Queueing Analysis of Opportunistic Access in Cognitive Radios

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Abstract—**This paper presents queueing analysis of opportunistic access in cognitive radios. The primary (licensed user) has priority over the secondary user and it does not need to care about the secondary user transmissions. A time slotted system is assumed, so that the secondary user can perform spectrum sensing at the beginning of the slot to know if it is occupied by primary or not. If the slot is free, it can be utilized for secondary transmissions. This leads to no interference with primary user communication, assuming perfect sensing. Finding waiting time and queue length of this type of system has not, according to our best knowledge, been performed before. We perform theoretical analysis by applying $M/D/1$ priority queueing scheme. The results were used to evaluate the performance of the cognitive network. Simulation are used to validate the results, and simulation results demonstrate a high degree of accuracy for the derived expressions. Results indicate that the performance of the secondary user depends on the data traffic characteristics of the primary user, and under high arrival rate for the primary, the average waiting and average queueing length of the secondary user grow especially when the combined arrival rate approach the queue utilization factor.**

I. Introduction

The current spectrum allocation scheme consisting of fixed allocations is not efficient, as typically only small parts of the spectrum are actually used at a certain time instant. The communication channel is licensed to a primary user. However, secondary users can opportunistically [1] utilize the channel when the primary user is idle [2], thus increasing the spectrum utilization. These type of radios may be called cognitive radios. Fig. 1 presents a wireless network with primary users (licensed) and secondary users (unlicensed or cognitive). The situation shown in Fig. 1 can also be interpreted to be example of direct terminal to terminal communication (DTT) [3], [4]. DTT refers to situation where traffic does not go through base station and it is possible that the terminal(s) opportunistically use free channels available for DTT communication [3], [4], [5]. One possible way to realize opportunistic access is to use spectrum sensing. Therein, the cognitive or opportunistic radios use signal detection techniques to decide if a particular channel is currently used or not. If the channel is free, cognitive radios may be allowed to transmit. If the primary user joins the channel again, then the cognitive radio must leave the channel within certain period of time. The problem with this is that the primary user may have to face interference for a certain period of time when it rejoins the channel. In the case of slotted systems, it is possible to synchronize to the primary user and use the beginning of the slot for detection. If there is no signal present, the remainder of the slot can be used by cognitive radios [6], see Fig. 2. In the case of perfect sensing, this lead to no interference to the primary user.

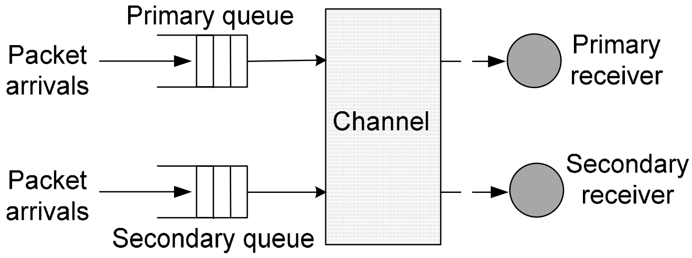

Fig. 1. A cognitive wireless network.

A great deal of research in the literature have focused on spectrum sensing as well as resource allocation in cognitive networks [6], [7]. However, few research/results on modelling the waiting time analysis in these networks have been reported, especially about time slotted systems. In this paper, we perform waiting time analysis of opportunistic access in a time slotted system. We utilize priority queueing to model cognitive radio systems. Namely, the primary user has higher priority than the secondary user and thus the secondary user has to leave the channel if the primary arrives. Primary users are assigned priority class 1 while secondary users are assigned priority class 2. Poisson processes are assumed for packet arrivals and we use modified $M/D/1$ system to analyze the network performance. Steady-state distribution of the queue lengths as well as mean delay time are derived. We use results from priority queueing to study time slotted cognitive radio system with one primary and one secondary link. The theoretical results from priority queuing assume perfect sensing, i.e, the secondary will never use the channel if it is occupied by the primary user. In practise, sensing is never perfect and there are two kinds of errors: false alarm and missed detections. We study imperfect sensing by using Monte Carlo simulations. In future work, multiple secondary flows should be studied so as to see the effects of the multiple access method. Additionally, different secondaries could be assigned different priorities.

