Article Chinese Science Bulletin

SPECIAL TOPIC
Basic Theories in Cognitive Wireless Networks

October 2012 Vol.57 No.28-29: 3705–3712
doi: 10.1007/s11434-012-5344-3

Delay performance analysis and access strategy design for a multichannel cognitive radio network

LI Xiao[1], WANG Jun[1*], LI HuSheng[2] & LI ShangQian[1]

[1] *National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology, Chengdu 611731, China;*
[2] *The Department of Electrical Engineering and Computer Science, the University of Tennessee, Knoxville 37996, USA*

Received March 5, 2012; accepted June 15, 2012; published online July 13, 2012

For a hierarchical cognitive radio network (CRN), the secondary users (SUs) may access the licensed spectrum opportunistically, whenever it is not occupied by the primary users (PUs). An important issue for this kind of CRN is the achievable quality-of-service (QoS) performance, such as traffic transmission delay, which is critical to the SUs' traffic experience. In this paper, we focus on the delay performance analysis of the SU system and the design of the corresponding optimal access strategy for the case of SUs sharing multiple licensed channels. In our analysis, the transmission of PU and SU traffic is modeled as M/G/1 queues. By merging the PU and SU traffic, we propose the model of a priority virtual queue on the licensed channels. Based on this model, we obtain the expected system delay expression for SU traffic through M/G/1 preemptive repeat priority queuing analysis. For the case of multiple licensed channel access, the access strategy is further investigated with respect to the expected system delay for SU traffic. By minimizing the expected transmission delay, the optimal access strategy is modeled as a nonlinear programming problem, which can be resolved by means of the classic Genetic Algorithm (GA). Numerical results validate our analysis and design of an optimal access strategy. Meanwhile, by considering the time taken by the GA approach, we can also adopt the inverse proportional access strategy to obtain near-optimal results in practice.

cognitive radio network, preemptive repeat priority queuing, nonlinear programming, optimal access strategy

Citation: Li X, Wang J, Li H S, et al. Delay performance analysis and access strategy design for a multichannel cognitive radio network. Chin Sci Bull, 2012, 57: 3705–3712, doi: 10.1007/s11434-012-5344-3

Currently, large parts of the radio spectrum are assigned to licensed radio services in a way that is often referred to as exclusive spectrum usage. As the demands on the wireless spectrum have increased rapidly in recent years, it is a common belief that the spectrum resource will soon be exhausted. However, measurements of actual spectrum usage obtained by the FCC's Spectrum Policy Task Force [1] have shown that the capacity of the licensed spectrum bands is not efficiently used for most of the given times and locations. To efficiently exploit the underused spectrum, cognitive radio (CR) techniques and CR networks (CRNs), which provide the capability to use or share the spectrum in an opportunistic manner, have been proposed [2,3].

In the application of CRNs [3], there is a need to provide regulators with the flexibility to achieve a more efficient use of the available spectrum. For CRNs, the authors in [3] categorized the dynamic spectrum access (DSA) strategies using three models and clarified the basic components of opportunistic spectrum access (OSA), i.e. the overlay approach under the hierarchical access model. In this paper, we will focus on this OSA approach. In the case of OSA, there is a group of channels assigned to a set of primary users (PUs) in a wireless network, and the secondary users (SUs) opportunistically use the channels that are not occupied by PUs. Here, we assume that the SUs are capable of detecting, through spectrum sensing, whether the licensed channel is currently occupied by the PUs.

Considering time domain spectrum sharing, researchers have recently contributed many novel ideas. In [4], Zhao et al. assumed that primary and secondary systems share the

---

*Corresponding author (email: junwang@uestc.edu.cn) same slot structure. The access strategy for the secondary system was derived based on a partially observable Markov decision process (POMDP) framework. In [5–7], the authors modeled the PU transmission as an approximation of a continuous-time Markov chain (CTMC). The cognitive medium access (CMA) scheme subject to collision constraints was proposed and the optimal cognitive access strategies of Markovian channels were discussed. However, the above research typically assumed full buffers, i.e. data for transmission always existed, and ignored the burst nature of SU data traffic, which required queuing analysis if the licensed channels were considered to be servers and the user traffic data were regarded as customers.

It is well known that delay is an important quality of service (QoS) metric in wireless networks. However, the delay performance is an underexplored area and not well understood, partially due to difficulties in analyzing it, especially in CRNs. In [8], the authors modeled the PU traffic emergences as interruptions of the queue and queuing analysis was carried out for the cases of single-queue-two-server and two-queue-single-server. The research in [9] is perhaps the work most closely related to this study. It modeled the PU and SU traffic transmission as a priority M/G/1 queue and the results for the case of accessing a single licensed channel were derived. However, the influence of PU traffic was not considered in [9] for the case where no SU traffic transmitting exists on a corresponding licensed channel when new SU traffic arrives. In this paper, we provided a more general analysis by considering all cases, i.e. whether there exists SU traffic transmitting on a current licensed channel, when new SU traffic arrives. Furthermore, we focus our discussion on a multichannel hierarchical cognitive radio network and the optimal access strategy based on the expected system delay is discussed. Other related work about multiple channels queuing delay analysis can be found in [10] and [11]. However, both ignore the influence of PU traffic emergence during SU traffic transmission.

