Opportunistic Spectrum Access in Cognitive Radio Based on Channel Switching

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***Abstract*—This paper investigates the performance of a cognitive radio transceiver that can monitor multiple channels and opportunistically use any one of them should it be available. In our work, we propose and compare two different opportunistic channel access schemes. The first scheme applies when the secondary user (SU) has access to only one channel. The second scheme applies when the SU has access to multiple channels but can at a given time monitor and access only one channel. Two switching strategies, namely the switch and examine and the switch and stay strategies, are proposed. For these proposed access schemes, we investigate their performance by deriving the analytical expression of the novel metric of the average access duration and the average waiting time and based on these two metrics a time average SU throughput formula is proposed to predict the performance of the secondary cognitive system.**

I. Introduction

Cognitive radio has been shown to be one of the potential solutions to radio spectrum resource scarcity [1], [2]. Extensive measurements indicated that in contrast with the spectrum scarcity, at any given time and location, a large portion of licensed spectrum is unused. As a matter of fact, new opportunistic spectrum access techniques for cognitive radio emerge. These techniques, have been considered as an efficient mean to opportunistic spectrum sharing between primary users (PU), which are licensed, and secondary user (SU), which will make use of the unused spectrum at a given time and place. Opportunistic spectrum access (OSA) are considered as dynamic spectrum access techniques that allow the SU to access channels when PU are not transmitting while protecting PU from interference. The OSA techniques, present an effective strategy for the SU access by achieving a high spectrum efficiency and quality of service [3], [4]. When SU may not be able to monitor all the spectrum and have energy constrains, decentralized cognitive protocols are attractive [5]. These protocols, allow the SU to independently search for spectrum holes without a coordinator or a dedicated communication channel. Spectrum holes can be either exploited in space domain, when the SU transmit in a location where no PU are active, or in time domain, when the PU is present in that location and is found to be idle. In this paper, the proposed OSA will focus on the temporal white spaces.

In OSA, one of the important issue is the modeling of the behavior of the PU, which depends on the application that is running in the PU. The PU activity can be modeled by a simple two-state Markov chain. This model is not always realistic, but some experimental studies have shown that this model can be a reasonable approximation of the PU behavior in some systems such as the IEEE 802.11 Wireless LAN for various traffic models [6].

In this paper, we assume that the transmission of the PU is unslotted, which means that the PU can transmit at any time, and the traffic of the PU can be modeled by continuous-time Markov-chain. The SU is assumed to implement a decentralized cognitive protocol, to have unslotted transmission and to be able to use and sense only one channel at a time. We propose two different OSA schemes, where the first one applies when the SU have access to only one channel. Thus, the SU will periodically sense the channel and access it once the PU is sensed to be OFF. The SU during transmission will sense continuously the used channel to avoid interference with PU and immediately evacuate the band as soon as the corresponding PU appears. The second proposed OSA scheme applies when the SU is able to access multi channel but can use and sense only one channel at a time. In this case, the studied access schemes are based on two different switching schemes. The first switching scheme is the switch and examine scheme (SEC), where, once the PU appears, the SU switch sequentially to the next channel and keep switching until it finds an unused channel. The second switching scheme is the switch and stay scheme (SSC), in which the SU, when the PU is ON in a channel, will switch to the next channel and transmit if it is free or wait until it will be free. In this work, two important metrics for the SU are proposed, which are the average waiting duration and the average service time, and based on these two metrics we propose a performance measure metric denoted by time average SU throughput. With these novel performance metrics and their accurate mathematical characterization, we can predict the types of application the secondary system can support based on different PU traffic pattern.

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II. System Model

In this work, we assume that we have a PU system that have L parallel channels available for transmission. A cognitive secondary system, constituted by one transmitter and one receiver, will try to access one of the available channels opportunistically. We assume that the occupancy of each channel by the PU system evolves independently according to a homogeneous continuous-time Markov chain with idle (OFF) and busy (ON) states, with the notion that the PU traffic is not slotted. We denote the duration of the ON and OFF period of the PU by T^p_{on} and T^p_{off}, respectively. Due to the Markovian assumption, the holding times, T^p_{on} and T^p_{off}, are exponentially distributed with parameters λ (average ON duration) for the OFF period and μ (average OFF duration) for the ON period, respectively.

