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Performance analysis of CSMA in an unslotted cognitive radio network with licensed channels and unlicensed channels

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Abstract

We consider a carrier sense multiple access (CSMA) in an unslotted cognitive radio network under a mixed spectrum environment of licensed channels and unlicensed channels. In this system, primary users use only licensed channels, while secondary users use unlicensed channels and opportunistically can use licensed channels unused by primary users temporally. If an arriving secondary user (SU) does not find any idle channels, then the SU either enters the retrial group with probability q for later retrial or gives up its service and leaves the system with probability $1 - q$. SUs in the retrial group retry independently after exponentially distributed random time. We analyze the system by continuous time Markov chain (CTMC) with level dependent QBD structure and obtain the steady state probability of the system by matrix analytic method. In numerical results, we compare the performance of two systems with retrial ($q > 0$) and without retrial ($q = 0$). It is shown that the retrial phenomenon of SUs has an impact on the performance of SUs in cognitive radio networks.

Keywords: Cognitive Radio Network, CSMA; Retry SU, Matrix Analytic Method, Throughput, Loss probability

1 Introduction

Advances in wireless communication systems and development of new services have significantly increased the demand for more frequency bands. Recently, the FCC has reported that the licensed bands are vastly underutilized [1]. To overcome spectrum scarcity, licensed spectrum bands need to be more intelligently utilized. For this purpose, cognitive radios have recently emerged as a promising technique to improve the utilization of the existing radio spectrum. Cognitive radio improves the spectrum efficiencies by enabling SUs to opportunistically access the channels unused by PUs.

There have been many studies on the opportunistic spectrum access for a cognitive radio network. Cognitive radio networks can be classified as single channel (e.g., [2,4,5,7]) and multi-channel (e.g., [3,6,8]). Both networks further can be classified a slotted structure (e.g., [2,3,6]) and an unslotted structure (e.g., [7-9]) where the slotted structure means the time axis for network is divided by

time slots and all PUs and SUs are synchronized at the time slot.

Most of these studies deal with temporal use of the SUs on licensed bands. Multiple accesses of SUs on a mixed environment of licensed and unlicensed bands have been investigated [10-12]. H. Al-Mahdi *et al.* [12] investigated CSMA in an unslotted cognitive radio networks under a mixed spectrum environment of licensed and unlicensed bands where the blocked SUs and the preempted SUs are forced to leave the system forever when there are no idle channels in the system. But in practical situation, the blocked SUs and the preempted SUs may do not leave the system forever and try to continue their services after random amount of time. This is a motivation of our work.

In this paper, we investigate the same model in [12] with an additional retrial phenomenon: the blocked SUs and the preempted SUs either enter a retrial group with probability q or leave the system with probability $1 - q$ if all channels are busy. We investigate the effect of the retrial phenomenon of SUs on the system performance of an unslotted cognitive radio network. We analyze the system by CTMC with a level dependent QBD structure

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and obtain the steady state probability of the system using matrix analytic method. Note that, when $q = 0$, our model reduces to the system model in [12].

The rest of this paper is organized as follows. In Section 2, the operation of CSMA in unslotted cognitive radio networks with a mixed spectrum environment is described in details. In Section 3, we analyze the performance of the system by using matrix analytic method. Numerical examples are presented in section 4 and conclusions are given in section 5.

2 System model

We consider CSMA in the unslotted cognitive radio networks with a mixed spectrum environment of c_1 primary channels and c_2 secondary channels (See Figure 1). PUs can use only c_1 primary channels but SUs can use c_2 secondary channels and can opportunistically use primary channels unused by PUs. PUs have preemptive priorities over SUs on primary channels. We assume that PUs and SUs arrive according to Poisson processes with rate λ_1 and λ_2 independently, the transmission times of messages for PUs and SUs are exponentially distributed with mean μ_1^{-1} and μ_2^{-1} , respectively.

On the arrival of a PU, if there are idle primary channels, the PU occupies one of those idle channels and send its message. If there is no idle primary channel but at least one primary channels are occupied by SUs, the arriving PU selects and preempts one of the primary channels occupied by SUs. If all primary channels are busy with PUs, the arriving PU is queued in the finite buffer with the size $N - c_1$ ($N \geq c_1$).

