Electronic Research Archive of Blekinge Institute of Technology
http://www.bth.se/fou/

This is an author produced version of a conference paper. The paper has been peer-reviewed but may not include the final publisher proof-corrections or pagination of the proceedings.

Citation for the published Conference paper:

Title:
On Prioritized Spectrum Access in Cognitive Radio Networks with Imperfect Sensing

Author:
Yong Yao, Alexandru Popescu, Said Rubatayiro Ngoga, Adrian Popescu

Conference Name:
Wireless Personal Multimedia Communications Symposium (WPMC'13)

Conference Year:
2013

Conference Location:
Atlantic City

Access to the published version may require subscription.
Published with permission from:
VPMC/IEEE

On Prioritized Spectrum Access in Cognitive Radio Networks with Imperfect Sensing

Yong Yao, Alexandru Popescu, Said Rutabayiro Ngoga and Adrian Popescu
School of Computing, Blekinge Institute of Technology,
371 79 Karlskrona, Sweden
Email: {yong.yao, alexandru.popescu, said.rutabayiro.ngoga, adrian.popescu}@bth.se

***Abstract*—Cognitive Radio networks allow the unlicensed users to share the available spectrum opportunities. However, this demands for solving the problem of contention among multiple unlicensed user packets for transmission. In our paper, we consider the Opportunistic Spectrum Access model for packet transmission between two unlicensed users. We suggest a priority scheme for a unlicensed user to concurrently transmit different types of packets. Our scheme reserves a fixed number of queueing places in the buffer for the prioritized packets. We study the transmission performance under both the priority scheme and imperfect spectrum sensing, with respect to the blocking probabilities, average transmission delay and transmission throughput of unlicensed users packets. The Markov chain based numerical analysis is validated by simulation experiments. Our results show that the suggested priority scheme is able to enhance transmission throughput of unlicensed users packets, together with significant decreased average transmission delay and minor decreased total transmission throughput.**

***Index Terms*—Cognitive radio, opportunistic spectrum access, priority scheme, Markov chain.**

I. Introduction

" The rapid growth of wireless services and applications raises the need of efficient utilization of the frequency spectrum. To meet this requirement, an attractive framework "Cognitive Radio (CR) networks" has been advanced [1], [2]. Generally, CR is an intelligent communication entity that is capable of autonomous adaptation to radio environment changes. An existing approach to implement CR networks is the Opportunistic Spectrum Access (OSA) model [3]. In OSA model, the licensed spectrum bands (i.e., channels) are authorized to Primary Users (PUs). When a channel is not occupied by PUs (known as a spectrum opportunity), it becomes available for temporal use by unlicensed users, the so-called Secondary Users (SUs).

In OSA based CR networks, SUs need to identify and access the spatio-temporally available channels. The identification can be done by either *spectrum sensing* or by *database* based solutions [4], [5]. Once the available channels are obtained, SUs can use them for packet transmission with respect to cognitive Media Access Control (MAC) protocols [3]. Naturally, a SU may transmit different types of packets to a receiver, e.g, another SU. Each packet type is generated from a particular higher layer application. Multiple applications have various performance requirements of the packet transmission. For instance, real-time traffic (e.g., voice streaming) may need the guarantee of low transmission delay rather than non real-time traffic. Ultimately, the motivation comes down to providing different transmission priorities to different types of packets.

The problem of prioritized transmission of SUs in OSA based CR networks has been recently studied. In [6], SU calls (i.e., packet transmission) are categorized into two classes with low-priory and high-priority, respectively. The goal is to accommodate more high-priority SU calls when spectrum handoff occurs[1]. In [7], the mobility behavior of SUs in CR cellular networks is considered. Further, the SU calls handed over from neighboring cells to a particular local cell are given higher priority to the SU calls originated within this local cell. However, these studies are based on the assumption that the spectrum sensing is perfect, meaning there is no error in sensing results. Due to various factors (like, e.g., limitations on hardware and sensing duration), the perfect spectrum sensing is not practical in the realistic implementation of CR networks.

In this paper, we focus on the one-hop based packet transmission from a SU transmitter to a SU receiver by sharing a licensed channel with PUs. The transmitted packets consist of multiple types, which are assigned different transmission priorities. Based on this, we suggest a priority scheme for packet transmission at SU transmitter side, and also take into consideration the imperfect spectrum sensing. To the best of knowledge, there has been little investigation so far on prioritized cognitive spectrum access in the presence of imperfect sensing. Further, we develop a two-stage parallel server, i.e., $M/H_2/1$, based queuing model to study the SU's transmission performance.

The rest of the paper is organized as follows. Section II describes the modeled network architecture and prioritization schemes for multiple types of packets. The queueing model is built up in Section III, together with the corresponding performance analysis. The numerical and simulation results are discussed in Section IV. Finally, we conclude the paper in Section V.

