

# A Novel Buffer-Aided Medium Access Control for Multichannel Cognitive Radio Networks

Mostafa Darabi<sup>1,\*</sup>, Behrouz Maham<sup>2</sup>

<sup>1</sup>School of ECE, College of Engineering, University of Tehran, Iran

<sup>2</sup>Department of Electrical and Electronic Engineering, Nazarbayev University, Astana, Kazakhstan

## Abstract

In this paper, a novel context aware medium access control scheme is proposed for multichannel buffer-aided cognitive networks. The proposed scheme allows management of the delay more efficiently by exploiting the packets' context. In the proposed multiple access policy, two different context aware approaches for packet prioritization are presented. In the first method, more delay sensitive packets in the primary and secondary networks are given a higher priority compared to delay tolerant packets. In the second proposed prioritization method, shorter packets in the primary and secondary networks are given a higher priority compared to longer packets and are transmitted over channels with lower service time. The average waiting time of the packets and the primary and secondary throughput are derived. Simulation results show that the proposed schemes improve the average waiting time of packets and average throughput compared to other existing MAC policies in cognitive networks.

Received on 20 February 2016; accepted on 1 March 2016; published on 10 January 2017

**Keywords:** Average waiting time of packet, context aware cognitive networks, little law, priority-based MAC scheme, slow truck effect

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doi:10.4108/eai.9-1-2017.152096

## 1. Introduction

Recently, cognitive radio networks have emerged as a promising way to efficiently exploit the scarce radio spectrum resources [2]. In a cognitive radio network, by smartly monitoring the radio environment, unlicensed, secondary users can share the spectrum resources with licensed, primary users. In essence, the primary and secondary users in a cognitive radio network can co-exist and use the same spectrum band provided that the interference of the secondary users to the primary users is maintained below a certain threshold [3].

Different access approaches exist for cognitive radio networks. In the most popular approach, secondary users can sense the wireless spectrum and transmit over the licensed bands, whenever these bands are not being utilized by the primary users [3], [4]. In this

approach, secondary users have to vacate the spectrum once the primary users reappear in their licensed band. Alternatively, both primary and secondary users can access the licensed bands simultaneously. Here, secondary users must adopt some coding techniques to facilitate the primary data transmission [5].

Queuing aspects of cognitive radio networks have recently received significant attention [6]-[12]. The average waiting time of the primary and secondary packets is derived in [6], [7] and [8] for various priority-based queuing systems. The work in [9] considers only one primary user and one secondary user while assigning two priority classes for each primary and secondary network. In [9], the effect of primary and secondary arrival rates and packet sizes on the average waiting time of packets is studied. In addition, it has been shown in [9] that the ability of continuous spectrum sensing for the secondary user can reduce the mean packet waiting time.

Multichannel cognitive radio network with similar channels and multiple primary and secondary users is considered in [10]. In the policy of [10], at each time

\*Corresponding author's email: [mostafa.darabi@ut.ac.ir](mailto:mostafa.darabi@ut.ac.ir)

<sup>†</sup>This is an extended paper for Special Issue of Software Defined Radio and Network of the EAI Transactions on Wireless Spectrum based on SDRANCAN 2015, a GLOBECOM 15 workshop paper [1].

slot, the primary and secondary packet are assigned to the channel having, respectively, the shortest queue of the primary and secondary packets. This policy is known as shortest queue rule [10]. In [11], a multichannel spectrum sharing policy is proposed for the secondary users, in which by using queuing theory the average data rate of the secondary users is enhanced. The authors in [12] introduced a queuing channel assembling protocol for multichannel cognitive networks. With the aid of allotting separate queues for different traffic kinds, the performance of dynamic channel assembling strategies are optimized. Even though [6]-[12] address cognitive access based on different traffic priority classes, they do not exploit the packets' context in the traffic prioritization schemes. In particular, in these works, urgent packets may experience excessive delays while delay tolerant packets may be served quickly. In addition, long packets in these papers may transmit sooner than short packets, and thus, due to the slow truck effect, the primary and secondary throughput may be decreased.

The main contribution of this paper is to propose a novel context aware priority-based medium access control (MAC) scheme for multichannel buffer-aided cognitive radio networks. The proposed scheme allows management of the average waiting time of the primary and secondary packets more efficiently based on the context of the packets. In particular, we consider a multichannel cognitive radio network with multiple primary users and multiple secondary users. Unlike [10], each channel in the considered network has its own service time for transmission the primary and secondary packets. Two different context aware prioritization methods are presented. In the first proposed scheme, delay sensitive packets in both the primary and secondary networks are given a higher priority compared to delay tolerant packets. Therefore, urgent primary and secondary packets are transmitted via best channels in terms of service time. In the second proposed scheme, the primary packets and short packets are given higher priority over the secondary packets and long packets, respectively. Thus, in each of the primary and secondary networks, the packets are served in an order which depends on the packet length. Hence, based on slow truck effect, the overall average waiting time of the primary and secondary packets is minimized, and therefore, the average primary and secondary throughput is maximized. By using a preemptive queuing system, we then calculate the average waiting time of the primary and secondary packets and the average throughput of the primary and secondary networks for the first and second proposed schemes, respectively. Simulation results show that the proposed priority based MAC scheme achieves lower average waiting time of packets and higher average primary and secondary throughput compared to the

recently proposed policies in [12], [11], [10] and the conventional first in first serve approach.