A SU always senses the channels before each message transmission. It is assumed that the sensing period of the channel is negligible. An arriving SU first senses unlicensed channels. If there are idle secondary channels, then the SU occupies one of the idle

secondary channels and transmits a message and leaves the system after its transmission. When the arriving SU does not find idle secondary channels, the SU senses the primary channels and transmits its message on an idle primary channel if any, otherwise the SU either enters the retrial group with probability q for later retrial or give up its service and leaves the system with probability $1 - q$.

When a SU is preempted by a PU, the SU performs spectrum handoff to a secondary channel. Spectrum handoff procedures aim to help SUs find another idle channel to send its message. If the preempted SU finds idle secondary channels, the SU handoffs to one of those idle channels, otherwise the SU either enters the retrial group with probability q or leaves the system with probability $1 - q$.

SUs in the retrial group retry to the system in order to transmit their messages. The retrial time of SUs is defined as the amount of time between two consecutive retrials made by a SU and is assumed to be independent of all previous retrial times. We assume that the retrial times are exponentially distributed with mean ν^{-1} . When a SU in the retrial group retries to the system, the SU repeats the same procedure as an arriving SU does.

3 Performance analysis of the system

In this section, we analyze CSMA in an unslotted cognitive radio network with a mixed spectrum environment of licensed and unlicensed channels by using matrix analytic method.

Let

$N_r(t)$ = the member of SUs in the retrial group at time t ,

$N_1(t)$ = the total number of PUs in service and PUs in the buffer at time t ,

$N_2(t)$ = the number of SUs in service at time t .

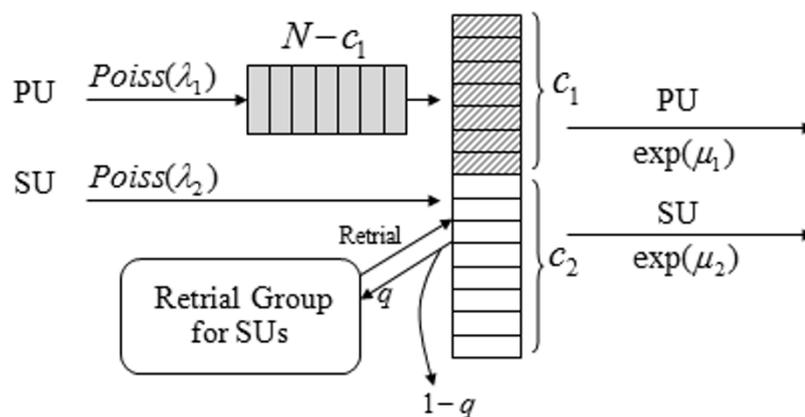


Figure 1 The system model.

unique solution of linear equations $\mathbf{\Pi Q} = 0$, $\mathbf{\Pi e}_\infty = 1$; where \mathbf{e}_∞ is an infinite dimensional column vector whose elements are all equal to 1. We partition $\mathbf{\Pi}$ as $\mathbf{\Pi} = (\mathbf{\Pi}_0, \mathbf{\Pi}_1, \mathbf{\Pi}_2, \dots)$ where $\mathbf{\Pi}_k = (\mathbf{\Pi}_{k,0}, \mathbf{\Pi}_{k,1}, \dots, \mathbf{\Pi}_{k,N})$, $\mathbf{\Pi}_{k,n} = (\pi_{k,n,0}, \pi_{k,n,1}, \dots, \pi_{k,n,d_n})$ and $\pi_{k,n,j}$ is the probability that Markov chain is in state (k, n, j) in the steady state. We can obtain the steady state probability vector $\mathbf{\Pi}$ by matrix analytic method (See an Appendix for detailed derivation).

The main performance measures of cognitive radio network are loss probability P_l and the throughput T_s of SUs.

Let $\pi_{n,j} \triangleq \sum_{k=0}^{\infty} \pi_{k,n,j}$ is the probability that there are n PUs in the system and j SUs in service. Note that, since $n + d_n \geq c$, $\sum_{n=0}^N \pi_{n,d_n}$ is the probability that all c channels are busy.

The loss probability P_l of SUs is defined by the ratio of the loss rate of SUs to the arrival rate of SUs. Loss of SUs occurs by the following three kinds of events:

- a new SU is blocked and then gives up its service and thus its loss rate is given by

$$\lambda_2(1 - q) \sum_{n=0}^N \pi_{n,d_n}$$

where $\sum_{n=0}^N \pi_{n,d_n}$ is the probability that all c channels are busy.