II. System Model

A. Network Architecture

We consider an one-hop based ad-hoc CR network with a single channel and two SUs, as shown in Fig. 1. The channel is denoted as c and it is licensed to PUs. Two SUs are denoted

[1]By spectrum handoff, we mean the switching of packets transmission in different available channels due to the channel occupancy by PUs

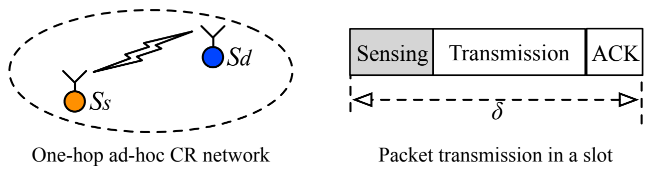


Fig. 1. One-hop based packet transmission between two SUs.

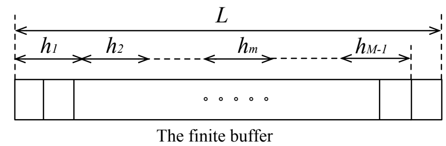


Fig. 2. Different numbers, i.e., the set $\{h_m|m=1,2,...,M\}$, of queueing places are reserved for different types of SU packets. The element values of this set are constrained by $(h_m|m \neq M) \in (0, L)$, $h_M = 0$ and $0 < \sum_{m=1}^{M-1} h_m < L$, where L is the buffer size.

as s_s and s_d, and they can opportunistically access the channel c when it is not used by PUs.

The PU activity in channel c is assumed to use a time-slotted basis. The length of every slot identically equals δ in time domain. In every slot, the PU is either present or absent in channel c during the whole slot duration. The channel occupancy by the PU is assumed to follow a two-state *busy-free* Markov process. The state *busy* means the event that the channel c is occupied by the PU for one or more consecutive slots. Similarly, state *free* means the event that there is no PU in channel c for one or more consecutive slots. The time periods of the two states *busy* and *free* are integer times of δ. They are assumed to be exponentially distributed with mean values $1/\alpha$ and $1/\beta$, respectively.

Two SUs s_s and s_d are assumed to be able to perceive the radio signals from each other. We further assume that they take roles as radio transmitter and receiver, respectively. When channel c is free (i.e., not used by PUs), the SU s_s transmits packets to SU s_d. The activity of two SUs is assumed to be synchronized with PUs. Meaning, packet transmission of SU s_s operates in a time-slotted basis, which has an uniform slot length δ same with PUs. Each SU slot consists of two phases: spectrum sensing and packet transmission. During the first phase, SU s_s performs the spectrum sensing on channel c. If channel c is sensed to be free, SU s_s transmits a packet during the second phase. A successful transmission can be acknowledged by SU s_d at the end of the slot.

Due to sensing-duration limitation, the spectrum sensing may be imperfect in terms of overlook error and misidentification error. Overlook means that a free channel is sensed to be busy, while misidentification means that a busy channel is sensed to be free. Since a successful transmission occurs only during the time period when the channel c is free[2], only the overlook error is considered in our paper. To simplify the analysis, the durations of both spectrum sensing and receiving acknowledgment message are assumed to be zero. Further, we let ϵ denote the occurrence probability of an overlook error, where $\epsilon \in (0, 1.0)$.

B. Transmission Prioritization

The packets transmitted by SU s_s are assumed to be categorized into M different types. Let $\mathbb{T}_m$ denote the m^{th} type of packets. The transmission priority of type $\mathbb{T}_m$ packets is higher than the type $\mathbb{T}_{m+1}$ packets, where $m = 1, 2, ..., M-1$.

[2]If SU s_s transmits a packet under the misidentification error, the packet transmission collides with PUs. Thus, SU s_s experiences unsuccessful transmission by missing acknowledgment message from SU s_d.

Furthermore, the arrivals of these M types of packets are assumed to independently follow Poisson processes with mean rates λ_1, λ_2, ..., λ_M, for type $\mathbb{T}_1$, $\mathbb{T}_2$, .., $\mathbb{T}_M$, respectively.

As hardware limitation, SU s_s is assumed to be equipped with a finite buffer. The goal is to queue the newly arrived packets (of different types) when SU s_s is transmitting a packet. The buffer length is denoted as L, indicating the maximum number of idle queueing places when the buffer is empty. Each queueing place can only be used by one packet at a time.

Based on the finite buffer assumption, the priority scheme for M types of packets is depicted in Fig. 2, together with descriptions as follows:

- Compared with the type $\mathbb{T}_{m+1}$ packets, a fixed number, h_m, of queueing places are reserved for the type $\mathbb{T}_m$ packets. If $h_m > 0$, the type $\mathbb{T}_m$ packets are given higher priority over the type $\mathbb{T}_{m+1}$ packets, where $m < M$. Because the type $\mathbb{T}_M$ packets have the lowest priority, we set $h_M = 0$. Subsequently, we obtain a set of reserved queueing places $h_1, h_2, ..., h_{M-1}$, for types $\mathbb{T}_1, \mathbb{T}_2, ..., \mathbb{T}_{M-1}$, respectively.
- When a type $\mathbb{T}_1$ packet arrives and one or more queueing places are idle, the $\mathbb{T}_1$ packet is accepted. Otherwise, the $\mathbb{T}_1$ packet packet is blocked. When a type $\mathbb{T}_m$ packet arrives where $m > 1$, it is accepted if at least $(1 + \sum_{i=1}^{m-1} h_i)$ queueing places are idle. Otherwise, the type $\mathbb{T}_m$ packet is blocked. To avoid that the type $\mathbb{T}_m$ packets are blocked altogether, the value of $\sum_{i=1}^{m-1} h_i$ must be less than L, where $m > 1$

III. Queueing Analysis

According to the above modeled system, we build up the Markov Chains based queueing model to study the transmission performance of SUs. This queueing model jointly takes into consideration the imperfect spectrum sensing and priority requirement for different types of SU packets.