The SU transmitter, is assumed to always have data to send, to have unslotted traffic protocol and to have the ability to sense and access only one channel at a time. Also, we assume that, when the SU is using an idle channel, the SU will sense continuously that channel and stop accessing immediately when the PU begins transmitting. Thus, the proposed OSA scheme will cause nearby zero interference to the PU system. We assume in this work that the channel sensing is perfect and the channel sensing results at the transmitter and receiver are the same. In this scenario, the receiver will expect to receive the signal from the transmitter when it senses the channel free. The transmitted signal from secondary transmitter should have some preamble known to the receiver to facilitate the synchronization for detection.

III. Performance Analysis

In this section, we study two important performance metrics for the SU which are the average SU transmission time and the average SU waiting time. These two metrics predict according to the PU activity, how much time the SU needs to wait in average to transmit and for how much time in average he can transmit. Thus, using these two metrics we can investigate when having the PU traffic statistics, what type of applications the SU system can support.

A. One Channel Access

In this subsection, we assume that the SU have access to only one channel. When the PU is sensed to be ON, the SU will periodically sense the channel every period of T_s. Once the SU find out that the PU is OFF, he starts transmitting while sensing the PU activity continuously until the PU is ON.

1) Average SU Service Time:

a) Case of Poisson Traffic: We denote by T^s_{on} and T^s_{off} the duration of the ON and OFF periods the SU, respectively, as shown in the block diagram in Fig. 1. Assuming a Poisson traffic for the PU, the duration of the ON (T^p_{on}) and OFF (T^p_{off}) period are exponentially distributed and their probability density functions (PDFs) are given by

$$f_{T^p_{on}}(t) = \frac{1}{\lambda} e^{-\frac{t}{\lambda}}\ U(t),\ \ f_{T^p_{off}}(t) = \frac{1}{\mu} e^{-\frac{t}{\mu}}\ U(t), \quad (1)$$

respectively, where λ and μ represent the average duration of the ON period and the average duration of the OFF period, respectively, and $U(.)$ is the unit step function.

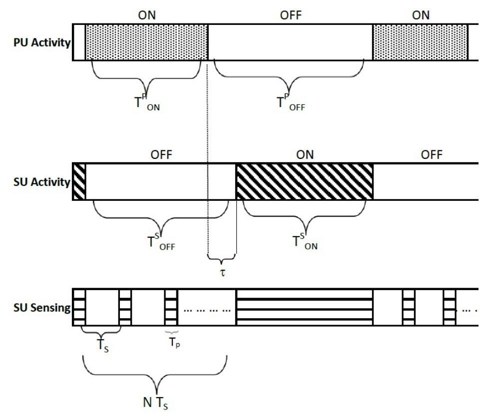

Fig. 1. Sample model of operation.

During the ON period of the PU, the SU performs a periodic sensing with period T_s, as shown in Fig 1, the OFF duration of the SU can be expressed as $T^s_{off} = N\ T_s$, where N is the number of the sensing periods before the SU switch to ON state. Note that N is a random variable that depends on the ON duration of the PU.

It can be seen from Fig. 1 that $T^p_{on} + T^p_{off} = T^s_{on} + T^s_{off}$. Thus, the ON duration of the SU can then be expressed as

$$T^s_{on} = T^p_{on} + T^p_{off} - NT_s = T^p_{off} - \tau, \quad (2)$$

where $\tau = NT_s - T^p_{on}$ represents the time duration when the PU is OFF and the SU is not transmitting, $\tau \in [0, T_s]$.

To get the average SU service duration, denoted by $\bar{T}^s_{on}$, we first need to get the statistics of T^s_{on}. Since T^s_{on} depend on the random variables T^p_{off} and τ and T^p_{off} is exponential distributed with parameter μ, we just need to get the statistics of τ. Conditioning on N, $T^p_{on}|N$ is between $(N-1)T_s$ and NT_s. Thus, knowing that T^p_{on} is exponentially distributed, $T^p_{on}|N$ is a truncated exponential random variable and its PDF is given by

$$f_{T^p_{on}|N}(t) = \frac{1}{\lambda} \frac{e^{-\frac{t}{\lambda}}}{e^{-\frac{(N-1)T_s}{\lambda}} - e^{-\frac{NT_s}{\lambda}}},\ (N-1)T_s \leq t \leq NT_s. \quad (3)$$

The PDF of τ conditioned on N can be determined as

$$f_{\tau|N}(t) = f_{T^p_{on}|N}(NT_s - t) = \frac{1}{\lambda} \frac{e^{\frac{x-T_s}{\lambda}}}{1 - e^{-\frac{T_s}{\lambda}}},\ 0 \leq t \leq T_s. \quad (4)$$

It can be seen from the previous PDF that $f_{\tau|N}(.)$ does not depend on N, thus the PDF of τ is the same as the conditioned PDF on N, i.e, $f_\tau(t) = f_{\tau|N}(t)$. This can be explained by the fact that the Poisson model for the PU activity is memoryless.

