Performance Comparison Between Two Kinds of Priority Schemes in Cognitive Radio Networks

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Abstract In this paper, we consider a cognitive radio network with multiple Secondary Users (SUs). The SU packets are divided into SU1 packets and SU2 packets, and the SU1 packets have higher priority than the SU2 packets. Different from the conventional preemptive priority scheme (called Scheme I), we propose a non-preemptive priority scheme for the SU1 packets (called Scheme II) to guarantee the transmission continuity of the SU2 packets. By constructing a three-dimensional Markov chain, we give the transition probability matrix of the Markov chain, and obtain the steady-state distribution of the system model. Accordingly, we derive some performance measures, such as the interrupted rate of the SU1 packets and the interrupted rate of the SU2 packets. Lastly, we provide numerical experiments to compare the system performance between the two priority schemes.

Keywords Cognitive radio networks · Preemptive priority · Non-preemptive priority · Markov chain

1 Introduction

In conventional cognitive radio networks there are two kinds of users, namely, Primary Users (PUs) and Secondary Users (SUs). The PUs have priority, with the SUs making use of the licensed spectrum only when the spectrum is not occupied by the PUs [1]. Most of studies in cognitive radio networks have been focused on the interaction between PUs and SUs. Hamza et al. assumed that the SU in the

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T.V. Do et al. (eds.), *Queueing Theory and Network Applications*,
Advances in Intelligent Systems and Computing 383,
DOI: 10.1007/978-3-319-22267-7_7

system acted as a relay for the PU in the event of transmission failure [2]. Using queueing analysis, they obtained the throughputs of the PUs and the SUs in the system. Considering that the transmission of the SUs may be interrupted by the PUs, Chu et al. proposed a spectrum handoff strategy in the overlay cognitive radio networks [3]. Their numerical results showed that their proposed spectrum handoff strategy could effectively reduce the waiting time during the spectrum handoff. However, the studies mentioned above did not attribute different priority levels to SUs.

We note that there are various types of data in communication networks, for example, real-time data and non-real-time data. The real-time data requires higher priority. So, it is also necessary to grade the SUs in cognitive radio networks. Lee et al. divided the SUs into SU1 and SU2 in a multi-channel cognitive radio network [4]. They assumed the SU1 calls have higher priority than the SU2 calls, and the SU1 calls can interrupt the transmission of the SU2 calls. By building a continuous-time Markov chain, they analyzed the performance of the SU1 and the SU2, respectively. Zhang et al. equipped the SUs with different priority levels to guarantee the quality of service for the SUs with higher priority [5]. By applying a preemptive resume priority M/M/1 queueing model, they evaluated the transmission delay for the interrupted SUs.

Moreover, we note that in most of the research considering the prioritization of the SUs in cognitive radio networks, the SUs with higher priority would interrupt the transmission of the SUs with lower priority immediately (preemptive priority scheme). However, in practical networks, in order to guarantee the transmission continuity of the SUs, the SUs with higher priority may wait until the transmission of the SUs with lower priority are completed.

In this paper, we propose a non-preemptive priority scheme for the SU packets with higher priority. Considering the digital nature of modern networks, we construct a three-dimensional discrete-time Markov chain and then derive some performance measures. In addition, we provide numerical experiments to compare the system performance between the two priority schemes.

2 System Model

In this paper, we consider a cognitive radio network with a single channel. The PU packets are supposed to have preemptive priority over the SU packets. The packets generated from the SUs are classified into SU1 packets and SU2 packets, and the SU1 packets have higher priority than the SU2 packets. Considering the lowest priority of the SU2 packets, a buffer is prepared for the SU2 packets to reduce possible loss of those packets. We call this buffer the “SU2 buffer".

When a PU packet arrives at the system, if the channel is occupied by another PU packet, this newly arriving packet will leave the system to find another available channel. If the channel is occupied by an SU1 packet, the transmission of that SU1 packet will be interrupted by the PU packet and the interrupted SU1 packet will leave the system to find another available channel. If the channel is occupied by an SU2 packet, the transmission of the SU2 packet will also be interrupted by the PU packet and the interrupted SU2 packet will return back to the SU2 buffer.

The SU1 packets have a higher priority access to the channel than the SU2 packets. For example, when an SU1 packet and an SU2 packet arrive at the system simultaneously (there is no PU packet arrival), if the channel is idle, the newly arriving SU1 packet will occupy the channel, while the newly arriving SU2 packet has to queue in the SU2 buffer.