A. Spectrum Access under Imperfect Sensing

We consider a particular time period of n consecutive slots, during which channel c is free for SU s_s to use. Let t denote this time period, and it equals $n\delta$. In each of these n slots, SU s_s may not transmit a particular packet (either type $\mathbb{T}_1$, $\mathbb{T}_2$,..., or $\mathbb{T}_M$) with probability ϵ due to the overlook error. In other words, the probability of a successful transmission in a slot is equal to $(1-\epsilon)$. Let $p_r(k; n, \epsilon)$ denote the probability of k successful transmissions within time period t, where $0 \leq k \leq$

n. Its value can be computed with respect to the probability mass function (pmf) of Binomial process.

$$p_r(k;n,\epsilon) = \binom{n}{k} \epsilon^{n-k}(1-\epsilon)^k \quad (1)$$

Note that the binomial pmf can be approximated by using the pmf of Poisson process [8]:

$$p_r(k;n,\epsilon) \simeq e^{-n(1-\epsilon)} \frac{(n(1-\epsilon))^k}{k!} = e^{-\gamma t} \frac{(\gamma t)^k}{k!} \quad (2)$$

where $\gamma t = n(1-\epsilon)$, and γ denotes the mean rate of successful transmissions within time interval $(0,t]$. The value of γ is equal to $(1-\epsilon)/\delta$.

Naturally, the successful transmission only takes place when channel c_r is free. Whereby, there is no transmission service when channel c_r is busy. Similar to [9][3], the packet transmission at SU s_s side can be modeled as an Interrupted Poisson Process (IPP), where its infinitesimal generator $\mathbf{Q}$ and rate matrix $\mathbf{\Lambda}$ are given by:

$$\mathbf{Q} = \begin{bmatrix} -\alpha & \alpha \\ \beta & -\beta \end{bmatrix} \qquad \mathbf{\Lambda} = \begin{bmatrix} \gamma & 0 \\ 0 & 0 \end{bmatrix} \quad (3)$$

Because an IPP is equivalent to a hyper-exponential process [10], the corresponding probability density function (pdf) of service time is given by:

$$f(t) = \theta\mu_a e^{-\mu_a t} + (1-\theta)\mu_b e^{-\mu_b t} \quad (4)$$

where:

$$\begin{cases} \mu_a = \dfrac{\gamma+\alpha+\beta+\left[(\gamma+\alpha+\beta)^2-4\gamma\beta\right]^{\frac{1}{2}}}{2} \\ \mu_b = \dfrac{\gamma+\alpha+\beta-\left[(\gamma+\alpha+\beta)^2-4\gamma\beta\right]^{\frac{1}{2}}}{2} \\ \theta = \dfrac{\gamma-\mu_b}{\mu_a-\mu_b} \end{cases} \quad (5)$$

B. Queueing Modeling under Priority Scheme

The pdf given by equation (4) can be expressed by a two-stage parallel server based queueing system [11], as shown in Fig 3. In the figure, the large oval represents the server facility, where a particular packet at SU s_s side approaches from the left. Transmitting this particular packet to SU s_d is proceeded to service stage a with probability θ or to service stage b with probability $(1-\theta)$. Transmission spends the exponentially distributed service time with mean values $1/\mu_a$ and $1/\mu_b$ for stages a and b, respectively. After that service time, a successful packet transmission is accomplished and only then a new packet transmission is allowed into the service facility.

We let a set of three integers (j_0, j_1, j_2) denote a system state that j_0 packets are in the buffer of SU s_s, and j_1 and j_2 packets being in transmission service are located in stages a and b, respectively. Given the buffer length equal to L, the value of j_0 is in the set $\{0, 1, ..., L\}$. Since only one of two service stages is active for transmission at a time, the values

[3]The authors of [9] considered the failure of the SU's channel selection, while they did not consider the transmission priority among SU packets

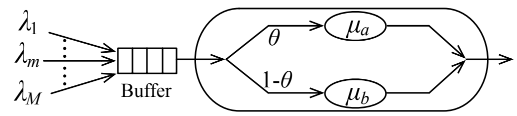


Fig. 3. A two-stage parallel server based queueing model.

of j_1 and j_2 are constrained by $0 \le (j_1 + j_2) \le 1$. Therefore, the system state space is given by $\mathcal{S} = \{(j_0, j_1, j_2) | j_0 \in \{0, 1, ..., L\}; j_1, j_2, (j_1+j_2) \in \{0, 1\}\}$. Considering a system state $(j_0, j_1, j_2) \in \mathcal{S}$, the state transitions are as follows.

