Improving the Quality of Service for Users in Cognitive Radio Network Using Priority Queueing Analysis

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Abstract:

The usage of the radio spectrum for wireless communication is considered to be inefficient. Therefore, through cognitive radio, unlicensed users can occupy idle spectrum bands without interference with the primary user. Generally, when the arrival rate of licensed users is high, secondary users may starve. In this paper, we propose two models to improve the average total waiting time for the secondary user. They are the M/D/1 model of a primary user delay system with non-pre-emptive priority and pre-emptive priority. They are compared to an M/D/1 model with primary user delay. Numerical analysis and Monte Carlo simulation are performed for all results. Improvements in the average total waiting time of 13%-18% for primary user and 24%-32% for secondary user in the non-pre-emptive priority scheme are obtained. In the pre-emptive priority scheme, 19%-22% and 5%-7% improvement are obtained for the primary and secondary user respectively. Furthermore, same models, but with finite buffer capacity for both users are investigated to model a real-time system. In these schemes, the system improves the average total waiting time by 20%-42% for the primary user and 34%-42% for the cognitive radio with non-pre-emptive priority. Similarly, the pre-emptive model shows 25%-44% and 6%-24% reduction in the primary and secondary user waiting times respectively.

1 Introduction

Investigations conducted by regulatory bodies, such as the FCC and Ofcom, revealed that some segments of the licensed radio spectrum are underutilised, to as low as 5% [1][2]. The underutilisation is indicated by large patches of white space [1], which can be occupied by secondary users (SUs).

SUs are required to possess some particular capabilities for operating in the primary frequency bands. The necessary specifications of this user include the ability to detect and sense its surroundings. It is basically a radio which enables identification of unoccupied licensed bands and undertakes transmission, as well as, vacates the frequency band upon appearance of a primary user (PU). These functions provide better spectrum efficiency and utilisation and the device offering such a service is better known as the cognitive radio (CR) [3].

In [4], a queueing system based on the M/D/1 model with infinite buffer size is studied with the scheme consisting of a PU delay (which is the number of time slots that PU packet is delayed before transmission). In our paper, a combination of the above technique, specifically the PU delay together with the non-pre-emptive and pre-emptive priorities are proposed. The aim of the two schemes is to provide both the PU and SU with reduced waiting times in the CR system without harmful effects on their quality. The delay models are further investigated by proposing finite buffer capacity for both users.

The remainder of the paper is outlined as follows. Section 2 provides a review of the literature in the area. Section 3 presents the derivation of the mathematical model required to evaluate the performance of the system. Section 4 shows the numerical analysis and the Monte Carlo simulations of the different models. The results are critically analysed. Section 5 concludes with an overall evaluation of the work.

2 Literature Review

Cognitive radio was initially presented by Joseph Mitola and Gerald Maguire in 1999 [3]. In its cognition cycle through Radio Knowledge Representation Language (RKRL), the CR user analyses the spectrum pool through stimuli to perform the essential tasks [3] for proper operation, such as spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility [5]. Consequently, the CR system helps in addressing the issue of ineffective radio spectrum use by exploiting vacant frequencies. In turn, this provides better performance and allows more users to benefit from the spectrum. In doing so, the issues of harmful interference with PUs and the quality of service for SUs should be considered [6][7][8].

In many research work, such as [9][10], the preferred spectrum access method has been denoted as opportunistic spectrum access (OSA) and this approach refers to adaptable devices like the CR. CR is the unlicensed user, also known as SU, which has to identify and track the radio spectrum and ensure that it is unoccupied in order to provide its service. However, as soon as the PU is detected, the CR has to vacate the spectrum. The notion of OSA in CR is reflected in [9][10][11][12].

In this work, the queueing analysis model is used for evaluating the efficiency of the CR network in order to enhance the grade of service (or quality of service (QoS)) [13]. The work in [9][14][15] make use of the queueing analysis and OSA to provide important results concerning the cognitive radio spectrum access. In queueing systems, since the QoS is of crucial importance, some of the performance measures are mean total waiting time, blocking probability and throughput. Research works in [4][9] incorporate the packet delay analysis for different users using the queueing models. In [16], the authors consider the analysis of an OSA system using a queueing model functioning with service interruptions. The paper makes use of the Markov chain model, to assess the system's performance. The M/D/1 queueing model is a special case, derived from the M/G/1, with similar characteristics, except for the deterministically distributed service time [13][17].

Analytically, priority queueing models, such as non-pre-emptive and pre-emptive priorities, are employed to enhance the QoS for a particular class of user over other classes [13]. In [18], the worst case scenario of the non-pre-emptive model for M/G/1 is compared to the average result model. A two queue system of M/G/1 and M/D/1 models, employing vacation queueing approach is studied in [19] and the traffic behaviour of SU is analysed in [20] for a pre-emptive model. Similarly, the pre-emptive priority model is considered in [21], but with a retrial rate of the user packet. Since the service for the SU is interrupted in the pre-emptive priority, there are various techniques for re-starting its transmission such as Resume, Repeat-Identical and Repeat-Different. The Pre-emptive Resume Priority is studied in [22] which proposes a generalised analytical framework for spectrum management. Similarly, in [23], the model together with non-pre-emptive priority is presented. Conversely, in [24], the Pre-emptive Repeat Priority is modelled for different spectrum access strategies of the SUs.

In our paper, we propose novel schemes which combine the PU delay and the priority queueing models. They are possible solutions for enhancing the average total waiting times of both the PU and the SU compared to previous models such as the work in papers [4][9]. The presented systems are further modelled with finite buffer capacity to provide a realistic approach for a reliable solution. The main advantage is considered to be an improvement in the average total waiting time of the users.

The addition of the PU delay decreases the SU waiting time to prevent its starvation. Therefore, the work in this paper can be used to design applications for bandwidth demanding multimedia (data, audio and video). Another possible implementation of this work is for mobile application [25]. Since our paper is based on opportunistic spectrum sharing, our schemes can also be used in white space TV bands for secondary access [26].

3 System Methodology

The performance of the different proposed schemes is evaluated by considering the PU and the SU average total waiting times for the different scenarios. First, a PU delay model, which has been adapted to provide better QoS for the SU in [4] is studied with the priority queueing models. These schemes with infinite buffer size are proposed for performance evaluation. The same schemes are then put forward, but with finite buffer size. For all the schemes, the M/D/1 model is taken into account for both the PU queue and the SU queue.