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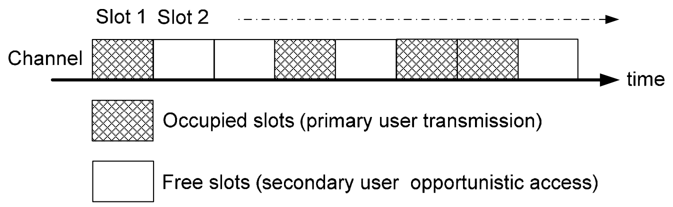

Fig. 2. Channel time slots.

The remainder of the paper is organized as follows. Section 2 describes the assumed system model. In Section 3, we presents theoretical expressions for average waiting time and average queue length for both primary and secondary users. In Section 4, we present simulation and analytical results. Finally, conclusions are drawn in Section 5.

II. System Model

We consider a time slotted [8], [9] cognitive wireless network where a primary users is the owner of the network. We adopted similar model as used in [9] where the authors considered a cognitive network with one primary and one secondary links. When the primary wishes to transmit, it is given a priority over the secondary user. This is implemented by having the secondary user perform spectrum sensing at the beginning of the slot. If there is no signal at the beginning of the slot, the remainder of the slot can be utilized for secondary transmission. Perfect time synchronization and perfect sensing are assumed. All packets are assumed to be one slot in duration. The network is assumed to operate in ideal channel conditions (e.g. no noise and error-free. Poisson process is used for packet arrivals, so that the interarrival times are exponentially distributed. The primary user arrival rate is λ_P and secondary user arrival rate is λ_S. Note that transmission of packets can only start at the beginning of the slot, so that even if a packet arrives at the middle of the slot, it has to wait half of the slot duration, even if the channel is free. Infinite buffers are assumed. Fig. 3 shows example of realization of packet arrivals and departures.

III. Analysis based on priority queuing

First, let us show the nomenclature in Table I. Fig. 1 shows the priority queuing system used for modelling the cognitive radio. The waiting time of a packet consists of three part: time until the beginning/start of the next slot, time spent in a queue waiting time for the service to begin, and the average service time (transmission time). For both classes, the packets are served according to a first come first served discipline (FCFS), but a packet of class 2 (at the secondary user queues) may start its transmission at the beginning of a time slot only if there are no packets of class 1 (i.e empty primary user queues) in the network. Given the fact that packets arrive according to Poisson process and that the system time is slotted with a fixed unit time slot, it is straightforward to

TABLE I
Model parameters

Symbol	Explanation
λ_P	Primary arrival rate
λ_S	Secondary arrival rate
μ	Service time
$\overline{X} = E[X] = {}^1/_\mu$	Average service time
N_Q^P	Average number of packets in queue for the primary user
N_Q^S	Average number of packets in queue for the secondary user
W_Q^P	Average queueing time for the primary user
W_Q^S	Average queueing time for the secondary user
W^P	Total time spent by primary packet in the system
W^S	Total time spent by secondary packet in the system
T_D	Waiting time until the beginning of a slot
$\rho^P = {}^{\lambda^P}/_{\mu}$	Utilization factor for the primary queue
$\rho^S = {}^{\lambda^S}/_{\mu}$	Utilization factor for the secondary queue

estimate the average time spent by a newly arrived packet waiting in a queue for the start of the next slot: on average, a packet has to spent 1/2 slot waiting for the next slot to start.

Recall the fact that $M/D/1$ (where services are deterministic and last exactly one slot regardless of user priority) is a special case of $M/G/1$, we start with the deriving expressions for the $M/G/1$, and then we obtain the expressions for the $M/D/1$ as special case. Starting from the well known analysis result of the $M/G/1$, known as Pollaczek-Khintchine and following similar approach as in [10]. The sojourn time of a secondary user packet depends not only on the packets found upon arrival (N_Q^P and N_Q^S), but also on subsequent arrivals at the primary user queue. We first drive expression for the waiting time W_Q^P for the primary user

$$W_Q^P = T_D + \frac{1}{\mu} N_Q^P \tag{1}$$

We can eliminate the N_Q^P from equation by using Little's theorem [10], $N_Q^P = \lambda_P W_Q^P$ we obtain

$$W_Q^P = T_D + \frac{1}{\mu}\lambda_P W_Q^P = T_D + \rho^P W_Q^P \tag{2}$$

where T_D is the delay time that an arrived packet has to wait until the beginning of a slot and we got

$$W_Q^P = \frac{T_D}{1-\rho^P} \tag{3}$$

For the secondary user, the waiting time W_Q^S of a newly arrived packet depends not only on the packets found upon arrival in primary and secondary queues (N_Q^P and N_Q^S), but also on subsequent arrivals at the primary user queue. Therefore we have to include this delay in the computation of the W_Q^S

