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PERFORMANCE SIMULATION OF FINITE-SOURCE COGNITIVE RADIO NETWORKS WITH SERVERS SUBJECTS TO BREAKDOWNS AND REPAIRS

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The present paper deals with the performance evaluation of a cognitive radio network with the help of a queueing model. The queueing system contains two interconnected, not independent sub-systems. The first part is for the requests of the Primary Units (PU). The number of sources is finite, and each source generates high priority requests after a exponentially distributed time. The requests are sent to a single server unit or Primary Channel Service (PCS) with a preemptive priority queue. The service times are assumed to be exponentially distributed. The second sub-system is for the requests of the Secondary Units (SU), which is finite sources system too; the inter-request times and service times of the single server unit or Secondary system Channel Service (SCS) are assumed to be exponentially distributed, respectively. A generated high priority packet goes to the primary service unit. If the unit is idle, the service of the packet begins immediately. If the server is busy with a high priority request, the packet joins the preemptive priority queue. When the unit is engaged with a request from SUs, the service is interrupted and the interrupted low priority task is sent back to the SCS. Depending on the state of the secondary channel, the interrupted job is directed to either the server or the orbit. In case the requests from SUs find the SCS idle, the service starts, and if the SCS is busy, the packet looks for the PCS. In the case of an idle PCS, the service of the low-priority packet begins at the high-priority channel (PCS). If the PCS is busy, the packet goes to the orbit. From the orbit it retries to be served after an exponentially distributed time.

The novelty of our investigation is that each server is subject to random breakdowns, in which case the interrupted request is sent to the queue or orbit, respectively. The operating and repair times of the servers are assumed to be generally distributed. Finally, all the random times included in the model construction are assumed to be independent of each other.

The main aim of the paper is to analyze the effect of the nonreliability of the servers on the mean and variance of the response time for the SUs by using simulation.

1. Introduction

In recent years the demand for radio spectrum has increased to a great extent. The concept of cognitive radio networks (CRN) is to make the misspent section of the spectrum useful. It takes part by operating unlicensed (secondary) networks over licensed (primary) frequency bands. The basic functionality of a CRN is to use the unused sections of the the licensed frequency band for the advantage of the unlicensed customers (users) without inducing disadvantageous interference to the licensed customers [1]. The licensed customers/users are called primary users (PUs), and the unlicensed customers/users are called secondary users (SUs). The concept of cognitive radio has been introduced into the wireless communications research community, and realizing the CNRs becomes more realistic. It is presumed to be an important component of the wireless communication networks [2].

The CRNs are divided into two categories, called the underlay and overlay networks. In the underlay CRNs, the SUs are authorized to access the licensed channels simultaneously with the PUs under some conditions. Therefore, in this types of CRNs, the frequency bands are always available for the SUS. For more details see [3–7]. In the overlay networks, the SUs are allowed to access licensed channels

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only when they are not used by the PUs. Therefore, the frequency bands are not always available for the secondary network. The SUs has to sense the frequency channels in order to identify the spectrum opportunities. In this paper, we work on the model of the overlay networking standard. Briefly, we use the term cognitive radio network CRN to define an overlay CRN.

In this paper, we model cognitive radio network by using a finite-source retrial queuing system with primary and secondary service units subject to breakdowns and repairs. A finite-source retrial queueing model with nonreliable single server has been used in [8] to analyze the effect of the server's failure in the system with the help of supported tools approach. In these papers, the authors generate figures to show the impact of the failure and repair rates of the service unit on the main performance measures of the system.

In [9] a cognitive radio network has been designed with the help of retrial queueing systems containing two finite sources of PUs and SUs, respectively. A continuous Markov chain was constructed since by assumption all the inter-event times were assumed to be exponentially distributed. Furthermore, the same software package as the above papers was used in order to illustrate the basic performance measures. For the more general situation of the model mentioned above, in [10] the same system model was introduced, and by assumption all the inter-event times (generation, service and retrial times) were non-exponentially distributed times. Different case studies and several sample examples illustrated the effect of the distribution on the main characteristic of the systems by using the stochastic simulation approach. It should be noted that in the earlier mentioned papers [9, 10], the service units were not subject to any breakdowns or repair but the transmission through the frequency channels were not reliable.

