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Resume and Starting-Over-Again Retransmission Strategies in Cognitive Radio Networks

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1. Introduction

Cognitive radio has emerged as a promising technology to realize dynamic spectrum access and increase the efficiency of a largely under utilized spectrum (Haykin, 2005). In a cognitive radio network, a cognitive or secondary user (SU) opportunistically makes use of temporary vacant licensed frequency bands (channels) to set up communication links with other devices. The SUs are capable of detecting channels that are unused by the primary users (PUs) and then making use of the idle channels. With respect to the licensed or PUs, such kind of spectrum access is unlicensed and secondary. To avoid interference to the PUs, SUs are forced to vacate the primary channels as soon as PUs return. Those prematurely terminated secondary sessions degrade quality of service. To reduce this adverse impact, interrupted SUs may be allowed to move to other vacant channels. This process is called spectrum handoff (Zhu et al., 2007). Additionally, to further reduce the impact of service interruption, for delay tolerant services, interrupted SUs can be queued in a buffer to wait for the releasing of an occupied channel.

When a SU detects or is informed of an arrival of a PU call/session in its current channel, it immediately leaves the channel and switches to an idle channel, if one is available, to continue its call. These unfinished cognitive transmissions may be simply discarded (Zhu et al., 2007; Zhang, 2008; Ahmed et al., 2008; Pacheco-Paramo et al., 2009). Nonetheless, prematurely terminated secondary sessions degrade quality of service. Alternatively, if at that time all the channels are occupied, the secondary call is queued in a buffer and the call waits until a channel becomes available. Queued secondary calls are served in first-come first-served (FCFS) order. That is, the secondary call at the head of the queue is reconnected to the system when a channel becomes available and transmits its information according to a given retransmission strategy.

In this Chapter, the performance of cognitive radio networks for two different retransmission strategies for interrupted secondary user's calls is mathematically analyzed and evaluated. Resume retransmission and Start Over Again retransmission strategies are considered.

2. Retransmission strategies

Two different retransmission strategies can be used to handle interrupted secondary calls: the Resume (RR) and Start-Over-Again (SOAR) retransmission strategies. In the Resume retransmission strategy, SU transmits its information starting at the point it was preempted. That is, in this strategy the SU does not need to transmit again the information bits transmitted before its previous connection was interrupted. The Resume retransmission strategy can be easily and directly implemented when automatic repeat request-based error control protocols[1] (i.e., Stop-and-wait ARQ, Go-Back-N ARQ, Selective Repeat ARQ, Hybrid ARQ) are used as the receiver must acknowledge received packets. On the other hand, in the Start Over Again retransmission strategy each time a secondary call is interrupted, SU retransmits its information starting at the initial point no matter that some part of its information was transmitted in its previous connection. Contrary to the Resume strategy, the Start Over Again retransmission strategy does not require a control protocol and, therefore, it is simpler.

Under the assumption that service (or call holding) time for SU calls is negative exponentially distributed, authors in (Tang & Mark, 2007; Tang & Mark, 2008), (Tang & Mark a; 2009) have developed system level models for the performance evaluation of cognitive radio networks with the RR strategy. In a related work (Tang & Mark, 2009), the RR strategy is analyzed under the assumption that service time of SUs is phase-type distributed. However, the RR strategy is neither evaluated under different traffic conditions nor the effect of characteristics of the SU service time is investigated. To the best of the authors' knowledge, the performance of cognitive radio networks with the SOAR retransmission strategy has been neither analyzed nor evaluated in the literature. Therefore, the performance of the RR and SOAR strategies has not been compared either. All these important tasks are addressed in this Chapter.

3. System model

The model of (Tang & Mark, 2007; Tang & Mark, 2008; Tang & Mark, 2009) is adopted. It is considered that two types of wireless networks are operating in a given common service area. The one that owns the license for spectrum usage is referred to as the primary system, and the calls generated from this network constitute the primary traffic (PT) stream. The other network in the same service area is referred to as the secondary system, which opportunistically shares the spectrum resource with the primary system. The calls generated from the secondary system constitute the secondary traffic (ST) stream. The system consisting of the primary and secondary systems is called an opportunistic spectrum sharing (OSS) system. A distinct feature of a well-designed OSS system is that the secondary users have the capability to sense channel usage and switch between different channels using appropriate communication mechanisms, while causing negligible interference to the primary users. Such functionality might be realized by cognitive radios (Haykin, 2005).

In the OSS system, the PT calls operate as if there are no ST calls in the system. When a PT call arrives to the system, it occupies a free channel if one is available; otherwise, it will be

[1] Modern wireless communication standards typically consider this type of data transmission protocols (i.e., LTE, WiMax).

blocked. Note that a channel being used by an ST call is still seen as an idle channel by the primary network, since here the primary network and secondary network are supposed not to exchange information. Secondary users detect the presence or absence of signals from primary users and maintain records of the channel occupancy status. The detection mechanism may involve collaboration with other secondary users and/or an exchange with an associated base station (BS) and it is assumed to be error free.

Secondary users opportunistically access the channels that are in idle status. If an initial secondary call finds an idle channel, it can make use of the channel. If all channels are busy, the secondary call is blocked and considered lost from the system. When an ongoing secondary user detects or is informed (by its BS or other secondary users) of an arrival of PT call in its current channel, it immediately leaves the channel and switches to an idle channel, if one is available, to continue the call. (This process is called spectrum handoff.) If at that time all the channels are occupied, the ST call is placed into a buffer located at its BS (for an infrastructured network) or a virtual queue (for an infrastructureless network). The queued ST calls are served in first-come first-served (FCFS) order. That is the ST call at the head of the queue is reconnected to the system when a channel becomes available. It is assumed that ST calls can wait indefinitely to be served. Additionally, to obtain simpler mathematical expressions, it is assumed that there exists no limit in the number of reconnections that an ongoing ST call can perform. Clearly, the maximum number of queued ST calls is M, which corresponds to the limiting case that all the M ongoing calls are ST calls and are eventually preempted to the queue due to the arrivals of PT calls. Thus, a finite queue of length M is considered.