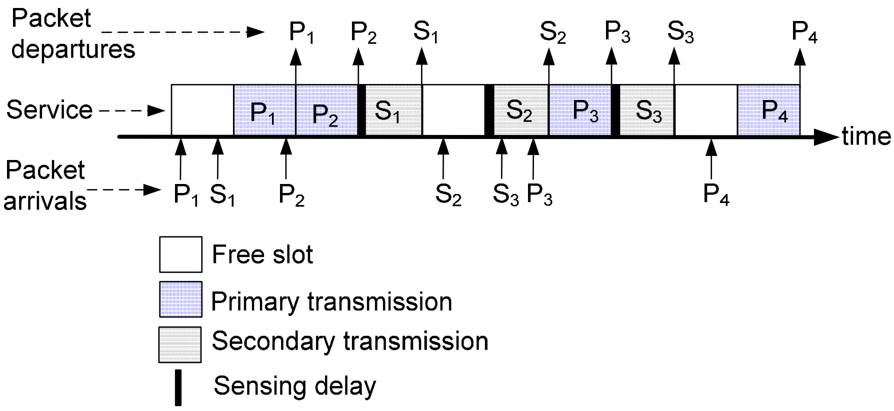

Fig. 3. Priority servicing.

$$W_Q^S = T_D + \frac{1}{\mu}N_Q^P + \frac{1}{\mu}N_Q^S + \frac{1}{\mu}\lambda_P W_Q^S \quad (4)$$

and by using Little's theorem,we obtain

$$\begin{aligned} W_Q^S &= T_D + \tfrac{1}{\mu}\lambda_P W_Q^P + \tfrac{1}{\mu}\lambda_S W_Q^S + \tfrac{1}{\mu}\lambda_P W_Q^S \\ &= T_D + \rho^P W_Q^P + \rho^S W_Q^S + \rho^P W_Q^S \end{aligned} \quad (5)$$

$$W_Q^S = \frac{T_D + \rho^P W_Q^P}{1 - \rho^P - \rho^S} \quad (6)$$

$$W_Q^S = \frac{T_D}{(1-\rho^P)(1-\rho^P-\rho^S)} \quad (7)$$

Recalling the fact that the total packet delay (time spent in the system) is given by summation of the waiting time in the queue and the average service time of the packet, we can express the average delay per packet for the primary user

$$W^P = \overline{X} + \frac{T_D}{1-\rho^P} \quad (8)$$

and that the average delay per packet for the secondary user is given by

$$W^S = \overline{X} + \frac{T_D}{(1-\rho^P)(1-\rho^P-\rho^S)} \quad (9)$$

We are now interested in addressing the special case where time is slotted with deterministic service time of one slot and the fact that packet service can only starts at the beginning of slot. We have already assumed that the service time is one slot and that a newly arrived packet has to wait for $^1\!/_2$ slot before the beginning of slot. We can substitute the corresponding values in and to obtain