The proposed priority based MAC scheme can be applied in the cognitive machine-to-machine communication networks (CM2M) in the future wireless networks. In CM2M networks, the primary network, which is a cellular network, shares the spectrum with machine type devices [13]. By exploiting the first proposed scheme, some of the delay intolerant machine type devices such as e-health sensors can be prioritized over the other delay tolerant machines in using the spectrum of the cellular network opportunistically. In addition, by using the second proposed scheme, packets of machines are served in order of the packet lengths, and hence, the throughput of machine type devices are enhanced.

The rest of this paper is organized as follows. Section 2 presents the system model. The proposed policy with two different prioritization procedures is presented and investigated in terms of the average waiting time of the packet and average throughput in Section 3. Simulation results are presented in Section 4, while conclusions are drawn in Section 5.

## 2. System Model

Consider a multichannel cognitive radio network composed of  $L$  different parallel channels,  $n_p$  primary users, and  $n_s$  secondary users, where each primary and secondary user has one source node and one destination node. The channels in the considered cognitive radio network are not similar, and each primary and secondary packet experiences a channel-dependent service time. At each time slot, the set of available primary and secondary channels are denoted by  $\mathcal{S}_p$  and  $\mathcal{S}_s$ , respectively. The total bandwidth of the considered cognitive radio network is denoted by  $B$  and the bandwidth of the  $l$ -th channel is  $B_l$ . As shown in Fig. 1, in the considered network, we assume a time division multiple access (TDMA) policy to schedule the primary and secondary data transmission. Here, the secondary users can only transmit in the vacant licensed radio spectrum, i.e., spectrum holes, and the secondary users have to vacate the spectrum once the primary users reappear. The primary and secondary users are assumed to be transmitting in time slots with equal duration. In a cognitive radio network with TDMA channels, secondary users can sense the radio spectrum either at the beginning of the time slots or continuously during the time slots [14]. Here, we assume that the secondary users sense the radio spectrum perfectly and have the ability of continuous spectrum sensing. Thus, the secondary users can transmit as soon as the primary users have finished their own data transmission. By using such a continuous spectrum sensing, the average

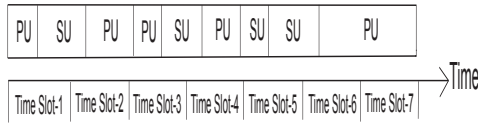


Figure 1. Considered TDMA cognitive radio network.

waiting time of the secondary packets can be reduced [9].

In Fig. 2, the system model for the traditional first come first serve approach in the multichannel cognitive radio network is shown as a benchmark approach. In this figure, there exist one primary queue and one secondary queue in front of the multichannel cognitive radio network. The primary packets have priority on the secondary packets, and therefore, if there exists no primary packet in the primary queue, secondary packets can be transmitted. In this procedure, as soon as one of the primary or secondary packet is transmitted, cognitive radio network can accept a new packet from the primary and secondary queue based on the first come first serve rule and the priority of primary packets over the secondary packets.

The proposed system model is illustrated in Fig. 3. In this figure, white and gray colors are used to show the primary and secondary users, respectively. Each queue in the multichannel cognitive radio network is stored in a buffer with infinite size. However, in the simulation results, we will analyze the impact of limited buffer size on the primary and secondary average throughput. As it is shown in this figure, it is assumed that the primary packets have higher priority over the secondary packets. In the queue management system of the considered network, multiple queues are formed and prioritized in terms of their delay sensitivity or packet lengths in first or second prioritization approach, respectively. Packet *delay sensitivity* is defined as the amount of delay which the packet can tolerate in order to be served in the considered multichannel cognitive radio network. Then, the primary and secondary queues are assigned to the channels with aid of channel assignment system. In Section III-C, the channel assignment procedure is explained in more details within related formulas. One of the secondary nodes, which is named controller, plays as central node and does the role of the queue management system and channel assignment system. In the considered cognitive radio network, each primary and secondary users has a random packet length and a stochastic delay sensitivity. The number of primary and secondary types of packets in the cognitive radio network are denoted by  $N_p$  and  $N_s$ , respectively, where  $1 \leq N_p \leq n_p$  and  $1 \leq N_s \leq n_s$  hold. Therefore, there exist  $N_p$  and  $N_s$  primary and secondary priority classes, respectively, and a total of  $N_p + N_s$  queues in the

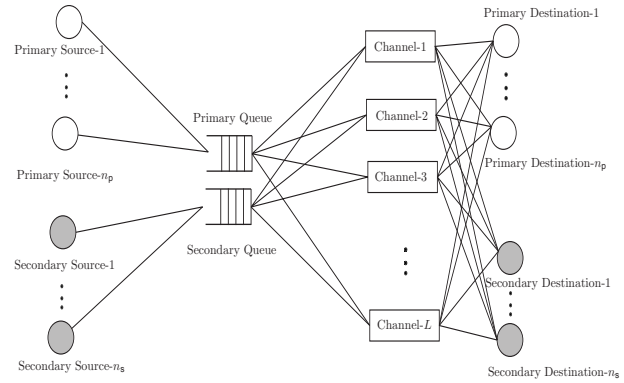


Figure 2. Traditional first come first serve queuing model for a multichannel cognitive radio network with multiple primary and secondary users.

