bandwidth allocation and admission control in wireless networks, in: INFOCOM 2002, Proceedings of the Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies, IEEE, 2002, pp. 676–684.
- [23] H.G. Ebersman, O.K. Tonguz, Handoff ordering using signal prediction priority queueing in personal communication systems, *IEEE Transactions on Vehicular Technology* 48 (1999) 20–35.
- [24] M. Naghshineh, M. Schwartz, Distributed call admission control in mobile/wireless networks, *IEEE Journal on Selected Areas in Communications* 14 (1996) 711–717.
- [25] D. Hong, S.S. Rappaport, Traffic model and performance analysis for cellular mobile radio telephone systems with prioritized and nonprioritized handoff procedures, *IEEE Transactions on Vehicular Technology* 35 (1986) 77–92.
- [26] A.E. Khafa, O.K. Tonguz, Dynamic priority queueing of handover calls in wireless networks: an analytical framework, *IEEE Journal on Selected Areas in Communications* 22 (2004) 904–916.
- [27] L.-C. Wang, C.-W. Wang, C.-J. Chang, Modeling and analysis for spectrum handoffs in cognitive radio networks, *IEEE Transactions on Mobile Computing* 11 (2012) 1499–1513.
- [28] L. Wang, C. Wang, C. Chang, Optimal target channel sequence design for multiple spectrum handoffs in cognitive radio networks, *IEEE Transactions on Communications* (2012) 2444–2455.
- [29] P. Zhu, J. Li, X. Wang, Scheduling model for cognitive radio, in: 2008 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom 2008), 2008, pp. 1–6.
- [30] P. Zhu, J. Li, K. Han, X. Wang, A new channel parameter for cognitive radio, in: 2007 2nd International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom 2007), 2007, pp. 482–486.
- [31] D. Aman, S. Mahfooz, M. Waheed Ur Rehman, A handoff using guard channels scheme (HGCS) for cognitive radio networks, *Global Journal of Computer Science and Technology* 11 (1965).
- [32] J. Heo, J. Shin, J. Nam, Y. Lee, J.G. Park, H.-S. Cho, Mathematical analysis of secondary user traffic in cognitive radio system, in: 68th Vehicular Technology Conference, 2008, VTC 2008-Fall, IEEE, 2008, pp. 1–5.
- [33] L.-C. Wang, C.-W. Wang, F. Adachi, Load-balancing spectrum decision for cognitive radio networks, *IEEE Journal on Selected Areas in Communications* 29 (2011) 757–769.
- [34] L.-C. Wang, C.-W. Wang, Spectrum management techniques with QoS provisioning in cognitive radio networks, in: 5th IEEE International Symposium on Wireless Pervasive Computing (ISWPC), 2010, 2010, pp. 116–121.