In this paper, we combine the discussion of delay with spectrum access strategy. We first focus on the system delay performance of SU traffic. The transmission of PU and SU traffic is modeled as M/G/1 queues. Considering the transmission on a given licensed channel, the PU traffic and SU traffic can be equivalent to customers with high and low priority in a single queue. Simultaneously, considering the influence of PU traffic emergence during SU traffic transmission, the system delay of SU traffic can be obtained based on M/G/1 preemptive repeat priority queuing theory [12–15]. It is the same for all licensed channels. We then derived the expression of the expected system delay for when SUs can access multiple licensed channels. We find that the delay performance is a function of the access strategy. When we adopt the optimal access strategy, the smallest expected system delay will be reached. Then the optimization problem of the access strategy is modeled as a nonlinear programming problem. By means of a classic Genetic Algorithm (GA) [16], we can finally obtain the globally optimal access strategy. Considering the usually unacceptable complexity of a GA, we also develop an approximate suboptimal pure access strategy, i.e. inverse proportional access strategy, to achieve near-optimal performance with implementable complexity.

In summary, we have: (i) proposed a model of priority virtual queues for PU and SU traffic transmissions on licensed channels; (ii) presented a general system delay analytical method for SU traffic based on priority preemptive queuing theory in a hierarchical cognitive radio scenario; (iii) obtained the optimal spectrum access strategy based on the smallest expected system delay in a multichannel dynamic spectrum access system. Meanwhile, considering the time consumption of the GA approach, we can also adopt the inverse proportional access strategy to obtain approximate optimal results in practice.

They can all eventually be used as guidelines for multiple channel access protocols in CRNs.

1 System model

In this paper, we consider a hierarchical cognitive radio scenario. We assume that there are M parallel licensed channels indexed from 1 to M and N SUs indexed from 1 to N. Each PU transmits on its dedicated licensed channel. Each SU can transmit on any one of the parallel licensed channels whenever it is vacated by the PUs. Moreover, the priority of PU traffic is higher than that of SU traffic when all of them are regarded as traffic stream on the same licensed channel. Figure 1 illustrates a realization of the traffic transmission of SUs on multiple licensed channels.

From the SUs' point of view, it is not necessary to differentiate PUs in one licensed channel. Hence, we consider the PUs in one licensed channel to be one aggregate PU in the following analysis, i.e. there are M PUs transmitting on M licensed channels and one PU can use only one of the licensed channels. To simplify analysis and without loss of generality, the following assumptions are used throughout the paper.

(i) Perfect sensing. SU can perfectly sense the existence

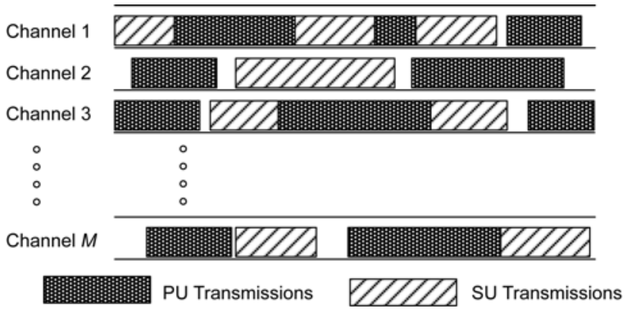

Figure 1 Channel occupation of PU and SU transmissions.

of PU traffic, i.e. there are no sensing errors.

(ii) Ideal collision detection. SU traffic transmission can be suspended as soon as possible once PU traffic is detected so that no interference is introduced to the incoming PU transmission. As soon as the PU completes its transmission, SU retransmit the interrupted data traffic including the portion that was transmitted before the emergence of PU traffic. In wireless communication networks, each transmitted data packet must carry signaling information such as the bits for the cyclic redundancy check (CRC), physical layer preambles and MAC addresses [9]. Consequently, whenever the SU transmission is aborted, the corresponding data must be entirely retransmitted.

(iii) Centralized scheduling. The traffic of multiple SUs is scheduled in order and the collisions between SUs can be avoided.

(iv) Traffic activity. Without loss of generality, we adopt M/G/1 models for PU and SU traffic descriptions. Note that this traffic model is more general than a Markov ON-OFF model, which is a subset of our queuing model with an exponential idle period and an exponential busy period.

2 Delay analysis based on a priority virtual queue

2.1 Priority virtual queue

In this section, we will analyze the system delay for SU traffic based on queuing theory. It is important to note that the data traffic of SUs transmitted on different licensed channels is physically waiting at different buffers. Figure 2 gives an example of the physical queues for the case of M licensed channels and N SUs. Each PU maintains one physical queue for its exclusive licensed channel. Meanwhile, each SU maintains M mutually independent physical queues corresponding to M different licensed channels. To simplify the analysis, once the SU traffic is assigned to a channel i.e. a queue, it will stay in the channel until the transmission is completed. If SU traffic is handed over to another licensed channel when transmission is interrupted, it can only join the end of the corresponding queue because of the same priority of SU traffic which will incur additional queuing delay. Therefore, the channel transition may not introduce any advantage other than fixed channel assignment when traffic transmission is interrupted by a PU. Further comparison is currently being studied but is outside the scope of this paper.