In the case of an SU1 packet arriving at the system (namely, there is no PU packet arrival) during the transmission of an SU2 packet, we propose a non-preemptive priority scheme. We assume the newly arriving SU1 packet will be blocked and leave the system to find another available channel in order to guarantee the transmission continuity of the SU2 packets. In the following, in order to clarify the presentation, we call the preemptive priority scheme where the newly arriving SU1 packet will interrupt the transmission of the SU2 packet and occupy the channel immediately "Scheme I" and the proposed non-preemptive priority scheme we call "Scheme II".

We assume an early arriving system with a slotted timing structure, and the time axis is ordered by $t = 1, 2, \ldots$. We suppose that the arrival intervals of the PU packets, the SU1 packets and the SU2 packets follow geometrical distributions with parameters λ_1, λ_{21} and λ_{22}, respectively. Moreover, we assume that the transmission time of a PU packet, an SU1 packet and an SU2 packet follow geometrical distributions with parameters μ_1, μ_{21} and μ_{22}, respectively.

We denote $L_n^{(1)}$, $L_n^{(21)}$ and $L_n^{(22)}$ as the number of PU packets, SU1 packets and SU2 packets in the system at the instant $t = n^+$, respectively, where n represents the time epoch of the slot boundary. Then, $\left\{L_n^{(22)}, L_n^{(21)}, L_n^{(1)}\right\}$ constitutes a three-dimensional discrete-time Markov chain with the state space $\boldsymbol{M}$ as follows:

$$\boldsymbol{M} = \{(i, 0, 0) \cup (i, 0, 1) \cup (i, 1, 0) : 0 \le i \le \infty\}. \tag{1}$$

3 Performance Analysis

Let $\boldsymbol{P}$ be the state transition probability matrix of the three-dimensional discrete-time Markov chain. $\boldsymbol{P}$ can be given in a block-structure form as follows:

$$\boldsymbol{P} = \begin{pmatrix} \boldsymbol{C}_0 & \boldsymbol{B}_0 & & & \\ \boldsymbol{A}_2 & \boldsymbol{A}_1 & \boldsymbol{A}_0 & & \\ & \boldsymbol{A}_2 & \boldsymbol{A}_1 & \boldsymbol{A}_0 & \\ & & \ddots & \ddots & \ddots \end{pmatrix} \tag{2}$$

where each non-zero block in $\boldsymbol{P}$ is a 3×3 matrix and can be discussed as follows. Hereafter, we use the overbar notation to denote the probability of a complement event, for instance, $\bar{\lambda}_1 = 1 - \lambda_1$. Moreover, we introduce $\zeta = \lambda_{21}\mu_{21} + \bar{\mu}_{21}$ and $\vartheta = \lambda_{22}\mu_{22} + \bar{\lambda}_{22}\bar{\mu}_{22}$ in following equations for compactness of presentation.

(1)$\boldsymbol{C}_0$ is the one-step transition probability matrix for the number of SU2 packets in the system being fixed at 0. $\boldsymbol{C}_0$ can be given by

$$\boldsymbol{C}_0 = \bar{\lambda}_{22}\boldsymbol{U} \tag{3}$$

where $\boldsymbol{U}$ can be given as follows:

$$\boldsymbol{U} = \begin{pmatrix} \bar{\lambda}_1\bar{\lambda}_{21} & \lambda_1 & \bar{\lambda}_1\lambda_{21} \\ \bar{\lambda}_1\bar{\lambda}_{21}\mu_1 & \lambda_1\mu_1 + \bar{\mu}_1 & \bar{\lambda}_1\lambda_{21}\mu_1 \\ \bar{\lambda}_1\bar{\lambda}_{21}\mu_{21} & \lambda_1 & \bar{\lambda}_1\zeta \end{pmatrix}. \tag{4}$$