1) A new packet arrives at SU s_s:

- For $j_0 = j_1 = j_2 = 0$, the server facility has no packet for transmission, and there is no queued packet in the buffer. Hence, the newly arrived packet is accepted for all M types and it is proceeded to service stages a and b with rates $(\theta \sum_{m=1}^{M} \lambda_m)$ and $((1-\theta)(\sum_{m=1}^{M} \lambda_m))$, respectively.
- When $0 \le j_0 < L$ and $j_1 + j_2 = 1$, there is a packet being in transmission service, so that the newly arrived packet is accepted in accordance with the priority scheme. For $0 \le j_0 < (L - \sum_{m=1}^{M-1} h_m)$, the new packet is accepted for M types with acceptance rate $\sum_{m=1}^{M} \lambda_m$. For $(L - \sum_{i=1}^{m+1} h_i) \le j_0 < (L - \sum_{i=1}^{m} h_i)$, the new packet is accepted only for types $\mathbb{T}_1$, $\mathbb{T}_2$,..., $\mathbb{T}_m$ and $\mathbb{T}_{m+1}$ with acceptance rate $\sum_{i=1}^{m+1} \lambda_i$. For $(L - h_1) \le j_0 < L$, only type $\mathbb{T}_1$ packets can be accepted with acceptance rate λ_1.

2) A packet is transmitted to SU s_d:

- For $j_0 = 0$ and $(j_1 + j_2) = 1$, there exists one packet being in transmission service and there is no packet queued in the buffer. Hence, the service rate is equal to μ_a and μ_b for stages a and b, respectively.
- For $j_0 \ne 0$, $j_1 = 1$ and $j_2 = 0$, a packet transmission is in stage a with service rate μ_a. When this transmission is finished, a queued packet is proceeded to service stages a and b with probabilities θ and $(1-\theta)$. Meanwhile, the system changes state from $(j_0, 1, 0)$ to $(j_0 - 1, 1, 0)$ and to $(j_0 - 1, 0, 1)$ with transition rates $\theta\mu_a$ and $(1-\theta)\mu_a$, respectively.
- For $j_0 \ne 0$, $j_1 = 0$ and $j_2 = 1$, a packet transmission is in stage b with service rate μ_b. Similar to the above case, after the packet is transmitted, the system changes state from $(j_0, 0, 1)$ to $(j_0 - 1, 0, 1)$ and to $(j_0 - 1, 1, 0)$ with transition rates $(1-\theta)\mu_b$ and $\theta\mu_b$, respectively.

Based on the above analysis, we illustrate the state transition diagram in Fig. 4. Let π_{j_0,j_1,j_2} denote the steady-state probability of state (j_0, j_1, j_2). Then, the following steady-state balance equations can be obtained from the diagram.

For the three particular states $(0,0,0)$, $(L,1,0)$ and $(L,0,1)$, we have:

$$\pi_{0,0,0} \sum_{m=1}^{M} \lambda_m = \pi_{0,1,0}\mu_a + \pi_{0,0,1}\mu_b \quad (6)$$

$$\pi_{L,1,0}\mu_a = \pi_{L-1,1,0}\lambda_1 \quad (7)$$

$$\pi_{L,0,1}\mu_b = \pi_{L-1,0,1}\lambda_1 \quad (8)$$

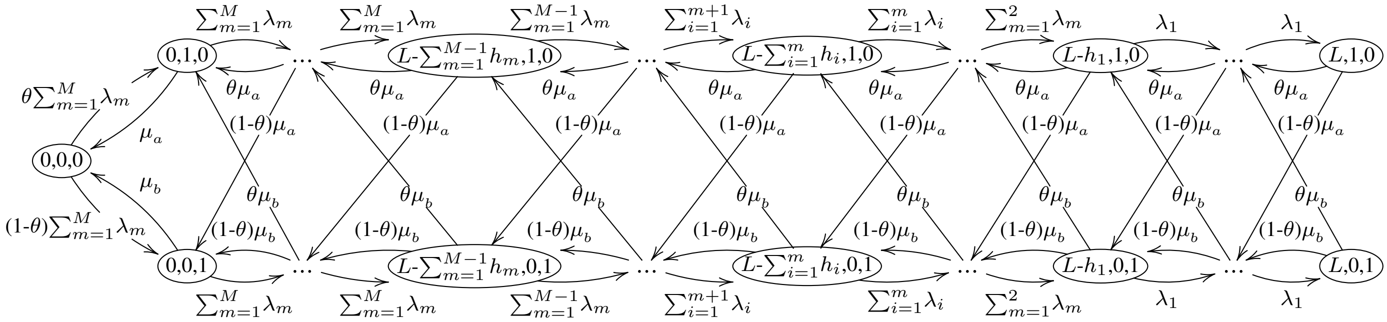


Fig. 4. State diagram of the modeled system.

