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Analysis of cumulative handoff delay for graded secondary users in cognitive radio networks

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Abstract: According to the fact that the secondary users' delay requirements for data transmission are not unitary in cognitive radio networks, the secondary users are divided into two classes, denoted by SU1 and SU2, respectively. It is assumed that SU1 has a higher priority to occupy the primary users' unutilized channels than SU2. A preemptive resume priority M/G/1 queuing network is used to model the multiple spectrum handoffs processing. By using a state transition probability matrix and a cost matrix, the average cumulative delays of SU1 and SU2 are calculated, respectively. Numerical results show that the more the primary user's traffic load, the more rapidly the SU2's cumulative handoff delay grows. Compared with the networks where secondary users are unitary, the lower the SU1's arrival rate, the more obviously both SU1's and SU2's handoff delays decrease. The admission access regions limited by the maximum tolerable delay can also facilitate the design of admission control rules for graded secondary users.

Key words: cognitive radio network; graded secondary users; multiple spectrum handoffs; cumulative handoff delay; admission access region

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Cognitive radio (CR) techniques can improve spectrum efficiency by allowing secondary users (SUs) to temporarily utilize the unused licensed spectrum of primary users (PUs)[1] in CR networks. In order to avoid the interference with PU signals, when the PU appears at its licensed spectrum occupied by an SU, the spectrum handoff procedure must be initiated to help the SU vacate the occupied spectrum and find a suitable target channel to resume the unfinished communications.

Spectrum handoff is an efficient method to guarantee quality of service (QoS) for SUs[2-4]. But in reverse, a frequent number of spectrum handoffs cannot ensure the delay requirements of various communications. So, some research works have been done to deal with it[5-7]. In general, spectrum handoff strategies can be categorized into four kinds: 1) No-handoff strategy[8], where the SU stays on the operating channel and does not occupy it until the channel becomes idle again; 2) Pure proactive handoff[9], where the target channel sequence is ready for handoff before an interruption occurs; 3) Pure reactive spectrum handoff[10], where the target channel is determined according to the spectrum sensing after the interruption; and 4) Hybrid handoff, where the target channel is prepared during SU's communication while spectrum handoff is performed after the interruption.

However, the existing spectrum handoff strategies are almost all based on unitary SUs. In fact, the SUs' delay requirements for data transmission are always different. Some SUs' communications may need a real-time characteristic such as VoIP service, while some others may have no need such as FTP data flow. So it is more useful to divide SUs into multiple classes according to different priorities to occupy the PU's idle channel. In Ref. [11], considering that multiple graded SUs share one channel with a PU, the waiting-time distributions for each class of SU are derived in detail under the proposed *T*-preemptive priority discipline. But there is no analysis for multiple spectrum handoffs as well as cumulative handoff delay for graded SUs.

In this paper, we divide the SUs into two classes, denoted by SU1 and SU2. In the proposed model, SU1 has a higher priority to use the PUs' unused spectrums than SU2. So the priority to occupy the spectrum for the three kinds of users PU, SU1 and SU2 decreases in turn. Based on the pure reactive spectrum handoff strategy, we focus on the analysis of the graded SUs with multiple spectrum handoffs in a CRN. The aim is to investigate the effects of PU's activity level on SU1's and SU2's multiple handoff delays. A Markov transition model combined with the preemptive resume priority (PRP) M/G/1 queuing network[12] is used to characterize various arrivals, services and waiting processes on different channels. The numerical results compare the differences between the unitary SUs and the graded SUs under various PU's activity levels. The final admission regions can also facilitate the designs of admission control rules for graded communication services.

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1 CR Network with Graded SUs

We consider a time-slotted CR network where the SUs are divided into two classes, SU1 and SU2. In order to detect and protect PUs, the spectrum sensing procedure must be executed by SUs at the beginning of each time slot. If the current operating channel is idle, the SU can use it in this time slot. Contrarily, the SU must perform a spectrum handoff procedure to select a target channel to resume its unfinished connections. This kind of listen-before-talk channel access scheme has been adopted in the quiet period of the IEEE 802. 22 standard[13]. When the SU1 connection is interrupted by the PU, the SU1 can grab one of the channels occupied by SU2s as its target channel if there is no idle channel in the network.

1. 1 System description and assumptions

In the system, we assume that there are M independent channels where each channel has three virtual distinct priority queues with unlimited capacity for PUs, SU1s and SU2s, respectively. Arrived data packets must wait in their queues before transmitting. We assume that the connections (consisting of data packets) with the same priority follow the first-come-first-served (FCFS) principle in each queue.