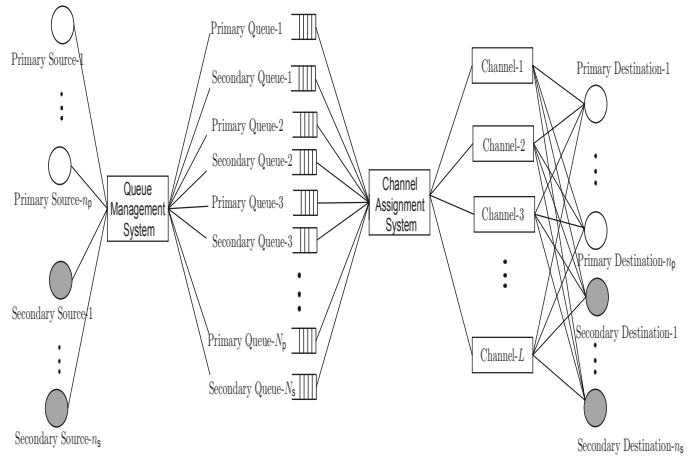


Figure 3. Proposed priority-based queuing model for a context aware multichannel cognitive radio network with multiple primary and secondary users.

network. Since there exist  $L$  different channels, each channel may serve multiple primary and secondary queues, based on its bandwidth. Therefore, in the  $l$ -th channel, there exist  $\lceil N_p \frac{B_l}{B} \rceil$  and  $\lceil N_s \frac{B_l}{B} \rceil$  primary and secondary queues, respectively. The sets of available primary and secondary queues in the  $l$ -th channel are denoted by  $S_{l,p}$  and  $S_{l,s}$ , respectively.

In the  $i$ -th priority class of the primary and secondary networks, the length of the packets are denoted by  $L_{i,p}$  and  $L_{i,s}$ , respectively. On the other hand, in the  $i$ -th priority class of the  $l$ -th channel,  $L_{c_{i,l},p}$  and  $L_{c_{i,l},s}$  are the length of the primary and secondary packets, respectively. The packets of the primary and secondary users are generated according to a Poisson process. The arrival rate of the packets of the  $i$ -th priority class in the primary and secondary networks are  $\lambda_{i,p}$  and  $\lambda_{i,s}$ , respectively. Furthermore, in the  $i$ -th priority class of the  $l$ -th channel,  $\lambda_{c_{i,l},p}$  and  $\lambda_{c_{i,l},s}$  are the arrival rate of the primary and secondary packets, respectively.

For the  $i$ -th priority class, the average serving time of the packet in the primary and secondary networks are denoted by  $\mathbb{E}\{X_{i,p}\}$  and  $\mathbb{E}\{X_{i,s}\}$ , respectively.  $\mathbb{E}\{\cdot\}$  denotes expectation. On the other hand, in  $i$ -th priority class of  $l$ -th channel,  $\mathbb{E}\{X_{c_i,l,p}\}$  and  $\mathbb{E}\{X_{c_i,l,s}\}$  are the average service time of the primary and secondary packet, respectively, and are given by [9], [10]

$$\mathbb{E}\{X_{c_i,l,p}\} = \frac{L_{c_i,l,p}}{B_l}, \quad (1)$$

$$\mathbb{E}\{X_{c_i,l,s}\} = \frac{L_{c_i,l,s}}{B_l}. \quad (2)$$

$\rho_{i,p}$  and  $\rho_{i,s}$  are the channel utilization of the  $i$ -th priority class in the primary and secondary networks. In addition, the channel utilization of the primary and secondary packets in the  $i$ -th priority class of the  $l$ -th channel are denoted by  $\rho_{c_i,l,p}$  and  $\rho_{c_i,l,s}$  and are given by

$$\rho_{c_i,l,p} = \lambda_{c_i,l,p} \mathbb{E}\{X_{c_i,l,p}\}, \quad (3)$$

$$\rho_{c_i,l,s} = \lambda_{c_i,l,s} \mathbb{E}\{X_{c_i,l,s}\}. \quad (4)$$

The average waiting time of the primary and secondary packets is thus,

$$W = Q + T + I, \quad (5)$$

where  $Q$  is the average time that the packet spends in the queue until the first transmission,  $T$  is the average transmission time of the packet, and  $I$  is the average interruption time when a higher priority packet appears in the network. We let  $W_{i,p}$  and  $W_{i,s}$  be the average waiting time of the  $i$ -th priority class in the primary and secondary networks, respectively. For the  $i$ -th priority class of  $l$ -th channel, the average waiting time of the primary and secondary packets are denoted by  $W_{c_i,l,p}$  and  $W_{c_i,l,s}$ , respectively.