Table 1 Model Parameters

Symbol	Explanation
λ_P	Primary arrival rate
λ_S	Secondary arrival rate
μ	Service rate
μ_P	Service rate of primary user
μ_S	Service rate of secondary user
$\overline{X} = E[X] = {}^{1}/_{\mu}$	Average service time
$\overline{X_P}$	Average service time of primary user
$\overline{X_S}$	Average service time of secondary user
N_Q^P	Average number of packets in the queue for the primary user
N_Q^S	Average number of packets in the queue for the secondary user
W_Q^P	Average waiting time for the primary user in queue

W_Q^S	Average waiting time for the secondary user in queue
W_P	Average total waiting time for the primary packet in the system
W_S	Average total waiting time for the secondary packet in the system
$W_P(d = i)$	Average total waiting time for the primary packet in the system after being delayed by *i* time slot
$W_S(d = i)$	Average total waiting time for the secondary packet in the system after delaying primary packet by *i* time slot
$\rho^P = {\lambda_P}/{\mu_P}$	Traffic density for the primary queue
$\rho^S = {\lambda_S}/{\mu_S}$	Traffic density for the secondary queue
d	Number of time slots that is delayed for the transmission of PU's packet (or PU delay)
W_0	Mean time until the packet terminates, if it is in the channel for transmission
r_k	Probability that a packet being served is of class k
m	Buffer size (or number of waiting positions) measured by the number of packets
C_k	Mean completion time for class k
k	Integer = 1 (primary), 2 (secondary), … , R
R	Last class packet
Z_j	State probability that j packets exist at an arbitrary point in time in the steady state

Note that the average total waiting time for the packet in the system, W_k, is the summation of the average service time of the user, $\overline{X_k}$, and average waiting time for the user in queue, W_Q^k.

$$W_k = \overline{X_k} + {W_Q}^k$$

3.1 M/D/1 with PU delay [4]

The work in [4] is based on the M/D/1 priority queueing model and the scheme includes a PU delay, which is the number of time slot(s) that is delayed for the transmission of PU's packet(s), which improves the SU waiting time preventing starvation. The delay will vary according to the number of times a delay is requested, and depending on the particular application, that this scheme is being used for. This model includes a delay time, T_D, until the beginning of a time slot [4]. Figure 1 shows the block diagram for the scheme proposed in [4].

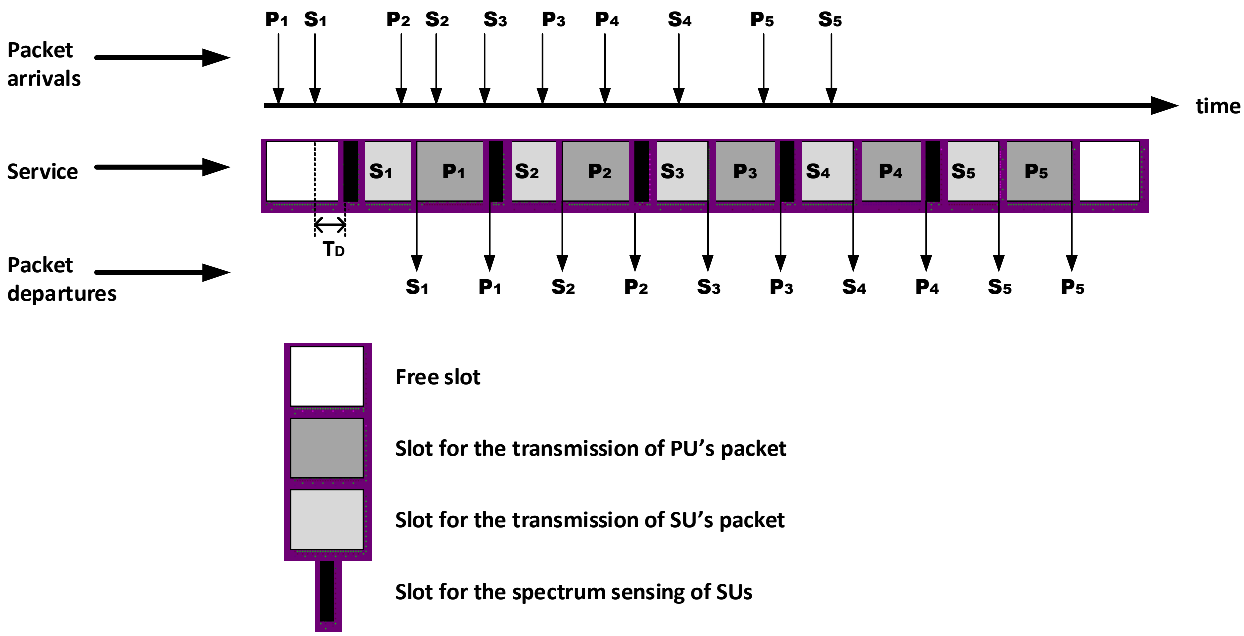

Fig. 1: *Block diagram for the scheme in [4]*

3.2 Scheme 1: M/D/1 with PU delay and non-pre-emptive priority model

In Scheme 1, the model presented in section 3.1 which uses PU latency [4], is enhanced with non-pre-emptive priority. The PU packet is delayed for a specified number of timeslot (in Figure 2, PU delay, $d = 1$). Therefore, the PU packet cannot interrupt the transmission, if there is a SU packet being served. Infinite buffer and no delay time are assumed. In this scheme, even though, there is no SU in the queue, the PU packet is still delayed and is transmitted in the next time slot. This model does not include the delay time, T_D, until the beginning of a time slot.

3.2.1 Block diagram for Scheme 1:

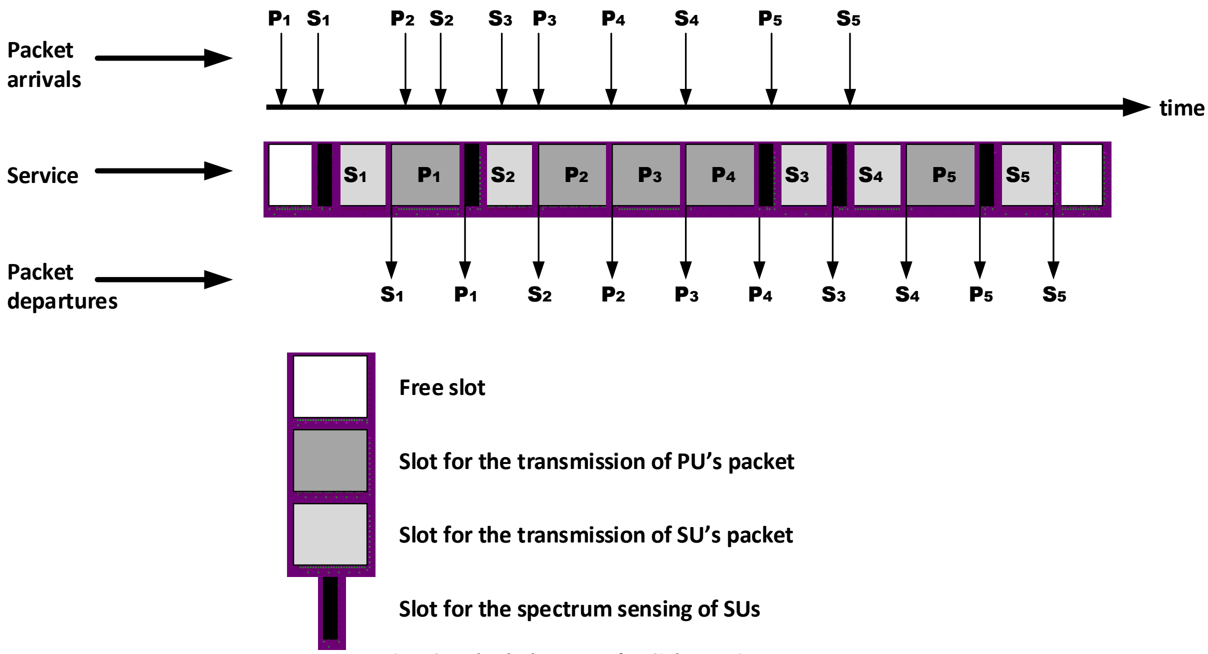

Fig. 2: *Block diagram for Scheme 1*

Figure 2 shows the M/D/1 model with PU delay merged with non-pre-emptive priority. The primary user packets are defined as P_i, and the secondary user packets are defined as S_i, where i is an integer. This scheme assumes that P_i is delayed by d = 1 on arrival. Thus, S_1 takes the time slot upon arrival. While S_1 is being serviced, P_1 (which does not pre-empt S_1 due to non-pre-emptive model) waits in its queue, after d = 1. After S_1, P_1 is transmitted and during that period P_2 and S_2 arrive. When the slot is empty, P_2 is delayed permitting S_2 to go first due to the PU delay, d = 1. Afterwards, P_2 exits the channel and P_3 (which has already gone through a PU delay, d = 1,) takes the next time slot, making S_3 wait. Then, P_4 occupies the channel after the PU delay, followed by S_3 and S_4 respectively. The model keeps repeating for other packets.