(2)$\boldsymbol{B}_0$ is the one-step transition probability matrix for the number of SU2 packets in the system increasing from 0 to 1. $\boldsymbol{B}_0$ can be given by

$$\boldsymbol{B}_0 = \lambda_{22}\boldsymbol{U}. \tag{5}$$

(3)$\boldsymbol{A}_2$ is the one-step transition probability matrix for the number of SU2 packets in the system decreasing from i to $i-1$ $(1 \le i \le \infty)$. $\boldsymbol{A}_2$ can be given by

$$\boldsymbol{A}_2 = \mu_{22}\bar{\lambda}_{22}\boldsymbol{V} \tag{6}$$

where $\boldsymbol{V}$ can be given as follows:

$$\boldsymbol{V} = \begin{pmatrix} \bar{\lambda}_1\bar{\lambda}_{21} & \lambda_1 & \bar{\lambda}_1\lambda_{21} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \tag{7}$$

(4)$\boldsymbol{A}_1$ is the one-step transition probability matrix for the number of SU2 packets in the system being fixed at i $(1 \le i \le \infty)$. $\boldsymbol{A}_1$ can be given as follows:
For the case of Scheme I, $\boldsymbol{A}_1$ can be given by

$$\boldsymbol{A}_1 = \begin{pmatrix} \bar{\lambda}_1\bar{\lambda}_{21}\vartheta & \lambda_1\vartheta & \bar{\lambda}_1\lambda_{21}\vartheta \\ \bar{\lambda}_{22}\bar{\lambda}_1\bar{\lambda}_{21}\mu_1 & \bar{\lambda}_{22}(\lambda_1\mu_1 + \bar{\mu}_1) & \bar{\lambda}_{22}\bar{\lambda}_1\lambda_{21}\mu_1 \\ \bar{\lambda}_{22}\bar{\lambda}_1\bar{\lambda}_{21}\mu_{21} & \bar{\lambda}_{22}\lambda_1 & \bar{\lambda}_{22}\bar{\lambda}_1\zeta \end{pmatrix}. \tag{8}$$

For the case of Scheme II, $\boldsymbol{A}_1$ can be given by

$$\boldsymbol{A}_1 = \begin{pmatrix} \bar{\lambda}_1(\bar{\lambda}_{22}\bar{\mu}_{22} + \lambda_{22}\mu_{22}\bar{\lambda}_{21}) & \lambda_1\vartheta & \bar{\lambda}_1\lambda_{21}\lambda_{22}\mu_{22} \\ \bar{\lambda}_{22}\bar{\lambda}_1\bar{\lambda}_{21}\mu_1 & \bar{\lambda}_{22}(\lambda_1\mu_1 + \bar{\mu}_1) & \bar{\lambda}_{22}\bar{\lambda}_1\lambda_{21}\mu_1 \\ \bar{\lambda}_{22}\bar{\lambda}_1\bar{\lambda}_{21}\mu_{21} & \bar{\lambda}_{22}\lambda_1 & \bar{\lambda}_{22}\bar{\lambda}_1\zeta \end{pmatrix}. \tag{9}$$

(5)$\boldsymbol{A}_0$ is the one-step transition probability matrix for the number of SU2 packets in the system increasing from i to $i+1$ $(1 \le i \le \infty)$. $\boldsymbol{A}_0$ can be given by

$$\boldsymbol{A}_0 = \lambda_{22}\boldsymbol{W}. \tag{10}$$

For the case of Scheme I, $\boldsymbol{W}$ can be given as follows:

$$\boldsymbol{W} = \begin{pmatrix} \bar{\lambda}_1\bar{\lambda}_{21}\bar{\mu}_{22} & \lambda_1\bar{\mu}_{22} & \bar{\lambda}_1\lambda_{21}\bar{\mu}_{22} \\ \bar{\lambda}_1\bar{\lambda}_{21}\mu_1 & \lambda_1\mu_1 + \bar{\mu}_1 & \bar{\lambda}_1\lambda_{21}\mu_1 \\ \bar{\lambda}_1\bar{\lambda}_{21}\mu_{21} & \lambda_1 & \bar{\lambda}_1\zeta \end{pmatrix}. \tag{11}$$

For the case of Scheme II, $\boldsymbol{W}$ can be given follows:

$$\boldsymbol{W} = \begin{pmatrix} \bar{\mu}_{22}\bar{\lambda}_1 & \bar{\mu}_{22}\lambda_1 & 0 \\ \bar{\lambda}_1\bar{\lambda}_{21}\mu_1 & \lambda_1\mu_1 + \bar{\mu}_1 & \bar{\lambda}_1\lambda_{21}\mu_1 \\ \bar{\lambda}_1\bar{\lambda}_{21}\mu_{21} & \lambda_1 & \bar{\lambda}_1\zeta \end{pmatrix}. \tag{12}$$

The steady-state distribution $\pi_{i,j,k}$ of $\left\{L_n^{(22)}, L_n^{(21)}, L_n^{(1)}\right\}$ is then defined as

$$\pi_{i,j,k} = \lim_{n\to\infty} P\left\{L_n^{(22)} = i, L_n^{(21)} = j, L_n^{(1)} = k\right\} \tag{13}$$

where $0 \le i \le \infty$, $j = 0, 1$, $k = 0, 1$. Moreover, we note that j and k can not be equate to 1 at the same time.