Having the PDF of τ and T^p_{off}, we can easily get the average SU transmission time as

$$\bar{T}^s_{on} = E[T^p_{off}] - E[\tau] = \mu + \lambda - \frac{T_s}{1 - e^{-\frac{T_s}{\lambda}}}. \quad (5)$$

It can be easily seen that when $T_s \to 0$ which mean that the SU continuously senses the channel, $\frac{T_s}{1-e^{-\frac{T_s}{\lambda}}} \to \lambda$. So $\bar{T}_{on}^s$ is approaching μ as expected, because in this case the SU will begin transmitting exactly when the PU finish and will finish exactly when the PU begin transmitting.

b) Case of General PU Traffic: This result can be generalized to any PU activity model where the truncated PDF of T_{on}^p, between $(N-1)T_s$ and NT_s, is available. If we denote by $F_{T_{on}^p}(.)$ the cumulative distribution function (CDF) of T_{on}^p, the PDF of T_{on}^p conditioned on N is given by

$$f_{T_{on}^p|N}(t) = \frac{f_{T_{on}^p}(t)}{F_{T_{on}^p}(NT_s) - F_{T_{on}^p}((N-1)T_s)}, \quad NT_s \le t \le (N-1)T_s. \tag{6}$$

Using this previous PDF, we can express the PDF of τ knowing N as

$$f_{\tau|N}(t) = \frac{f_{T_{on}^p}(NT_s - t)}{F_{T_{on}^p}(NT_s) - F_{T_{on}^p}((N-1)T_s)}, \ 0 \le t \le T_s. \tag{7}$$

If we denote by $P_n = \Pr\{N = n\}$, we can express the probability mass function (PMF) of N as a function of the CDF of T_{on}^p as

$$P_n = F_{T_{on}^p}(nT_s) - F_{T_{on}^p}((n-1)T_s) \tag{8}$$

Having P_n and $f_{\tau|N}(.)$, we can obtain $f_\tau(.)$ as $f_\tau(t) = \sum_{n=1}^{+\infty} P_n f_{\tau|n}(t) = \sum_{n=1}^{+\infty} f_{T_{on}^p}(nT_s - t), \ 0 \le t \le T_s$. and the average SU service duration, $\bar{T}_{on}^s$, as

$$\bar{T}_{on}^s = \bar{T}_{off}^p - \sum_{n=1}^{+\infty} \int_0^{T_s} t \ f_{T_{on}^p}(nT_s - t) \ dt, \tag{9}$$

where $\bar{T}_{off}^p$ is the mean value of T_{off}^p, given by the statistics of the OFF period of the PU traffic.

2) Average Waiting Time: The average SU waiting time, denoted by δ, is the average time for which the SU will need to wait to get access to the channel. This metric in our case can be given by $\delta = NT_s$. Since we have the PMF of N which is given in general case by (8), we can calculate the average value of δ as

$$\bar{\delta} = \sum_{n=1}^{+\infty} \delta \ P_n = \sum_{n=1}^{+\infty} n \ T_s \ P_n. \tag{10}$$

In the case of Poisson PU traffic, $P_n = e^{-(n-1)\frac{T_s}{\lambda}} \left(1 - e^{-\frac{T_s}{\lambda}}\right)$. Thus $\bar{\delta}$ is expressed as

$$\bar{\delta} = \sum_{n=1}^{+\infty} n \ T_s \ e^{-(n-1)\frac{T_s}{\lambda}} \ \left(1 - e^{-\frac{T_s}{\lambda}}\right) = \frac{T_s}{1 - e^{-\frac{T_s}{\lambda}}}. \tag{11}$$

B. Multi-Channel Access Based on SEC Scheme

In this section, we assume that the SU can access any one of all the available channels at a time. If the sensed channel is idle, the SU will transmit in this channel and sense the channel continuously until the PU is present. Once the PU is present in the channel, the SU will switch to the next channel. If the channel is available, the SU will use it otherwise the SU switches again. We will assume that when the SU switches to a new channel, the switching duration can keep neglected and sensing duration is T_p.

