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PERFORMANCE ANALYSIS AND OPTIMIZATION OF COGNITIVE RADIO NETWORKS WITH INTERRUPT AND DROP MECHANISM

Yuan Zhao*, Jia Liu and Luyi Bai

School of Computer and Communication Engineering
Northeastern University at Qinhuangdao
No. 143, Taishan Road, Qinhuangdao 066004, P. R. China
*Corresponding author: yuanzh85@163.com

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Abstract. *In this paper, we focus on the transmission interruption of the secondary users (SUs) in cognitive radio networks. In order to reduce the average delay of the SU packets, we propose an interrupt and drop mechanism for the interrupted SU packets. By building a discrete-time Markov chain, we give the transition probability matrix of the system and derive some performance measures of the SU packets, such as the loss rate, the throughput and the average delay of the SU packets. Then, with the obtained performance measures, by using an unobservable queueing analysis, we give the individually optimal strategy and the socially optimal strategy for the SU packets. Moreover, in order to verify the effectiveness of the proposed interrupt and drop mechanism, we compare the system performance and the optimization results between the 1 persistent retransmission mechanism and the proposed interrupt and drop mechanism with numerical examples.*
Keywords: Cognitive radio networks, Interrupt and drop, Markov chain, Optimization

1. **Introduction.** With the rapidly increasing number of wireless communication demand, spectrum resources have become scarcity in recent years. However, some researches indicated that the spectrum had not been fully utilized due to the exclusive spectrum usage in conventional communication networks [1, 2]. In order to solve the spectrum under-utilization problem, cognitive radio networks have thus emerged. In cognitive radio networks, the secondary users (SUs) can exploit those spectrum bands which are not used by the primary users (PUs) opportunistically [3, 4].

In cognitive radio networks, the PUs have absolute priority to occupy the spectrum. As a result, if a PU packet arrives at the licensed spectrum during the transmission of an SU packet, the SU packet must vacate the spectrum unconditionally and the transmission of the SU packet will be interrupted [5]. For the interrupted SU packets, some references assumed that these interrupted SU packets could return back to the SU buffer and wait for future transmission [6, 7]. Obviously, this kind of 1 persistent retransmission mechanism can guarantee the transmission of the interrupted SU packets.

However, we note that a larger number of interrupted SU packets returning back will increase the average delay of the SU packets. On the other hand, considering the inevitable spectrum sensing errors in cognitive radio networks [8], a large number of interrupted SU packets returning back will bring negative influence to the transmission of both the PU packets on the channels and the SU packets already in the SU queue. In order to reduce the average delay of the SU packets and avoid the possible interference from the interrupted SU packets, references [9, 10] assumed that the interrupted SU packets without available channels will leave the system permanently. By applying the $M/M/C/C$ queueing model, they derived some performance measures of the SU packets.

However, the analytical models used in references [9, 10] were both continuous-time models. Considering the digital nature of modern networks, discrete-time models are more suitable to analyze the system performance of networks [11]. So, different from the analytical models built in references [9, 10], in this paper, we evaluate the system performance of a cognitive radio network with interrupt and drop mechanism by using a discrete-time Markov chain model. The PU packets can interrupt the transmission of the SU packets, and the interrupted SU packets will leave the system. We derive some analytical results for the performance measures of the system and also operate optimization for the SU packets. Specially, we also compare the system performance and the optimization results between the 1 persistent retransmission mechanism and the interrupt and drop mechanism with numerical examples.

The paper is organized as follows. We present the system model and model analysis in Section 2. We then derive the expressions of some system performance measures and perform the optimization with an unobservable queueing assumption for the SU packets in Section 3. In Section 4, with numerical examples, we compare the performance measures and the optimal results between the 1 persistent retransmission mechanism and the interrupt and drop mechanism. Finally, we conclude our work in Section 5.