The arrival processes of PU and SU connections are Poisson. The arrival rates for PU, SU1 and SU2 at channel k are denoted by $\lambda_{\mathrm{p}}^{(k)}$, $\lambda_{\mathrm{s1}}^{(k)}$ and $\lambda_{\mathrm{s2}}^{(k)}$, respectively. We denote $R_{\mathrm{p}}^{(k)}$, $R_{\mathrm{s1}}^{(k)}$ and $R_{\mathrm{s2}}^{(k)}$ as the data rate of PU, SU1 and SU2 connections at channel k. And denote $L_{\mathrm{p}}^{(k)}$, $L_{\mathrm{s1}}^{(k)}$ and $L_{\mathrm{s2}}^{(k)}$ as the sizes of connections at channel k, respectively. Let $f_{\mathrm{p}}^{(k)}(l)$, $f_{\mathrm{s1}}^{(k)}(l)$ and $f_{\mathrm{s2}}^{(k)}(l)$ be the probability mass functions of $L_{\mathrm{p}}^{(k)}$, $L_{\mathrm{s1}}^{(k)}$ and $L_{\mathrm{s2}}^{(k)}$, respectively. Hence, the service time of PU, SU1 and SU2 at channel k is $X_{\mathrm{p}}^{(k)} \triangleq \frac{L_{\mathrm{p}}^{(k)}}{R_{\mathrm{p}}^{(k)}}$, $X_{\mathrm{s1}}^{(k)} \triangleq \frac{L_{\mathrm{s1}}^{(k)}}{R_{\mathrm{s1}}^{(k)}}$ and $X_{\mathrm{s2}}^{(k)} \triangleq \frac{L_{\mathrm{s2}}^{(k)}}{R_{\mathrm{s2}}^{(k)}}$ (slots/arrival). The PRP M/G/1 queuing network is shown in Fig. 1.

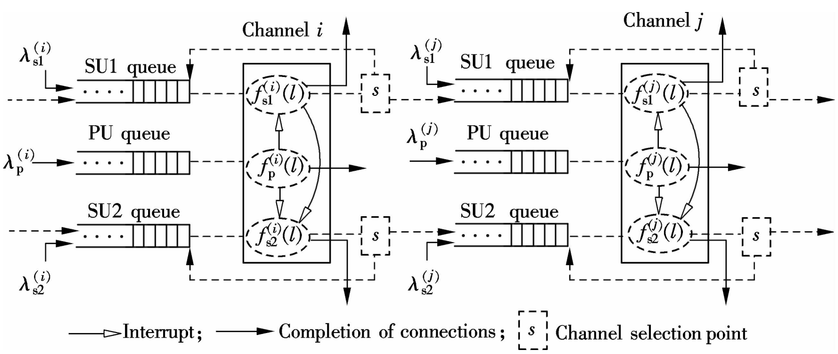

Fig. 1 The PRP M/G/1 queuing network model for three queues with distinct priorities

As shown in Fig. 1, the SU1s and SU2s can opportunistically utilize the idle channels of PUs. If there is no interruption during an SU connection, the SU will complete its data transmitting on the operating channel. Or it will experience one or more spectrum handoffs. The interruptions for SU1 are from PUs' arrivals, while the interruptions for SU2 can be from not only the PUs but also SU1s because the SU1's priority is higher than SU2's. After each interruption, the spectrum sensing procedure must be initiated instantly to search the target channel under the pure reactive spectrum handoff strategy. Once the target channel is selected, the interrupted SU will switch its operating channel to the target one to continue its unfinished connection.

The spectrum sensing time, the handshaking time which is spent to achieve a consensus on the target channel between the transmitter and the receiver, and the channel switching time are denoted by τ, τ_{h}, τ_{s}, respectively, for any SUs.

For SU1, the spectrum sensing results can be classified into the following three cases: 1) Exiting one or more idle channels; 2) Other channels are all busy while at least one of them is occupied by SU2; 3) The rest of channels are all occupied by other PUs or SU1s. In the first case, SU1 will randomly select one as its target channel and switch its operating channel to it; in the second case, SU1 can push one of the SU2s away from its operating channel and occupy it, and the SU2 who is pushed away has to wait at the current channel because there must be no idle channels in the network at this moment; in the third case, SU1 has to stay on the current channel and does not continue its unfinished connection until all the arrival PUs depart. Hence, we can know that the total processing time in each case (denoted by δ_{c1}, δ_{c2} and δ_{stay}) to execute a spectrum handoff procedure is $\delta_{\mathrm{c1}} \triangleq \tau + \tau_{\mathrm{h}} + \tau_{\mathrm{s}}$, $\delta_{\mathrm{c2}} \triangleq \tau + \Delta\tau + \tau_{\mathrm{h}} + \tau_{\mathrm{s}}$ ($\Delta\tau$ is the extra time spent on grabbing the channel from an SU2) and $\delta_{\mathrm{stay}} \triangleq \tau + \tau_{\mathrm{h}}$, respectively.

For SU2, its connection can be interrupted by the PU or SU1. When SU2 is interrupted by the PU, the spectrum sensing results may be the following two cases: 1) Exiting one or more idle channels, where SU2 will randomly select one as its target channel and switch the operating channel to it. In this case, the total processing time (denoted by $\hat{\delta}_{\mathrm{c}}$) is $\hat{\delta}_{\mathrm{c}} \triangleq \tau + \tau_{\mathrm{h}} + \tau_{\mathrm{s}}$; and 2) The rest of the channels are all occupied by other users, where SU2 will stay on the current channel, and the total processing time (denoted by $\hat{\delta}_{stay}$) is $\hat{\delta}_{stay} \triangleq \tau + \tau_h$. When SU2 is interrupted by SU1, there must be no idle channels because SU1 has the higher priority to occupy the idle channels. SU2 has to stay on the current operating channel until all the connections caused by the arrived SU1 are finished. In this case, the total processing time is also equal to $\hat{\delta}_{stay}$.