To the best of the authors' knowledge, most existing MAC approaches in [6]-[12] for cognitive radio networks have not been exploited the packets' context in the channel assignment and traffic prioritization schemes. Therefore, urgent packets may experience excessive delays while delay tolerant packets may be served quickly. Given the system model in Fig. 3, we will introduce a novel context aware priority-based MAC scheme for buffer-aided multichannel cognitive radio network in which the average waiting time of the primary and secondary packets are managed more efficiently based on the context of the packets. Our proposed policy will include two approaches for prioritization the packets. In the proposed first prioritization scheme, in both primary and secondary networks, the packets are prioritized in order of their delay sensitivity. Therefore, urgent packets have higher priority over delay tolerant packets, and hence, the average waiting time of the urgent packets are

minimized. In the proposed second prioritization policy, in both primary and secondary networks, the packets are prioritized in order of their lengths. Thus, allowing short packets to have higher priority over long packets, and therefore, based on the slow truck effect, the overall average waiting time of the primary and secondary packets are minimized.

### 3. Proposed Policy

In this section, we propose a novel context aware priority-based MAC scheme for buffer-aided cognitive radio networks in an effort to manage the average waiting time of the primary and secondary packets based on the context of the packets. In the proposed context aware MAC scheme, the primary packets have higher priority over the secondary packets. Two different prioritization approaches are proposed in the multichannel cognitive radio network. In the proposed first prioritization procedure, the packet urgency will determine the priority class of each packet. In addition, in the proposed second prioritization scheme, the packet length will specify the packet priority order.

In the considered cognitive radio network, a queue management system receives the user service requests. Then, the packets are arranged in order of their urgency (in our first scheme) and length (in our second scheme), and are stored in the buffer of queue related to its delay sensitivity or length. Thus, in the proposed context aware MAC scheme, delay sensitive and short packets are processed faster than delay tolerable and long packets, respectively.

In our scheme, when a higher priority packet arrives, the transmission of the lower priority packet is halted. Furthermore, as soon as the transmission of the higher priority packet is completed, the transmission of the lower packet is resumed at the point at which it was interrupted. Thus, we can model the proposed priority-based MAC scheme as an M/G/1 preemptive queuing system. Our two context aware prioritization approaches, the proposed channel assignment procedure, the average waiting time of the primary and secondary packets, and the average primary and secondary throughput are discussed next.

#### 3.1. Context Aware First Prioritization Approach

In the proposed first prioritization procedure, the primary packets have higher priority over the secondary packets, and the packet urgency determines the priority class of each packet in the primary and secondary networks, i.e., delay sensitive packets are in the higher priority classes. The delay sensitivity is defined as the amount of delay which packet can tolerate in order to be served. In the primary and secondary networks, at each time slot, the queue management system arranges



the user service requests in order of their delay sensitivity. Then, the channel assignment system assigns the queues to the available channels, based on their urgency. Therefore, for the proposed first prioritization scheme, the average waiting time of the delay sensitive packets in the higher priority classes are lower than the average waiting time of the delay tolerant packets in the lower priority classes, i.e.,

$$W_{1,p} \leq W_{2,p} \leq \dots \leq W_{N_p,p}, \quad (6)$$

$$W_{1,s} \leq W_{2,s} \leq \dots \leq W_{N_s,s}. \quad (7)$$

The channel assignment procedure will be discussed in detail in Section III-C.

**Remark 1.** The context of the packets determines the delay sensitivity of the packets in the primary and secondary networks. For example, video packets are more delay sensitive compared to data packets. In the proposed first context aware MAC scheme, by assigning channels with minimum serving time to the urgent packets, the delay intolerant packets are processed faster than the delay tolerant packets. Therefore, the average waiting time of the urgent packets in the proposed policy can be minimized.

**Remark 2.** The serving time of each channel in the considered cognitive radio network is a function of the capacity and bandwidth of the channel. Hence, in the proposed first prioritization method, the channels with more capacity and bandwidth are selected for transmission of the urgent packets, and thus, the delay sensitive packets have more reliability too.

### 3.2. Context Aware Second Prioritization Approach

In our second prioritization method, in each of the primary and secondary networks, the priority class of each packet is determined by the packet length, i.e., shorter packets are in the higher priority classes. Hence, for the proposed second prioritization procedure we have

$$L_{1,p} \leq L_{2,p} \leq \dots \leq L_{N_p,p}, \quad (8)$$

$$L_{1,s} \leq L_{2,s} \leq \dots \leq L_{N_s,s}. \quad (9)$$

More specifically, in the primary and secondary networks, at each time slot, the queue management system arranges the user service requests in order of their packet length. Then, the queues are assigned to the available channels in the primary and secondary networks with aid of the channel assignment system. The channel assignment procedure will be discussed in detail in Section III-C.

**Remark 3.** In the proposed second context aware MAC scheme, short packets are processed faster than long packets. In queuing theory, it has been shown that by allowing short packets to be transmitted faster, the network traffic and

average waiting time of the packets can be reduced. This phenomenon is known as the slow truck effect [15]. Thus, according to the slow truck effect, the total average waiting time of the packets in the proposed policy can be minimized, and hence, the average primary and secondary throughput can be maximized.