2. **System Model and Model Analysis.** We focus on a cognitive radio network with a single channel. There is a buffer with finite capacity for the SU packets. We assume that on the arrival instant of an SU packet, the SU will perform spectrum sensing to avoid the interference to the transmission of the PU packets. In this paper, we assume the spectrum sensing results are correct and ideal. In future works, we will consider the unreliable spectrum sensing.

On the arrival instant of a PU packet, if the channel is being occupied by another PU packet, this newly arriving PU packet has to leave the system to find another available channel. Considering the priority of the PU packets in cognitive radio networks, if a PU packet arrives at the system during the transmission of an SU packet, the PU packet will interrupt the transmission of the SU packet and occupy the channel. In order to reduce the average delay of the SU packets and avoid the interference to the PU packets, the interrupted SU packets will be dropped.

Following the digital nature of modern networks, we consider an early arriving system with a slotted timing structure in this paper. According to the slotted timing structure, we assume the arrival intervals of the PU packets and the SU packets follow geometrical distributions with arrival rates λ_1 and λ_2, respectively. We also suppose the transmission time of the PU packets and the SU packets follow geometrical distributions with service rates μ_1 and μ_2, respectively.

Let T_n be the total number of packets (including PU packets and SU packets) in the system at the instant n^+. Let P_n be the number of PU packets in the system at the instant n^+. Then $\{T_n, P_n\}$ constitutes a discrete-time Markov chain with the state space $\boldsymbol{\Omega}$ as follows:

$$\boldsymbol{\Omega} = (0,0) \cup \{(i,j) : 1 \le i \le K+1, j = 0,1\}, \tag{1}$$

where K $(K > 0)$ is the capacity of the SU packet buffer.

The one-step transition probability matrix $\boldsymbol{W}$ of $\{T_n, P_n\}$ can be given as follows:

$$\boldsymbol{W} = \begin{pmatrix} \boldsymbol{C}_0 & \boldsymbol{B}_0 & \boldsymbol{A}_0 & & & & \\ \boldsymbol{D}_0 & \boldsymbol{C} & \boldsymbol{B} & & & \mathbf{0} & \\ & \boldsymbol{D} & \boldsymbol{C} & \boldsymbol{B} & & & \\ & & \ddots & \ddots & \ddots & & \\ & & & \boldsymbol{D} & \boldsymbol{C} & \boldsymbol{B} \\ \mathbf{0} & & & & \boldsymbol{D} & \boldsymbol{B}+\boldsymbol{C} \end{pmatrix}. \tag{2}$$

The non-zero blocks in $\boldsymbol{W}$ can be given as follows:

$$\boldsymbol{C}_0 = \left(\bar{\lambda}_1\bar{\lambda}_2\right)_{1\times 1}, \quad \boldsymbol{B}_0 = \left(\begin{array}{cc} \bar{\lambda}_1\lambda_2 & \lambda_1\bar{\lambda}_2 \end{array}\right)_{1\times 2}, \quad \boldsymbol{A}_0 = \left(\begin{array}{cc} 0 & \lambda_1\lambda_2 \end{array}\right)_{1\times 2},$$

$$\boldsymbol{D}_0 = \left(\begin{array}{c} \bar{\lambda}_1\bar{\lambda}_2\mu_2 \\ \bar{\lambda}_1\bar{\lambda}_2\mu_1 \end{array}\right)_{2\times 1}, \quad \boldsymbol{D} = \left(\begin{array}{cc} \bar{\lambda}_1\bar{\lambda}_2\mu_2 & 0 \\ \bar{\lambda}_1\bar{\lambda}_2\mu_1 & 0 \end{array}\right)_{2\times 2},$$

$$\boldsymbol{C} = \left(\begin{array}{cc} \bar{\lambda}_1(\bar{\lambda}_2\bar{\mu}_2 + \lambda_2\mu_2) & \lambda_1\bar{\lambda}_2 \\ \bar{\lambda}_1\lambda_2\mu_1 & \bar{\lambda}_2(\lambda_1\mu_1 + \bar{\mu}_1) \end{array}\right)_{2\times 2}, \quad \boldsymbol{B} = \left(\begin{array}{cc} \bar{\lambda}_1\lambda_2\bar{\mu}_2 & \lambda_1\lambda_2 \\ 0 & \lambda_2(\lambda_1\mu_1 + \bar{\mu}_1) \end{array}\right)_{2\times 2}.$$