From the perspective of the licensed channels, there are two classes of data traffic for transmission, i.e. PU and SU traffic. Since the priority of PU traffic is higher than that of SU traffic, we can establish a priority virtual queue on each licensed channel. Here the priority customers represent the PU and SU traffic, and the licensed channels represent the servers. Therefore, N SU physical queues and one PU physical queue can be equivalent to one priority virtual queue on each licensed channel. This model is illustrated in Figure 2.

2.2 System delay analysis

Considering the case of sharing multiple licensed channels between SUs, more attention must be paid to the access strategy. Let us use $\boldsymbol{a}_i=[a_{i1},a_{i2},...,a_{iM}]$ to denote the actions of SUi, where $a_{ij}\in\{0,1\}$, and $a_{ij}=1$ indicates that the SUi

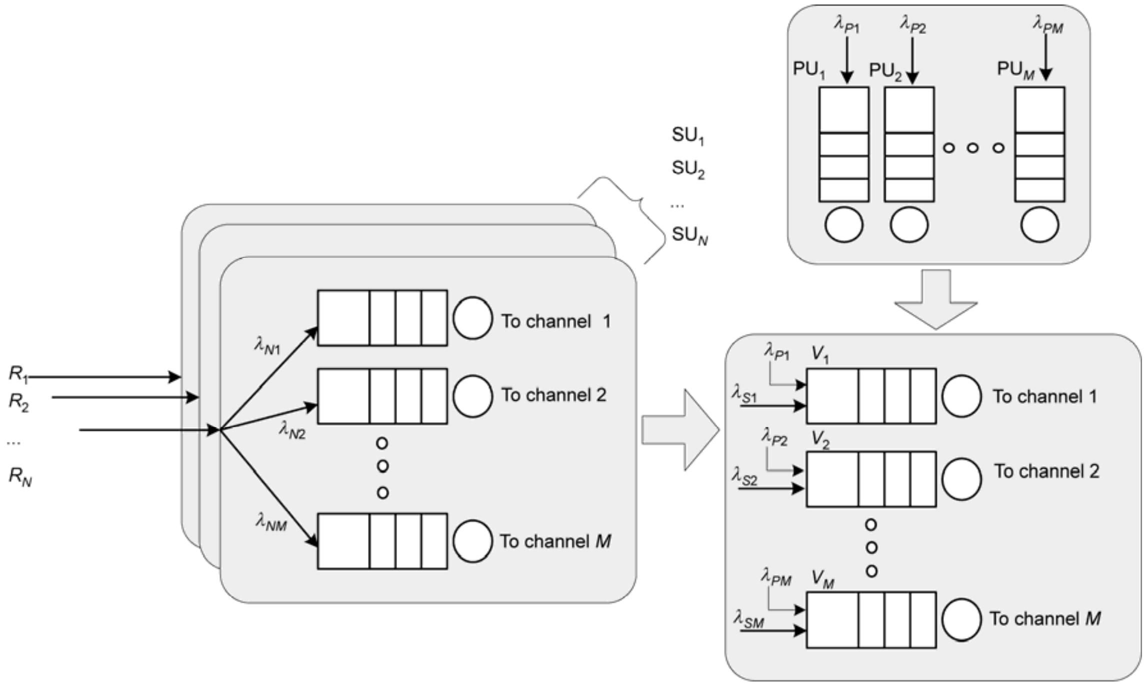

Figure 2 Physical queues and priority queues for licensed channels.

chooses to transmit the traffic on licensed channel *j*, and vice versa. The access strategy for SU *i* on multiple licensed channels can then be defined as $s_i=[s_{i1},s_{i2},\ldots,s_{iM}]$, where $s_{ij}\in\{0,1\}$ represents the probability of the SU*i* taking the action $a_{ij}=1$. Consequently, the summation of the access strategy on all licensed channels is $\sum_{j=1}^{M} s_{ij}=1$.

As indicated in Figure 2, the data traffic arrival rate of the PU on licensed channel *j* is denoted as λ_{Pj}, and the data traffic arrival rate for SU*i* is denoted as R_i. The traffic arrival rate of the second user *i* on licensed channel *j* can then be set as λ_{ij}, where $\lambda_{ij}=R_i\cdot s_{ij}$. At the same time, the SU traffic arrival stream on licensed channel *j* is formed by merging the traffic of different SUs. As mentioned in section 1, all SU traffic transmissions are described as M/G/1 models, i.e. all SU traffic arrival streams are Poisson processes. It is not difficult to prove this merged SU traffic stream is also a Poisson process [17] with parameter $\lambda_{Sj}=\sum_{i=1}^{N}\lambda_{ij}=\sum_{i=1}^{N}R_i\cdot s_{ij}$.

We now consider the system delay for SUs on licensed channel *j*. Due to the homogeneity, we drop the subscript *j* in the following discussion without causing confusion. Considering the influence of PU traffic emergence during the SU traffic transmission, the priority virtual queue on licensed channel *j* can be regarded as an M/G/1 preemptive repeat priority queue. The system delay of SU traffic consists of two parts: transmission delay and queuing delay, i.e. service time and waiting time in queuing theory.