$$W^P = 1 + \frac{^1\!/_2}{1-\rho^P} \quad (10)$$

$$W^S = 1 + \frac{^1\!/_2}{(1-\rho^P)(1-\rho^P-\rho^S)} \quad (11)$$

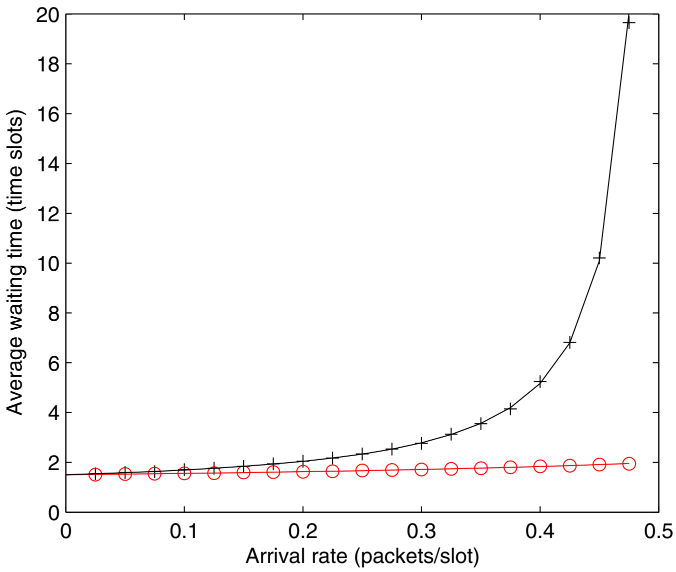

Fig. 4. Average waiting time for the primary and the secondary users. Packets arrive to each priority queue with equal rate. Solid lines are theoretical results and markers denote simulation results.

Applying Little's formula to W^P and W^S, we get the expected number of packets for the primary user N^P and the secondary user N^S:

$$N^P = \lambda_P + \frac{\lambda_P}{2(1-\rho^P)} \quad (12)$$

$$N^S = \lambda_S + \frac{\lambda_S}{2(1-\rho^P)(1-\rho^P-\rho^S)} \quad (13)$$

IV. Numerical and Simulation Results

We consider two scenarios: in the first the primary and secondary packets arrive with equal rate so that $\lambda_P = \lambda_S$. In the second scenario, the primary user rate is fixed while the secondary user rate is varied.

A. Scenario 1

Figs. 4 presents the delay for the primary and secondary users. Solid lines are theoretical results and markers denote

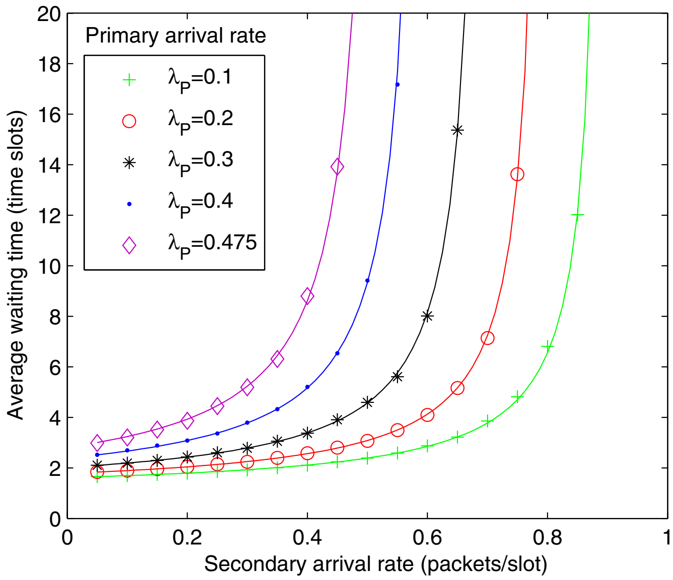

Fig. 5. Average waiting time for the primary and the secondary users. Secondary user arrival rate is varied for different fixed arrival rate for the primary user. Solid lines are theoretical results and markers denote simulation results.