We define the steady-state distribution $\pi_{i,j}$ of $\{T_n, P_n\}$ as follows:

$$\pi_{i,j} = \lim_{n\to\infty} P\left\{T_n = i, P_n = j\right\}. \tag{3}$$

We denote $\boldsymbol{\Pi} = \left(\pi_{0,0}, \pi_{1,0}, \pi_{1,1}, \ldots, \pi_{K,0}, \pi_{K,1}, \pi_{K+1,0}, \pi_{K+1,1}\right)$. As the dimension of $\boldsymbol{W}$ is finite, with the equilibrium equation $\boldsymbol{\Pi}\boldsymbol{W} = \boldsymbol{\Pi}$ and the normalization condition $\boldsymbol{\Pi}\boldsymbol{e} = 1$ [11], we can obtain the numerical results of the steady-state distribution $\pi_{i,j}$ by using a Gaussian elimination method.

3. Performance Measures and Performance Optimization.

3.1. Performance measures. We define the loss rate β of the SU packets as the average number of SU packets that are blocked or interrupted to drop. These blocked or interrupted SU packets will lose their transmission chances. So, the expression of the loss rate β of the SU packets can be given as follows:

$$\beta = \lambda_2\left(\left(\lambda_1 + \bar{\mu}_2\bar{\lambda}_1\right)\pi_{K+1,0} + \left(\lambda_1 + \bar{\mu}_1\bar{\lambda}_1\right)\pi_{K+1,1}\right) + \sum_{i=1}^{K+1}\pi_{i,0}\bar{\mu}_2\lambda_1. \tag{4}$$

We define the throughput θ of the SU packets as the average number of SU packets that are transmitted successfully. So, the expression of the throughput θ of the SU packets can be given as follows:

$$\theta = \lambda_2 - \beta. \tag{5}$$

We define the average delay δ of the SU packets as the average time interval from an SU packet arriving at the sytem to this SU packet being transmitted successfully. By using Little's equation [11], the expression of the average delay δ of the SU packets can be given as follows:

$$\delta = \frac{(K+1)\pi_{K+1,0} + \sum_{j=0}^{K} j\left(\pi_{j,0} + \pi_{j+1,1}\right)}{\theta}. \tag{6}$$

3.2. Optimization analysis. In the proposed interrupt and drop mechanism, an SU packet may be blocked or interrupted by the system. That is to say, the transmission for an SU packet is not guaranteed. So, for a newly arriving SU packet, it is necessary to decide whether or not to access the system. In this subsection, we will perform the optimization with an unobservable queueing assumption for the access actions of the SU packets.

We assume a newly arriving SU packet cannot know the number of SU packets already in the system before making the access decision. We suppose R is the reward from a successful transmission, and C is the cost of staying in the system per slot. From the perspective of a single SU packet, we can give the individual net benefit function $I(\lambda_2)$ for an SU packet who chooses to join the system as follows:

$$I(\lambda_2) = R\eta(\lambda_2) - C\delta(\lambda_2), \tag{7}$$

where $\eta(\lambda_2) = \theta(\lambda_2)/\lambda_2$ is the probability that an SU packet can be transmitted successfully.

We denote the potential arrival rate of the SU packets as Λ, the individually optimal join probability as q_e, and the individually optimal join rate as $\lambda_e = q_e\Lambda$.

As will be seen in the numerical examples, as the arrival rate of the SU packets increases, the individual net benefit function shows a decreasing tendency. Then we can give the individually optimal strategy for the SU packets in two cases (to avoid a trivial solution, we assume $I(0^+) > 0$).