3.2.2 Equations for Scheme 1

In scheme 1, the average total waiting time of the tagged PU packet includes the mean service time and the service times of current PU and SU (if present) for the non-pre-emptive system.

The generic equation for the average total waiting time, assuming the PU delay is i (an integer) timeslots, is derived as follows. The derivation for the first term is provided in Appendix 1.

$$W_{Q(NPr)}^{P}(d=i)=\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2}+\frac{\lambda_S}{{\mu_S}^2}\right)+\frac{N_Q^P}{\mu_P}+\frac{i}{\mu_S} \tag{1}$$

Then, using Little's hypothesis, $N_Q=\lambda W_Q$,

$$W_{Q(NPr)}^{P}(d=i)=\frac{\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2}+\frac{\lambda_S}{{\mu_S}^2}\right)+\frac{i}{\mu_S}}{1-\rho^P} \tag{2}$$

Next, the average service time of the primary user, $\overline{X}_P$, is added to obtain the average total waiting time of the tagged PU packet.

$$W_{P(NPr)}(d=i)=\overline{X}_P+W_{Q(NPr)}^{P}(d=i) \tag{3}$$

The equation of the average total waiting time of the PU in Scheme 1 is as shown.

$$W_{P(NPr)}(d=i)=\overline{X}_P+\frac{\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2}+\frac{\lambda_S}{{\mu_S}^2}\right)+\frac{i}{\mu_S}}{1-\rho^P} \tag{4}$$

The mean total waiting time of the tagged SU packet is expressed afterwards. It sums the mean service time, together with the service time of the tagged SU packet and the total service times of the PU and SU. It does not depend on the subsequent arrivals at the PU queue.

$$W_{Q(NPr)}^{S}(d=i)=\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2}+\frac{\lambda_S}{{\mu_S}^2}\right)+\frac{N_Q^P}{\mu_P}+\frac{N_Q^S}{\mu_S} \tag{5}$$

By using Little's theorem, this follows as shown.

$$W_{Q(NPr)}^{S}(d=i)=\frac{\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2}+\frac{\lambda_S}{{\mu_S}^2}\right)}{(1-\rho^P)(1-\rho^S)} \tag{6}$$

Finally, adding the average service time of secondary user, $\overline{X}_S$, results in the expression as follows.

$$W_{S(NPr)}(d=i) = \overline{X}_S + W^S_{Q(NPr)}(d=i) \tag{7}$$

The equation of the average total waiting time for the SU in Scheme 1 is obtained.

$$W_{S(NPr)}(d=i) = \overline{X}_S + \frac{\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2} + \frac{\lambda_S}{{\mu_S}^2}\right)}{(1-\rho^P)(1-\rho^S)} \tag{8}$$

For the purpose of simulation in this paper, the following two equations are obtained, after the assumption of $service\ time = \overline{X}_S = \overline{X}_P = 1\ time\ slot$ is applied.

$$W_{P(NPr)}(d=i) = 1 + \frac{\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2} + \frac{\lambda_S}{{\mu_S}^2}\right) + \frac{i}{\mu_S}}{1-\rho^P} \tag{9}$$

$$W_{S(NPr)}(d=i) = 1 + \frac{\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2} + \frac{\lambda_S}{{\mu_S}^2}\right)}{(1-\rho^P)(1-\rho^S)} \tag{10}$$

3.3 Scheme 2: M/D/1 with PU delay and pre-emptive priority model

Scheme 2 proposes to improve the average total waiting time of the PU at the expense of the QoS of the SU. This is due to the dependence of the performance for the SU on the PU arrival rate.

In this model, the pre-emptive priority system combined with the model in [4] is proposed. The PU packet is to be delayed for a specified number of time slots. However, after the PU delay, if there is a SU packet being served, the PU packet can interrupt the transmission for its service. Though, this depends on the arrival of the packets. The PU packet is delayed for d = 1 as shown in Figure 3. Similar to the non-pre-emptive priority with PU delay scheme, infinite buffer capacity is assumed. Furthermore, this scheme does not include the delay time, T_D, until the beginning of a time slot, compared to the Scheme in [4].

3.3.1 Block diagram for Scheme 2:

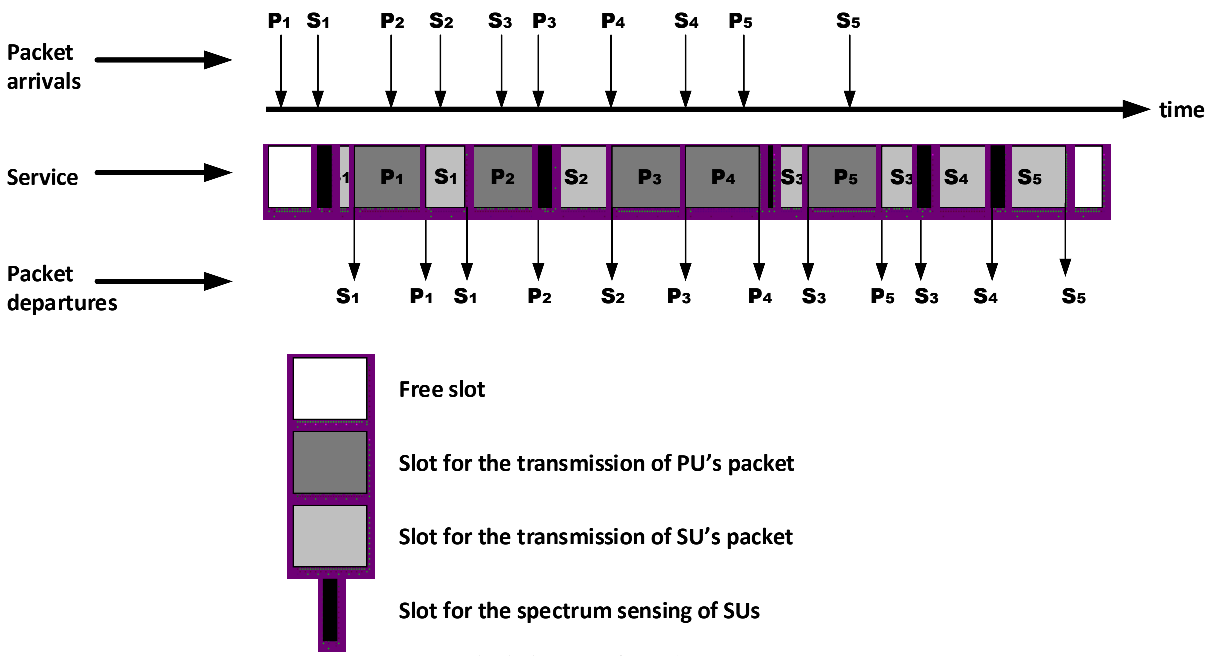

Fig. 3: *Block diagram for Scheme 2*

The M/D/1 model with PU delay and pre-emptive priority is illustrated in Figure 3. PU packet, P_1, is not served upon its arrival, due to PU delay, d = 1. Hence, it is possible for S_1 to transmit as soon as it arrives. However, after the PU delay, P_1 then pre-empts the current service for its transmission. During the transmission of P_1, P_2 arrives and undergoes a PU delay, d = 1. After the transmission of P_1, S_1 completes its service. Then, P_2 occupies the channel, since its PU delay is over. During this interval, S_2 and S_3 wait in the SU queue, and upon the completion of P_2's transmission, then S_2 enters the next time slot. Hence, S_2 is served and P_3 (which is delayed by d = 1) is transmitted afterwards. This is followed by the transmission of P_4, which has already waited for a PU delay, d = 1. Subsequently, S_3 transmits after P_4. However, after the PU delay, P_5 interrupts S_3 due to pre-emption and it starts transmitting. Afterwards, S_3 proceeds with its service, followed by the transmission of S_4 and S_5.