(i) Computation of transmission delay. We first focus on the transmission delay of SU traffic. According to the assumption in section 1, i.e. ideal collision detection, Figure 3 indicates a realization of traffic transmission of SUs on licensed channel *j*. Here, $X^{(i)}(i=1,2,\ldots)$ represents the invalid transmission time because of the interruptions caused by PU traffic. $B^{(i)}(i=1,2,\ldots)$ represents the busy period in which licensed channel *j* is taken over by the PU traffic. X represents the time in which SUs complete a transmission without interruptions, and X_S represents the duration in which SUs complete a transmission on licensed channel *j* including the interruptions caused by PU traffic.

As indicated in Figure 3, we can obtain the following equation

$$X_S=\sum_{i=1}^{n}\left(X^{(i)}+B^{(i)}\right)+X. \tag{1}$$

Since PU traffic transmission cannot be influenced by SU traffic, i.e. the SU traffic transmission on licensed channel *j* is transparent to PU. Hence, the PU traffic transmission on licensed channel *j* can still be regarded as an M/G/1 queue. According to the assumptions in section 1, the PU traffic arrives according to a Poisson process with rate parameter λ_P. The distribution of PU traffic transmission time is an arbitrary distribution with the expected value $1/\mu_P$. We can then obtain the expected value of a busy period for a licensed channel [14], i.e.

$$E[B]=\frac{1}{\mu_P-\lambda_P}. \tag{2}$$

The idle period of the licensed channel *j*, has the same distribution as PU traffic arrivals' [14], i.e. it is exponentially distributed with rate parameter λ_P, and the corresponding distribution function is given as

$$F(I)=1-\mathrm{e}^{-\lambda_P\cdot I},\ \ I\geqslant 0. \tag{3}$$

Let us further assume the value of X is t in Figure 3. The condition for the interruption of SU transmission is that the idle period on a licensed channel must be smaller than the value of X, i.e. t. Hence, the interruption probabilities of SU transmission with $X=t$ can be defined as

$$P\left(K=n\mid t\right)=\left(1-\mathrm{e}^{-\lambda_P t}\right)^n\mathrm{e}^{-\lambda_P t},\quad n=0,1,2\ldots, \tag{4}$$

where K represents the number of interrupts. Its expected value can be obtained by

$$\begin{aligned}E[K]&=\int_0^{\infty}(\mathrm{e}^{-\lambda_P t}-1)f(t)\mathrm{d}t\\&=E\left[\mathrm{e}^{-\lambda_P X}-1\right],\end{aligned} \tag{5}$$

where $f(t)$ denotes the probability density function (PSD) of X.

When $X=t$, the expected value of X_S can then be obtained by

$$\begin{aligned}E\left[X_S\mid t\right]&=E\left[\sum_{i=1}^{n}\left(X^{(i)}\mid t+B^{(i)}\mid t\right)+t\right]\\&=E[K]\left(E\left[X\mid t\right]+E\left[B\mid t\right]\right)+t,\end{aligned} \tag{6}$$

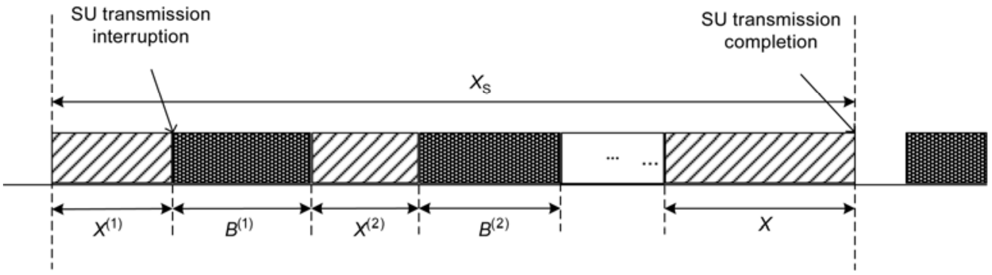

Figure 3 SU traffic transmission on a licensed channel.

where

$$E\left[B \mid t\right]=E[B]=\frac{1}{\mu_P-\lambda_P}, \tag{7}$$

and

$$\begin{aligned} E\left[X \mid t\right] &= E\left[I \mid I \leqslant t\right] \\ &= \frac{1}{\lambda_P}-t\frac{\mathrm{e}^{-\lambda_P t}}{1-\mathrm{e}^{-\lambda_P t}}, \end{aligned} \tag{8}$$

based on the transmission of PU traffic. By combining eqs. (5)–(8), the expected value of the transmission delay X_S is given by

$$\begin{aligned} E[X_S] &= E[E[X_S \mid t]] \\ &= E[K]\left(E\left[E\left[X \mid t\right]\right]+E\left[B \mid t\right]\right)+E[t] \\ &= \left(\frac{1}{\lambda_P}+\frac{1}{\mu_P-\lambda_P}\right)E\left[\mathrm{e}^{-\lambda_P X}-1\right]. \end{aligned} \tag{9}$$

(ii) Computation of queuing delay. Next, we focus on the queuing delay for SU traffic. To obtain the expected queuing delay, we consider the following two situations.