**Remark 4.** Due to practical implementation considerations, infinite buffers can not be used in a cognitive radio network, thus, we can modify the proposed context aware MAC policy to account a limited-size buffer. In fact, if the buffer of any queue is full, that queue will not accept any new packet and be only transmitting packets since its buffer has capacity to accept a new service request. In Section IV, we will analyze the impact of limited buffer size on the primary and secondary average throughput.

### 3.3. Channel Assignment Approach

In this subsection, the channel assignment procedure for two proposed prioritization approaches is discussed in detail. Furthermore, the proposed context aware MAC scheme is investigated in terms of average waiting time of the packets and average throughput by modeling the proposed policy as an M/G/1 preemptive queuing system. At each time slot, at first, queue management system forms and prioritizes the primary and secondary queues based on the packet urgency or packet length. Then, the packets in the first priority class of the primary and secondary network are assigned to primary and secondary first priority class in  $m$ -th channel and  $n$ -th channel, respectively, such that the average waiting time of the packet is minimized, i.e., we have

$$W_{1,p} = \arg \min_{m \in \mathcal{S}_p} W_{c_{1,m},p}, \quad (10)$$

$$W_{1,s} = \arg \min_{n \in \mathcal{S}_s} W_{c_{1,n},s}, \quad (11)$$

in which according to M/G/1 preemptive queuing system,  $W_{c_{1,m},p}$  and  $W_{c_{1,n},s}$  are given, respectively [15]

$$W_{c_{1,m},p} = \mathbb{E}\{X_{c_{1,m},p}\} + \frac{\lambda_{c_{1,m},p} \mathbb{E}\{X_{c_{1,m},p}^2\}}{2(1 - \rho_{c_{1,m},p})}, \quad (12)$$

$$W_{c_{1,n},s} = \mathbb{E}\{X_{c_{1,n},s}\} + \frac{\lambda_{c_{1,n},s} \mathbb{E}\{X_{c_{1,n},s}^2\}}{2(1 - \rho_{c_{1,n},s})}. \quad (13)$$

After the channel assignment, the first priority queue is reduced from the sets of available primary and secondary queues in the  $m$ -th and  $n$ -th channel, respectively.

After the channel assignment of the packets in the primary and secondary first priority class, the packets in the primary and secondary second priority class will be assigned to available channels similarly. The channel assignment procedure will be continued in

the same way for the primary packets in the  $u$ -th priority class ( $2 \leq u \leq N_p$ ), and the secondary packets in  $v$ -th priority class ( $2 \leq v \leq N_s$ ). More specifically, the primary packets in the  $u$ -th priority class and the secondary packet in  $v$ -th priority class are assigned to  $i$ -th priority class in  $m$ -th channel and  $k$ -th priority class in  $n$ -th channel, respectively, such that the average waiting time of the packet is minimized, i.e., we have

$$W_{u,p} = \arg \min_{m \in \mathcal{S}_p, i \in \mathcal{S}_{m,p}} W_{c_{i,m,p}}, \quad (14)$$

$$W_{v,s} = \arg \min_{n \in \mathcal{S}_s, k \in \mathcal{S}_{n,s}} W_{c_{k,n,s}}, \quad (15)$$

in which  $W_{c_{i,m,p}}$  and  $W_{c_{k,n,s}}$  are given, respectively [15]

$$W_{c_{i,m,p}} = \frac{\mathbb{E}\{X_{c_{i,m,p}}\}}{1 - \sum_{j=1}^{i-1} \rho_{c_{j,m,p}}} + \frac{\sum_{j=1}^i \lambda_{c_{j,m,p}} \mathbb{E}\{X_{c_{j,m,p}}^2\}}{2(1 - \sum_{j=1}^{i-1} \rho_{c_{j,m,p}})(1 - \sum_{j=1}^i \rho_{c_{j,m,p}})}, \quad (16)$$

$$W_{c_{k,n,s}} = \frac{\mathbb{E}\{X_{c_{k,n,s}}\}}{1 - \sum_{j=1}^{k-1} \rho_{c_{j,n,s}}} + \frac{\sum_{j=1}^k \lambda_{c_{j,n,s}} \mathbb{E}\{X_{c_{j,n,s}}^2\}}{2(1 - \sum_{j=1}^{k-1} \rho_{c_{j,n,s}})(1 - \sum_{j=1}^k \rho_{c_{j,n,s}})}. \quad (17)$$

After each channel assignment, the sets of available primary and secondary queues in the  $m$ -th and  $n$ -th channel, are reduced as

$$\mathcal{S}_{m,p} = \mathcal{S}_{m,p} \setminus \{i \mid W_{u,p} = W_{c_{i,m,p}}\}, \quad (18)$$

$$\mathcal{S}_{n,s} = \mathcal{S}_{n,s} \setminus \{k \mid W_{v,s} = W_{c_{k,n,s}}\}. \quad (19)$$