3.3.2 Equations for Scheme 2

The expression for the average total waiting time of the tagged PU packet consists of the mean service time and the total service times of PU and SU packets in the system. It is also delayed by i instances before it transmits and hence, it is as follows.

$$W_{Q(Pr)}^{P}(d=i)=\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2}\right)+\frac{N_Q^P}{\mu_P}+\frac{i}{\mu_S} \tag{11}$$

Using Little's theorem, we obtain

$$W_{Q(Pr)}^{P}(d=i)=\frac{\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2}\right)+\frac{i}{\mu_S}}{1-\rho^P} \tag{12}$$

Eventually, the equation for the average total waiting time of the PU packet is obtained.

$$W_{P(Pr)}(d=i)=C_P+W_{Q(Pr)}^{P}(d=i) \tag{13}$$

Where, C_P is the mean completion time [13] and it is provided in the Appendix 2. The equation of the average PU waiting time is obtained.

$$W_{P(Pr)}(d=i)=\overline{X}_P+\frac{\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2}\right)+\frac{i}{\mu_S}}{1-\rho^P} \tag{14}$$

For the tagged SU packet, the mean waiting time in the system aggregates the mean service time, the average service times of all PUs and SUs present and that of the tagged packet as well. This results in the following expression.

$$W_{Q(Pr)}^{S}(d=i)=\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2}+\frac{\lambda_S}{{\mu_S}^2}\right)+\frac{N_Q^P}{\mu_P}+\frac{N_Q^S}{\mu_S} \tag{15}$$

When Little's theorem is applied, it is as given:

$$W_{Q(Pr)}^{S}(d=i)=\frac{\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2}+\frac{\lambda_S}{{\mu_S}^2}\right)}{(1-\rho^P)(1-\rho^S)} \tag{16}$$

Last of all, the derivation ends with this resulting expression for the SU average total waiting time.

$$W_{S(Pr)}(d=i)=C_S+W_{Q(Pr)}^{S}(d=i) \tag{17}$$

Where, C_S is the mean completion time [13] and it is provided in the Appendix 2. The average total waiting time for SU is given as,

$$W_{S(Pr)}(d=i) = \frac{\overline{X}_S}{(1-\rho^P)} + \frac{\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2} + \frac{\lambda_S}{{\mu_S}^2}\right)}{(1-\rho^P)(1-\rho^S)} \tag{18}$$

Then, the previous assumption of one slot for service time is used and the equations of the average total waiting time for PU and SU are derived.

$$W_{P(Pr)}(d=i) = 1 + \frac{\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2}\right) + \frac{i}{\mu_S}}{1-\rho^P} \tag{19}$$

$$W_{S(Pr)}(d=i) = \frac{1}{(1-\rho^P)} + \frac{\frac{1}{2}\left(\frac{\lambda_P}{{\mu_P}^2} + \frac{\lambda_S}{{\mu_S}^2}\right)}{(1-\rho^P)(1-\rho^S)} \tag{20}$$

3.4 Scheme 3: M/D/1/m with PU delay and non-pre-emptive priority model

This section presents a model similar to that in Scheme 1, but it is undertaken with finite buffer capacity. All the assumptions are similar as well. However, the buffer size is finite for both PU and SU individually, which implies finite waiting room with *m* positions for the PU and *m* positions for the SU packets. The system can be evaluated through average total waiting time performance measure and the result is compared with that of Scheme 1.

3.4.1 Equations for Scheme 3

The equation for the mean number of waiting packets is obtained from [13], which provides the entire derivation for the finite buffer size model. The mean number of waiting packets, N_Q, is as follows,

$$N_Q = \sum_{j=1}^{m+1} (j-1)\, Z_j \tag{21}$$

where Z_j is the state probability and it is defined by the probability that j packets exist at an arbitrary point in time in the steady state.

The mean number of waiting PU and SU packets can be calculated from (21). For non-pre-emptive scheme with finite buffer, (21) is used in (1) and (5) for each user. Then, the mean completion time is added to obtain the average total waiting time, $W_{P(NPr)}(d = i)$ and $W_{S(NPr)}(d = i)$, of the specific user packet.

3.5 Scheme 4: M/D/1/m with PU delay and pre-emptive priority model

In Scheme 4, the model is similar to that of Scheme 2. However, the buffer capacity is considered to be finite. All assumptions are similar to Scheme 2. It comprises of finite buffer size for both PU and SU. This means finite waiting room with *m* positions for PU packets and *m* positions for SU packets. Basically, the average total waiting time is evaluated for comparison with the results of Scheme 2.

3.5.1 Equations for Scheme 4

The equation for the mean number of waiting packets is obtained from [13] for the finite buffer size model. The mean number of waiting packets, N_Q, is obtained using (21). It is used to calculate the mean number of waiting PU and SU packets. In the pre-emptive scheme with finite buffer, (21) is computed and used in (11) and (15) for each user. Lastly, the mean completion time is added to calculate the average total waiting time, $W_{P(Pr)}(d = i)$ and $W_{S(Pr)}(d = i)$ of the particular user packet.

4 Results and Discussion

The numerical and simulation results of the four schemes, described in section 3, are presented in this section. The work in [4], introduced in section 2, have been used to compare our results. All the result figures include plots from [4] as comparison. Monte Carlo simulation has been performed for all the results and they are included in all figure plots. In the legend of the graphs, the plot for the scheme proposed in [4] has been indicated as 'Scheme ref [4]'. The Monte Carlo simulation has been specified as 'MCS' and it is indicated by markers only. The numerical graph is shown as 'num' with the number of PU delays (d = 0, 1, 2) and it is indicated as lines.

4.1 Scheme 1: M/D/1 with PU delay and non-pre-emptive priority model

In this model, Scheme 1, the non-pre-emptive priority, presented in section 3.2, is assessed.