In this paper, we use the same model of retrial queueing system for the cognitive radio networks with primary channel service (PCS) and secondary channel service (SCS). The novelty of this work is that the primary and secondary service units are assumed to be subject to breakdown and repair. For a primary service modeled as a priority queueing system, PUs have a licensed frequency band applying preemptive priority discipline to the SUs. At the secondary service modeled as a retrial queueing system, SUs have a nonlicensed frequency band. By assumption, the request generation, service, and retrial times are exponentially distributed. However, we assume that the failure and repair time of the servers are generally distributed, and from this point forward, we investigate the impact of the failure and repair time distribution on the main characteristic of the system.

In this paper our objective is to analyze the effect of the repair and failure time distribution on the the expectation and variance of the sojourn time of the PUs and SUs, respectively. With the help of simulation, we obtain several sample comparisons illustrated in different figures. The reason for using simulation is that we can estimate the variance, which cannot be calculated easily except by using algorithmic approaches.

2. System's operation model

The finite source retrial queueing system which is used to model the considered cognitive radio network is illustrated in Fig. 1. The queueing system contains two interacting, not independent subsystems. The first subsystem of the network is for the calls of the PUs. The number of sources is finite and denoted by N_1. Each source generates high priority requests according to an exponentially distributed inter-request time with the parameter λ_1. The arriving customers are sent to a single server unit (Primary Channel Service — PCS) connected by a preemptive priority queue. The service times are assumed to be also exponentially distributed with the parameter μ_1.

The second subsystem is for the calls of the SUs. There are N_2 sources; the secondary calls generation times and service times of the single server unit (Secondary Channel Service — SCS) are assumed to be exponentially distributed random variables with parameter λ_2 and μ_2, respectively.

A generated high priority call is transmitted to the primary service unit. If the server is idle, the service of the request starts immediately. If the server is busy with a high priority packet, the

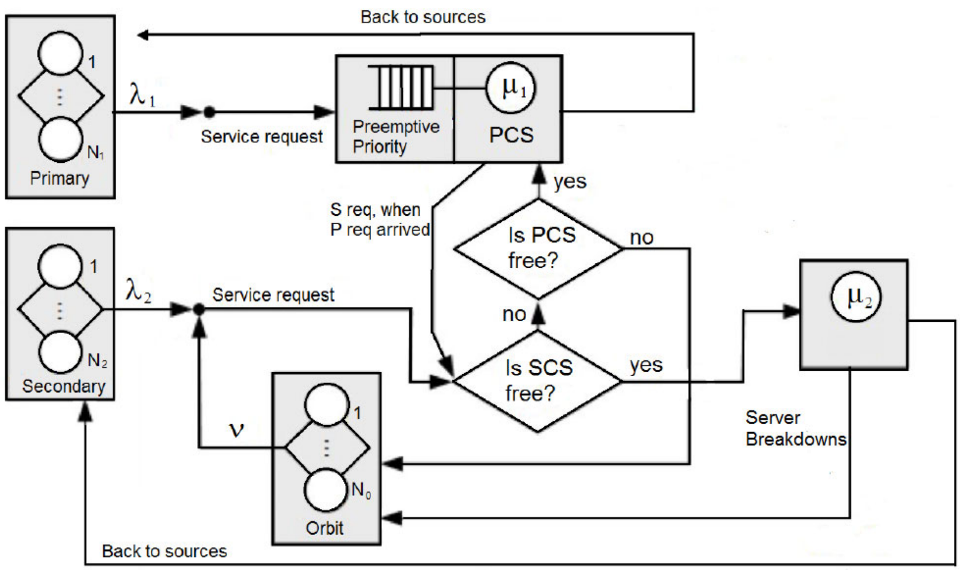

Fig. 1. Finite-source retrial queueing system: modeling the cognitive radio network.

request is sent to the preemptive priority queue. When the unit is servicing a customer from SUs, the service is interrupted and the interrupted low priority task joins the SCS. Depending on the state of secondary channel, the interrupted job is directed to either the server or the orbit. The primary server can break down during an idle or busy state according to exponentially, hypo-exponentially, and hyper-exponentially distributed time with the same rate γ_1 . In case the server fails in the busy state, the service is stopped, and the interrupted task joins the preemptive priority queue or the SCS, depending on the request type. The repair time is also assumed to be an exponentially, hypo-exponentially, and hyper-exponentially distributed random variable with the same rate σ_1.