1.2 Example for mutiple handoffs

In order to explain the processing of multiple spectrum handoffs in detail, we show an SU1 and an SU2 connection in Fig. 2 and Fig. 3, respectively, where D_i ($i = 1, 2, 3$) denotes the handoff delay of the i-th interruption. The handoff delay is defined as the duration from the instant that connection is interrupted until the instant that the unfinished connection is resumed.

Fig. 2 shows a SU1's connection flow with 24 slots which encounters three interruptions. The default channel is Ch3 which can be determined by the spectrum decision algorithm[14]. It includes all three kinds of spectrum sensing results given in section 1.1. The process is described as follows:

At the first interruption, the spectrum sensing result affirms that Ch2 is idle, SU1 switches its operating channel to Ch2 to continue its connection. So the first handoff delay is $D_1 = \delta_{c1}$.

At the second interruption, it is found that all the channels are busy but Ch1 is occupied by SU2. With the higher priority, SU1 will grab Ch1 from SU2 and switch its operating channel to it. Hence, the second handoff delay is $D_2 = \delta_{c2}$.

At the third interruption, SU1 will stay on Ch1 because all the other channels are occupied by PUs or SU1s. SU1 cannot use Ch1 until all the PUs' connections at Ch1 are finished. So the handoff delay is the sum of δ_{stay} and the busy period $Y_p^{(1)}$ of PUs (i.e. $D_3 = \delta_{stay} + Y_p^{(1)}$). In the following, the busy period resulting from PUs at Chk is denoted by $Y_p^{(k)}$ which is the duration from the instant that the first PU appears until the instant that the PUs' queue becomes empty.

Finally, the SU1's connection is completed at Ch1.

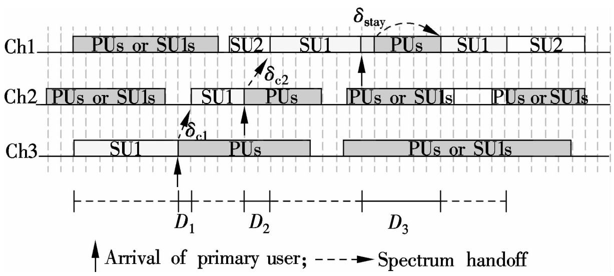

Fig. 2 An example of SU1's multiple spectrum handoffs

Fig. 3 shows an SU2's connection flow with 17 slots whose default channel is Ch2. All three spectrum sensing results analyzed in section 1.1 are mentioned. The transmission process experienced three interruptions in which we assume that the first and the second one are from PUs but the third one is from SU1. The fourth interruption aims at SU1 not SU2. Here we show it in order to indicate that the busy period resulting from SU1 can be interrupted again by PUs.

It is easy to know that the handoff delay of the first interruption is $D_1 = \hat{\delta}_c$, and the second one is $D_2 = \hat{\delta}_{stay} + Y_p^{(1)}$. The third handoff delay is $D_3 = \hat{\delta}_{stay} + Y_{ps}^{(1)}$ where $Y_{ps}^{(1)}$ is the sum of the cumulative effective transmission time of SU1 and the busy period resulting from PUs during the effective transmissions of the SU1 at Ch1. Finally, the SU2's connection is finished at Ch1.

It is important to note that, at the third interruption, there must be no idle channels even in a multi-channel system, otherwise SU1 will first occupy the idle channel rather than grab SU2's operating channel. In other words, if there are one or more idle channels, the interruption for SU2 must be only from PU rather than SU1.

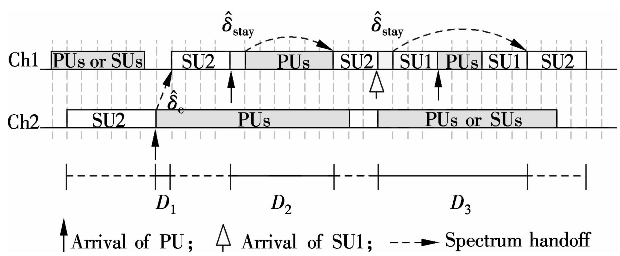

Fig. 3 An example of SU2's multiple spectrum handoffs

2 Performance Analysis

2.1 Markov transition model

Without loss of generality, we denote the M channels as Ch1, Ch2, …, ChM. Chk ($1 \leqslant k \leqslant M$) is determined to be the default channel of the SUs. The cumulative handoff delay of an SU with default channel Chk is denoted by $D^{(k)}$.