4.1.1 Simulations for Scheme 1:

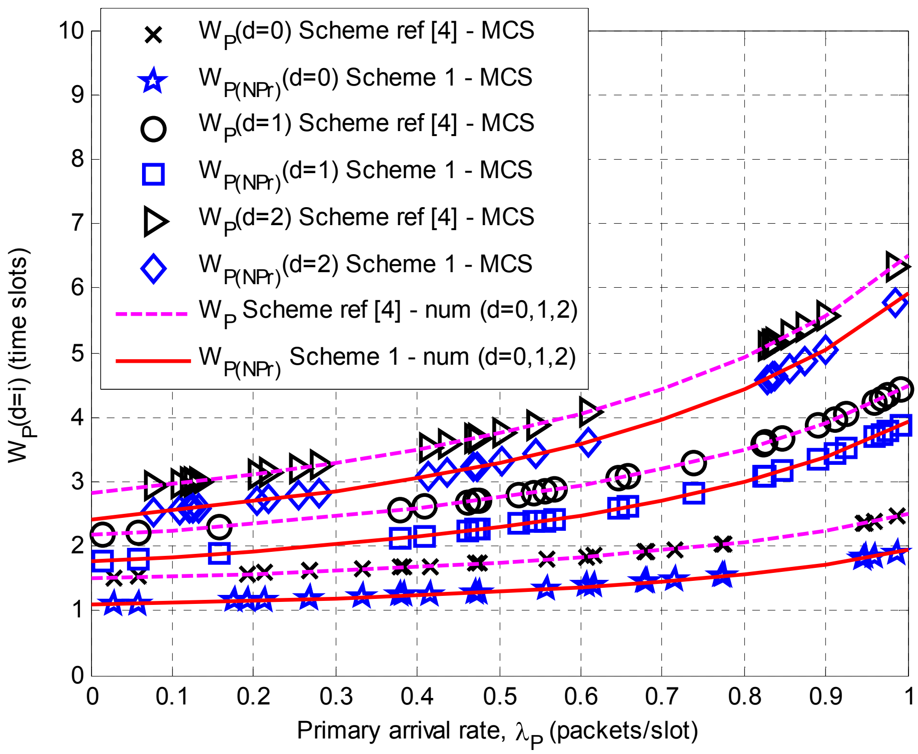

Fig. 4: *PU waiting time for Scheme 1*

Figure 4 shows the results of the M/D/1 model with non-pre-emptive priority including the PU delay, where the PU average total waiting time, $W_P(d = i)$ is displayed as a function of its arrival rate, λ_P. The figure displays the waiting time experienced by PU when the SU arrival rate is kept constant at $\lambda_S = 0.4$ and the PU delay is varied from 0 to 2. Both the PU and SU are considered to have equal service rate of $\mu_P = \mu_S = 1.5$. It can be observed that the PU average total waiting time increases as the number of delay, d, increases from $d = 0$ to $d = 2$. In comparison to the waiting time performance in [4], the average total waiting time of the PU for Scheme 1 is reduced for all λ_P, by approximately 13%-18% for $d = 1$. As shown in Figure 4, the Monte Carlo simulation results match the numerical analysis plots obtained from equations in section 3.2.

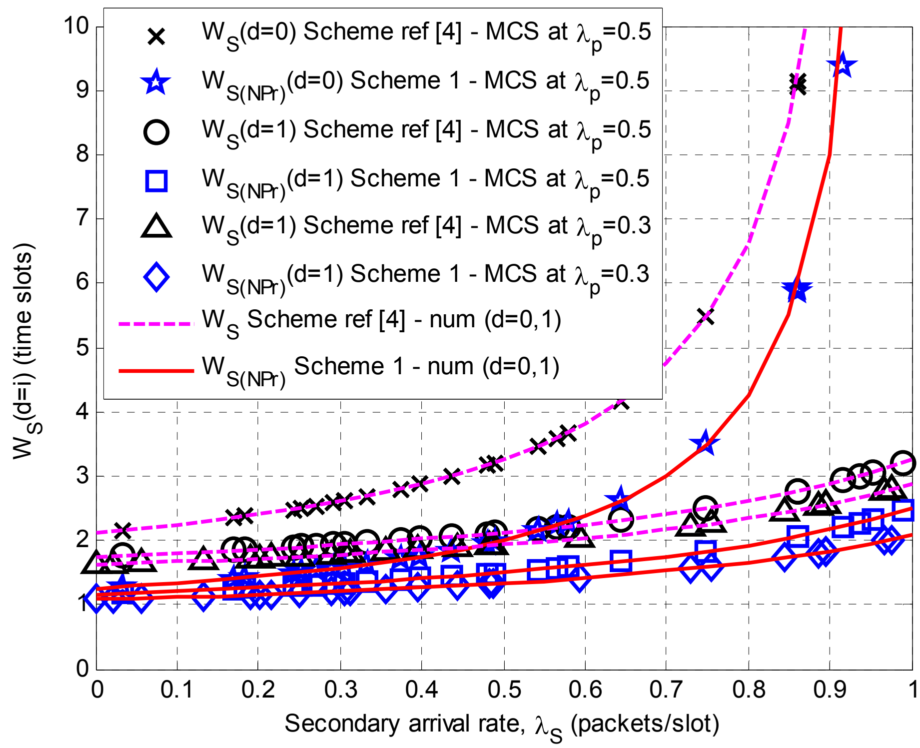

Fig. 5: *SU waiting time for Scheme 1*

Figure 5 shows the SU average total waiting time for the M/D/1 model with non-pre-emptive priority combined with PU delay. The SU waiting time, $W_S(d = i)$, is presented as a function of its arrival rate, λ_S. The waiting time for the SU is evaluated for fixed PU arrival rates of $\lambda_P = 0.5$ and $\lambda_P = 0.3$ and for PU delays of $d = 0, 1$. The PU and SU service rates are $\mu_P = \mu_S = 1.5$. It is observed that an increase in the PU arrival rate causes the SU waiting time to increase when there is no delay. At low PU arrival rate ($\lambda_P = 0.3$), it is observed that the waiting time for the SU decreases, when the PU is delayed by $d = 1$ in comparison to the scheme in [4]. Similarly, when the PU delay is varied from 0 to 1, at high PU arrival rate ($\lambda_P = 0.5$), it is observed that the SU waiting time decreases by 31.8% at $\lambda_S = 0.8$. Furthermore, the average total waiting time performance of the SU is reduced when compared to the SU waiting time in [4]. As shown in Figure 5, both the Monte Carlo simulation results and the numerical analysis plots (obtained from equations in section 3.2) correspond.

4.2 Scheme 2: M/D/1 with PU delay and pre-emptive priority model

The pre-emptive priority with PU delay model is defined in Scheme 2 in the section 3.3. In this model, we are trying to improve the PU waiting time without compromising the SU waiting time.