We define the term band as a bandwidth unit in the primary system; and the term sub-band as a bandwidth unit in the secondary system. Accordingly, a PT call needs one band for service and an ST call needs one sub-band for service. The spectrum consists of M bands and each band is divided into N sub-bands. Thus, there exist NM sub-bands (channels) that are shared by the primary and cognitive users. To avoid interference to PU, for a specific band used by a PT call, the underlying N subbands are then unavailable for ST calls. For the sake of clarity and without loss of generality, it is assumed that both types of traffic occupy one channel per call; that is, N=1. Arrivals of the PT and ST calls are assumed to form independent Poisson processes with rates $\lambda^{(P)}$ and $\lambda^{(S)}$, respectively. Service time for primary users is considered exponentially distributed with rate $\mu_s^{(P)}$. The corresponding service time for cognitive users is modeled as a Coxian order 2 distributed random variable. The random variable (RV) used to represent this time is $\mathbf{X}_S^{(S)}$. It is important to remark that the Coxian order 2 distribution includes as particular cases several relevant phase-type distributions (i.e., negative-exponential, Erlang, hypo-exponential). Fig. 1 shows a diagram of phases of a n-th order Coxian distribution. Notice that β_i (for i = 1, 2, …, n-1) represents the probability that the absorbing state is reached after the i-th phase. For a Coxian order 2 distribution, β_2=1. The i-th phase of this distribution is an independent exponential random variable with parameter $\mu_i^{(S)}$ for (i = 1, 2). The mean service time for secondary users is denoted by $1/\mu_s^{(S)}$. For the Coxian order 2 model, the probability density function (pdf) of secondary service time and its mean value are, respectively, given by

$$f_{X_S^{(S)}}(t) = \beta\mu_1^{(S)} e^{-\mu^{(S)}t} + (1-\beta)\frac{\mu_1^{(S)}\mu_2^{(S)}}{\mu_1^{(S)} - \mu_2^{(S)}}\left(e^{-\mu_2^{(S)}t} - e^{-\mu_1^{(S)}t}\right) \tag{1}$$

$$E\left\{\mathbf{X}_S^{(S)}\right\} = \int_0^\infty t f_{\mathbf{X}_S^{(S)}}(t)\,dt \tag{2}$$

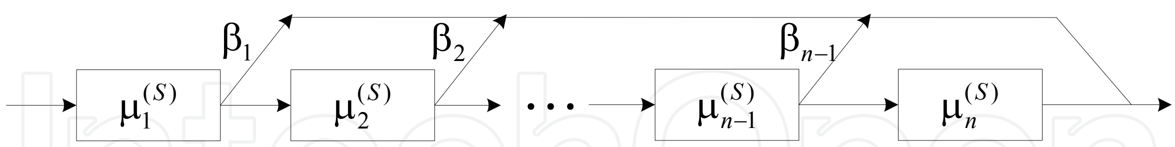

Fig. 1. Diagram of phases of a n-th order Coxian distributed service time

4. Resume retransmission strategy teletraffic analysis

In the RR strategy, when a secondary queued user is reconnected to the system, it transmits its information starting at the point it was preempted. Due to the memory-less property, the probability distribution of the residual permanence time in phase i is also negative-exponential with the same parameter $\mu_i^{(S)}$ of the service time of new secondary calls. Then, it is possible to keep track in a single state variable the number in each phase of the service time of initial and ongoing secondary users.

In this sub-section, the teletraffic analysis for the performance evaluation of cognitive radio networks with RR strategy is developed. A multi-dimensional birth and death process is required for modeling this system. Each state variable is denoted by k_i (for i = 0, 1, 2, …, n). k_0 represents the number of ongoing primary users, k_1 the number of ongoing SUs in phase 1, k_2 the number of ongoing and queued SUs in phase 2, and k_3 the number of SU in the queue that were interrupted in phase 1. Fig. 2 shows the transition state diagram. On the basis of the transition state diagram, we develop the set of global balance equations. To simplify mathematical notation the following vectors are defined $\mathbf{k} = (k_0, k_1, \ldots, k_n)$, $\mathbf{e}_i$ is defined as a unit vector of n elements, whose all entries are 0 except the i-th position which is 1 (for i = 0, 1, 2, …, n).

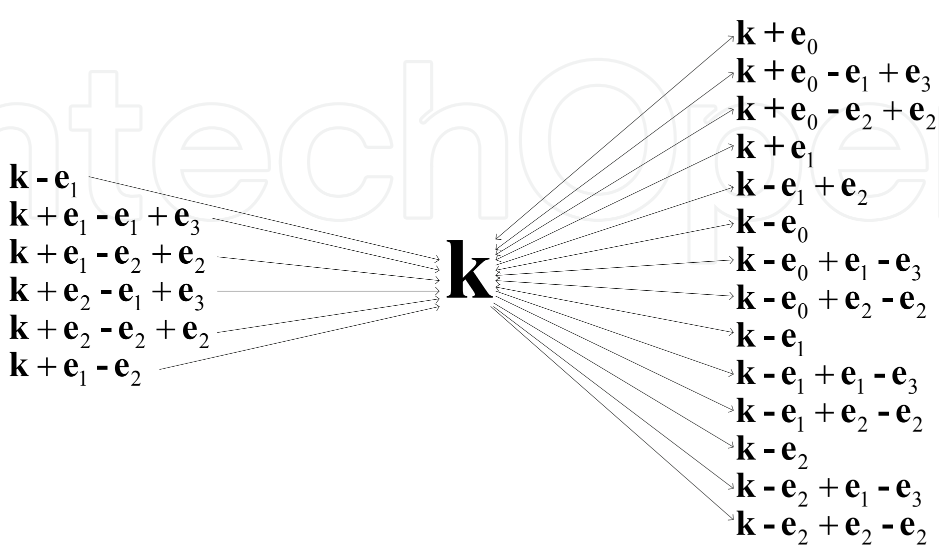

Fig. 2. Transition states diagram

The state space Ω_0 is given by

$$\Omega_0 = \left\{ \mathrm{k} \mid k_i \geq 0, \sum_{i=0}^{3} k_i \leq 2M, \sum_{i=1}^{3} k_i \leq M, \sum_{i=0}^{1} k_i \leq M;\ k_3 = 0 \Big|_{\sum_{i=0}^{2} k_i < M} \quad i = 0,1,2,3 \right\} \tag{3}$$