In addition, the average waiting time of the primary and secondary packets in the first proposed scheme are, respectively,

$$\bar{W}_p = \frac{\sum_{i=1}^{N_p} W_{i,p}}{N_p}, \quad \bar{W}_s = \frac{\sum_{i=1}^{N_s} W_{i,s}}{N_s}. \quad (20)$$

Based on the little law, in the second proposed scheme, the average number of primary and secondary packets in the queues of the considered multichannel cognitive radio network are given, respectively

$$\bar{m}_p = \bar{\lambda}_p(\bar{Q}_p + \bar{I}_p) = \bar{\lambda}_p(\bar{W}_p - \bar{T}_p), \quad (21)$$

$$\bar{m}_s = \bar{\lambda}_s(\bar{Q}_s + \bar{I}_s) = \bar{\lambda}_s(\bar{W}_s - \bar{T}_s), \quad (22)$$

in which  $\bar{m}_p$ ,  $\bar{\lambda}_p$ ,  $\bar{Q}_p$ , and  $\bar{I}_p$  are the average number of primary packets in the cognitive radio network, the primary average arrival rate, the primary average queuing time, and the primary average interruption

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#### Algorithm 1 Context Aware Channel Assignment Approach

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- 1: **for** the packets in the first priority class of the primary and secondary networks, **do**
  - 2: The primary and secondary channel assignment is done via (10)-(13).
  - 3: After the channel assignment, the first priority queue is reduced from the sets of available primary and secondary queues in the  $m$ -th and  $n$ -th channel, respectively.
  - 4: **end for**
  - 5: **for** the primary packets in the  $u$ -th priority class ( $2 \leq u \leq N_p$ ), and the secondary packets in  $v$ -th priority class ( $2 \leq v \leq N_s$ ), **do**
  - 6: The primary and secondary channel assignment is done via (14)-(17).
  - 7: After each channel assignment, the sets of available primary and secondary queues in the  $m$ -th and  $n$ -th channel, are reduced via (18) and (19).
  - 8: **end for**
- 

time, respectively. In addition,  $\bar{m}_s$ ,  $\bar{\lambda}_s$ ,  $\bar{Q}_s$ , and  $\bar{I}_s$  are the average number of secondary packets in the cognitive radio network, the secondary average arrival rate, the secondary average queuing time, and the secondary average interruption time, respectively. According to the little law, the average primary throughput and the average secondary throughput in the second proposed scheme are as follows, respectively

$$\tau_p = \frac{\bar{m}_p}{\bar{W}_p} = \frac{\bar{\lambda}_p(\bar{W}_p - \bar{T}_p)}{\bar{W}_p}, \quad (23)$$

$$\tau_s = \frac{\bar{m}_s}{\bar{W}_s} = \frac{\bar{\lambda}_s(\bar{W}_s - \bar{T}_s)}{\bar{W}_s}, \quad (24)$$

where  $\tau_p$  and  $\tau_s$  are the average throughput of the primary and the secondary network, respectively. The proposed channel assignment approach is summarized in Algorithm 1.

## 4. Simulation Results

For our simulation, the time slot duration and the maximum cognitive radio network bandwidth at each channel are assumed to be 25 ms and 2 MHz, respectively. It is assumed that there exist 6 parallel channels in the considered cognitive radio network. Each channel in the cognitive radio network has a random bandwidth in the range [0, 2] MHz. In the considered cognitive radio network, there exist 6 primary users and 6 secondary users, in which each user has one packet either video or data. For simulation results in Fig. 4, 5 and 6, the arrival rate of primary video packets is in the range [0, 6] packets per time slot and the arrival rate of primary data packets is 3 packets

per time slot. In addition, the arrival rates of secondary video and data packets are 6 and 3 packets per time slot, respectively. On the other hand, for simulation in Fig. 7, the arrival rate of primary video packets is 6 packets per time slot and the arrival rate of primary data packets is 3 packets per time slot. Furthermore, the arrival rates of secondary video and data packets are in the range of  $[0, 6]$  and 3 packets per time slot, respectively. Here, as is common in practice, the video packets are longer and more sensitive to the delay. We assume that both the video and data packets of the primary network can have 3 different lengths. The primary data packet lengths are  $L_{1,p} = 25$  bytes,  $L_{2,p} = 35$  bytes and  $L_{3,p} = 45$  bytes. Furthermore, the primary video packet lengths are  $L_{4,p} = 55$  bytes,  $L_{5,p} = 65$  bytes and  $L_{6,p} = 75$  bytes. It is assumed that the secondary network has the same size video and data packets as the primary network.

It is commonly assumed that the distribution of the service time of the video and data packets are exponential [14]. Then, by using an exponential distribution for the service time of the packets in the  $i$ -th priority class of the  $l$ -th channel, the second moment of the service time can be given by [9], [10]

$$\mathbb{E}[X_{c_i,l,p}^2] = \frac{2L_{c_i,l,p}}{B_l}, \quad \mathbb{E}[X_{c_i,l,s}^2] = \frac{2L_{c_i,l,s}}{B_l} \quad (25)$$

Fig. 4 shows the analytical and simulation results of the average waiting time of the primary and secondary video and data packets for the first prioritization procedure in the proposed context aware MAC scheme. Moreover, Fig. 5 compares the average waiting time of the primary and secondary video and data packets of our proposed policy with the policies in [10] and [12]. It can be seen from both figures that our analytical and simulation results are consistent with one another. In addition, Figs. 4 and 5 show that the first prioritization procedure in the proposed context aware scheme achieves lower average waiting time of the primary and secondary video and data packets compared with the policies in [10] and [12]. This improvement reaches up to 50% and 40% for the primary and secondary users, relative to [12] and [10], respectively.