4.2.1 Simulations for Scheme 2:

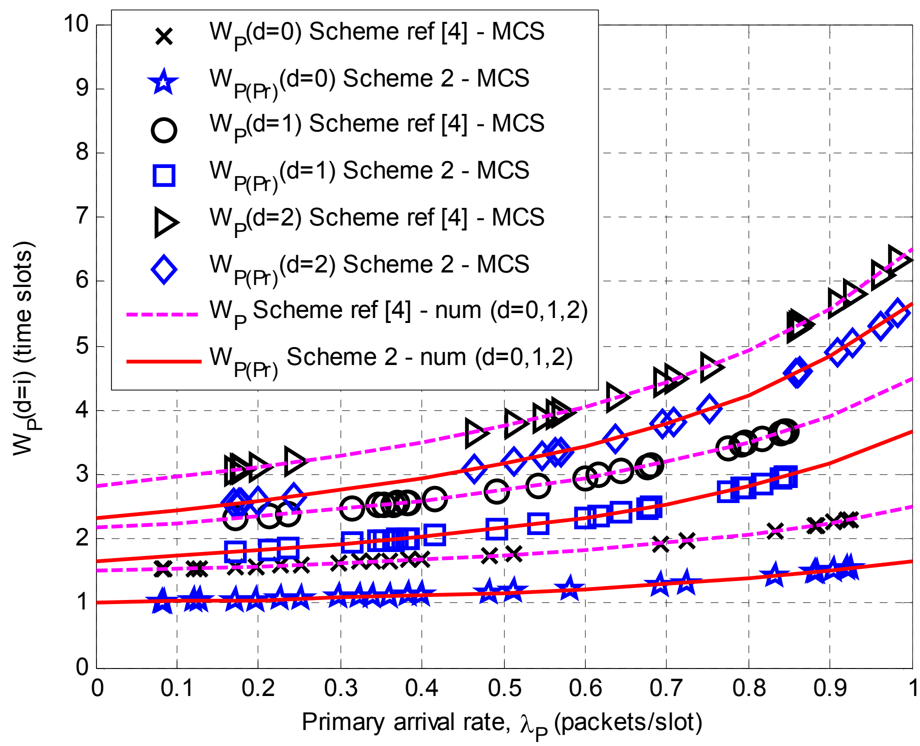

Fig. 6: PU waiting time for Scheme 2

Figure 6 represents the results of the M/D/1 model with pre-emptive priority including PU delay, where the PU average total waiting time, $W_P(d=i)$, is obtained as a function of PU arrival rate, λ_P. The service rate is $\mu_P = \mu_S = 1.5$ and the number of PU delays is varied from 0 to 2. As expected, the PU waiting time is observed to increase with an increase in PU delay. Nevertheless, at $\lambda_P = 1$, with $d = 1$, the average total waiting time is improved by approximately 18.5%, when compared to the PU waiting time performance in [4] and the PU waiting time improves by 6.8% when compared to Scheme 1 which is of non-pre-emptive nature. In Figure 6, it is noted that the Monte Carlo simulation results agree with the numerical analysis plots obtained from the equations in section 3.3.

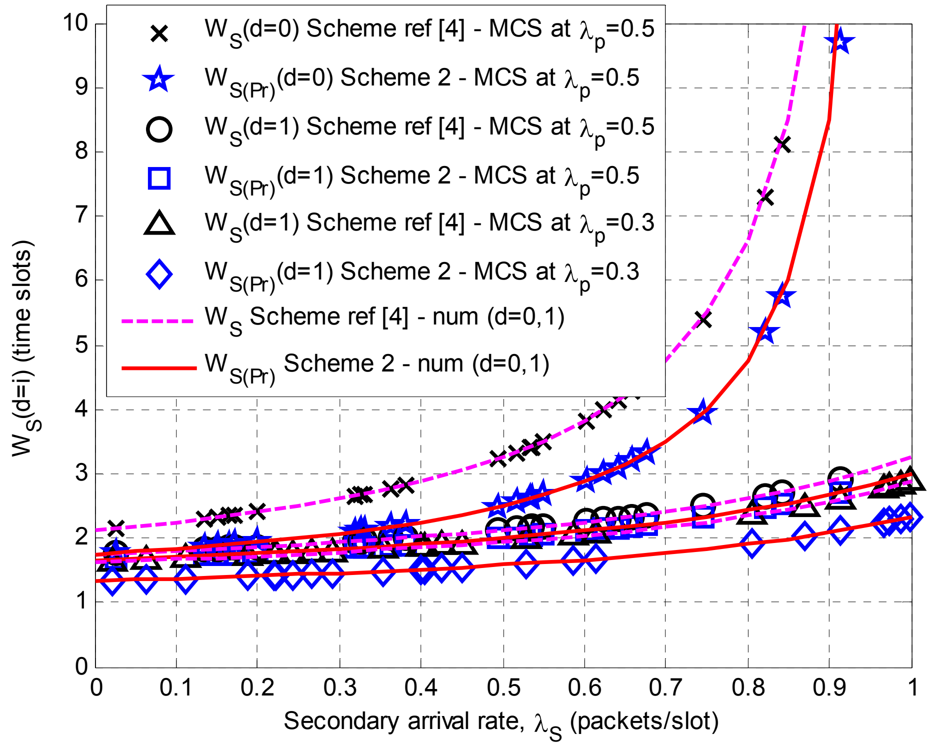

Fig. *7: SU waiting time for Scheme 2*

In Figure 7, the result of the M/D/1 with pre-emptive priority and PU delay request model is displayed with the SU average total waiting time, $W_S(d = i)$, displayed as a function of secondary arrival rate, λ_S. The SU average total waiting time is considered for fixed PU arrival rates, $\lambda_P = 0.5$ and $\lambda_P = 0.3$, with service rate, $\mu_P = \mu_S = 1.5$, and PU delay of $d = 0, 1$. When it is compared to [4], the SU waiting time decreases, but slightly less than that in Scheme 1, for $d = 1$ at both PU arrival rates. At PU arrival rate, $\lambda_P = 0.5$, there is a small decrease of 0.2 timeslot in SU average total waiting time. The small decrement in the SU waiting time is 6%, and the PU waiting time has improved compared to Scheme 1 and [4], as the PU is the licensed user. In Figure 7, the Monte Carlo simulation results are observed to match up with the numerical analysis plots obtained from equations in section 3.3.

4.3 Scheme 3: M/D/1/m with PU delay and non-pre-emptive priority model

In this section, the M/D/1/m model with PU delay and non-pre-emptive priority model is evaluated through PU and SU average total waiting times. For the simulations, the buffer size is taken to be $m = 50$ [27].

4.3.1 Simulations for Scheme 3:

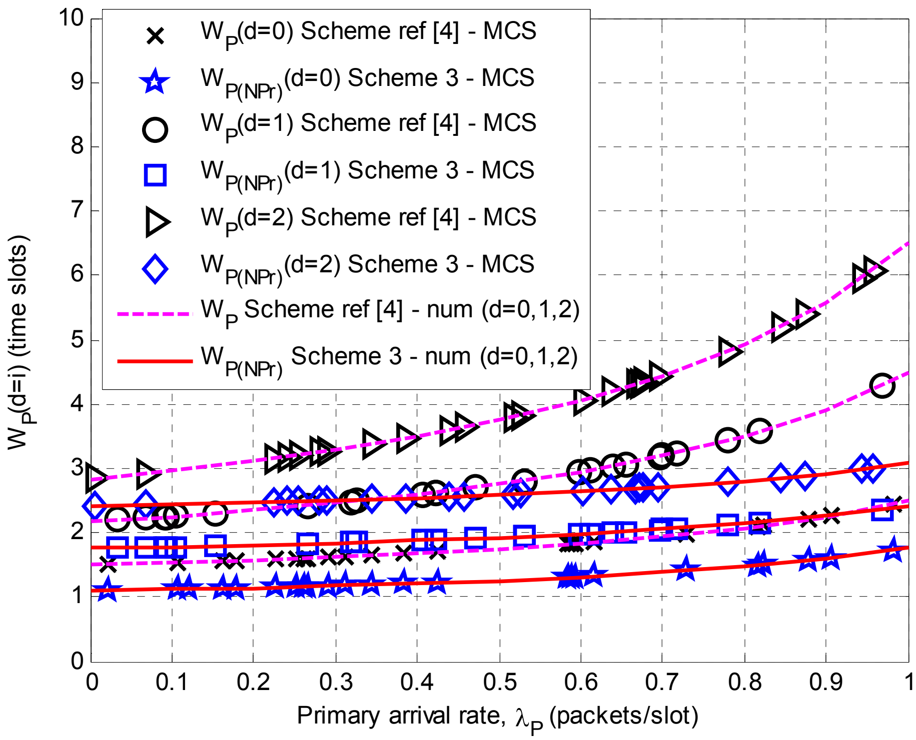

Fig. 8: *PU waiting time for Scheme 3*

Figure 8 displays the results for model similar to Scheme 1, but with finite buffer size, where $m = 50$ waiting positions for PU packets. The PU average total waiting time, $W_P(d = i)$ is displayed as a function of its arrival rate, λ_P and the following assumptions for the service rate, $\mu_P = \mu_S = 1.5$ and the SU arrival rate of $\lambda_S = 0.4$ for $d = 0, 1, 2$ are considered. The results in Figure 8 are compared to Figure 4, it is noted that at high PU arrival rate, the average total waiting time decreases significantly (for instance for $d = 1$, at $\lambda_P = 1$, it decreases by 38.4%). Hence, this model gives a better performance than that of Scheme 1 for high λ_P. As shown in Figure 8, the Monte Carlo simulation results match the numerical analysis plots obtained from the equations in section 3.4.