The steady state probabilities balance equation is given by

$$\begin{aligned}
&\left[\sum_{i=0}^{1} a_i(\mathbf{k}) + \sum_{i=0}^{2} b_i(\mathbf{k}) + c(\mathbf{k}) + \sum_{i=1}^{2} d_i(\mathbf{k}) + \sum_{i=0}^{5} e_i(\mathbf{k}) \right] P(\mathbf{k}) = \\
&= \sum_{i=0}^{1} a_i(\mathbf{k}-\mathbf{e}_i) P(\mathbf{k}-\mathbf{e}_i) + \sum_{i=0}^{2} b_i(\mathbf{k}+\mathbf{e}_i) P(\mathbf{k}+\mathbf{e}_i) + c(\mathbf{k}+\mathbf{e}_1-\mathbf{e}_2) P(\mathbf{k}+\mathbf{e}_1-\mathbf{e}_2) + \\
&+ d_1(\mathbf{k}-\mathbf{e}_0+\mathbf{e}_1-\mathbf{e}_3) P(\mathbf{k}-\mathbf{e}_0+\mathbf{e}_1-\mathbf{e}_3) + d_2(\mathbf{k}-\mathbf{e}_0+\mathbf{e}_2-\mathbf{e}_2) P(\mathbf{k}-\mathbf{e}_0+\mathbf{e}_2-\mathbf{e}_2) + \\
&+ e_0(\mathbf{k}+\mathbf{e}_0-\mathbf{e}_1+\mathbf{e}_3) P(\mathbf{k}+\mathbf{e}_0-\mathbf{e}_1+\mathbf{e}_3) + e_1(\mathbf{k}+\mathbf{e}_0-\mathbf{e}_2+\mathbf{e}_2) P(\mathbf{k}+\mathbf{e}_0-\mathbf{e}_2+\mathbf{e}_2) + \\
&+ e_2(\mathbf{k}+\mathbf{e}_1-\mathbf{e}_1+\mathbf{e}_3) P(\mathbf{k}+\mathbf{e}_1-\mathbf{e}_1+\mathbf{e}_3) + e_3(\mathbf{k}+\mathbf{e}_1-\mathbf{e}_2+\mathbf{e}_2) P(\mathbf{k}+\mathbf{e}_1-\mathbf{e}_2+\mathbf{e}_2) + \\
&+ e_4(\mathbf{k}+\mathbf{e}_2-\mathbf{e}_1+\mathbf{e}_3) P(\mathbf{k}+\mathbf{e}_2-\mathbf{e}_1+\mathbf{e}_3) + e_5(\mathbf{k}+\mathbf{e}_2-\mathbf{e}_2+\mathbf{e}_2) P(\mathbf{k}+\mathbf{e}_2-\mathbf{e}_2+\mathbf{e}_2)
\end{aligned} \tag{4}$$

where $a_i(\cdot)$ represents the call birth rate for cognitive users (for i=1) and primary users (for i=0); $b_i(\cdot)$ represents the call death rate for cognitive users (for i =1, 2) and primary users (for i =0); $c(\cdot)$ represents the transition rate from phase 1 to 2; $d_i(\cdot)$ (for i = 1, 2) represents transition rate of queueing a SU in phase i due to the arrival of a PU; $e_i(\cdot)$ (for i = 0, 1, 2,…, 5) represents the reconnection rate of one cognitive user in phase 1 or 2 due to death of a PU or SU. These coefficient rates are given below.

The call birth rate for PUs or SUs generating a transition from state $\mathbf{k}$ to state $\mathbf{k}+\mathbf{e}_i$ is given by

$$a_i(\mathbf{k}) = \begin{cases} \lambda^{(P)} & \sum_{j=0}^{2} k_j < M;\ k_0 \geq 0;\ k_3 = 0;\ i = 0 \\ \lambda^{(S)} & \sum_{j=0}^{2} k_j < M;\ k_1 \geq 0;\ k_3 = 0;\ i = 1 \\ 0 & ;\text{otherwise} \end{cases} \tag{5}$$

The call death rate for PUs or SUs generating a transition from state $\mathbf{k}$ to state $\mathbf{k}-\mathbf{e}_i$ is given by

$$b_i(\mathbf{k}) = \begin{cases} k_0 \mu_s^{(P)} & \sum_{i=0}^{2} k_i \leq M;\ k_3 = 0;\ i = 0 \\ \beta k_1 \mu_1^{(S)} & \sum_{i=0}^{2} k_i \leq M;\ k_3 = 0;\ i = 1 \\ k_2 \mu_2^{(S)} & \sum_{i=0}^{2} k_i \leq M;\ k_3 = 0;\ i = 2 \\ 0 & ;\text{otherwise} \end{cases} \tag{6}$$

The transition rate of the service time of a SU from phase 1 to phase 2 generating a transition from state $\mathbf{k}$ to state $\mathbf{k}-\mathbf{e}_1+\mathbf{e}_2$ is given by

$$c(\mathbf{k})=\begin{cases}(1-\beta)k_1\mu_1^{(S)} & ;\sum_{i=0}^{1}k_i\le M;\ \sum_{i=0}^{3}k_i\le 2M;\ \sum_{i=1}^{3}k_i\le M;\ k_2\ge 0\\ 0 & ;\text{otherwise}\end{cases}\tag{7}$$

The transition rate of queuing a SU in phase 1 (due to the arrival of a PU at the first stage of its service time) generating a transition from state $\mathbf{k}$ to state $\mathbf{k}+\mathbf{e}_0-\mathbf{e}_1+\mathbf{e}_3$ is given by

$$d_1(\mathbf{k})=\begin{cases}\dfrac{k_1}{M-k_0}\lambda^{(P)} & ;0\le k_0<M;\ \sum_{j=0}^{2}k_j\ge M;\ \sum_{j=0}^{3}k_j<2M;\ k_3\ge 0;\\ & ;\sum_{j=1}^{3}k_j\le M\\ 0 & ;\text{otherwise}\end{cases}\tag{8}$$

The transition rate of queuing a SU in phase 2 (due to the arrival of a PU at the second stage of its service time) generating a transition from state $\mathbf{k}$ to state $\mathbf{k}+\mathbf{e}_0-\mathbf{e}_2+\mathbf{e}_2$ is given by

$$d_2(\mathbf{k})=\begin{cases}\dfrac{M-k_0-k_1}{M-k_0}\lambda^{(P)} & ;0\le k_0<M;\ \sum_{j=0}^{2}k_j\ge M;\ \sum_{j=0}^{3}k_j<2M;\\ & ;\sum_{j=1}^{3}k_j\le M\\ 0 & ;\text{otherwise}\end{cases}\tag{9}$$

The reconnection rate of a SU in phase 1 due to the death of a PU generating a transition from state $\mathbf{k}$ to state $\mathbf{k}-\mathbf{e}_0+\mathbf{e}_1-\mathbf{e}_3$ is given by

$$e_0(\mathbf{k})=\begin{cases}\dfrac{k_3}{k_3+\sum_{j=0}^{2}k_j-M}k_0\mu^{(P)} & ;k_0<M;\ \sum_{j=0}^{2}k_j\ge M;\ \sum_{j=0}^{3}k_j\le 2M;\\ & ;k_1\ge 0;k_3>0;\sum_{j=1}^{3}k_j\le M;i=0\\ 0 & ;\text{otherwise}\end{cases}\tag{10}$$