Case 1: when SU traffic arrives, there is no SU traffic transmitting on the licensed channel.

In this case, the queuing delay of SU traffic only depends on the PU traffic because of the centralized scheduling mentioned in section 1. From the PUs' point of view, the queuing delay can be expressed as the same as the case of M/G/1 queues [13], i.e.

$$W_P=\frac{\lambda_P E\left[X_P^2\right]}{2\left(1-\rho_P\right)}, \tag{10}$$

where the traffic density $\rho_P=\lambda_P/\mu_P$ and $E[X_P^2]$ denotes the second moment of the transmission time of PU traffic.

From the SUs' point of view, in the process of waiting, other PU traffic may arrive, i.e. the delay should be given as

$$W_P+\lambda_P W_{S1}\cdot\frac{1}{\mu_P}=W_{S1}. \tag{11}$$

Then we obtain

$$W_{S1}=\frac{\lambda_P E\left[X_P^2\right]}{2\left(1-\rho_P\right)^2}. \tag{12}$$

Case 2: when SU traffic arrives, there is existing SU traffic transmitting on the licensed channel.

Under such conditions, because the influence of PU traffic emergence has been contained in the analysis of transmission delay, the queuing delay of SUs has nothing to do with the PU traffic. Therefore, it is just the same as the M/G/1 queuing system. The corresponding waiting time for SU traffic is denoted as [13]

$$W_{S2}=\frac{\lambda_S E\left[X_S^2\right]}{2\left(1-\rho_S\right)\rho_S}. \tag{13}$$

By taking into account the conditional probability for these two cases, the expected queuing delay is given by

$$\begin{aligned} E\left[W_S\right] &= W_{S1}\left(1-\rho_S\right)+W_{S2}\rho_S \\ &= \frac{\lambda_P E\left[X_P^2\right]}{2\left(1-\rho_P\right)^2}\left(1-\rho_S\right)+\frac{\lambda_S E\left[X_S^2\right]}{2\left(1-\rho_S\right)}, \end{aligned} \tag{14}$$

where

$$\begin{aligned} E\left[X_S^2\right] &= 2\left(E[B]+1/\lambda_P\right)^2 E\left[\left(\mathrm{e}^{\lambda_P X}-1\right)^2\right] \\ &\quad +\left(E[B^2]+2E[B]/\lambda_P+2/\lambda_P^2\right)\left(E\left[\mathrm{e}^{\lambda_P X}-1\right]\right) \\ &\quad -2\left(E[B]+1/\lambda_P\right)E\left[X\,\mathrm{e}^{\lambda_P X}\right], \end{aligned} \tag{15}$$

according to [8]. All the terms in eq. (15) are known to us, except for the second moment of the busy period for licensed channel j, which can be expressed as in [14,15]

$$E\left[B^2\right]=\frac{E\left[X_P^2\right]}{\left(1-\rho_P\right)^3}. \tag{16}$$

(iii) System delay. Finally, the system time for SU traffic on licensed channel is the summation of the transmission and queuing delays, i.e.

$$E\left[T_S\right]=E\left[W_S\right]+E\left[X_S\right]. \tag{17}$$

By combining the corresponding eqs. (9), (14)–(16), we obtain the final results.

2.3 Numerical results

In the numerical computation, the system parameters are set as follows. The PU traffic transmission time and the SU traffic transmission time without interruptions are all exponentially distributed. For the SU traffic transmission, we set the parameter $\mu_S^{-1}=1$ ms, and the traffic density is $\rho_s=\lambda_s/\mu_s$. For PU traffic transmission, we set $\mu_P^{-1}=1.5$ ms.

Figure 4 shows the SU traffic system delay $E[T_S]$ when the SU traffic density ρ_s increases from 0 to 1. It can be seen that the value of $E[T_S]$ increases approximately exponentially with the rise of ρ_s. In Figure 5, we present the results for the delay under different PU traffic densities ρ_P for specific SU traffic density ρ_s. We find that the higher the value of ρ_P, the larger the value of $E[T_S]$.

3 Optimization of multiple channel access strategy

3.1 Optimization of access strategy

As mentioned in section 2.2, the access strategy for the traffic transmission of SU i for multiple licensed channels can be rewritten as $\boldsymbol{s}_i=[s_{i1},s_{i2},\ldots,s_{iM}]$, where $\sum_{j=1}^{M}s_{ij}=1$.