$$\pi_{0,1,0}(\sum_{m=1}^{M}\lambda_m+\mu_a) = \theta(\pi_{0,0,0}\sum_{m=1}^{M}\lambda_m+\mu_a\pi_{1,1,0}+\mu_b\pi_{1,0,1}) \quad (9)$$
$$\pi_{0,0,1}(\sum_{m=1}^{M}\lambda_m+\mu_b) = (1-\theta)(\pi_{0,0,0}\sum_{m=1}^{M}\lambda_m+\mu_a\pi_{1,1,0}+\mu_b\pi_{1,0,1}) \quad (10)$$
$$\pi_{j_0,1,1}(\lambda_1+\mu_a) = \pi_{j_0-1,1,1}\lambda_1+\theta(\pi_{j_0+1,1,0}\mu_a+\pi_{j_0+1,0,1}\mu_b) \quad (11)$$
$$\pi_{j_0,0,1}(\lambda_1+\mu_b) = \pi_{j_0-1,0,1}\lambda_1+(1-\theta)(\pi_{j_0+1,1,0}\mu_a+\pi_{j_0+1,0,1}\mu_b) \quad (12)$$
$$\pi_{j_0,1,0}(\sum_{i=1}^{m}\lambda_i+\xi_m\lambda_{m+1}+\mu_a) = \pi_{j_0-1,1,1}\sum_{i=1}^{m+1}\lambda_i+\theta(\pi_{j_0+1,1,0}\mu_a+\pi_{j_0+1,0,1}\mu_b) \quad (13)$$
$$\pi_{j_0,0,1}(\sum_{i=1}^{m}\lambda_i+\xi_m\lambda_{m+1}+\mu_b) = \pi_{j_0-1,0,1}\sum_{i=1}^{m+1}\lambda_i+(1-\theta)(\pi_{j_0+1,1,0}\mu_a+\pi_{j_0+1,0,1}\mu_b) \quad (14)$$

For another two particular states $(0,1,0)$ and $(0,0,1)$, we have equations (9) and (10).

For other states $(j_0,j_1,j_2)\in\mathcal{S}$ satisfying $0<j_0<L$, if $(L-h_1)<j_0<L$, we have have equations (11) and (12). While, if $\psi_m(L-\sum_{i=1}^{m+1}h_i)<j_0\le(L-\sum_{i=1}^{m}h_i)$, we have equations (13) and (14), where $1\le m<M$, ψ_m equals zero if $m=(M-1)$ and one otherwise, ξ_m equals zero if the value of j_0 is in the set $\{(L-\sum_{i=1}^{m}h_i|1\le m<M)\}$ and one otherwise.

By summing up all steady-state probabilities in conjunction with normalization constraint, we have:

$$\sum_{\forall j_0,j_1,j_2}^{(j_0,j_1,j_2)\in\mathcal{S}}\pi_{j_0,j_1,j_2}=1 \quad (15)$$

The equations (6-15) help us in constructing a set of linear equations. By solving them, all steady-state probabilities can be computed.

C. Performance Metrics

To study the packet transmission performance at SU s_s side, we use the following performance metrics.

1) Blocking Probability: the newly arrived packets to SU s_s consist of M types. For a state $(j_0,j_1,j_2)\in\mathcal{S}$, blocking of the type $\mathbb{T}_1$ packets occurs for $j_0=L$. And, blocking of the type $\mathbb{T}_m$ packets, where $1<m\le M$, occurs for $j_0\ge(L-\sum_{i=1}^{m-1}h_i)$. Let $\mathcal{P}_{bl,m}$ denote the blocking probability of the type $\mathbb{T}_m$ packets, where $m=1,2,...,M$. We obtain:

$$[\mathcal{P}_{bl,m}|m=1]=\sum_{\forall j_0,j_1,j_2}^{(j_0,j_1,j_2)\in\mathcal{S}}[\pi_{j_0,j_1,j_2}|j_0=L] \quad (16)$$

$$[\mathcal{P}_{bl,m}|m>1]=\sum_{\forall j_0,j_1,j_2}^{(j_0,j_1,j_2)\in\mathcal{S}}\left[\pi_{j_0,j_1,j_2}|j_0\ge(L-\sum_{i=1}^{m-1}h_i)\right] \quad (17)$$

Given these blocking probabilities, the actual average arrival rate of packets to SU s_s, denoted by λ_{eff}, is formulated as:

$$\lambda_{eff}=\sum_{m=1}^{M}\lambda_m(1-\mathcal{P}_{bl,m}) \quad (18)$$

2) Transmission Throughput: it is defined as the average rate of packets completing the transmission from SU s_s to SU s_d. Let $\mathcal{R}$ denote the transmission throughput for all types of SU packets. For every particular system state $(j_0,j_1,j_2)\in\mathcal{S}$ for $j_0\neq0$, since there is only a single packet in transmission service, $\mathcal{R}$ is given by:

$$\mathcal{R}=\sum_{j_0=0}^{M}(\mu_a\pi_{j_0,1,0}+\mu_b\pi_{j_0,0,1}) \quad (19)$$

Further, let $\mathcal{R}_m$ denote the transmission throughput of the type m packets. It is given by:

$$\mathcal{R}_m=\mathcal{R}\frac{\lambda_m(1-\mathcal{P}_{bl,m})}{\lambda_{eff}},\quad m=1,2,...,M \quad (20)$$