The reconnection rate of a SU in phase 2 due to the death of a PU generating a transition from state $\mathbf{k}$ to state $\mathbf{k}-\mathbf{e}_0+\mathbf{e}_2-\mathbf{e}_2$ is given by

$$e_1(\mathbf{k}) = \begin{cases} \dfrac{\sum_{j=0}^{2} k_j - M}{k_3 + \sum_{j=0}^{2} k_j - M} k_0 \mu^{(P)} & ; \sum_{j=0}^{1} k_j \leq M;\ \sum_{j=0}^{2} k_j \geq M; \\ & ; \sum_{j=0}^{3} k_j \leq 2M;\ \sum_{j=1}^{3} k_j \leq M;\ i = 1 \\ 0 & ; \text{otherwise} \end{cases} \tag{11}$$

The reconnection rate of a SU in phase 1 due to the death of a SU in phase 1 generating a transition from state $\mathbf{k}$ to state $\mathbf{k} - \mathbf{e}_1 + \mathbf{e}_1 - \mathbf{e}_3$ is given by

$$e_2(\mathbf{k}) = \begin{cases} \dfrac{k_3}{k_3 + \sum_{j=0}^{2} k_j - M} \beta k_1 \mu_1^{(S)} & ; k_0 < M;\ \sum_{j=0}^{2} k_j \geq M;\ \sum_{j=0}^{3} k_j \leq 2M; \\ & ; k_3 > 0;\ \sum_{j=1}^{3} k_j \leq M;\ i = 2 \\ 0 & ; \text{otherwise} \end{cases} \tag{12}$$

The reconnection rate of a SU in phase 2 due to the death of a SU in phase 1 generating a transition from state $\mathbf{k}$ to state $\mathbf{k} - \mathbf{e}_1 + \mathbf{e}_2 - \mathbf{e}_2$ is given by

$$e_3(\mathbf{k}) = \begin{cases} \dfrac{\sum_{j=0}^{2} k_j - M}{k_3 + \sum_{j=0}^{2} k_j - M} \beta k_1 \mu_1^{(P)} & ; \sum_{j=0}^{1} k_j \leq M;\ \sum_{j=0}^{2} k_j > M; \\ & ; \sum_{j=0}^{3} k_j \leq 2M;\ \sum_{j=1}^{3} k_j \leq M;\ i = 3 \\ 0 & ; \text{otherwise} \end{cases} \tag{13}$$

The reconnection rate of a SU in phase 1 due to the death of a SU in phase 2 generating a transition from state $\mathbf{k}$ to state $\mathbf{k} - \mathbf{e}_2 + \mathbf{e}_1 - \mathbf{e}_3$ is given by

$$e_4(\mathbf{k}) = \begin{cases} \dfrac{k_3}{k_3 + \sum_{j=0}^{2} k_j - M} (M - k_0 - k_1) \mu_2^{(S)} & ; \sum_{j=0}^{2} k_j \geq M;\ \sum_{j=0}^{3} k_j \leq 2M \\ & ; k_1 \geq 0;\ k_3 > 0;\ \sum_{j=1}^{3} k_j \leq M;\ i = 4 \\ 0 & ; \text{otherwise} \end{cases} \tag{14}$$

The reconnection rate of a SU in phase 2 due to the death of a SU in phase 2 generating a transition from state $\mathbf{k}$ to state $\mathbf{k} - \mathbf{e}_2 + \mathbf{e}_2 - \mathbf{e}_2$ is given by

$$e_5(\mathbf{k}) = \begin{cases} \dfrac{\sum_{j=0}^{2} k_j - M}{k_3 + \sum_{j=0}^{2} k_j - M} (M - k_0 - k_1)\mu_2^{(P)} & ; \sum_{j=0}^{2} k_j > M;\ \sum_{j=0}^{3} k_j \le 2M; \\ & ; \sum_{j=1}^{3} k_j \le M;\ i = 5 \\ 0 & ; \text{otherwise} \end{cases} \tag{15}$$

An arrival of a new cognitive call is blocked when there is not idle sub-bands. That is, new call blocking probability $P_B^{(S)}$ can be computed as follows

$$P_B^{(S)} = \sum_{\substack{k_0=0 \\ \left\{\mathbf{k} \middle| \sum_{i=0}^{2} k_i \ge M \right\}}}^{M} \sum_{k_1=0}^{M-k_0} \sum_{k_2=0}^{M-(k_0+k_1)} P(\mathbf{k}) \tag{16}$$

On the other hand, for the RR strategy is considered, the probability that a SU be interrupted can be computed as follows (Zhang, 2008)

$$P_{Int} = \frac{\sum_{\left\{\mathbf{k}\in\Omega \middle| \sum_{i=0}^{2} k_i \ge NM; k_0 < M \right\}} \dfrac{1}{M - k_0} P(\mathbf{k})}{\sum_{\left\{\mathbf{k}\in\Omega \middle| \sum_{i=0}^{2} k_i \ge NM; k_0 < M \right\}} P(\mathbf{k})} \tag{17}$$

Finally, the forced termination probability for SUs equals zero. This is due to the fact that ST calls are assumed to wait indefinitely to be served.

5. Performance evaluation of SOAR

In the SOAR strategy each time a queued secondary user is reconnected to the system, it retransmits its whole information no matter that some part of this information was transmitted in its previous connection. That is, the service time of a given ongoing secondary call does not change after it experiences an interruption. However, it is evident that SU calls with greater service time are interrupted with higher probability. Then, due to this fact, a bias effect is observed in the distribution of the service time of interrupted SU calls. Specifically, compared with the corresponding parameters of the service time of SU, the mean value of interrupted SUs increases and depends on the number of times a SU in service is interrupted. More important, it is found that, in general, the service time distributions for interrupted SUs are no longer phase-type distributed, and consequently it is not possible to employ a Markovian model. Then, the performance of the SOAR strategy is evaluated through discrete-event computer simulation.

6. Transmission delay

The mean value of the normalized transmission delay, denoted by $E\{\mathbf{X}_{delay}\}$, is computed as follows

$$E\left\{\mathbf{X}_{delay}\right\} = \frac{E\left\{\mathbf{X}_{system}\right\} - E\left\{\mathbf{X}_{S}^{(S)}\right\}}{E\left\{\mathbf{X}_{S}^{(S)}\right\}} \tag{18}$$

where $E\{\mathbf{X}_{system}\}$ represents the mean value of the elapsed time between the epoch the SU arrives to the system to the epoch it finally leaves the system. The numerical results for the mean value of the normalized transmission delay are obtained by a developed discrete event computer simulator. In our simulation, we compute this parameter as follows

$$E\left\{\mathbf{X}_{system}\right\} = \frac{\sum_{i=0}^{n}\left(\mathbf{X}_{arrival(i)} - \mathbf{X}_{death(i)}\right)}{n} \tag{19}$$

where the random variable $\mathbf{X}_{arrival(i)}$ represents the epoch at which the i-th SU enters the system, the random variable $\mathbf{X}_{death(i)}$ represents the epoch at which the i-th SU leaves the system, and n represents the total number of no blocked SU.