In Fig. 2 and Fig. 3, we can see that the SU1's and SU2's cumulative handoff delays are $D^{(3)} = D_1 + D_2 + D_3$ and $D^{(2)} = D_1 + D_2 + D_3$, respectively. If the default channel Chk is denoted by s_0 and an n-element target channel sequence is denoted by $\boldsymbol{s}_n = \{s_1, s_2, \ldots, s_n\}$ where $s_i \in \Omega$ ($i = 1, 2, \ldots, n$) is defined as the i-th target channel, $\Omega = \{\text{Ch1, Ch2, } \ldots, \text{Ch}M\}$, there will be $n + 2$ states including the default channel and the channel denoted by End at which the connection is finished. The state transition path is "$s_0 \to s_1 \to s_2 \to \ldots \to s_n \to$End". Hence, the target channel transition model is a Markov chain. Let $P_{i,j}$ and $C_{i,j}$ be the transition probability and transmission cost from state i to state j, respectively. The SU1's or SU2's average cumulative handoff delay $E[D^{(k)}]$ is the expectation of all the transmission costs over all the possible target channel sequences. It can be regarded as Eq. (2) in Ref. [10].

If we examine all the possible transition paths in the Markov model, the time complexity of evaluating the cumulative handoff delay is $O(M^L)$, where L is the maximum number of interruptions.

However, if we use the PRP M/G/1 queuing, according to the memoryless property of exponential distribution, we can easily calculate the cumulative handoff delay in a two-channel CR network. The multi-channel case can be extended from the two-channel case easily. In the following, there are only two channels Ch1 and Ch2 in the CR network. The average service time of the PU, SU1 and SU2 at Chk are denoted by $E(X_{\mathrm{p}}^{(k)})$, $E(X_{\mathrm{s1}}^{(k)})$ and $E(X_{\mathrm{s2}}^{(k)})$, respectively.

In the two-channel system, there are only three states Ch1, Ch2 and End. For SU1 and SU2 connection, the interrupted probabilities from PU on Chk($k=1,2$) are separately denoted by $P_{\mathrm{p}}^{(k)}$ and $\hat{P}_{\mathrm{p}}^{(k)}$, respectively. For SU2, another interrupted probability from SU1 is denoted by $\hat{P}_{\mathrm{s1}}^{(k)}$. The probabilities that Chk is occupied by PU, SU1 and SU2 are denoted by $\rho_{\mathrm{p}}^{(k)}$, $\rho_{\mathrm{s1}}^{(k)}$ and $\rho_{\mathrm{s2}}^{(k)}$, respectively. Hence, the probability that Chk is idle is $\rho_0^{(k)}=1-\rho_{\mathrm{p}}^{(k)}-\rho_{\mathrm{s1}}^{(k)}-\rho_{\mathrm{s2}}^{(k)}$.

2.2 Cumulative handoff delay for SU1

We assume that the current channel of the SU1 connection is Ch1. When an interruption occurs, this SU1 will switch its operating channel to Ch2 if Ch2 is idle or Ch2 is occupied by SU2. The probability of changing the operating channel is $P_{\mathrm{p}}^{(1)}(\rho_0^{(2)}+\rho_{\mathrm{s2}}^{(2)})$. If Ch2 is occupied by PU or other SU1s, it will stay on Ch1. The probability of staying on the operating channel is $P_{\mathrm{p}}^{(1)}(\rho_{\mathrm{p}}^{(2)}+\rho_{\mathrm{s1}}^{(2)})$. Furthermore, if no interruption occurs, this SU1 will finish its transmission on Ch1 with probability $1-P_{\mathrm{p}}^{(1)}$. Similarly, if the current channel is Ch2, the above probability can be obtained in the same way. The state transition probability matrix can be obtained as

$$\boldsymbol{P}=\begin{bmatrix} P_{\mathrm{p}}^{(1)}(\rho_{\mathrm{p}}^{(2)}+\rho_{\mathrm{s1}}^{(2)}) & P_{\mathrm{p}}^{(1)}(\rho_0^{(2)}+\rho_{\mathrm{s2}}^{(2)}) & 1-P_{\mathrm{p}}^{(1)} \\ P_{\mathrm{p}}^{(2)}(\rho_0^{(1)}+\rho_{\mathrm{s2}}^{(1)}) & P_{\mathrm{p}}^{(2)}(\rho_p^{(1)}+\rho_{\mathrm{s1}}^{(1)}) & 1-P_{\mathrm{p}}^{(2)} \\ 0 & 0 & 0 \end{bmatrix} \tag{1}$$

The cost of state transition is defined as each handoff delay. So the corresponding state transition cost matrix is

$$\boldsymbol{C}=\begin{bmatrix} \delta_{\mathrm{stay}}+E[Y_{\mathrm{p}}^{(1)}] & \delta_{\mathrm{c}} & 0 \\ \delta_{\mathrm{c}} & \delta_{\mathrm{stay}}+E[Y_{\mathrm{p}}^{(2)}] & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2}$$

where δ_{c} is either δ_{c1} if the other channel is idle or δ_{c2} if the other channel is occupied by SU2.