In the case of SU's calls, if the SCS is idle, the service begins; if the SCS is busy, the packet senses the PCS. In case of an idle PCS, the service of the low-priority request starts at the high-priority channel (PCS). If the PCS is busy, the packet joins the orbit. From the orbit it retries to be served after an exponentially distributed time with parameter ν. Similarly, to the first part of the network, the breakdown can occur at the secondary server unit according to an exponentially, hypo-exponentially, and hyper-exponentially distributed time with the same intensity γ_2. The repair time of the secondary service unit is also an exponentially, hypo-exponentially, and hyper-exponentially distributed random variable with the same intensity σ_2.

The operation of the system can be described by using a stochastic model. Let us introduce the following notations:

- $k_1(t)$ is the number of high-priority sources at time t;
- $k_2(t)$ is the number of low-priority (normal) sources at time t;
- $q(t)$ denotes the number of high priority requests in the priority queue at time t;
- $o(t)$ is the number of requests in the orbit at time t;
- $y(t) = 0$ if there is no job in the PCS unit, and $y(t) = 1$ if the PCS unit is busy with a job coming from the high priority class, and $y(t) = 2$ when the PCS unit is servicing a job coming from the secondary class at time t;
- $c(t) = 0$ when the SCS unit is idle, and $c(t) = 1$ when the SCS is busy at time t.

It is easy to see that

$$k_1(n) = \begin{cases} N_1 - q(t), & y(t) = 0{,}2, \\ N_1 - q(t) - 1, & y(t) = 1, \end{cases}$$

$$k_2(n) = \begin{cases} N_2 - o(t) - c(t), & y(t) = 0{,}1, \\ N_2 - o(t) - c(t) - 1, & y(t) = 2. \end{cases}$$

In the special case where all inter-event times are exponentially distributed as in [9] for systems with reliable servers, the authors described the operation of the system with the help of a continuous-time Markov chain and calculated the main stationary performance measures. However, in this work we deal with a more general situation by supposing non-exponential distribution for the failure and repair time of the servers as was done in [10, 11] for the service, request generation, and retrial times. Our main objective is to analyze the expectation and the variance of the response times of the requests in the system.

The input parameters of the simulation are collected in Table 1.

Table 1. List of simulation parameters

Parameter	Maximum	Value at t
Active primary sources	N_1	$k_1(t)$
Active secondary sources	N_2	$k_2(t)$
Primary generation rate		λ_1
Secondary generation rate		λ_2
Requests in the priority queue	$N_1 - 1$	$q(t)$
Requests in the orbit	$N_2 - 1$	$o(t)$
Primary service rate		μ_1
Secondary service rate		μ_2
Retrial rate		ν
Primary failure rate		γ_1
Secondary failure rate		γ_2
Primary repair rate		σ_1
Secondary repair rate		σ_2

3. Simulation results

This section presents different graphs illustrating some sample examples which show the effect of the failure and repair time distributions having the same mean but different variance. This is done with the help of the hypo-exponentially and hyper-exponentially distributions and comparing the results of the exponential distribution. By using the batch mean method within the stochastic simulation program, an estimation of the mean and variance of the sojourn time of the PUs and SUs can be obtained. The batch mean method is the most used technique for output analysis of the steady-state simulation. For more details see, for example [12–18].

For the numerical values of the input parameters, see Table 2.

In Figs. 2 and 3, we assume that the primary server is reliable; thus, $\gamma_1 = 0$ and $\sigma_1 = 0$. Therefore, we concentrate on the second sub-system of the network and observe the impact of the secondary breakdown and repair times distribution on the mean response time of the secondary customers when the failure and repair intensities are increasing (γ_2, σ_2), respectively.