7. Numerical results

The goal of the numerical evaluations presented in this section is to investigate the performance of cognitive radio networks with the RR or SOAR strategies considering different phase-type probability distributions for the service time of SU calls. Specifically, numerical results for the following relevant phase-type distributions for modeling service time of SU are presented: negative-exponential, Erlang order 2, and Coxian order 2. System performance is evaluated in terms of both SU new call blocking probability and SU mean normalized transmission delay. Unless otherwise specified, the following values of the system parameters were used in the plots of this section: total number of primary bands M = 3, each primary band is divided into N=1 sub-bands, mean service time for primary users $1/\mu_s^{(P)}$=16.7 s, and mean service time for secondary users $1/\mu_s^{(S)}$=1.22 s. Other system parameters used in this section are summarized in Table 1.

Figs. 3 and 4 (5 and 6) {7 and 8} show, respectively, SU new call blocking probability and SU transmission delay as function of both primary and secondary mean arrival rate for the case when service time for SU is exponentially (Erlang order 2) {Coxian order 2} distributed. As expected, Figs. 3-8 show that blocking probability and transmission delay are monotonically increasing functions of the primary mean arrival rate. This behavior indicates a detrimental effect of the primary arrival rate on the cognitive radio network performance. However, the main conclusion that can be extracted from Figure 3 (5) is that, from the blocking probability point of view and assuming that the service time of SU follows a negative-exponential (Erlang order 2) distribution, the performance of RR and SOAR strategies is very similar irrespective of the values of both primary and secondary mean arrival rates. On the other hand, Fig. 4 shows that, from the point of view of the transmission delay, the RR strategy slightly outperforms the behavior of the SOAR strategy. Specifically, Fig. 4 shows that the

difference in performance between this two strategies increases as the mean arrival rate of PUs increases. From Fig. 6, a similar behavior can be observed when service time for SU is modeled as an Erlang order 2 distributed random variable. The reason of this behavior is evident: Contrary to the SOAR strategy, in the RR strategy an interrupted SU does not need to transmit again the information bits transmitted before its previous connection was interrupted. This fact contributes to improve delay transmission.
On the other hand, Figs. 7 and 8 show that, for values of the mean arrival rate of PUs greater than 0.04, the RR strategy significantly outperforms the SOAR strategy when the service time of SU is modeled as a Coxian order 2 distributed random variable. This behavior becomes more evident as the mean arrival rate of PUs increases. The reason of this behavior is due to the bias effect on the service time distribution of preempted SUs. To explain this effect let us considerer Table 2 and Figs. 9-11.

Service time distribution	$\mu_1^{(S)}$	$\mu_2^{(S)}$	β	CV	SK
Negative Exponential	0.82	N/A	1	1	2
Erlang order 2	1.6399	1.6399	0	0.7071	1.4142
Coxian order 2	8.1842	0.018	0.9801	9	15

Table 1. System parameters for the different service time distributions considered in this section

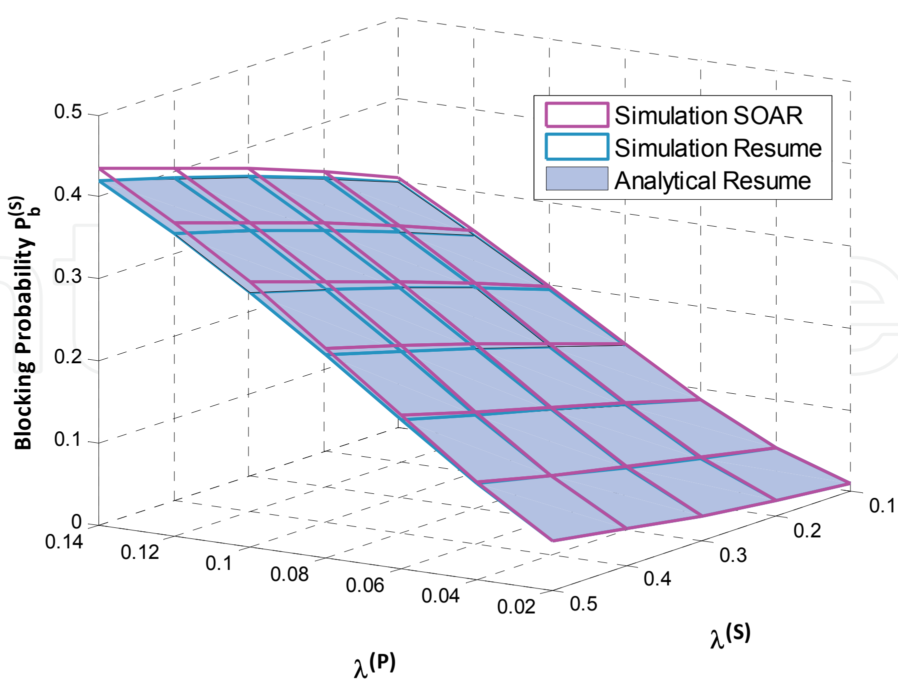

Fig. 3. Analytical and Simulation results for blocking probability for SOAR and Resume retransmission with exponentially distributed service time