- a retrial SU is blocked and then gives up its service and thus its loss rate is given by

$$\sum_{k=1}^{\infty} \sum_{n=0}^N k \nu (1 - q) \pi_{k,n,d_n}$$

where $k\nu$ is a retrial rate when there are k SUs in a retrial group.

- a SU is preempted by a PU and then gives up its service and thus its loss rate is given by

$$\lambda_1(1 - q) \sum_{n=0}^{c_1-1} \pi_{n,d_n}$$

where a SU is preempted when all c channels are busy and at least one SU occupy primary channel.

Hence the total loss rate of SUs is

$$(1 - q) \left(\lambda_2 \sum_{n=0}^N \pi_{n,d_n} + \sum_{k=1}^{\infty} \sum_{n=0}^N k \nu \pi_{k,n,d_n} + \lambda_1 \sum_{n=0}^{c_1-1} \pi_{n,d_n} \right).$$

Therefore the loss probability of SUs is given by

$$P_l = \frac{1 - q}{\lambda_2} \left(\lambda_2 \sum_{n=0}^N \pi_{n,d_n} + \sum_{k=1}^{\infty} \sum_{n=0}^N k \nu \pi_{k,n,d_n} + \lambda_1 \sum_{n=0}^{c_1-1} \pi_{n,d_n} \right). \quad (2)$$

The throughput T_s of SUs is defined as the number of SUs who successfully transmit their messages per unit time, i.e., we have

$$T_s = \lambda_2(1 - P_l). \quad (3)$$

4 Numerical results

In this section, we present numerical examples to investigate the performance evaluation of CSMA in unslotted cognitive radio networks with a mixed spectrum environment. We set the parameters $c_1 = 4$, $c_2 = 3$ channels, $\mu_1^{-1} = 2$, $\mu_2^{-1} = 2.5$ (sec).

In Figure 2 and Figure 3, we compare the throughput and loss probability of SUs between the case with retrials ($q = 0.7$) and the case without retrials ($q = 0$).

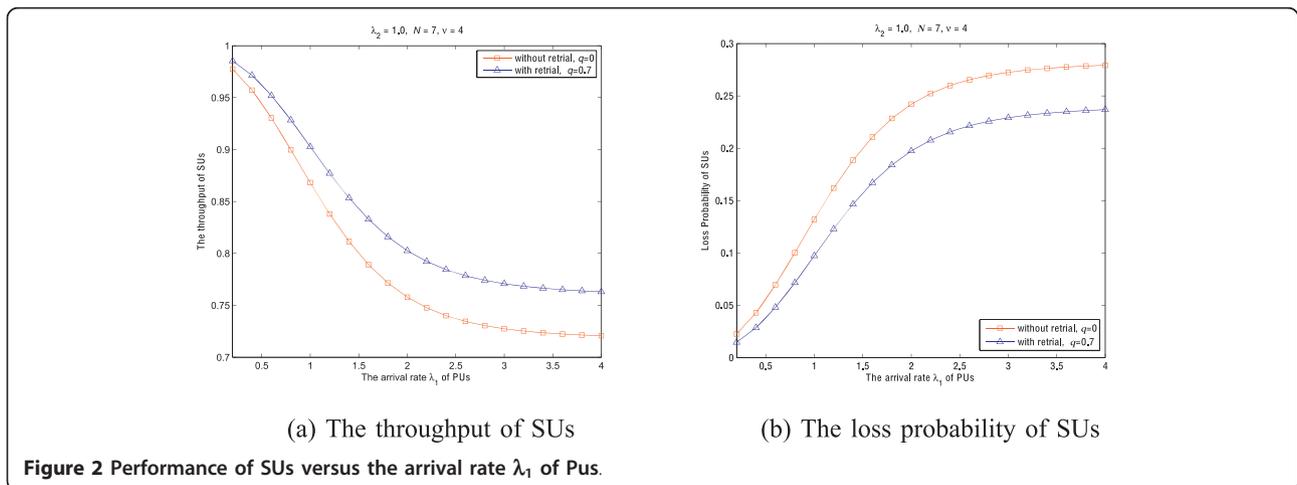


Figure 2 Performance of SUs versus the arrival rate λ_1 of PUs.