Figure 2 shows that the distribution of the secondary repair time has an effect on the mean response time of the SUs by having greater sojourn time when the distribution is hyper-exponential than hypo-exponential. In [10], the same results of the impact of the secondary service time distribution was

Table 2. Numerical values of the parameters

No.	N_1, N_2	λ_1, λ_2	μ_1, μ_2	ν	γ_1	γ_2	σ_1	σ_2
Fig.2	10	0.1	4	0.4	0	0.05	0	x-axis
Fig.3	10	0.1	4	0.4	0	x-axis	0	0.05
Fig.4	10	0.1	4	0.4	x-axis	0	0.05	0
Fig.5	10	0.1	4	0.4	0.05	0	x-axis	0
Fig.6	10	0.1	4	0.4	0,0.05	0.05,0	0,x - axis	x - axis, 0
Fig.7	10	0.1	4	0.4	0,x - axis	x - axis,0	0,0.05	0.05,0
Fig.8	10	0.1	4	0.4	0	0.05	0	x-axis
Fig.9	10	0.1	4	0.4	0.05	0	x-axis	0
Fig.10	10	0.1	4	0.4	x-axis	0	0.05	0

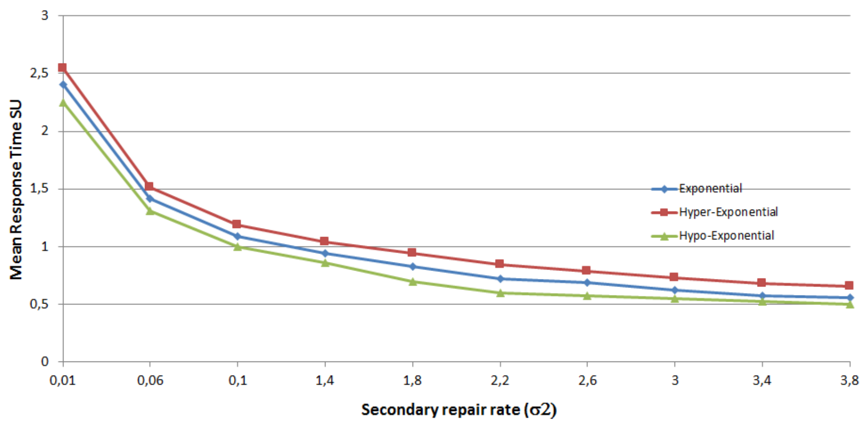

Fig. 2. The impact of the secondary repair time distribution on the expectation of the sojourn time of the SUs vs σ_2.

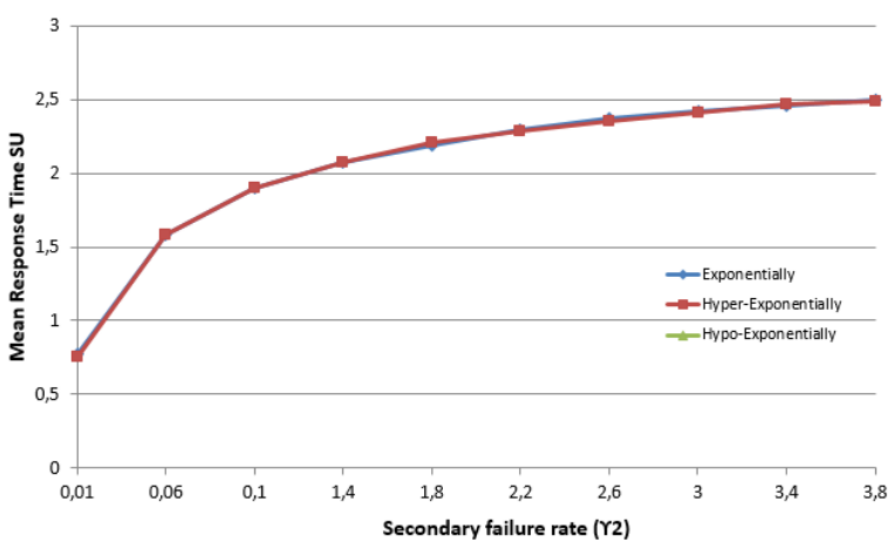

Fig. 3. The effect of the secondary failure time distribution on the mean response time of the SUs vs γ_2.

illustrated. As known already, the squared coefficient of variation of the hyper-exponential distribution is always greater than 1, contrary to the hypo-exponential distribution, which is always less than 1.