If the service time follows the exponential distribution, the residual service time after an interruption will follow the identical exponential distribution. The service rates for a new arrival PU, SU1 and SU2 on channel k are denoted by $\mu_{\mathrm{p}}^{(k)}$, $\mu_{\mathrm{s1}}^{(k)}$ and $\mu_{\mathrm{s2}}^{(k)}$, respectively. When the default channel is Chk, the potential average cumulative delay is still $E[D^{(k)}]$ if the target channel is Chk after an interruption. Hence, the potential average cumulative delay matrix is

$$\boldsymbol{D}=\begin{bmatrix} E[D^{(1)}] & E[D^{(2)}] & 0 \\ E[D^{(1)}] & E[D^{(2)}] & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{3}$$

The cumulative handoff delay can be obtained by solving the following matrix equation,

$$\boldsymbol{R}=\boldsymbol{P}\cdot(\boldsymbol{C}+\boldsymbol{D})^{\mathrm{T}} \tag{4}$$

where $\boldsymbol{R}=[E[D^{(1)}]\quad E[D^{(2)}]\quad 0]^{\mathrm{T}}$. From Eq. (4), we have

$$E[D^{(1)}]=\varphi_1+\varepsilon_2+\phi_2+(1-P_{\mathrm{p}}^{(1)})0 \tag{5}$$

$$E[D^{(2)}]=\varphi_2+\varepsilon_1+\phi_1+(1-P_{\mathrm{p}}^{(2)})0 \tag{6}$$

where $\varphi_i=P_{\mathrm{p}}^{(i)}(\rho_{\mathrm{p}}^{(i^*)}+\rho_{\mathrm{s1}}^{(i^*)})(\delta_{\mathrm{stay}}+E[Y_{\mathrm{p}}^{(i)}]+E[D^{(i)}])$, $\varepsilon_i=P_{\mathrm{p}}^{(i^*)}\rho_0^{(i)}(\delta_{\mathrm{c1}}+E[D^{(i)}])$, $\phi_i=P_{\mathrm{p}}^{(i^*)}\rho_{\mathrm{s2}}^{(i)}(\delta_{\mathrm{c2}}+E[D^{(i)}])$, $i,i^*\in\{1,2\}$ but $i^*\neq i$.

According to Ref. [3], the average busy period of PUs on channel k is

$$E[Y_{\mathrm{p}}^{(k)}]=\frac{E[X_{\mathrm{p}}^{(k)}]}{1-\lambda_{\mathrm{p}}^{(k)}E[X_{\mathrm{p}}^{(k)}]}=\frac{1}{\mu_{\mathrm{p}}^{(k)}-\lambda_{\mathrm{p}}^{(k)}} \tag{7}$$

The average busy period of SU1s on channel k is

$$E[Y_{\mathrm{s1}}^{(k)}]=\frac{E[X_{\mathrm{s1}}^{(k)}]}{1-\lambda_{\mathrm{s1}}^{(k)}E[X_{\mathrm{s1}}^{(k)}]}=\frac{1}{\mu_{\mathrm{s1}}^{(k)}-\lambda_{\mathrm{s1}}^{(k)}} \tag{8}$$

Referring to (2) and (3) in Ref. [15], the interrupted probability of SU1 on channel k is

$$P_{\mathrm{p}}^{(k)}=\frac{\lambda_{\mathrm{p}}^{(k)}}{\lambda_{\mathrm{p}}^{(k)}+\mu_{\mathrm{s1}}^{(k)}} \tag{9}$$

The probabilities that Chk is occupied by PU, SU1 and SU2 are $\rho_{\mathrm{p}}^{(k)}=\dfrac{\lambda_{\mathrm{p}}^{(k)}}{\mu_{\mathrm{p}}^{(k)}}$, $\rho_{\mathrm{s1}}^{(k)}=\dfrac{\lambda_{\mathrm{s1}}^{(k)}}{\mu_{\mathrm{s1}}^{(k)}}$ and $\rho_{\mathrm{s2}}^{(k)}=\dfrac{\lambda_{\mathrm{s2}}^{(k)}}{\mu_{\mathrm{s2}}^{(k)}}$, respectively.

2.3 Cumulative handoff delay for SU2

For SU2, the staying probability on channel k when an interruption occurs is denoted by $\hat{P}_{\mathrm{stay}}^{(k)}$, and the average cumulative handoff delay with default Chk is denoted by $E[\hat{D}^{(k)}]$. We know that SU2 must stay on the operating channel if its connection is interrupted by SU1. So the event that SU2 changes its operating channel to another one only occurs when the interruption is from a PU. Hence, the states transition probability matrix is

$$\hat{\boldsymbol{P}}=\begin{bmatrix} \hat{P}_{\mathrm{p}}^{(1)}\hat{P}_{\mathrm{stay}}^{(1)}+\hat{P}_{\mathrm{s1}}^{(1)} & \hat{P}_{\mathrm{p}}^{(1)}(1-\hat{P}_{\mathrm{s}}^{(1)}) & 1-\hat{P}_{\mathrm{p}}^{(1)}\hat{P}_{\mathrm{s1}}^{(1)} \\ \hat{P}_{\mathrm{p}}^{(2)}(1-\hat{P}_{\mathrm{stay}}^{(2)}) & \hat{P}_{\mathrm{p}}^{(2)}\hat{P}_{\mathrm{stay}}^{(2)}+\hat{P}_{\mathrm{s1}}^{(2)} & 1-\hat{P}_{\mathrm{p}}^{(2)}\hat{P}_{\mathrm{s1}}^{(2)} \\ 0 & 0 & 0 \end{bmatrix}$$