(1) $I(\Lambda) \geq 0$. Under this case, the individually optimal join probability is $q_e = 1$, and the individually optimal join rate is $\lambda_e = \Lambda$.

(2) $I(\Lambda) < 0$. Under this case, based on the Nash equilibrium theory [12], by solving $I(\lambda_2) = 0$, we can obtain the individually optimal join rate λ_e and the individually optimal join probability $q_e = \lambda_e/\Lambda$.

Then, we focus on the socially optimal strategy. By referencing [12], based on the individual net benefit function (7), we can give the social net benefit function $S(\lambda_2)$ as follows:

$$S(\lambda_2) = \lambda_2 I(\lambda_2) = \lambda_2 \left(R\eta(\lambda_2) - C\delta(\lambda_2)\right). \tag{8}$$

We denote λ^* as the socially optimal join rate, and $q^* = \lambda^*/\Lambda$ as the socially optimal join probability. Based on the social net benefit function $S(\lambda_2)$, we can give the socially optimal join rate λ^* as follows:

$$\lambda^* = \arg \max_{0<\lambda_2\leq\Lambda} \left\{\lambda_2 \left(R\eta(\lambda_2) - C\delta(\lambda_2)\right)\right\}. \tag{9}$$

With the socially optimal join rate λ^*, the socially optimal join probability can be obtained as $q^* = \lambda^*/\Lambda$.

4. **Numerical Examples.**

4.1. **Numerical examples for the performance measures.**

In this subsection, we compare the change trends for the throughput of the SU packets and the average delay of the SU packets between the 1 persistent retransmission mechanism and the proposed interrupt and drop mechanism with numerical examples. Some common parameters in the numerical examples are set as follows: $\lambda_1 = 0.16$, $\lambda_2 = 0.12$, $\mu_2 = 0.15$. Moreover, in order to avoid complex expressions, we denote the 1 persistent retransmission mechanism as Mechanism I and the proposed interrupt and drop mechanism as Mechanism II in following paper.

Figures 1 and 2 compare the change trends for the throughput and the average delay of the SU packets between Mechanism I and Mechanism II, respectively.