However, Fig. 3 shows that under the present parameter setup the distribution of the secondary failure time has no effect on the expectation of the sojourn time of the secondary users.

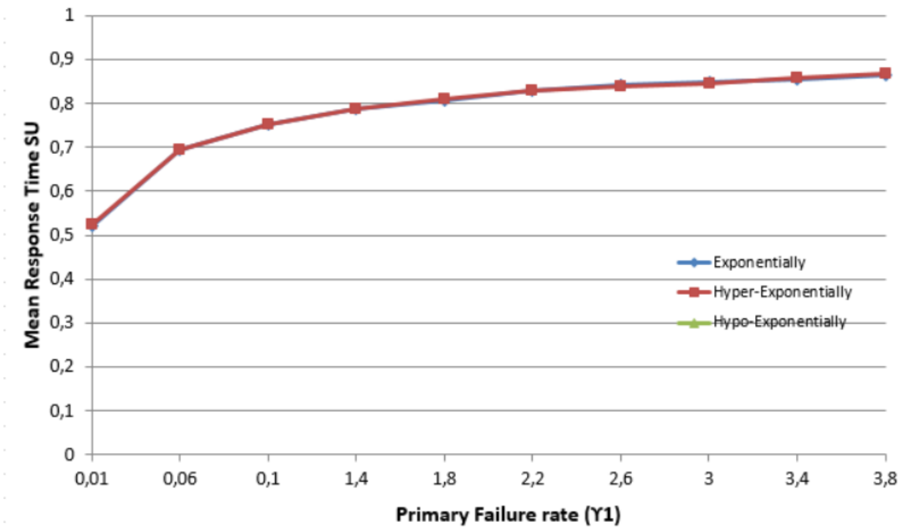

Fig. 4. The effect of the failure time distribution on the mean response time of the SUs vs γ_1.

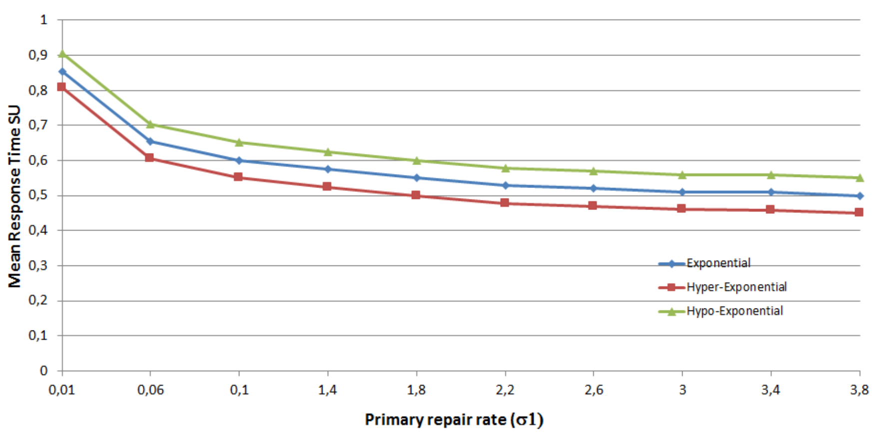

Fig. 5. The impact of the primary repair distribution on the expectation of the sojourn time of the SUs vs σ_1.

In Figs. 4 and 5, we assume that the secondary server is reliable, which means $\gamma_2 = 0$ and $\sigma_2 = 0$. Again we are interested in the second sub-system of the network and we would like to investigate the effect of the primary breakdown and repair time distribution on the mean response time of the secondary calls when the failure and repair rates are increasing (γ_1, σ_1), respectively.

Figure 4 illustrates that the distribution of the primary failure rate has no effect on the expectation of the sojourn time of the SUs. Similarly to Fig. 3, we have the same response time of the customers whether the distribution of the primary or secondary breakdown time is exponentially, hypo-exponentially, or hyper-exponentially.

Also, in Fig. 5, as in Fig. 2, the distribution of the primary repair has an effect on the mean response time of the SUs. Contrary to Fig. 2, here we have a greater value of the sojourn time when the distribution is hypo-exponential than hyper-exponential. This is a particular case of the cognitive radio networks. As was mentioned earlier, secondary customers must release the primary server unit when a high-priority packet requests the server unit.