Fig. 6 and 7 show the analytical and simulation results of the primary and secondary throughput for the second prioritization procedure in the proposed context aware MAC scheme, respectively. It can be seen from both figures that our analytical and simulation results are consistent with one another. In addition, in Fig. 6 and 7, we show the average primary and secondary throughput of the proposed second prioritization procedure for infinite and limited buffer size of 30 packets, the policies in [12], [11] and [10], and the traditional first come first serve scheme. As this figure shows, our proposed policy has better performance in terms of the average primary and secondary throughput compared with scheme proposed in [12], [11], [10] and

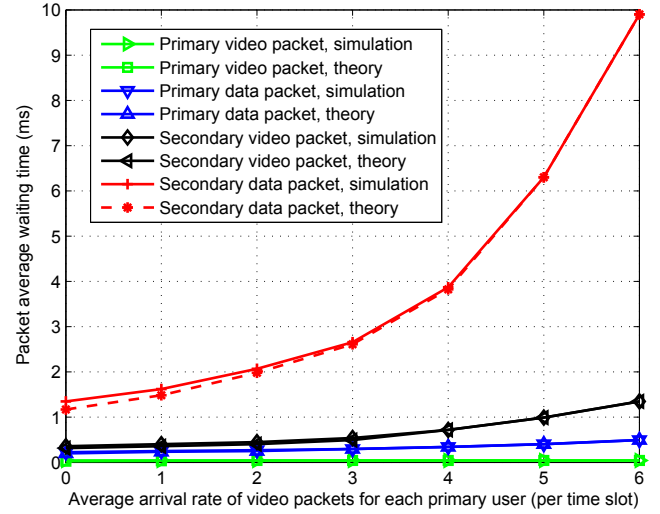


Figure 4. Experimental and analytical results of average waiting time of the primary and secondary video and data packets for first prioritization scheme in our proposed MAC scheme.

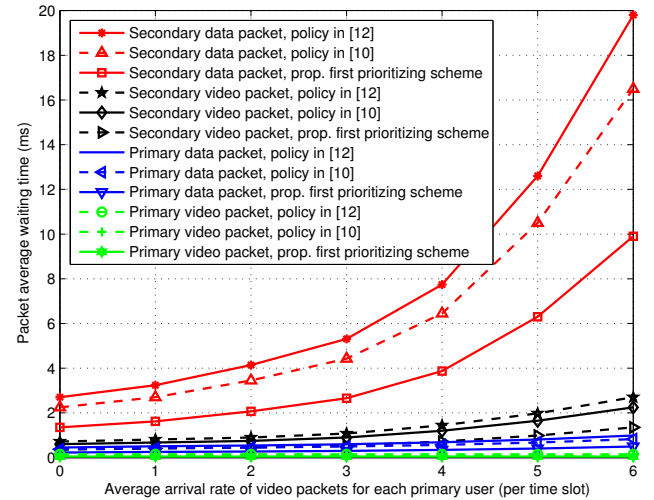
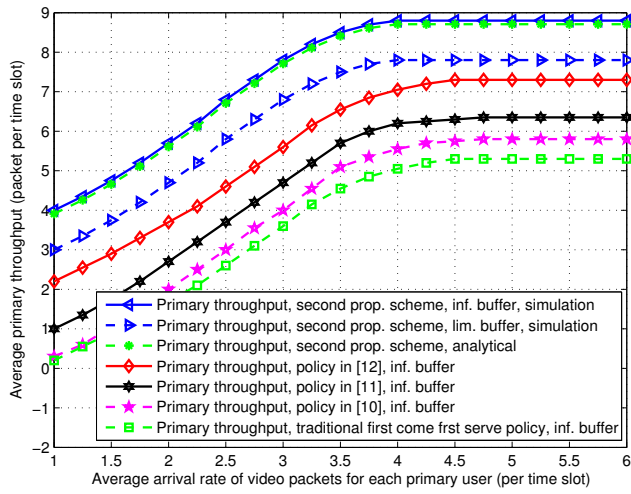