1) Average SU Service Time: We again assume Poisson traffic for the PU. When the SU find an available channel after switching, the availability duration of the channel access is exponential with the same mean μ. Once the SU switches and find an available channel, it will take T_p to begin transmitting. Thus, if we denote by X the availability duration of the channel, the service time can be given by $T_{on}^s = X - T_p$, and the average SU transmission time is given by $\bar{T}_{on}^s = \mu - T_p$.

2) Average Waiting Time:

a) Case of a large number of channels: Given the channel and sensing time T_p, the waiting time is a multiple of T_p and can be given by $\delta = N \ T_p$, where N is a random variable that represents the number of channels that the SU has examined before finding a free channel. The discrete random variable N is a Bernoulli random variable with probability $p = \frac{\lambda}{\lambda+\mu}$. If there is a large number of channels, the switched-to channels will have independent statistics. Therefore, the PMF of N is $\Pr\{N = n\} = (1-p) \ p^{n-1} = \left(\frac{\mu}{\lambda+\mu}\right)\left(\frac{\lambda}{\lambda+\mu}\right)^{n-1}$, and we can calculate $\bar{\delta}$ as $\bar{\delta} = \frac{T_p}{\mu}(\lambda + \mu)$.

b) Case of small number of channel: The results for the waiting time obtained in the previous paragraph are for the case when we have many channels so that the SU when switching sequentially can find an available channel before going back to the first channel examined. A much more interesting case for the SEC scheme is when the number of channels is not large enough and the SU while switching over the channels can switch back to the first channel after checking all the available channels. In this case the waiting time will be different from the one obtained previously. We take as an example the two channel case. In this case during the waiting time the SU will switch between the two channels until he finds a free channel. The difference here with the previous case is that when the user switch back to the previous channel the probability of non access p is no longer equal to $\frac{\lambda}{\lambda+\mu}$ because we know the state of the channel in the last T_p period. It can be shown that PMF of N is

$$\begin{aligned}
\Pr\{N=1\} &= \frac{\mu}{\lambda+\mu} \\
\Pr\{N=2\} &= \frac{\mu}{\lambda+\mu}\Pr\left\{0 < T_{on_1}^p < T_p\right\} \\
&= \frac{\lambda}{\lambda+\mu} \ \left(1 - e^{-\frac{2T_s}{\mu}}\right) \\
\Pr\{N=3\} &= \frac{\mu}{\lambda+\mu}\Pr\left\{T_{on_1}^p > T_p\right\}\Pr\left\{T_p < T_{on_2}^p < 3T_p\right\} \\
&= \frac{\lambda}{\lambda+\mu} \ e^{-\frac{T_p}{\mu}} \left(e^{-\frac{T_p}{\mu}} - e^{-\frac{3T_p}{\mu}}\right) \ldots \\
\Pr\{N=n\} &= \frac{\lambda}{\lambda+\mu} \ e^{-\frac{(n-2)T_p}{\mu}} \left(e^{-\frac{(n-2)T_p}{\mu}} - e^{-\frac{nT_p}{\mu}}\right),
\end{aligned} \tag{12}$$

where $T_{on_1}^p$ and $T_{on_2}^p$ are the ON duration of the PU in the first channel and second channel, respectively. Using the PMF of N above, we can obtain the average waiting time as

$$\bar{\delta} = \sum_{n=1}^{+\infty} \delta \ P_n \ = \frac{T_p}{\mu+\lambda}\left(\mu + \lambda \ \frac{2-e^{-\frac{2T_p}{\mu}}}{1-e^{-\frac{2T_p}{\mu}}}\right). \quad (13)$$

C. Multi-Channel Access Based on SSC Scheme

In this section, we assume that the SU has access to all the available channels and sense the channels sequentially. If the sensed channel is idle, the SU transmits and senses the channel continuously until the PU is present. Once the PU is present in the channel, the SU switches to the next channel. If the next channel is available the SU transmits. Else he stays on that channel and wait until it is free. During the waiting time the SU senses periodically (every T_s) the PU activity. In this part, we denote by T_p and T_s the duration of sensing and the period of sensing, respectively. Note that the switching duration is assumed to be negligible.