Figure 6 illustrates the effect of the nonreliability of the server on the expectation of the response time when the failure intensity is increasing (γ). We compare two cases, namely when the secondary server is nonreliable and when the primary server is nonreliable. As was expected, increasing the secondary failure intensity causes a longer response time for the secondary users. Also, by increasing the primary failure intensity, the secondary customers cannot access the primary channel service, which involves a constant values of the sojourn time.

Figure 7 shows the impact of the nonreliability of the server unit on the mean sojourn time of the SUs. It illustrates the difference on the value of the mean response time while the repair intensity is increasing (σ). As shown in this figure, in cognitive radio networks, having a reliable server leads to a shorter response time, and the difference of the values is small.

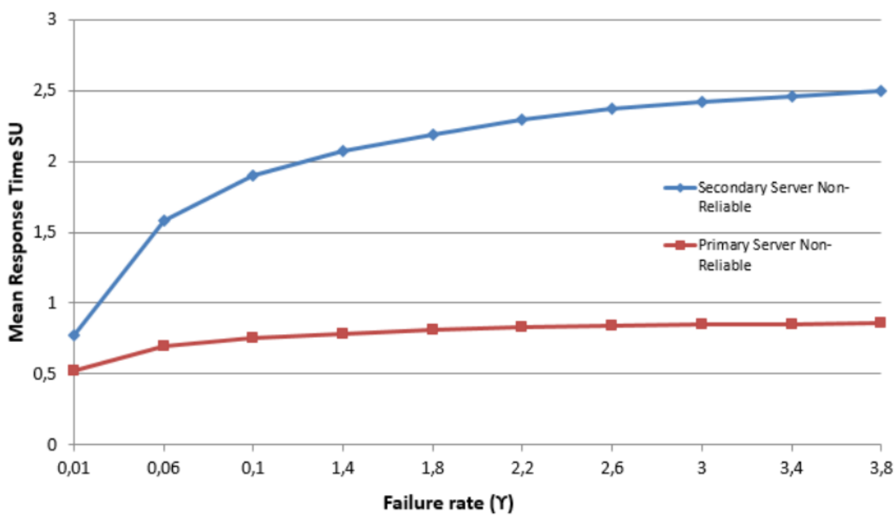

Fig. 6. The impact of the nonreliability of the server on the mean response time of the SUs vs failure rate (γ).

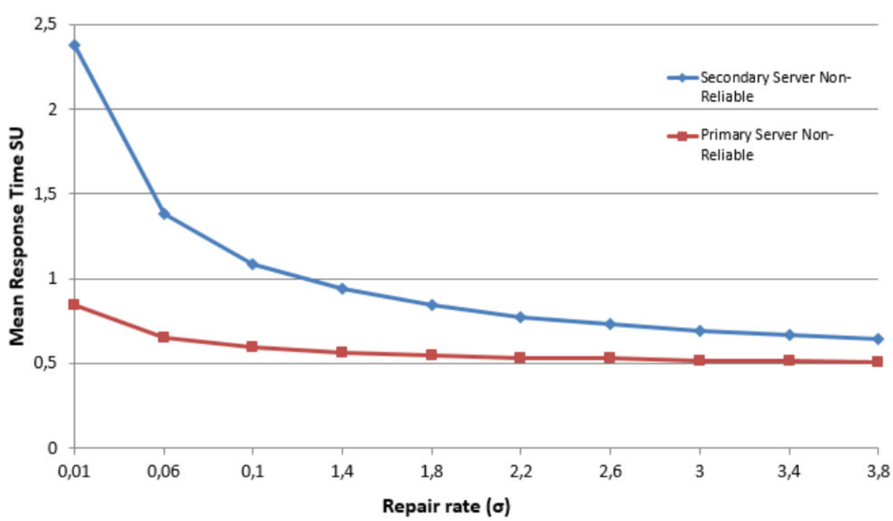

Fig. 7. The effect of the nonreliability of the server on the mean response time of the SUs vs repair rate (σ).

In Figs. 8 and 9, we show the effect of the repair times distribution on the variance of the response time of the SUs.