3) Average Transmission Delay: the transmission delay of a packet means the total time spent by this packet for the transmission from SU s_s to SU s_d. Let $\mathcal{D}$ denote the average delay time of a packet, including both time for queueing in the buffer and for transmission. To compute it, we need to consider the average number of packets in the system, which is denoted by $\mathcal{N}$ and is given by:

$$\mathcal{N}=\sum_{\forall j_0,j_1,j_2}^{(j_0,j_1,j_2)\in\mathcal{S}}\left[(j_0+j_1+j_2)\pi_{j_0,j_1,j_2}\right] \quad (21)$$

According to Little's Theorem, $\mathcal{D}$ is computed by:

$$\mathcal{D} = \frac{\mathcal{N}}{\lambda_{eff}} \quad (22)$$

IV. Performance Evaluation

In this section, we report numeric and simulation results for performance evaluation of the modeled system. The evaluation focuses on the effectiveness of the suggested priority scheme for transmitting different types of packets in the presence of imperfect sensing.

A. Parameter Settings and Simulation Experiment

Without loss of generality, we consider two different types of SU packets like, e.g., type $\mathbb{T}_1$ and $\mathbb{T}_2$. The type $\mathbb{T}_1$ packets have higher priority than the type $\mathbb{T}_2$. According to the CR network standard IEEE 802.22 [12], we set the slot length δ equal to $10^{-2}s$. To make an adequate approximation using equation (2), we set the overlook error probability $\epsilon = 0.93$, the arrival rates of type $\mathbb{T}_1$ and $\mathbb{T}_1$ packets $\lambda_1 = 5.0$ and $\lambda_2 \in \{2.5, 3.0\}$. According to [7], other parameter settings are: $\alpha = 0.05$, $\beta = 0.06$, $L = 16$, $h_1 \in \{2, 7, 12, 17\}$ and $h_2 = 0$.

TABLE I
Simulation Statistics in a Simulation Run

Notation	Definition
x_1, x_2	numbers of arrived types $\mathbb{T}_1$ and $\mathbb{T}_2$ SU packets.
y_1, y_2	numbers of blocked types $\mathbb{T}_1$ and $\mathbb{T}_2$ SU packets.
z_1, z_2	numbers of transmitted types $\mathbb{T}_1$ and $\mathbb{T}_2$ SU packets.
w:	number of loopings used by all transmitted SU packets for waiting in the buffer.

The simulation experiment is conducted to demonstrate the validity of the numerical analysis. The simulator is developed in C++. For every specific parameter setting, the simulator runs in looping manner within $\tau = 10^8 s$ simulation time, and each looping indicates a slot length $\delta = 10^{-2}s$ in time domain. Seven simulation statistics with notations and definitions are shown in Table I. With these statistics, the performance metrics derived in Section III-C are computed by $\mathcal{P}_{bl,1} = y_1/x_1$, $\mathcal{P}_{bl,2} = y_2/x_2$, $\mathcal{D} = w\delta/(z_1 + z_2)$, $\mathcal{R} = (z_1 + z_2)/\tau$, $\mathcal{R}_1 = z_1\mathcal{R}/(z_1 + z_2)$ and $\mathcal{R}_2 = z_2\mathcal{R}/(z_1 + z_2)$.

B. Results and Discussions

The results of six performance metrics $\mathcal{P}_{bl,1}/\mathcal{P}_{bl,2}$, $\mathcal{D}$, $\mathcal{R}_1/\mathcal{R}_2$ and $\mathcal{R}$ are shown in Figs. 5(a), 5(b), 5(c) and 5(d), respectively. In each figure, the marker '+' indicates the simulation results. From these figures, we observe that the simulation results closely match the numerical results. Detailed discussions are as follows.

1) For the same setting of $\{\lambda_1, \lambda_2\}$: in Fig. 5(a), we observe that $\mathcal{P}_{bl,1}$ decreases with h_1, while $\mathcal{P}_{bl,2}$ increases with h_1. Fig. 5(b) shows that $\mathcal{R}_1$ increases with h_1, while $\mathcal{R}_2$ decreases with h_1. The reason for these is because when h_1 is increasing, the priority given to the type $\mathbb{T}_1$ SU packets over the type $\mathbb{T}_2$ becomes higher. As a result, the numbers of the blocked SU packets are decreased and increased for types $\mathbb{T}_1$ and $\mathbb{T}_2$, respectively. Subsequently, the number of the transmitted type $\mathbb{T}_1$ SU packets becomes larger, but the one for type $\mathbb{T}_2$ becomes smaller.

Figs. 5(c) and 5(d) show that both $\mathcal{R}$ and $\mathcal{D}$ decrease with h_1. Further, the percentage decrease in $\mathcal{D}$ is much larger than the one in $\mathcal{R}$. Taking for example the case of $\lambda_2 = 2.5$, the value of $\mathcal{R}$ under $h_1 = 17$ is only about 0.6% smaller than the one under $h_1 = 2$. Whereas, the value of $\mathcal{D}$ under $h_1 = 17$ is about 18.5% smaller than the one under $h_1 = 2$.