1) Average SU Transmission Time: To calculate the average service time for this switching scheme, we need to consider two cases, which are i) the case when the SU switches to another channel and find it idle. We denote the service duration in this case by T_1. ii) the case when the switch to channel is found to be busy. We denote the service duration in this case by T_2. The average service time is in this cases given by

$$T_{on}^{s} = p_1 T_1 + p_2 T_2, \quad (14)$$

where p_1 and p_2 are the probability to find the channel idle and busy, respectively, and are given by $p_1 = \frac{\mu}{\mu+\lambda}$ and $p_2 = \frac{\lambda}{\mu+\lambda}$, respectively. Thus the average service time is given by

$$\bar{T}_{on}^{s} = \frac{\mu}{\mu+\lambda}\bar{T}_1 + \frac{\lambda}{\mu+\lambda}\bar{T}_2. \quad (15)$$

When the switch to channel is found to be idle, the SU waits for T_p duration the time to switch and to sense the channel and then transmit. Thus in this case knowing that we found the switch to channel idle, the average service time will be exactly the same as of the case of SEC scheme, given by $\bar{T}_1 = \mu - T_p$.

When the switch to channel is found to be busy, the SU will stay in that channel and wait until the channel is free. During the waiting time the SU will sense the channel periodically every T_s. Thus the service time in this case is exactly equal to the one channel case. So the average service time knowing that the switch to channel is found to be busy is given by

$$\bar{T}_2 = \mu + \lambda - \frac{T_s}{1-e^{-\frac{T_s}{\lambda}}}. \quad (16)$$

Using the previous results we can get $\bar{T}_{on}^{s}$ and represented as

$$\bar{T}_{on}^{s} = \lambda + \frac{\mu(\mu - T_p)}{\mu+\lambda} - \frac{1}{\mu+\lambda}\left(\frac{T_s}{1-e^{-\frac{T_s}{\lambda}}}\right). \quad (17)$$

2) Average Waiting Time: For this switching scheme, the average waiting time is exactly equal to the waiting time of the case when we have only one channel access if we neglect the channel switching time. Thus the average waiting time is given by

$$\bar{\delta} = \frac{T_s}{1-e^{-\frac{T_s}{\lambda}}}. \quad (18)$$

D. Time Average SU Throughput

In this part, we propose a third performance metric namely time average SU throughput based on the two previously proposed metrics, average service time and average waiting time. The time average SU throughput for all the considered access scheme is given by

$$\Gamma = \frac{\bar{T}_{on}^{s}}{\bar{\delta} + \bar{T}_{on}^{s}} \log_2(1+\gamma), \quad (19)$$

where γ is the signal-to-noise ratio of the SU.

IV. Numerical Results and Discussions

In this section, we present some numerical results for the average service time and average waiting time to compare the different proposed SU access schemes.

Fig. 2, shows the normalized average service time of the SU for the different studied access schemes as a function of the average OFF duration of the PU μ. In this figure, we assume that $T_s = 0.2$, $T_p = 0.05$ and $\lambda = 1$. It is clear that as μ increases the service duration for the SU and for all the considered schemes increases and this is because the OFF period of the PU will be longer. On the other hand, it can be seen that the switching based schemes have better service duration compared to the one channel access scheme. Moreover, if we compare the two studied switching schemes, we can see that, in terms of service duration,the SEC is better then the SSC.

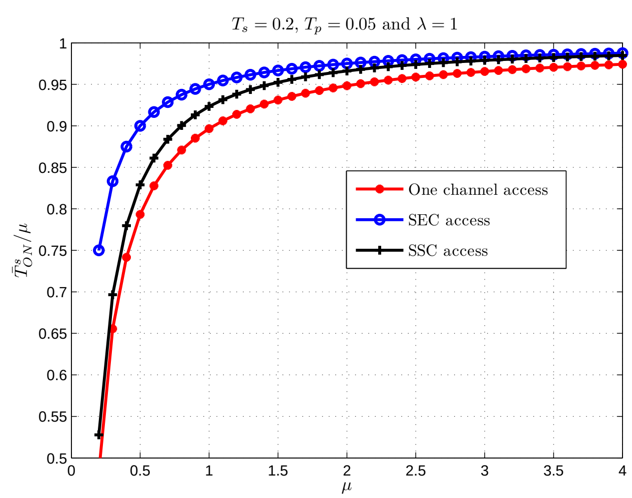

Fig. 2. Normalized average service time of the cognitive radio for the different studied access schemes.

Fig. 3, shows the normalized average waiting time of the SU for the different studied access schemes as a function of the average ON duration of the PU λ. In this figure, we assume that $T_s = 0.2$, $T_p = 0.05$ and $\lambda = 1$. It is clear that as λ increases the SU waiting duration for all the considered schemes decreases and this is because the ON period of the PU will be longer. On the other hand, it can be seen that the switching based schemes present less waiting duration for the SU compared to the one channel access scheme. Moreover, if we compare the two studied switching schemes, we can see that, in terms of waiting duration, the SEC provides lower waiting time compared to the SSC scheme.