The structure of the transition probability matrix $\boldsymbol{P}$ indicates that the three-dimensional Markov chain follows a Quasi Birth and Death (QBD) process. By using the matrix-geometric solution method [6], we can obtain the numerical results for the steady-state distribution $\pi_{i,j,k}$ defined in Eq. (13).

Next, by using the steady-state distribution $\pi_{i,j,k}$, we present various performance measures of this system model.

We define the interrupted rate γ_{21} of the SU1 packets as the number of SU1 packets that are interrupted by the PU packets per slot. The expression of the interrupted rate γ_{21} of the SU1 packets can be given as follows:

$$\gamma_{21} = \sum_{i=0}^{\infty} \pi_{i,1,0}\bar{\mu}_{21}\lambda_1. \tag{14}$$

We define the interrupted rate γ_{22} of the SU2 packets as the number of SU2 packets that are interrupted by the SU1 packets or the PU packets per slot. The expression of the interrupted rate γ_{22} of the SU2 packets can be given for two cases.

For the case of Scheme I:

$$\gamma_{22} = \sum_{i=1}^{\infty} \pi_{i,0,0}\bar{\mu}_{22}(1 - \bar{\lambda}_1\bar{\lambda}_{21}). \tag{15}$$

For the case of Scheme II:

$$\gamma_{22} = \sum_{i=1}^{\infty} \pi_{i,0,0}\bar{\mu}_{22}\lambda_1. \tag{16}$$

4 Numerical Experiments

In this section, we compare the interrupted rate of the SU1 packets and the interrupted rate of the SU2 packets between Scheme I and Scheme II. The time length of one slot is assumed to be 1 ms. By referencing [7] and following the IEEE 802.11 b/g standard, the data rate in Physical Layer is assumed to be 11 Mbps. The average packet size is assumed to be 2, 750 Bytes. Moreover, the arrival rate λ_{22} of the SU2 packets is assumed to be $\lambda_{22} = 0.1$.

Figures 1 compares the interrupted rate γ_{21} of the SU1 packets between Scheme I and Scheme II.

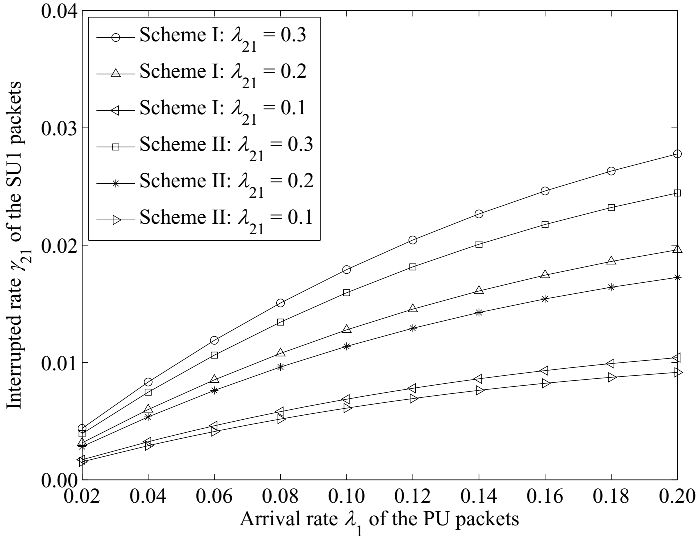

Fig. 1 Change trend for the interrupted rate γ_{21} of the SU1 packets.

From Fig. 1, we observe that the interrupted rate γ_{21} of the SU1 packets increases as the arrival rate λ_1 of the PU packets increases. This is because as the arrival rate of the PU packets increases, the possibility for the transmission of the SU1 packets to be interrupted by the PU packets will be higher, and this will increase the interrupted rate of the SU1 packets.