In Figure 9, the result of the PU delay with non-pre-emptive priority and finite buffer scheme is investigated with the SU average total waiting time, $W_S(d = i)$, as a function of the SU arrival rate. Similar service rate, $\mu_P = \mu_S = 1.5$, and fixed values of PU arrival rate, $\lambda_P = 0.5$ and $\lambda_P = 0.3$, as in Scheme 1, are considered. In comparison to Figure 5, it is observed that, for all λ_S, the SU average total waiting time for the non-pre-emptive model, $W_S(d = i)$, is significantly reduced for both, $d = 0, 1$. Therefore, the SU waiting time is further enhanced for $d = 1$ with the finite buffer model. This is shown, for the given λ_P, the maximum SU average total waiting time (for $d = 1$) is below 1.9 time slots, as opposed to Figure 5, where it is above 2 time slots at $\lambda_S = 1$. Therefore, the non-pre-emptive priority with finite buffer further improves the SU waiting time for all λ_S. In Figure 9, the Monte Carlo simulation results correspond with the numerical analysis plots obtained from the equations in section 3.4.

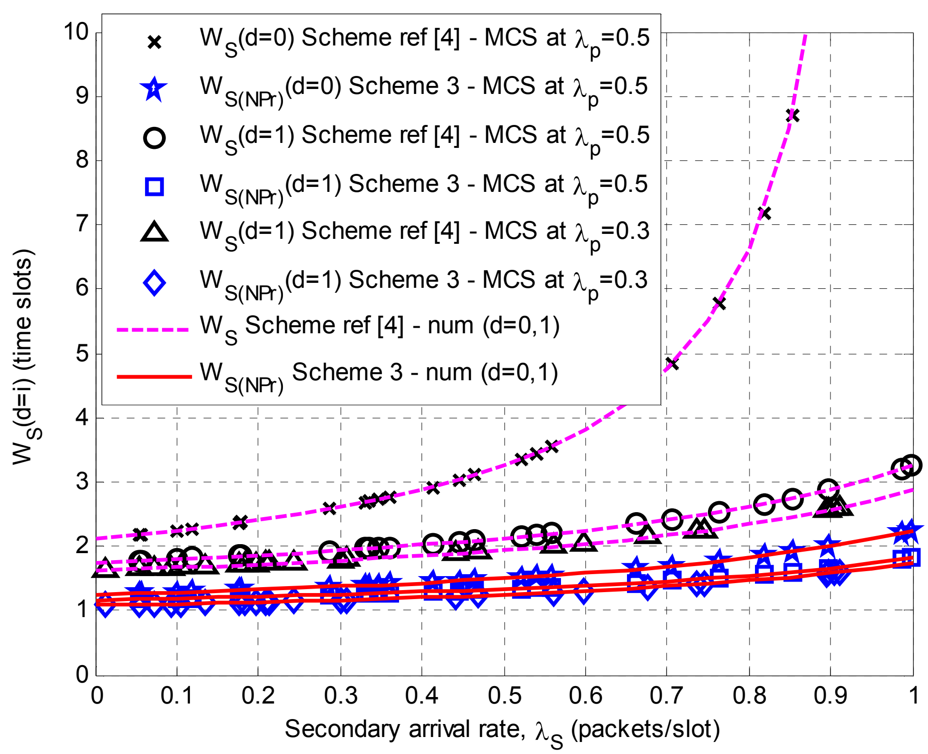

Fig. 9: *SU waiting time for Scheme 3*

4.4 Scheme 4: M/D/1/m with PU delay and pre-emptive priority model

This section presents the M/D/1/m model with PU delay and pre-emptive priority model. It is assessed by using the PU and SU average total waiting time. For the purpose of simulation, the buffer size is taken to be $m = 50$ [27].

4.4.1 Simulations for Scheme 4:

In Figure 10, the result of the PU average total waiting time with PU delay and pre-emptive priority for finite buffer size, $m = 50$, is observed. The PU waiting time, $W_P(d = i)$, is assessed as a function of the PU arrival rate. The SU arrival rate, $\lambda_S = 0.4$, and the service rate, $\mu_P = \mu_S = 1.5$, are taken into account as in Scheme 2. In comparison to Figure 6 at $\lambda_P = 1$, the PU waiting time, $W_P(d = 1)$, decreases drastically by 36%. For small values of λ_P, the waiting time is reduced by about 0.1 time slot. Thus, it can be deduced that the finite buffer scheme enhances the PU waiting time for all λ_P. In Figure 10, it is observed that the Monte Carlo simulation results agree with the numerical analysis plots obtained from equations in section 3.5.

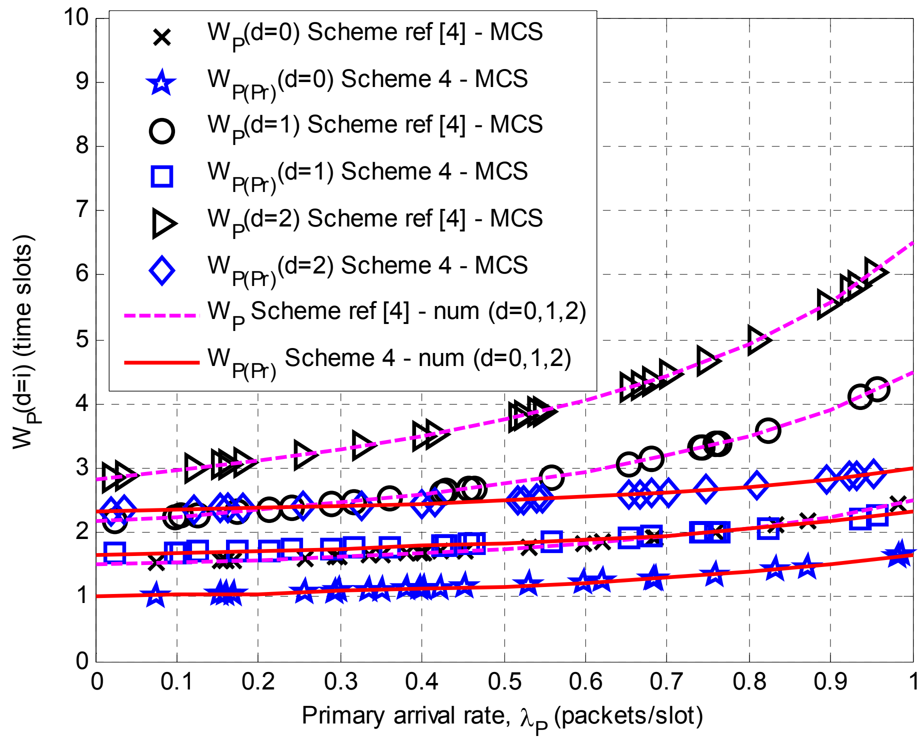

Fig. 10: *PU waiting time for Scheme 4*

Figure 11 displays the results for pre-emptive priority model as in Scheme 2, but with finite buffer size of $m = 50$. The SU average total waiting time is displayed as a function of its arrival rate. Assumptions for fixed PU arrival rates, $\lambda_P = 0.5$ and $\lambda_P = 0.3$, and the service rate, $\mu_P = \mu_S = 1.5$, are considered. For $\lambda_P = 0.3$, the SU waiting time, $W_S(d = 1)$, is reduced at large values of λ_S, compared to Figure 7. However, at small values of λ_S, the SU waiting time decreases marginally compared to Figure 7, for instance, at $\lambda_S = 0.2, W_S(d = 1)$ at $\lambda_P = 0.5$ changes very slightly for pre-emptive priority. Therefore, for all λ_P, the SU waiting time, $W_S(d = 1)$, improves slightly as opposed to Figure 7, but there is a significant decrease, when compared to the SU waiting time performance in [4]. As shown in Figure 11, the Monte Carlo simulation results match the numerical analysis plots obtained from equations in section 3.5.