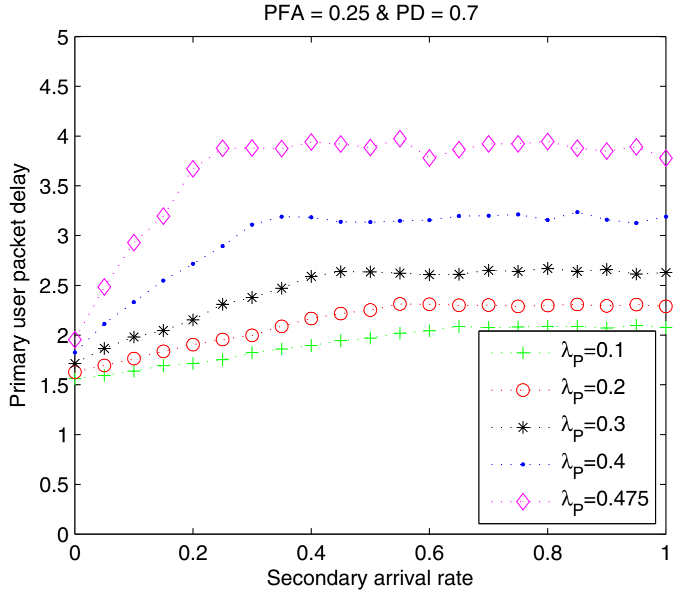

Fig. 6. Primary users packet delay, $P_{\mathrm{FA}} = 0.25$, $P_{\mathrm{D}} = 0.7$.

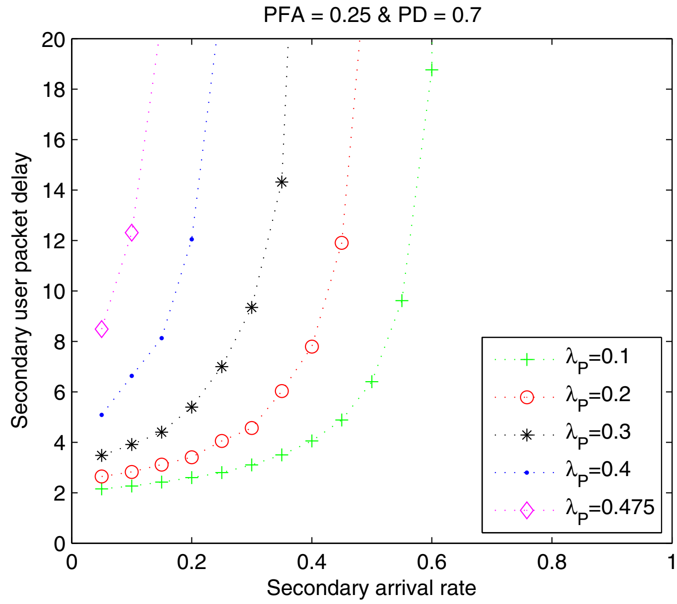

Fig. 7. Secondary user delay, $P_{\mathrm{FA}} = 0.25$, $P_{\mathrm{D}} = 0.7$.

simulation results. We can see that when the arrival rate is small, the average waiting time for the primary and secondary queues are comparable. However, as the arrival rates increase, the gap between the primary and secondary average waiting time starts to increase. For higher values of the arrival rates, primary waiting time stay at almost the same value.

B. Scenario 2

Figs. 5 presents the delay for the primary and secondary users. Solid lines are theoretical results and markers denote simulation results. It can be seen that theoretical and simulation results match very well.

C. Imperfect sensing

Opportunistic access requires setting some limits on the interference that the secondaries cause to the primary user. These limits translate into requirements for the detection process. The detection process is characterized by false alarm probability P_{FA} and detection probability P_{D}. The false alarm probability is the probability that a free slot is decided to be occupied. The detection probability is the probability that an occupied slot is detected correctly as an occupied slot. Typically, there is a tradeoff between these two probabilities. Too large detection probability means that secondary users lose transmission opportunities due to false alarms. Too small detection probability means that primary user is not sufficiently protected. The performance of the priority queueing with imperfect sensing has been evaluated using Monte Carlo simulations. Fig. 6 shows the primary user packet delay when the probability of detection $P_{\mathrm{D}} = 0.7$ and the probability of false alarm $P_{\mathrm{FA}} = 0.25$. Similarly, Fig. 7 shows the secondary user packet delay when the probability of detection $P_{\mathrm{D}} = 0.7$ and the probability of false alarm $P_{\mathrm{FA}} = 0.25$. It can be seen that the imperfect sensing conditions have affected the performance of both primary and secondary user delays.

V. Conclusions

In this paper we used priority queuing to model opportunistic access in cognitive networks. Waiting time and queue length were theoretically derived using modified M/D/1 model. Simulations results showed good match with the theoretical results. The results are important for studying the feasibility of opportunistic access in slotted systems. In future work we could analytically study the effect of imperfect sensing on the performance of the cognitive network (priority queueing). The analysis could also be extended to model a multi-channel system.

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