Supposing the same access strategy for every SU

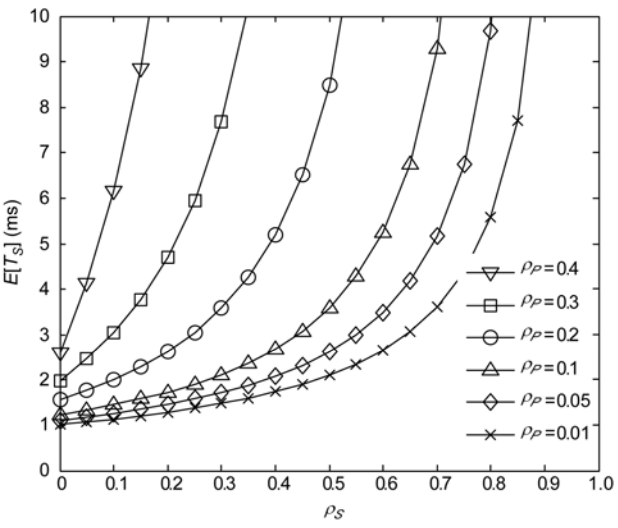

Figure 4 The variation tendency of the SU system delay under different SU traffic densities ρ_S.

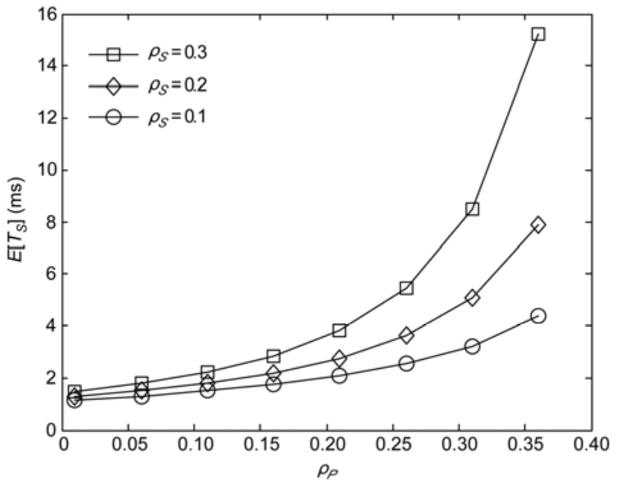

Figure 5 The variation tendency of the SU system delay under different PU traffic densities ρ_P.

$i(i=1,2,3...,N)$, we can drop the SU index i in the following discussion without causing confusion, i.e. the access strategy for all SU traffic can be unified as s_j, where $\sum_{j=1}^{M} s_j = 1$.

Based on the analysis in section 2, it is obvious that the expected system delay for SU traffic transmission can be given as

$$E[T_S] = \sum_{j=1}^{M} E[T_{Sj}] \cdot s_j , \tag{18}$$

where $E[T_{sj}]$ represents the system delay of the SU traffic transmission on licensed channel j. Intuitively, when the PU traffic arrival rate parameter λ_{Pj} is lower, the corresponding SU traffic system delay is smaller, as shown in Figures 4 and 5. However, if all SU traffic is transmitted on the licensed channel which has the lowest arrival rate, the SU traffic system delay will increase rapidly. On the other hand, if some of the SU traffic is transmitted on other licensed channels, the expected system delay may be smaller than that for the previous case. Consequently, there should be an optimal access strategy for SU traffic, in which the expected SU traffic system delay can be the smallest in the long-term steady state.

To obtain the optimal access strategy, we can establish the following optimization problem by nonlinear programming:

$$\begin{aligned} &\text{Min} \quad \mathbf{S}_{Op} = \underset{\mathrm{s}=\{s_j\}}{\arg\min} \left\{ E[T_S] = \sum_{j=1}^{M} E[T_{Sj}] \cdot s_j \right\} \\ &\text{st.} \quad \sum_{j=1}^{M} s_j = 1, \ \ s_j \geqslant 0. \end{aligned} \tag{19}$$

where j is used to identify different channels and M represents the total channel number.

The above optimization problem can be resolved using the Genetic Algorithm (GA) [16] to obtain the globally optimal result.

3.2 Low complexity access strategy

As is well known, the GA approach can lead us to finding the globally optimal results. However, because of its computational complexity, which will bring a lot of extra time overhead, we can adopt in practice some simple access strategy, such as inverse proportional access and equiprobability access, to get the suboptimal results but save more unnecessary time overhead.

Here, inverse proportional access can be defined as the access probability proportional to the inverse of the PU traffic arrival rate in each licensed channel, i.e.

$$s_j = \frac{1/\lambda_{Pj}}{\sum_{j=1}^{M} 1/\lambda_{Pj}}. \tag{20}$$

The equiprobability access is to access each licensed channel with equal probability, i.e.

$$s_j = \frac{1}{M}, \tag{21}$$

where j is used to identify different channels and M represents the total channel number. The corresponding results will be shown in the next subsection.

3.3 Numerical results

For the purpose of illustration, we consider the case of SU traffic accessing two licensed channels. When the same or different PU traffic arrival rates are set in two licensed channels, Figures 6 and 7 show the corresponding optimal

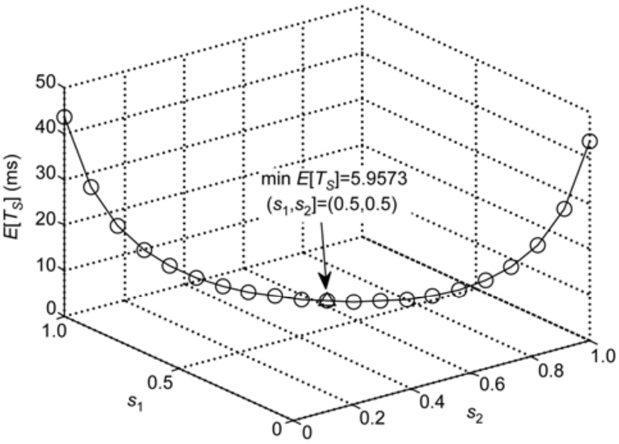

Figure 6 Expected system delay when the PU traffic arrival rate is the same $\lambda_{P1}=\lambda_{P2}=0.3$.