Figure 2(a) depicts the throughput of SUs versus the arrival rate λ_1 of PUs. As expected, the throughput of SUs decreases as the arrival rate λ_1 of PUs increases. We see that the throughput of SUs in the case with retrials is larger than that in the case without retrials, because the retrial phenomenon of SUs leads to higher channel utilization of SUs. Figure 2(b) shows the loss probability of SUs increases as the arrival rate λ_1 of PUs increases. We also see that the loss probability of SUs in the case without retrials is larger than that in the case with retrials because all blocked SUs are lost in the model without retrials. Figure 3(a) and 3(b) depict the throughput of SUs and loss probability of SUs versus the arrival rate λ_2 of SUs. Figure 2 and Figure 3 show the retrial phenomenon of SUs has an impact on the performance of CSMA scheme in unslotted cognitive radio networks.

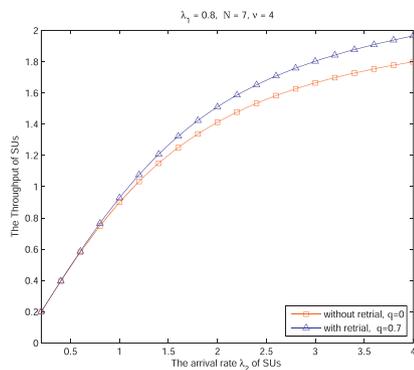
Figure 4(a) and 4(b) depict the throughput of SUs and the loss probability of SUs versus the buffer size $N - c_1$ of PUs. It is show that the throughput of SUs decreases

and the loss probability of SUs increases as the buffer size $N - c_1$ of PUs increases. But when the buffer size larger than certain point, the effect of PU's buffer size on the performance of SUs is very small because when PUs wait in the buffer, SUs can't use primary channels and only can use secondary channels.

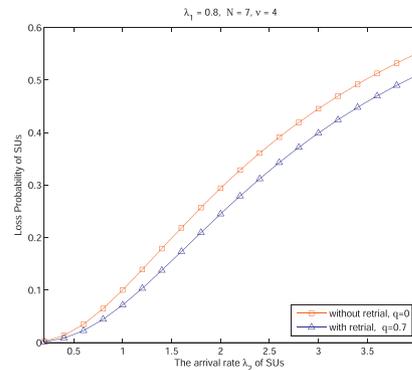
Figure 5(a) and 5(b) depict the throughput of SUs and the loss probability of SUs versus the retrial rate ν of PUs. It is show that the throughput of SUs decreases and the loss probability of SUs increases as the retrial rate ν of PUs increases because the loss rate of SUs increases.

5 Conclusions

We have considered CSMA in an unslotted cognitive radio network under a mixed spectrum environment of licensed and unlicensed channels and investigated the effect of retrial phenomenon of SUs. We analyze the system by CTMC with a level dependent QBD structure and obtain the steady state probability of the system using matrix analytic method, and then obtain

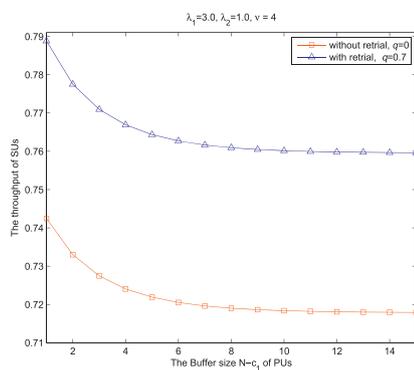


(a) The throughput of SUs

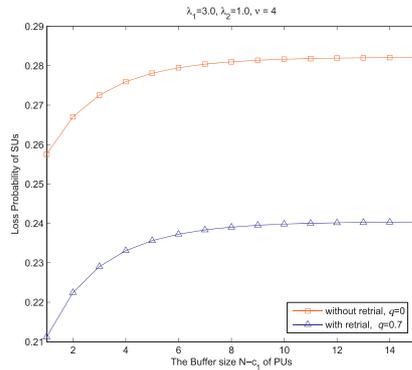


(b) The loss probability of SUs

Figure 3 Performance of SUs versus the arrival rate λ_2 of Pus.



(a) The throughput of SUs



(b) The loss probability of SUs

Figure 4 Performance of SUs versus the buffer size $N - c_1$ of Pus.

Conflicts of interests

The authors declare that they have no competing interests.

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