These results show the effectiveness of the suggested priority scheme. Meaning, it can improve the the transmission throughput of the particularly prioritized SU packets, and it can also reduce the average transmission delay for an arbitrary SU packet. The price is only a small decrease in the total transmission throughput of all SU packets.

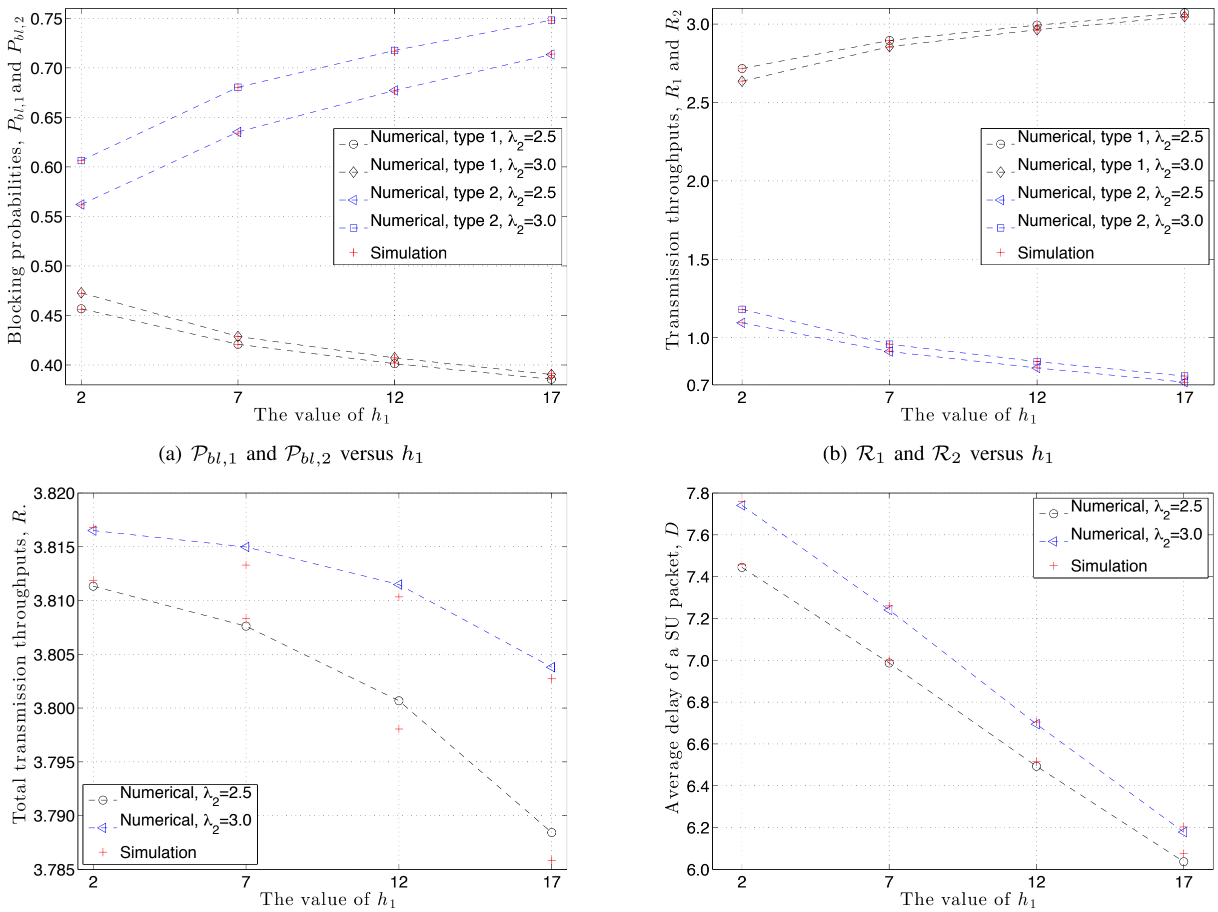
2) For the same value of h_1: Fig. 5(a) shows that, under the same setting of $\{\lambda_1, \lambda_2\}$, $\mathcal{P}_{bl,1}$ is smaller than $\mathcal{P}_{bl,2}$. This is because the higher priority (i.e., $h_1 > 0$ and $h_0 = 0$) is given to the type $\mathbb{T}_1$ SU packets over the type $\mathbb{T}_2$. Thus, the transmission throughput of the type $\mathbb{T}_1$ SU packets is larger than the one of the type $\mathbb{T}_2$, as shown in Fig. 5(b).

Fig. 5(a) also shows that both $\mathcal{P}_{bl,1}$ and $\mathcal{P}_{bl,2}$ increases with λ_2. This is because of the larger arrival rate of the type $\mathbb{T}_2$ SU packets, which increases the competition for transmission among all newly arrived SU packets at SU transmitter side. Since the mean arrival rate of the type $\mathbb{T}_1$ SU packets does not change, i.e., $\lambda_1 = 5.0$, the increase in $\mathcal{P}_{bl,1}$ leads to the decrease in $\mathcal{R}_1$, as shown in Fig. 5(b). However, when λ_2 is increasing, more type $\mathbb{T}_2$ SU packets may compete for transmission and $\mathcal{R}_2$ is increased. Further, because the total arrival rate (on average) of SU packets becomes larger, their total transmission throughput, i.e., $\mathcal{R}$ is increased, as shown in Fig. 5(c). Accordingly, the average transmission delay of SU packets, i.e., $\mathcal{D}$, is also increased, as shown in Fig. 5(d).