With the same way in section 2.2, the cumulative handoff delay of SU2 can be obtained by

$$E[\hat{D}^{(1)}] = \hat{\varphi}_1 + \hat{\gamma}_1 + \hat{\varepsilon}_2 + (1 - \hat{P}_{\mathrm{p}}^{(1)})0 \qquad (10)$$

$$E[\hat{D}^{(2)}] = \hat{\varphi}_2 + \hat{\gamma}_2 + \hat{\varepsilon}_1 + (1 - \hat{P}_{\mathrm{p}}^{(2)})0 \qquad (11)$$

where $\hat{\varphi}_i = \hat{P}_{\mathrm{p}}^{(i)} \hat{P}_{\mathrm{stay}}^{(i)} (\hat{\delta}_{\mathrm{stay}} + E[Y_{\mathrm{p}}^{(i)}] + E[\hat{D}^{(i)}])$, $\hat{\gamma}_i = \hat{P}_{\mathrm{s1}}^{(i)} \left(\hat{\delta}_{\mathrm{stay}} + \frac{1}{2}(E[Y_{\mathrm{s1}}^{(i)}] + \lambda_{\mathrm{p}}^{(i)} E[Y_{\mathrm{s1}}^{(i)}] E[Y_{\mathrm{p}}^{(i)}]) + E[\hat{D}^{(i)}]\right)$, $\hat{\varepsilon}_i = \hat{P}_{\mathrm{p}}^{(i)} (1 - \hat{P}_{\mathrm{stay}}^{(i)}) (\hat{\delta}_{\mathrm{c}} + E[\hat{D}^{(i)}])$, $i = 1, 2$.

The second part in Eq. (10) and Eq. (11) is explained as follows: When SU2 is interrupted by SU1, this SU2 must stay on the operating channel. So $Y_{\mathrm{ps}}^{(i)}$ is the sum of the cumulative effective transmission time of SU1 and the busy period resulting from PUs arrived at Chi during the effective transmission time of SU1. SU1 may be interrupted repeatedly by PUs and it may stay on the operating channel or change. For simplicity, we can reasonably consider its cumulative effective transmissions as half of its average busy period in the two-channel system. Naturally, $\frac{1}{2}E[Y_{\mathrm{s1}}^{(i)}]\lambda_{\mathrm{p}}^{(i)}$ is the number of PUs arrived during the SU1's cumulative effective transmission time on Chi.

2.4 Expression of cumulative handoff delay

If we assume that the arrival rates for the same priority users on Ch1 and Ch2 are equal and so are the service rates, the same indicated variables for different channels will be also equal such as $P_{\mathrm{p}}^{(1)} = P_{\mathrm{p}}^{(2)} = P_{\mathrm{p}}$. Other variables clearing the superscript are also denoted by this form. Substituting (7) and (9) into (5) and (6), we have $E[D^{(1)}] = E[D^{(2)}]$ and the cumulative handoff delay is obtained as

$$E[D] = \frac{P_{\mathrm{p}}}{1 - P_{\mathrm{p}}}[(\rho_{\mathrm{p}} + \rho_{\mathrm{s1}})(\delta_{\mathrm{stay}} + E[Y_{\mathrm{p}}]) + \rho_0 \delta_{\mathrm{c1}} + \rho_{\mathrm{s2}} \delta_{\mathrm{c2}}] \qquad (12)$$

By solving Eqs. (10) and (11) synchronously, we have $E[\hat{D}^{(1)}] = E[\hat{D}^{(2)}]$ and the expression of the cumulative handoff delay for SU2 can be obtained as

$$E[\hat{D}] = \frac{\hat{P}_{\mathrm{p}} \hat{P}_{\mathrm{stay}} (\hat{\delta}_{\mathrm{stay}} + E[Y_{\mathrm{p}}]) + \hat{P}_{\mathrm{s1}} \left[\hat{\delta}_{\mathrm{stay}} + \frac{1}{2}E[Y_{\mathrm{s1}}](1 + \lambda_{\mathrm{p}} E[Y_{\mathrm{p}}])\right] + \hat{P}_{\mathrm{p}} \hat{\delta}_{\mathrm{c}} (1 - \hat{P}_{\mathrm{stay}})}{1 - \hat{P}_{\mathrm{p}} - \hat{P}_{\mathrm{s1}}} \qquad (13)$$

where $\hat{P}_{\mathrm{p}} = \frac{\lambda_{\mathrm{p}}}{\lambda_{\mathrm{p}} + \mu_{\mathrm{s2}}}$, $\hat{P}_{\mathrm{s1}} = \frac{\lambda_{\mathrm{s1}}}{\lambda_{\mathrm{s1}} + \mu_{\mathrm{s2}}}$, $\hat{P}_{\mathrm{stay}} = \rho_{\mathrm{p}} + \rho_{\mathrm{s1}} + \rho_{\mathrm{s2}}$.