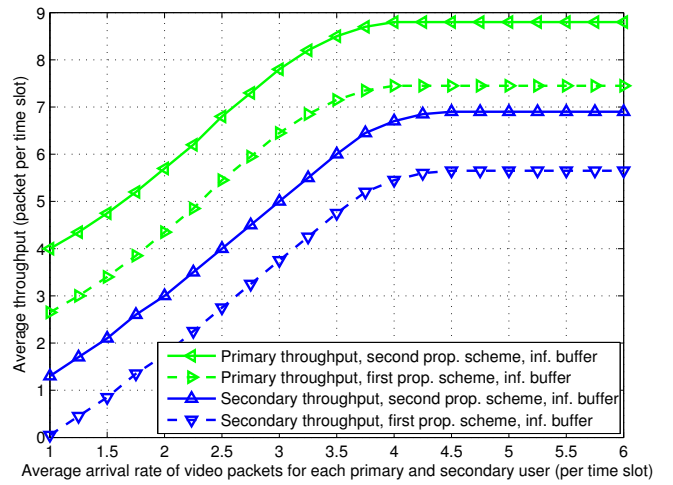
Figure 5. Average waiting time of the primary and secondary video and data packets for first prioritization scheme in our proposed scheme and the policy in [10].

first come first serve policy. This improvement reaches up to 20%, 38%, 52%, and 66% for the average primary and secondary throughput, relative to [12], [11], [10], and first come first serve policy, respectively.

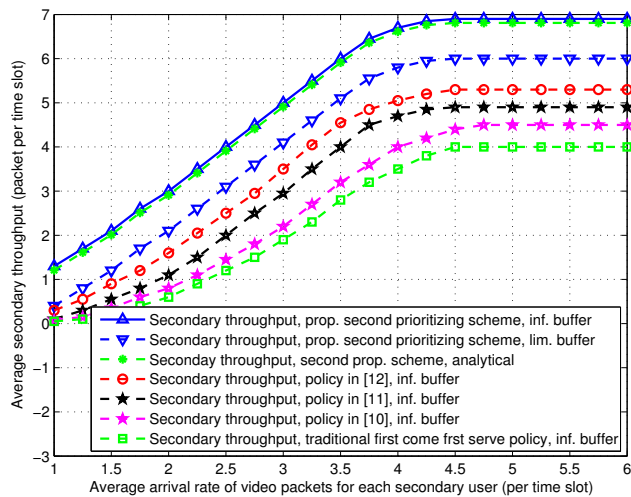
In Fig. 8 and 9, the average throughput and the packet average waiting time in the first and second proposed prioritization schemes are compared with each other, respectively. As can be seen from these figures, the first proposed policy has better performance in terms of average waiting time of the



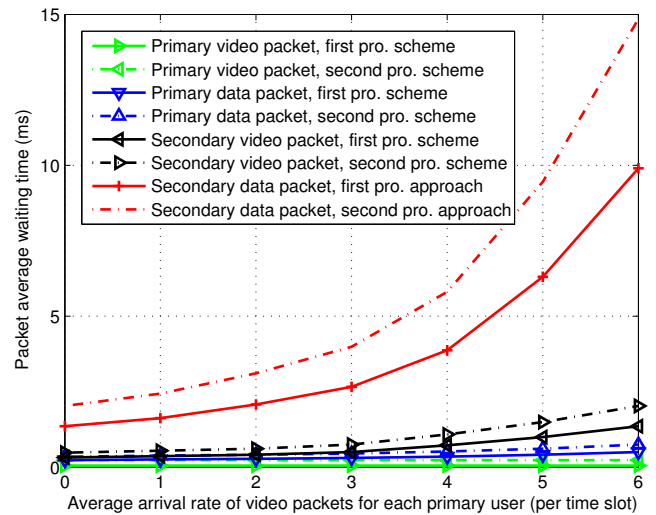
**Figure 6.** Experimental and analytical results of the primary throughput for second prioritization scheme in our proposed MAC scheme.



**Figure 8.** Comparison of the average throughput in the first and second proposed schemes.



**Figure 7.** Experimental and analytical results of the secondary throughput for second prioritization scheme in our proposed MAC scheme.



**Figure 9.** Comparison of the packet average waiting time in the first and second proposed schemes.

urgent video packets, but has worse average primary and secondary throughput compared with the second proposed policy. In addition, the second proposed protocol has better average primary and secondary throughput, while its average waiting time of primary and secondary video packets is worse than the first proposed prioritization scheme.

### 5. Conclusions

In this paper, we have introduced a novel context aware priority-based MAC scheme for the cognitive

radio network such that the average waiting time of the primary and secondary packets are managed more efficiently based on the context of the packets. Two different context aware prioritization approaches have been proposed. In the first prioritization method, more delay sensitive packets in both the primary and secondary networks are given a higher priority compared to delay tolerant packets. In the second prioritization procedure, shorter packets in both the primary and secondary networks are given a higher priority compared to longer packets and are transmitted through channels with lower service time. In addition, we have investigated the performance



of the proposed scheme in terms of the average waiting time of the packets and average throughput. Simulation results have been shown that the first channel assignment in the proposed scheme reduces the average waiting time for both the primary and secondary video and data packets of up to 50% and 40% when compared to shortest queue rule in [10] and queuing channel assembling protocol in [12], respectively. Furthermore, second channel assignment in the proposed context aware policy outperforms the proposed schemes in [12], [11], [10] and first come first serve policy in terms of the average primary and secondary throughput. This improvement reaches up to 20%, 38%, 52%, and 66% for the average primary and secondary throughput, relative to [12], [11], [10], and first come first serve policy, respectively.

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