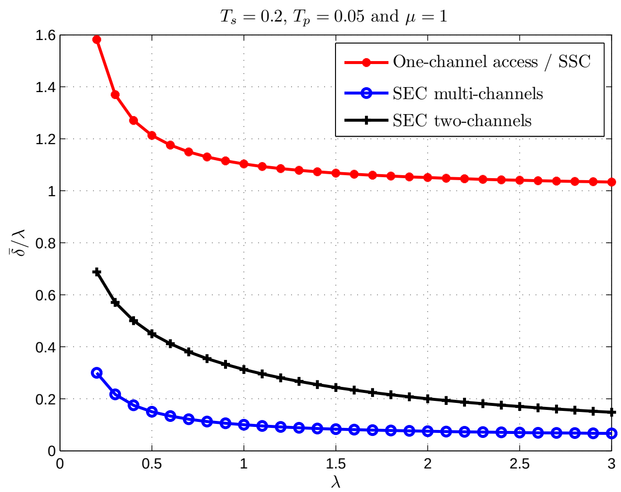

Fig. 3. Normalized average waiting time of the cognitive radio for the different studied access schemes.

Fig. 4, shows the normalized average service duration for the switched based access schemes for different values of T_p as a function of the average OFF duration μ of the PU. In this figure, we assume that $T_s = 0.2$ and $\lambda = 1$. It is clear that as T_p decreases the service time decreases for the two switching considered cases, as expected. This is because when the sensing duration decreases the SU can quickly make use of the available channel.

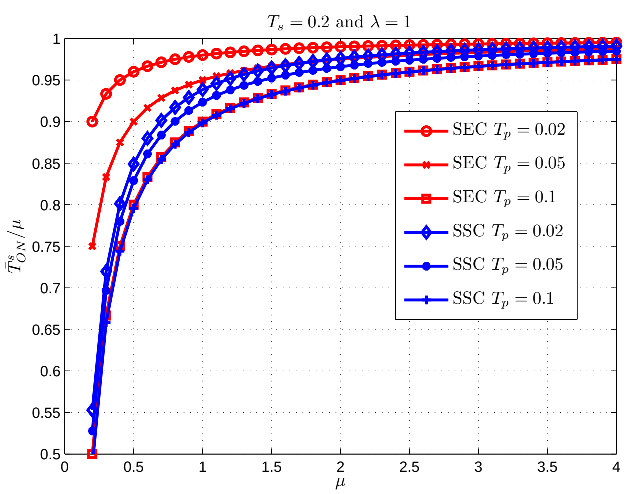

Fig. 4. Normalized average service duration for the switched based access schemes for different values of T_p.

Fig. 5, shows the normalized average waiting duration for the switched based access schemes for different values of T_p as a function of the average ON duration λ of the PU. In this figure, we present the results for the average waiting time of the SEC for multi-channels and two-channels case. Also in this figure, we assume that $T_s = 0.2$ and $\mu = 1$. It is clear that as T_p increases the waiting time increases for the different considered access schemes. This is because the waiting time for the SEC is directly related to T_p. Besides, this figure shows that the multi-channels switching SEC scheme provides a smaller waiting time than the two channel case. This can be explained by the fact that when switching over multi-channels it is more likely to find a free channel.

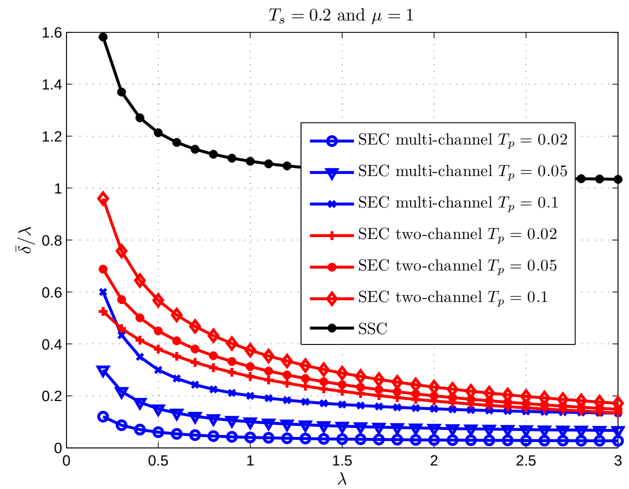

Fig. 5. Normalized average waiting duration for the switched based access schemes for different values of T_p.

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