In conventional analysis, the priorities of SUs are the same. The interrupt is only from a PU, and the probability of staying on the operating channel when an interruption occurs is the channel busy probability. Considering the above changes, the cumulative handoff delay of unitary SUs is

$$E[D_{\Phi}] = \frac{PP_{\mathrm{stay}}(\delta_{\mathrm{stay}} + E[Y_{\mathrm{p}}] - \delta_{\mathrm{c}}) + P\delta_{\mathrm{c}}}{1 - P} \qquad (14)$$

where $P = \frac{\lambda_{\mathrm{p}}}{(\lambda_{\mathrm{p}} + \mu_{\mathrm{s1}} + \mu_{\mathrm{s2}})}$, $P_{\mathrm{stay}} = \rho_{\mathrm{p}} + \rho_{\mathrm{s1}} + \rho_{\mathrm{s2}}$, $\delta_{\mathrm{stay}} = \tau + \tau_{\mathrm{h}}$, and $\delta_{\mathrm{c}} = \tau + \tau_{\mathrm{h}} + \tau_{\mathrm{s}}$.

3 Numerical Results

Fig. 4 shows the effects of ρ_{p} on the average cumulative handoff delay, where $\rho_{\mathrm{s1}} = \rho_{\mathrm{s2}} = 0.2$, $\tau = \tau_{\mathrm{h}} = \tau_{\mathrm{s}} = \Delta\tau = 0.1$. It is shown that the cumulative handoff delays of SU1 and SU2 increase as ρ_{p} increases with the chance to access channels decreasing. But, the delay of SU2 is higher than that of SU1 when ρ_{p} is identical since SU1 can grab SU2's operating channel. In particular, when ρ_{p} is over 0.2, the SU2's average delay increases rapidly. When ρ_{p} increases from 0.2 to 0.5, the delay increases almost fourfold.

Fig. 5 gives the comparison of the cumulative handoff delay for SU1, SU2 and the unitary SU, where $\lambda_{\mathrm{s2}} = 0.1$, $\mu_{\mathrm{s1}} = \mu_{\mathrm{s2}} = 0.4$, $\mu_{\mathrm{p}} = 0.5$, $\tau = \tau_{\mathrm{h}} = \tau_{\mathrm{s}} = \Delta\tau = 0.1$. Comparing Figs. 5(a) and (b), we find that the SU2's cumulative handoff delay decreases largely around 57% as λ_{s1} decreases from 0.1 to 0.02. Other SU1's arrival rates with the same gap will also lead to the same effects for SU2. And the SU1's cumulative handoff delay can be shortened around 36% at the cost of around 20% SU2's addition compared to the unitary SU in Fig. 5(a). Hence, the network with graded SUs can obtain a better performance under an appropriate SU1's arrival rate.

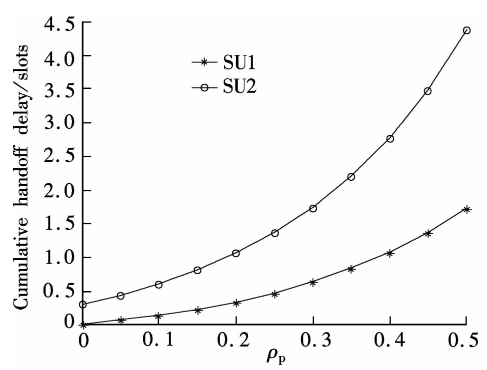

Fig. 4 The effect of the probability that a channel is occupied by a PU on the average cumulative handoff delay

The SU1 and SU2's admission regions painted gray are shown in Fig. 6 and Fig. 7, respectively, where $\tau = \tau_{\mathrm{h}} = \tau_{\mathrm{s}} = 0$, $\Delta\tau = 0.1$, $\mu_{\mathrm{p}} = 0.6$, $\mu_{\mathrm{s1}} = \mu_{\mathrm{s2}} = 1$. In Fig. 6, we assume that the maximum allowable average handoff delay for SU1 is 0.5 slots, while in Fig. 7 for SU2 it is 2.5 slots. In Fig. 6 (a) when $\lambda_{\mathrm{p}} < 0.22$, the SU1's arrival rate must be limited by the channel occupied probability, i. e.

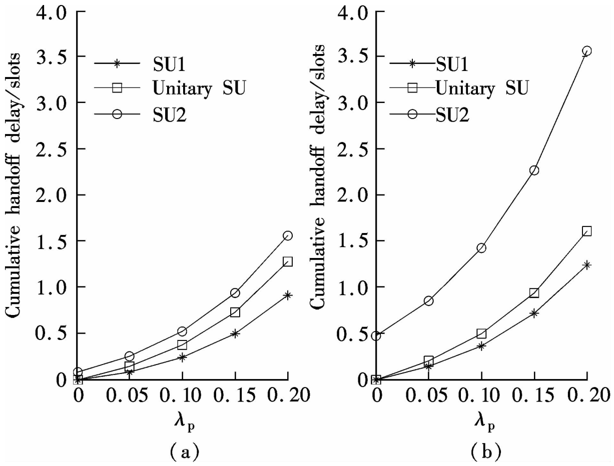

Fig. 5 Comparison of the cumulative handoff delay for SU1, SU2 and unitary SU. (a) $\lambda_{s1}=0.02$; (b) $\lambda_{s1}=0.10$

$\rho_{s1}+\rho_{s2}\leqslant 1-\rho_p$. When $\lambda_p>0.22$, the SU1's arrival rate must satisfy the delay constraint, but when $\lambda_p>0.296$, no SU1 can be allowed access. Compared with Fig. 6(a), in Fig. 6(b) the admissible region shrinks because the larger SU2's arrival rate leads to the smaller remainder of the traffic loads for SU1. This means that SU1 has to spend extra time $\Delta\tau$ to find the target channel. In Fig. 7, the admissible region for SU2 shrinks as λ_{s1} increases from 0.2 to 0.4 for the same reason.