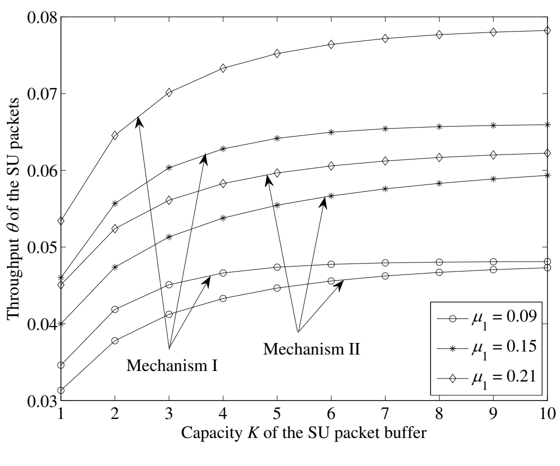

FIGURE 1. Change trend for the throughput of the SU packets

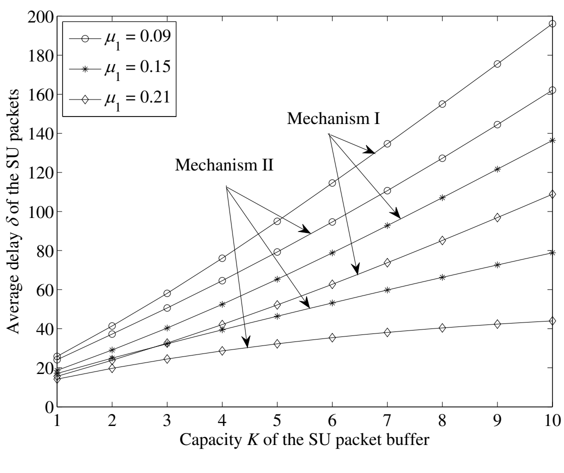

FIGURE 2. Change trend for the average delay of the SU packets

From Figures 1 and 2, we find that as the capacity K of the SU packet buffer increases, both the throughput θ and the average delay δ of the SU packets will increase. This is because as the capacity of the SU packet buffer increases, more SU packets can join the system and more SU packets will be transmitted. On the other hand, we also find that the higher the service rate μ_1 of the PU packets is, the greater the throughput θ of the SU packets is, and the shorter the average delay δ of the SU packets is. The reason may be that as the service rate of the PU packets increases, the PU packets will be transmitted more quickly, and the SU packets will have more chances to be transmitted. Moreover, we conclude that compared with Mechanism I, Mechanism II realizes a shorter average delay of the SU packets. However, as a cost, the throughput of the SU packets in Mechanism II is lower. So, we conclude from the numerical examples that Mechanism II is more suitable for the networks with strict delay limit.

4.2. **Numerical examples for the performance optimization.** In this subsection, we compare the individually optimal and socially optimal results between Mechanism I and Mechanism II. With some common parameters used in Subsection 4.1, by setting $K = 10$, $\Lambda = 0.5$, $R = 50$, and $C = 0.2$, Figures 3 and 4 compare the change trends for the individual net benefit function and the social net benefit function between Mechanism I and Mechanism II, respectively.

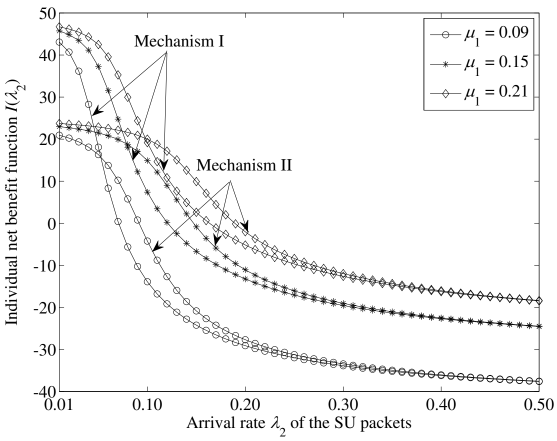

FIGURE 3. Change trend for individual net benefit function

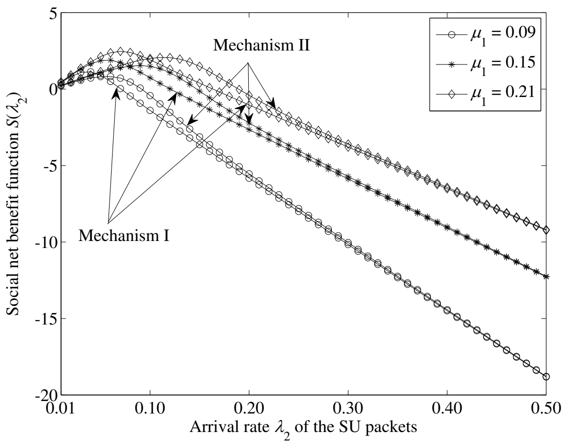

FIGURE 4. Change trend for social net benefit function

With the numerical results in Figures 3 and 4, by applying the analysis in Subsection 3.2, we can summarize the value range of the individually optimal join rate λ_e (probability q_e), and also the value of the socially optimal join rate λ^* (probability q^*) with Mechanism I and Mechanism II in Table 1.