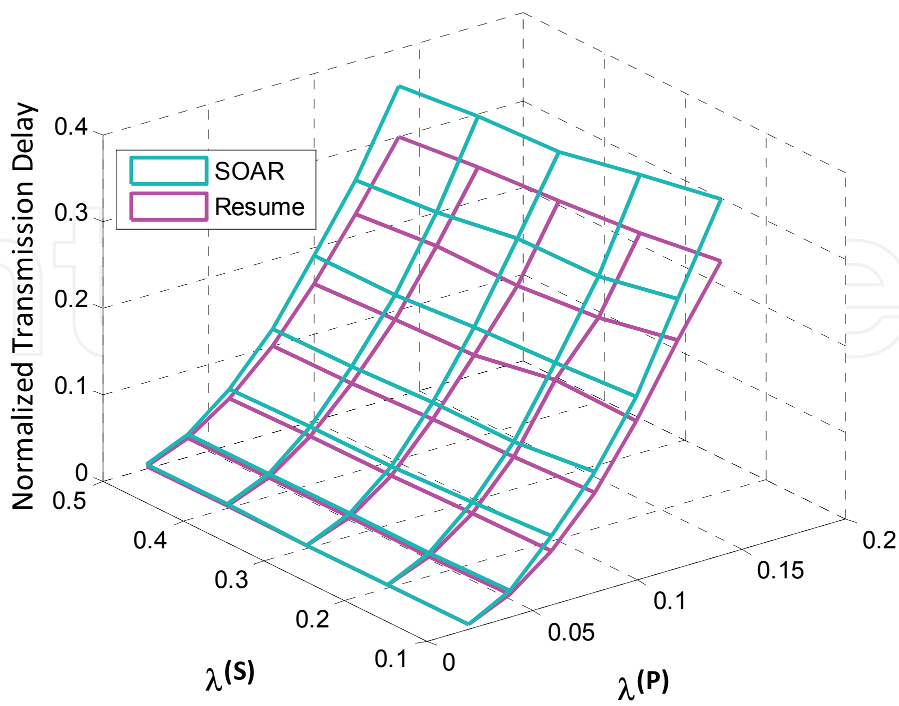

Fig. 4. Simulation results for transmission delay for SOAR and Resume retransmission with exponentially distributed service time

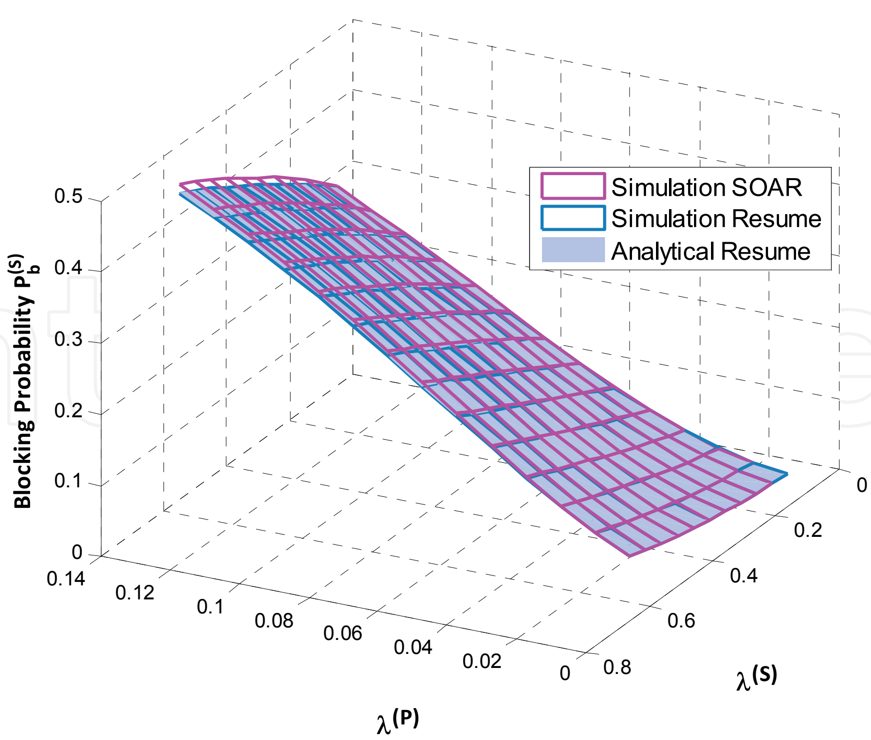

Fig. 5. Analytical and Simulation results for blocking probability for SOAR and Resume retransmission with Erlang order 2 distributed service time

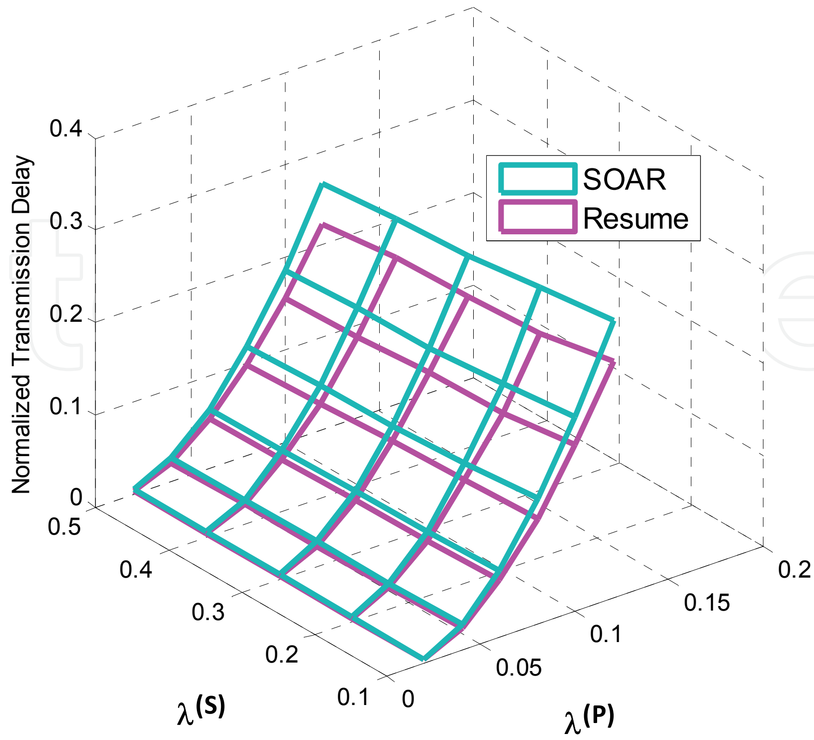

Fig. 6. Simulation results for transmission delay for SOAR and Resume retransmission with Erlang order 2 distributed service time