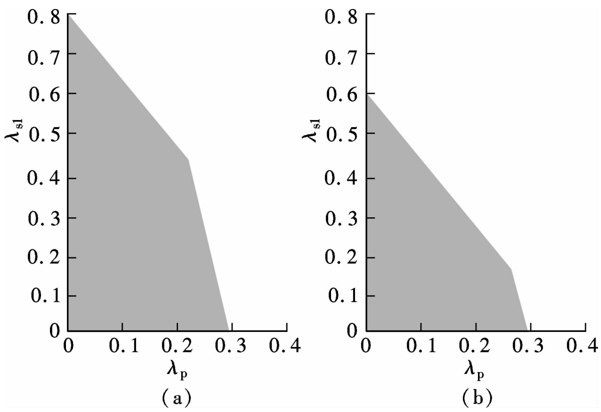

Fig. 6 Admissible region (λ_p, λ_{s1}). (a) $\lambda_{s2}=0.2$; (b) $\lambda_{s2}=0.4$

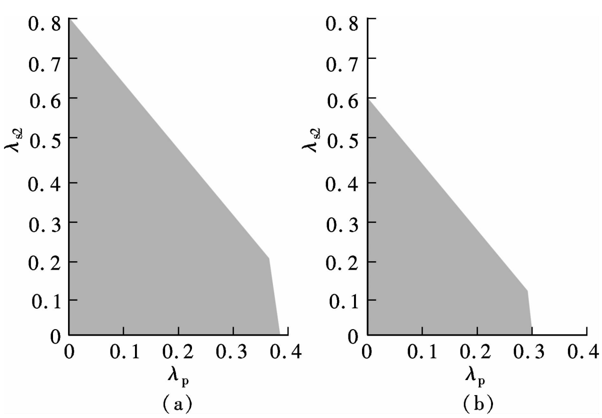

Fig. 7 Admissible region (λ_p, λ_{s2}). (a) $\lambda_{s1}=0.2$; (b) $\lambda_{s1}=0.4$

Fig. 8 gives the admissible region for SU2 with SU1 when the PU's traffic load is known and the maximum allowable average handoff delays of SU1 and SU2 are 0.8 and 2 slots, respectively, where $\tau=\tau_h=\tau_s=0$, $\Delta\tau=0.1$, $\rho_p=0.5$, $\mu_{s1}=\mu_{s2}=1$. It is shown that if $\lambda_{s2}>0.4$, SU2 must be rejected with $\lambda_{s1}=0.1$. If $\lambda_{s1}>0.276$, no SU2 can be accepted.

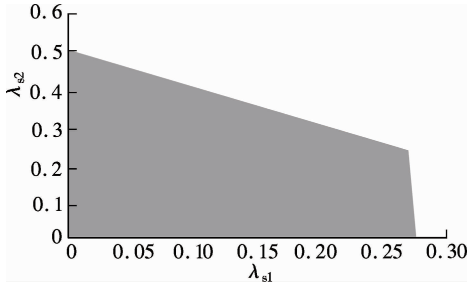

Fig. 8 Admissible region (λ_{s1}, λ_{s2})

4 Conclusion

This paper proposes an analytical approach for the graded SUs' average cumulative handoff delay resulting from multiple spectrum handoffs in CR networks. Analytical results provide an intuitive explanation for the effect of traffic load on the graded SUs' performance. The Admissible region can help us to design the admission control rules to meet different latency requirements of graded SUs. In future work, the hybrid spectrum handoff scheme can be considered to find an optimal handoff strategy for graded SUs in order to minimize the cumulative handoff delay.

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认知无线网络中分级下的从用户累积切换延时分析

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摘要:根据认知无线网络中从用户数据传输延时需求的不同,将从用户分成 SU1 和 SU2 两类. 并假设 SU1 比 SU2 优先使用主用户的空闲频谱. 利用基于优先级的 M/G/1 排队网络,对多重频谱切换过程进行建模. 根据状态转移概率和转移消耗矩阵,分别计算出 2 类从用户的平均累积延时. 数值结果表明,主用户业务负载越大,SU2 的累积切换延时增加得越快. 与从用户不分级的认知网络比较表明,分级下的 SU1 到达率越低,2 类从用户的累积切换延时减少得越明显. 对 2 类从用户在最大可容忍延时下的允许接入区域的分析,可较好地适用于分级下的从用户接入控制方案的设计.

关键词:认知无线网络;分级的从用户;多重频谱切换;累积切换延时;允许接入区域
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