By comparing Fig. 5(c) and 5(d), we can observe one other second effectiveness of the suggested priority scheme. That is, when both $\mathcal{R}$ and $\mathcal{D}$ increase with λ_2, increasing h_1 can enhance the increase in $\mathcal{R}$ and reduces the increase in $\mathcal{D}$. For instance, when λ_2 is increased from 2.5 to 3.0, the percentage increase in $\mathcal{R}$ under $h_1 = 17$ is about 197.2 % larger than the one under $h_1 = 2$. Meanwhile, the percentage increase in $\mathcal{D}$ under $h_1 = 17$ is about 52.1% smaller than the one under $h_1 = 2$.

V. Conclusion

The opportunistic spectrum access with imperfect spectrum sensing in one-hop based ad-hoc cognitive radio networks has been studied. A buffer reservation based priority scheme has been suggested to give priorities to different types of unlicensed user packets according to their transmission requirements. A two-stage parallel server based queueing model $M/H_2/1$ was used to investigate the transmission performance of unlicensed users. For different type of unlicensed user packets, we derived blocking probability of each packet type,



(a) $\mathcal{P}_{bl,1}$ and $\mathcal{P}_{bl,2}$ versus h_1

(b) $\mathcal{R}_1$ and $\mathcal{R}_2$ versus h_1

(c) $\mathcal{R}$ versus h_1

(d) $\mathcal{D}$ versus h_1

Fig. 5. Numerical and simulation results of $\mathcal{P}_{bl,1}$, $\mathcal{R}_1$, $\mathcal{R}_2$, $\mathcal{R}$ and $\mathcal{D}$ versus the number of reserved queueing places for type T_1 SU packets, h_1.

average transmission delay of an arbitrary packet and transmission throughput of all packet types. Performance evaluation shows that the suggested priority scheme can decrease the average transmission delay of unlicensed user packets only at the expense of small decrease in transmission throughput. Moreover, when mean arrival rate of unlicensed user packets is increased, the suggested priority scheme can reduce the increase of average transmission delay. The analytical results were validated by simulation results. Future work is about the performance analysis of a centralized cognitive radio network with multiple unlicensed users in the presence of imperfect spectrum sensing.

REFERENCES

[1] S. Haykin, "Cognitive radio: brain-empowered wireless communications", *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201-220, February 2005.

[2] FCC Spectrum Policy Task Force, "Report of the spectrum efficiency working group", *Technical Report 02-135*, Federal Communications Commission, Washington, D.C., 2002.

[3] Q. Zhao, L. Tong, A. Swami, and Y. Chen "Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: a POMDP framework", *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 25, no. 3, pp.589-600, April. 2007.

[4] I.F. Akyildiz, W.-Y. Lee, M.C. Vuran, and S. Mohanty, "A Survey on Spectrum Management in Cognitive Radio Networks", *IEEE Communications Magazine*, vol. 46, issue 4, pp. 40-48, April. 2008.

[5] A.O. Popescu, D. Erman, M. Fiedler, A.P. Popescu, and D. Kouvatsos, "A Middleware Framework for Communication in Cognitive Radio Networks", *International Congress on Ultra Modern Telecommunications and Control Systems*, Moscow, Russia, October. 2010.

[6] V.K. Tumuluru, P. Wang, D. Niyato, and W Song, "Performance Analysis of Cognitive Radio Spectrum Access With Prioritized Traffic", *IEEE Transactions on Vehicular Technology (TVT)*, vol. 61, no. 4, pp.1895-1906, May 2012.

[7] Y. Yao, S.R. Ngoga, D. Erman, and A.P. Popescu, "Performance of Cognitive Radio Spectrum Access with Intra- and Inter-Handoff", *IEEE International Conference on Communications (ICC)*, Ottawa, Canada, June 2012.

[8] K.S. Trivedi, *Probability and Statistics with Reliability, Queuing, and Computer Science Applications*, John Wiley & Sons, Inc., 2002.

[9] Y.L. Wu and G.Y. Min, "Delay and Throughput Analysis in Multi-Hop Cognitive Radio Networks", *IEEE International Conference on Communications (ICC)*, Cape Town, South Africa, June 2010.

[10] J.E. Beyer and B.F. Nielsen, "Predator Foraging in Patchy Environments: The Interrupted Poisson Process (IPP) Model Unit", *Dana*, Vol. 11, no.2, pp.65-130, 1996.

[11] L. Kleinrock, "Part II: Elementary Queueing Theory", *Queueing Systems, Volume 1: Theory*, pp. 89-147, John Wiley & Sons, Inc, 1975.

[12] IEEE 802.22 Wireless Regional Area Networks, "Enabling Rural Broadband Wireless Access Using Cognitive Radio Technology", June 2010.