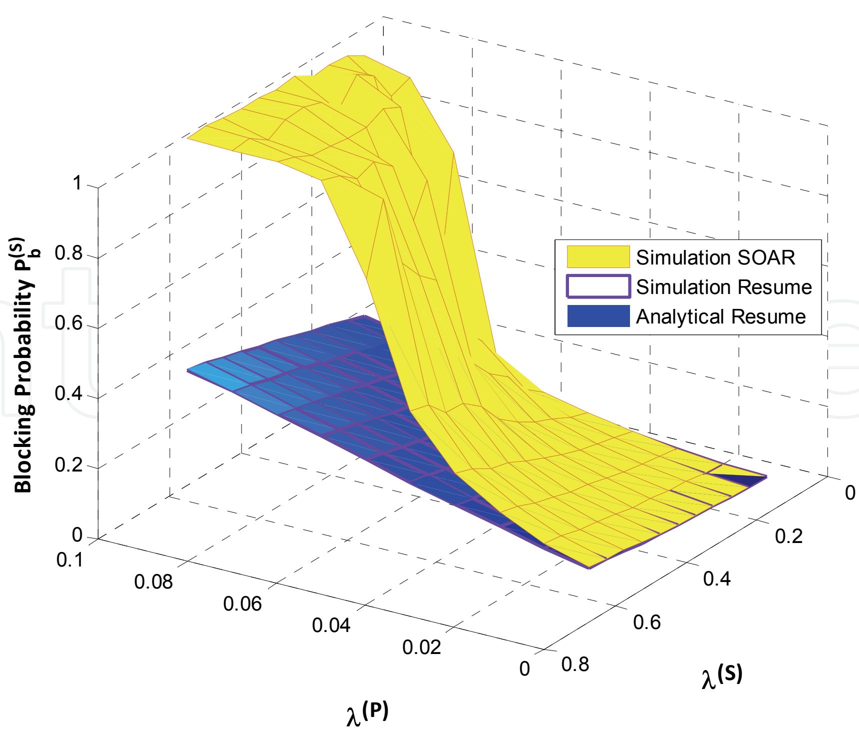

Fig. 7. Analytical and simulation results for blocking probability for SOAR and Resume retransmission with Coxian order 2 distributed service time

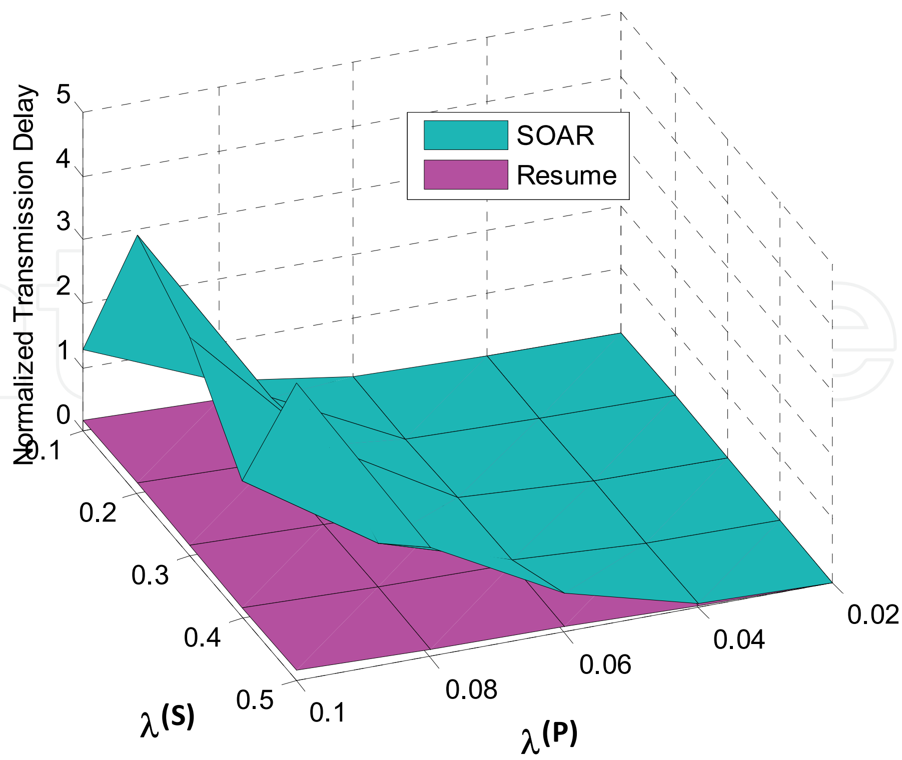

Fig. 8. Simulation results for transmission delay for SOAR and Resume retransmission with Coxian order 2 distributed service time

Moments	EXP-NEG	ERLANG-2	COXIAN-2
$E\left\{X_{S}^{(S)}\right\}$	1.2195	1.2195	1.2195
$E\left\{X_{S_1}^{(S)}\right\}$	2.4305	1.8263	89.545
$E\left\{X_{S_2}^{(S)}\right\}$	3.4119	2.3472	125.16
$E\left\{X_{S_3}^{(S)}\right\}$	4.3038	2.837	147.99
$CV\left\{X_{S}^{(S)}\right\}$	1	0.7071	9
$CV\left\{X_{S_1}^{(S)}\right\}$	0.7069	0.5771	0.8443
$CV\left\{X_{S_2}^{(S)}\right\}$	0.5818	0.5019	0.6387
$CV\left\{X_{S_3}^{(S)}\right\}$	0.505	0.4475	0.5778
$SK\left\{X_{S}^{(S)}\right\}$	2	1.4142	15
$SK\left\{X_{S_1}^{(S)}\right\}$	1.4077	1.1471	1.3162
$SK\left\{X_{S_2}^{(S)}\right\}$	1.1551	0.9907	1.2768
$SK\left\{X_{S_3}^{(S)}\right\}$	0.9976	0.8832	1.1538

Table 2. First three standardized moments of the service time for SU calls interrupted i times (the particular cases for i = 0, 1, 2, 3 are presented in this table)

Table 2 shows the first three standardized moments of the service time for SU calls preempted i times. The particular cases for i = 0, 1, 2, 3 are presented in this table. CV and SK denote the coefficient of variation and skewness operators, respectively. Fig. 9 (10) {11} shows the pdf of the service time for the SU calls preempted 1, 2 and 3 times for SOAR with negative-exponentially (Erlang order 2) {Coxian order 2} distributed service time.

From Figs. 9-11, a bias effect is observed in the distribution of the service time of interrupted SU calls. This behavior is due to the fact that SU calls with greater service time are interrupted with higher probability. Moreover, Table 2, shows that, compared with the corresponding parameters of the service time of SU, we found that the mean value of preempted SUs increases and, at the same time, both skewness and CoV decrease as the number of times a SU in service is interrupted increases. This behavior of the SOAR strategy indicates a detrimental effect on system performance as the number of times an active SU is interrupted increases. This is especially true in situations where high values of the coefficient of variation of service time of SU are presented. Thus, numerical results reported in Table 2 clearly show that, in general, as the CoV of the service time of SU increases, the system performance improvement becomes significantly for the RR strategy relative to the SOAR strategy. On the other hand, when the service time of SUs is considered either exponentially (i.e., CV = 1) or Erlang order 2 (i.e., $CV = 1/\sqrt{2}$) distributed, numerical results show that similar system performance is obtained with both retransmission strategies.