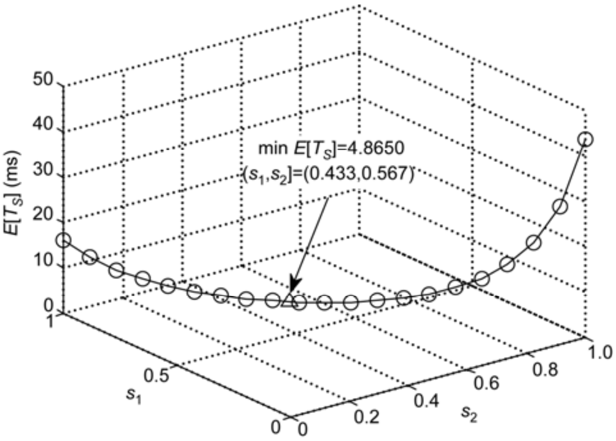

Figure 7 Expected system delay when the PU traffic arrival rate is different $\lambda_{P1}=0.3$, $\lambda_{P2}=0.25$.

Table 1 PU traffic arrival rate set for the case of three licensed channels

PU traffic parameter index	$(\lambda_{P1},\lambda_{P2},\lambda_{P3})$	PU traffic parameter index	$(\lambda_{P1},\lambda_{P2},\lambda_{P3})$
1	(0.3, 0.3, 0.3)	7	(0.3,0.05,0.05)
2	(0.3, 0.3, 0.25)	8	(0.25,0.05,0.05)
3	(0.3, 0.3, 0.15)	9	(0.2,0.05,0.05)
4	(0.3, 0.3, 0.05)	10	(0.15,0.05,0.05)
5	(0.3,0.25,0.05)	11	(0.1,0.05,0.05)
6	(0.3, 0.15, 0.05)	12	(0.05,0.05,0.05)

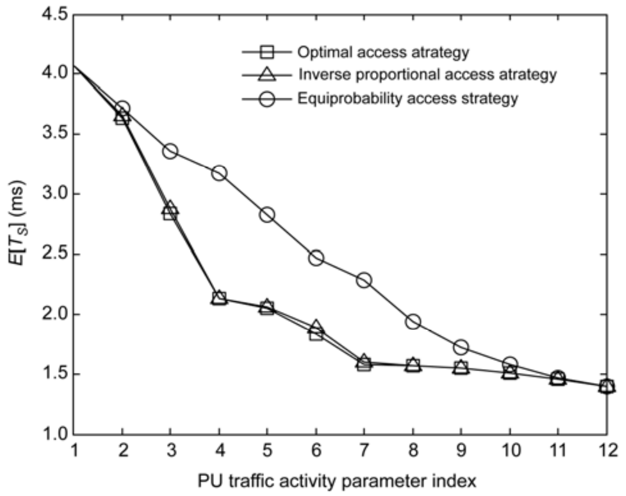

Figure 8 Comparison of the expected system delay with different access strategies.

access probability. It validates the conclusion that there is an optimal access strategy (s_1,s_2), with which the expected system delay $E[T_s]$ of SU traffic transmission is reduced to the smallest. When considering more than two licensed channels, we can find the optimal access strategy with the method mentioned in section 3.1.

The PU traffic arrival rate parameter set for the case of three licensed channels is given in Table 1. The comparison of the expected system delay with different access strategies is represented in Figure 8. According to the analysis of system delay in section 2, we find that the performance result $E[T_S]$ becomes larger as the PU traffic density increases. An inverse proportional access is a good fit for the interaction between the system delay and PU traffic density diversity, while equiprobability access only reflects the situation in which all the PU traffic densities are the same in each licensed channel. As shown in Figure 8, the inverse proportional access strategy can achieve nearly the same expected system delay performance as the optimal access strategy based on GA. Simultaneously, when all PU traffic arrival rates are the same, the performance for the three access strategies are the same. Consequently, considering the time consumption of the GA approach, we can adopt the inverse proportional access strategy to obtain the approximate optimal results in practice.

Furthermore, when all PU traffic arrival rates are the same, Figures 6 and 8 show that the optimal access strategy is to access every licensed channel with equal probability. Under this condition, more channels mean lower SU traffic arrival rates in each licensed channel, and the corresponding system delay will be much smaller according to the interaction between system delay and SU traffic density variations represented in section 2. As shown in Figure 9, we find that the performance of minimum expected system delay will be better when more licensed channels are presented, and such improvement becomes more evident as the PU traffic activities grow heavier.