TABLE 1. Numerical results for the optimization

	μ_1	λ_e		q_e		λ^*	q^*
		Min	Max	Min	Max		
Mechanism I	0.09	0.07	0.08	0.14	0.16	0.04	0.08
	0.15	0.12	0.13	0.24	0.26	0.06	0.12
	0.21	0.16	0.17	0.32	0.34	0.07	0.14
Mechanism II	0.09	0.09	0.10	0.18	0.20	0.06	0.12
	0.15	0.14	0.15	0.28	0.30	0.09	0.18
	0.21	0.18	0.19	0.36	0.38	0.11	0.22

From Table 1, we find that as the service rate μ_1 of the PU packets increases, the optimal join rate will increase. The reason for this finding is easy to be understood. From Table 1, we also find that compared with Mechanism I, both the individually and the socially optimal join rate (probability) are higher in Mechanism II. The reason for this interesting finding may be that the average delay in Mechanism II is lower, and the cost for staying in the system will be lower, so more SU packets would like to choose to join the system in Mechanism II.

5. **Conclusions.** In this paper, in order to reduce the average delay of the SU packets, we consider an interrupt and drop mechanism for the interrupted SU packets. By building a discrete-time Markov chain model, we derived some performance measures of the SU packets. Then, we showed the individually optimal strategy and the socially optimal strategy for the SU packets with unobservable queueing analysis. The numerical examples showed that compared with the 1 persistent retransmission mechanism, the proposed interrupt and drop mechanism could reduce the average delay of the SU packets effectively. Moreover, numerical examples also showed that in the proposed interrupt and drop mechanism, more SU packets would like to join the system.

As future work, we plan to extend the system model by considering multiple channels and unreliable sensing results of the SU packets.

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REFERENCES

[1] Q. Zhao and B. M. Sadler, A survey of dynamic spectrum access, *IEEE Signal Processing Magazine*, vol.24, no.3, pp.79-89, 2007.

[2] B. Wang and K. J. R. Liu, Advances in cognitive radio networks: A survey, *IEEE Journal of Selected Topics in Signal Processing*, vol.5, no.1, pp.5-23, 2011.

[3] J. Marinho and E. Monteiro, Cognitive radio: Survey on communication protocols, spectrum decision issues, and future research directions, *Wireless Networks*, vol.18, no.2, pp.147-164, 2012.

[4] C. Liang and F. R. Yu, Wireless network virtualization: A survey, some research issues and challenges, *IEEE Communications Surveys & Tutorials*, vol.17, no.1, pp.358-380, 2015.

[5] Y. Saleem and M. H. Rehmani, Primary radio user activity models for cognitive radio networks: A survey, *Journal of Network and Computer Applications*, vol.43, pp.1-16, 2014.

[6] Y. Lee, C. G. Park and D. B. Sim, Cognitive radio spectrum access with prioritized secondary users, *Applied Mathematics & Information Sciences*, vol.6, no.2S, pp.595S-601S, 2012.

[7] J. Zhang, Y. Lu, X. Gao and F. Zheng, Sensing-then-transmission slot scheduling optimization for opportunistic spectrum access under the interference constraint of primary users, *Journal on Communications*, vol.34, no.12, pp.42-48, 2013 (in Chinese).

[8] A. Ghasemi and E. S. Sousa, Spectrum sensing in cognitive radio networks: Requirements, challenges and design trade-offs, *IEEE Communications Magazine*, vol.46, no.4, pp.32-39, 2008.

[9] H. Al-Mahdi, M. A. Kalil, F. Liers and A. Mitschele-Thiel, Increasing spectrum capacity for ad hoc networks using cognitive radios: An analytical model, *IEEE Communications Letters*, vol.13, no.9, pp.676-678, 2009.

[10] A. Turhan, M. Alanyali and D. Starobinski, Optimal admission control of secondary users in preemptive cognitive radio networks, *Proc. of the 10th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*, Paderborn, Germany, pp.138-144, 2012.

[11] A. S. Alfa, *Queueing Theory for Telecommunications: Discrete Time Modelling of a Single Node System*, Springer, New York, 2010.

[12] R. Hassin and M. Haviv, *To Queue or Not to Queue: Equilibrium Behavior in Queueing Systems*, Kluwer Academic Publishers, Boston, 2003.