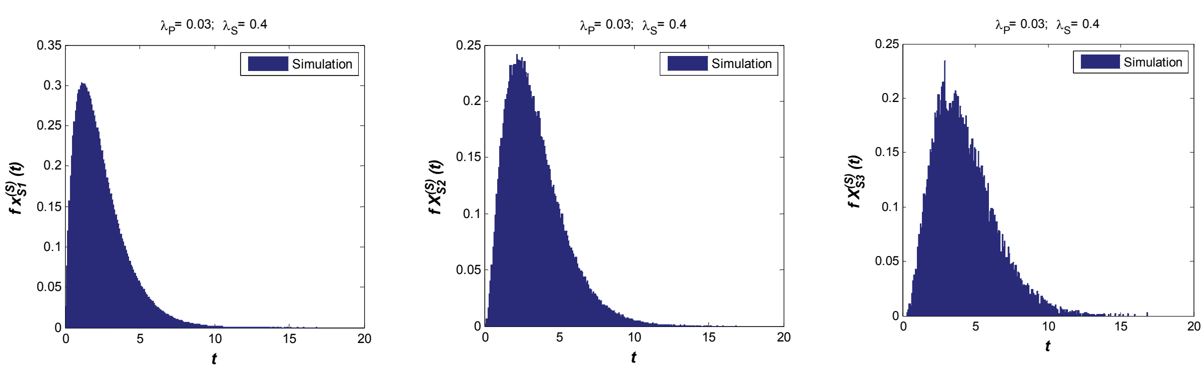

Fig. 9. Service time distribution for the SU calls preempted 1, 2 and 3 times for SOAR with exponentially distributed service time

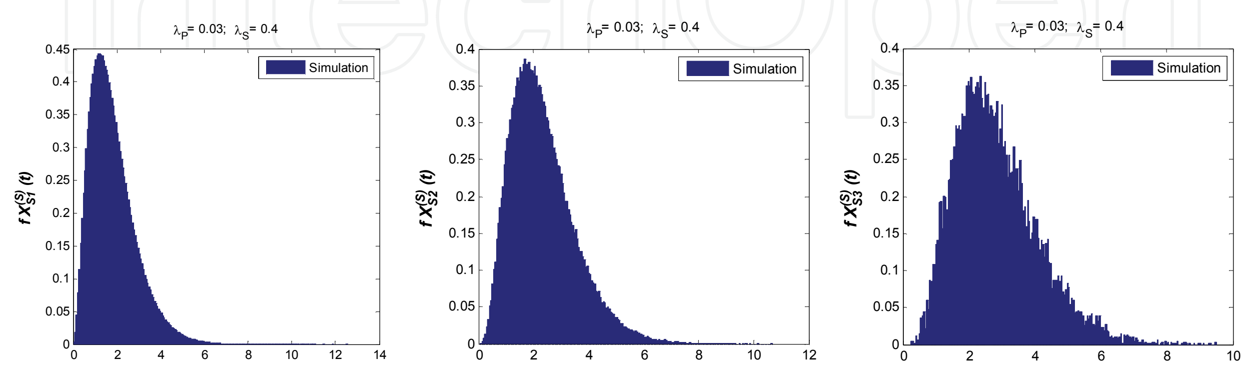

Fig. 10. Service time distribution for the SU calls preempted 1, 2 and 3 times for SOAR with Erlang order 2 distributed service time

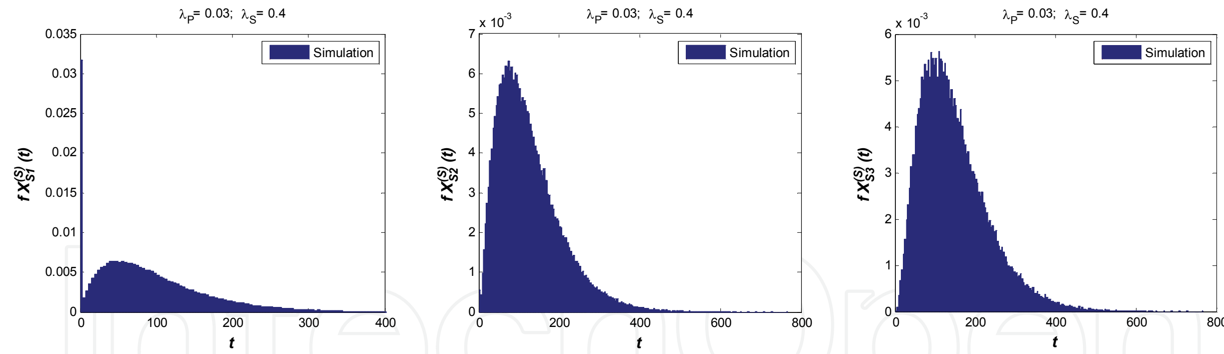

Fig. 11. Service time distribution for the SU calls preempted 1, 2 and 3 times for SOAR with Coxian order 2 distributed service time

8. Conclusions

Performance comparison between the RR and SOAR strategies were performed for different traffic conditions and characteristics of the SU service time. Numerical results show relevant system implications. We found that the value of the coefficient of variation (CoV) of service time of SUs plays a major role in the system performance of cognitive radio networks when RR or SOAR strategies are considered. For instance, we found that as the (CoV) of the service time of SU increases, the system capacity improvement becomes significantly greater for the RR strategy relative to the SOAR strategy. On the other hand, when the service time of SUs is considered either exponentially or Erlang order 2 distributed (i.e., CoV $\leq$ 1), numerical results show that similar system performance is obtained with both retransmission strategies. Thus, we conclude that for scenarios where the coefficient of variation of service time for SU has values around 1, the SOAR strategy is preferred over the more complicated RR strategy. On the contrary for scenarios where the CoV has high values, the RR strategy is preferred over the SOAR one due to its much better performance.

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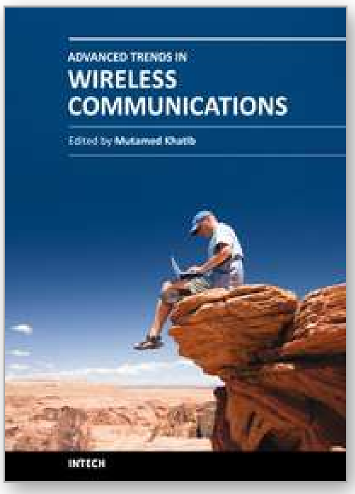

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Physical limitations on wireless communication channels impose huge challenges to reliable communication. Bandwidth limitations, propagation loss, noise and interference make the wireless channel a narrow pipe that does not readily accommodate rapid flow of data. Thus, researches aim to design systems that are suitable to operate in such channels, in order to have high performance quality of service. Also, the mobility of the communication systems requires further investigations to reduce the complexity and the power consumption of the receiver. This book aims to provide highlights of the current research in the field of wireless communications. The subjects discussed are very valuable to communication researchers rather than researchers in the wireless related areas. The book chapters cover a wide range of wireless communication topics.

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