On the other hand, as shown in Fig. 1, the interrupted rate γ_{21} of the SU1 packets increases as the arrival rate λ_{21} of the SU1 packets increases. The reason is that the larger the arrival rate of the SU1 packets is, the more the SU1 packets will occupy the channel, and this will result in a greater interrupted rate of the SU1 packets.

Furthermore, the interrupted rate γ_{21} of the SU1 packets in Scheme I is greater than that in Scheme II for the same parameter settings. The reason is that in Scheme I, a newly arriving SU1 packet can interrupt the transmission of the SU2 packet on the channel. In other words, in the case of Scheme I, the possibility of the SU1 packets occupying the channel is higher, and the possibility for the transmission of the SU1 packets to be interrupted by the PU packets will also be higher. As a result, the interrupted rate of the SU1 packets will be greater in Scheme I.

Figure 2 compares the interrupted rate γ_{22} of the SU2 packets between Scheme I and Scheme II.

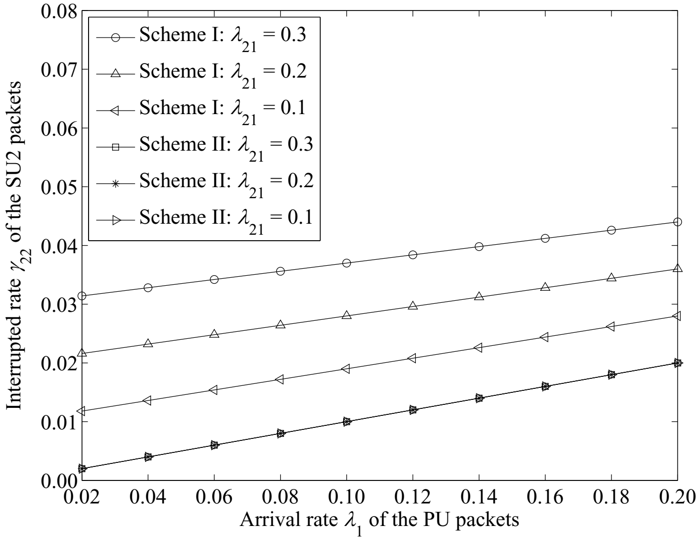

Fig. 2 Change trend for the interrupted rate γ_{22} of the SU2 packets.

From Fig. 2, we find that as the arrival rate λ_1 of the PU packets increases, the interrupted rate γ_{22} of the SU2 packets shows an increasing tendency. This is obviously because the greater the arrival rate of the PU packets is, the higher the possibility that the transmission of the SU2 packets to be interrupted, so the larger the interrupted rate of the SU2 packets will be.

On the other hand, Fig. 2 shows an increasing arrival rate λ_{21} of the SU1 packets causes an increase in the interrupted rate γ_{22} of the SU2 packets in Scheme I. This is because in Scheme I, a newly arriving SU1 packet can interrupt the transmission of the SU2 packet, and this will result in a higher interrupted rate of the SU2 packets.

Furthermore, as the arrival rate λ_{21} of the SU1 packets increases, the interrupted rate γ_{22} of the SU2 packets will not be changed in Scheme II. This is because in Scheme II, a newly arriving SU1 packet will not interrupt the transmission of the SU2 packets, so the arrival rate of the SU1 packets will not influence the interrupted rate of the SU2 packets. Moreover, because of the preemptive priority mechanism, Scheme I experiences a higher interrupted rate γ_{22} of the SU2 packets than Scheme II.

5 Conclusions

In this paper, we investigated the system performance of cognitive radio networks, in which the SU packets in the system were divided into SU1 packets with higher priority and SU2 packets with lower priority. For the purpose of guaranteeing the transmission continuity of the SU2 packets, a non-preemptive priority scheme was proposed for the SU1 packets. A three-dimensional discrete-time Markov chain was constructed and the transition probability matrix was given. With the steady-state distribution, some performance measures for the SU1 packets and SU2 packets were derived. Finally, with numerical experiments, we showed that compared with the preemptive priority scheme, the proposed non-preemptive priority scheme for the SU1 packets could reduce the interrupted rate of the SU2 packets effectively.

Acknowledgments This work was supported in part by National Natural Science Foundation (No. 61472342), China and was supported in part by MEXT, Japan.

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