4 Conclusions

For OSA approach based CNRs, we have investigated the delay performance of SU traffic and the corresponding optimal access strategy for sharing multiple licensed channels. We have proposed an M/G/1 priority virtual queuing system model, which provides an effective approach for the analysis

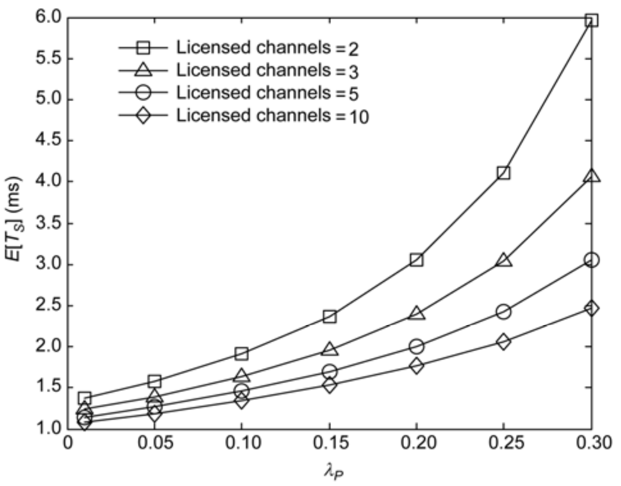

Figure 9 Comparison of the minimum expected system delay for the case with different licensed channels when the PU traffic arrival rate is the same.

of the PU and SU traffic transmissions in the same queue. We obtained the corresponding expressions for the SU traffic system delay and further investigated the performance of a multiple licensed channel access schemes with respect to the expected system delay of SU traffic. By means of minimizing the expected transmission delay, the optimal access strategy is modeled as a nonlinear programming problem. According to the classic Genetic Algorithm (GA), we find the corresponding globally optimal access probability for each licensed channel. Numerical results have been provided to validate our analysis and the design of an optimal access strategy. Meanwhile, considering the time taken by the GA approach, we can also adopt the inverse proportional access strategy to obtain the approximate optimal results in practice.

This work was supported by the National Basic Research Program of China (2009CB320405), National Natural Science Foundation of China (61071102), National Science and Technology Major Project of China (2010ZX03006-002-02 and 2010ZX03005-003), and the Foundation Project of National Key Laboratory of Science and Technology on Communications (9140C0202061004).

1 Hossain E, Niyato D, Han Z. Dynamic Spectrum Access and Management in Cognitive Radio Networks. London: Cambridge University Press, 2009
2 Akyildiz I F, Lee W Y, Vuran M C, et al. Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey. Comput Netw, 2006, 50: 2127–2159
3 Zhao Q, Sadler B M. A survey of dynamic spectrum access. IEEE Signal Proc Mag, 2007, 24: 79–89
4 Zhao Q, Tong L, Swami A, et al. Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework. IEEE J Sel Area Comm, 2007, 25: 589–600
5 Geirhofer S, Tong L, Sadler B M. Cognitive medium access: Constraining interference based on experimental models. IEEE J Sel Area Comm, 2008, 26: 95–105
6 Geirhofer S, Tong L, Sadler B M. Dynamic spectrum access in the time domain: Modeling and exploiting whitespace. IEEE Commun Mag, 2007, 45: 66–72
7 Li X, Zhao Q C, Guan X H, et al. Optimal cognitive access of Markovian channels under tight collision constraints. IEEE J Sel Area Comm, 2011, 29: 746–756
8 Li H S, Han Z. Queuing analysis of dynamic spectrum access subject to interruptions from primary users. In: Hayar A, Larsson E G, eds. Proceedings of the Fifth International Conference on Cognitive Radio Oriented Wireless Networks and Communications, 2010 Jun 9–11, Cannes. Piscataway: IEEE Computer Society, 2010. 1–5
9 Borgonovo F, Cesana M, Fratta L. Throughput and delay bounds for cognitive transmissions. Adv Ad hoc Netw, 2008, 265: 179–190
10 Shiang H P, Scharr M. Queuing-based dynamic channel selection for heterogeneous multimedia applications over cognitive radio networks. IEEE Trans Multimedia, 2008, 10: 896–909
11 Wang S S, Zhang J S, Tong L. Delay analysis for cognitive radio networks with random access: A fluid queue view. In: Mandyam G, Westphal G, eds. Proceedings IEEE INFOCOM, 2010 Mar 14–19, San Diego. Piscataway: Institute of Electrical and Electronics Engineers Incorporated, 2010. 1–9
12 Graver D P. A waiting line with interrupted services, including priorities. J R Statist Soc, 1962, 24: 73–90
13 Hock N C, Hee S B. Queueing Modeling Fundamentals with Applications in Communication Networks. Chichester: John Wiley and Sons Limited, 2008
14 Kleinrock L. Queueing Systems-Volume 1: Theory. Chichester: John Wiley and Sons Limited, 1976
15 Kleinrock L. Queueing Systems-Volume 2: Computer Applications. Chichester: John Wiley and Sons Limited, 1976
16 Goldberg D E. Genetic Algorithms in Search, Optimization and Machine Learning. Chichester: John Wiley and Sons Limited, 1989
17 Ross S M. Stochastic Processes. Chichester: John Wiley and Sons Limited, 1995