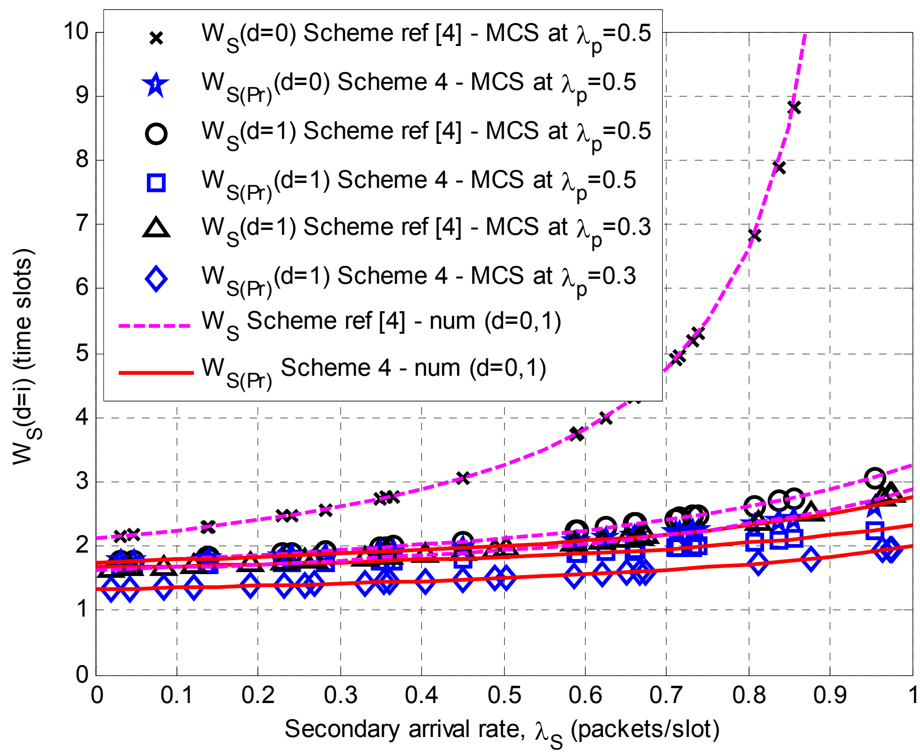

Fig. 11: SU waiting time for Scheme 4

5 Conclusion

Radio spectrum, which is utilised for wireless communication, is a scarce resource. In this work, various OSA schemes are investigated to provide both the PU and SU with better QoS. This paper presents the novel priority queueing models with PU delay and finite buffer size, which has shown to significantly improve the QoS of both PU and SU. With the model in [4] only, the SU faces no difficulty in being served without waiting too long. However, the PU undergoes a slight increment in its waiting time. Hence, further research is undertaken in this paper by involving the priority models with the PU delay. Based on previous studies, the non-pre-emptive priority with PU delay brings about additional reduction in the SU average total waiting time. Likewise, the performance in the PU average total waiting time is also much improved through the pre-emptive priority with PU delay model. The non-pre-emptive priority and PU delay combination undeniably has a positive impact on the system compared to the PU delay model in [4]. This ranges from 13% to 18% and from 24% to 32% for the reduction in PU and SU waiting time respectively, for a delay $d = 1$. Furthermore, the pre-emptive priority with PU delay model improves in the range 19% to 22% for the PU and 5% to 7% for the SU.

In the different schemes shown by figures 4-7, the assumption is infinite capacity and it positively improves the network performance. However, for more realistic scenarios, the system is assumed to use finite buffer size of $m = 50$ for both PU and SU, as shown in Schemes 3 and 4. The results shown in figures 8-11 improve compared to the results of schemes 1 and 2. As opposed to [4], the non-pre-emptive scheme with finite capacity causes a decrement in the range of 34% to 42% and 20% to 42% for a delay, $d = 1$, in the waiting times of the SU and PU respectively. Even the pre-emptive scheme with finite buffer size results in a reduction ranging from 25% to 44% and 6% to 24% for PU and SU waiting times respectively for a delay of, $d = 1$. All the schemes have been evaluated using numerical calculations and Monte Carlo simulations.

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6 Appendix 1

6.1 Mean time, W_0

The term mean time is represented by W_0 and it is derived using this equation.

$$W_0 = \sum_{k=1}^{R} r_k \frac{\frac{1}{\mu_k^2}}{2\overline{X}_k} = \frac{1}{2}\sum_{k=1}^{R} \lambda_k \frac{1}{\mu_k^2}$$

Where k is the class of the packet, R is the last class packet and r_k is the probability that a packet being served is of class k.

This term has been used to derive the time period for a particular packet to wait until it can occupy the channel. As soon as the timeslot is free, the packet is allowed to undertake its service.

7 Appendix 2

7.1 Mean completion time

The time during which a packet is being served until it leaves the system, possibly suffered from pre-emption due to higher priority packets is called the mean completion time. It is denoted by C_i. [13]

$$C_k = \frac{1}{\mu_k} + C_k \sum_{j=1}^{k-1} \lambda_j \frac{1}{\mu_j}, \qquad k = 1, 2, \dots, R$$

$$C_k = \frac{1}{\mu_k} + C_k \sum_{j=1}^{k-1} \rho_j$$

Where C_k is the mean completion time for class k packet, and R is the last class packet.

During the mean completion time, the term, $\lambda_j \frac{1}{\mu_j}$, packets of class j, j = 1, 2,…,k-1, arrive, and each packet occupies the channel for $\frac{1}{\mu_j}$ on average.

Therefore,

$$C_k = \frac{\frac{1}{\mu_k}}{1 - \sum_{j=1}^{k-1} \rho_j}, \qquad k = 1, 2, \dots, R$$

Since in the proposed paper, there are two classes, that is, the primary user packet and the secondary user packet, k = 1 and 2 respectively.

$$C_1 = \frac{\frac{1}{\mu_1}}{1}, \qquad k = 1 = class\ 1 = Primary\ user\ packet, P$$

$$C_2 = \frac{\frac{1}{\mu_2}}{1 - \sum_{j=1}^{2-1} \rho_j}, \qquad k = 2 = class\ 2 = Secondary\ user\ packet, S$$

$$C_2 = \frac{\frac{1}{\mu_2}}{1 - \rho_1}$$

which result in

$$C_1 = C_P = \frac{1}{\mu_1} = \frac{1}{\mu_P} = \overline{X}_P$$

and

$$C_2 = C_S = \frac{\frac{1}{\mu_2}}{1 - \rho_1} = \frac{\overline{X}_S}{(1 - \rho^P)}$$