Figure 8 shows the same behavior of the variance as the average of the response time. It should be noted that, in this case, the primary service unit is reliable. The value of the variance is greater than

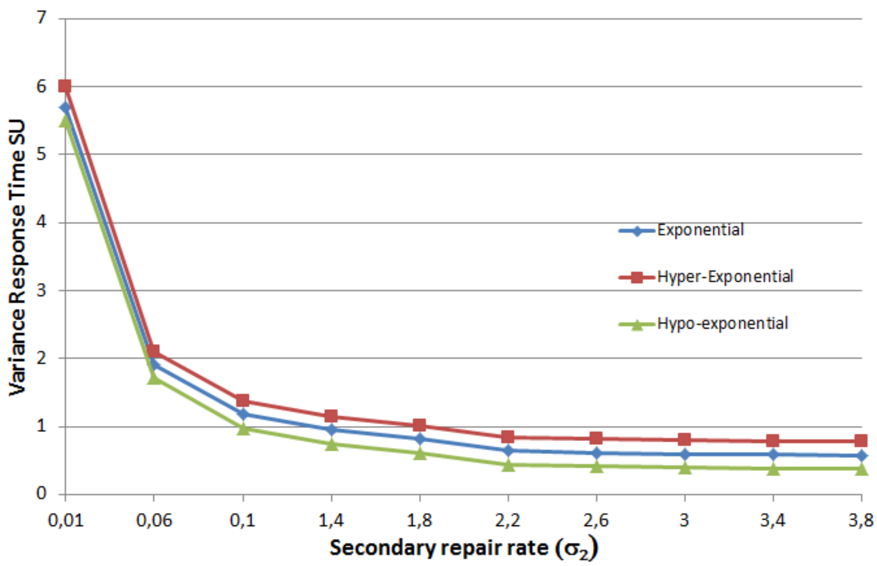

Fig. 8. The impact of the secondary repair time distribution on the variance of the response time of the SUs vs σ_2.

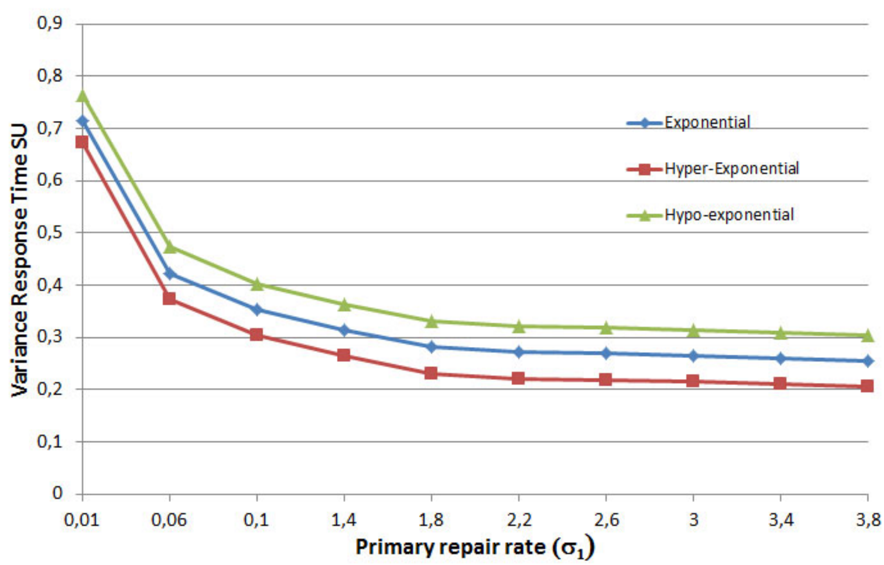

Fig. 9. The impact of the primary repair time distribution on the variance of the sojourn time of the SUs vs σ_1.

the value of the mean response time, and the distribution of the secondary repair time has an impact on the second moment of the response time of the SUs.

Similarly, in Fig. 9, as in Fig. 4, when the secondary service unit is reliable, the distribution of the primary repair time has an effect on the variance of the response time of secondary customers. In this case the value of the variance is smaller than the value of the expectation. Similarly, the variance value is greater when the repair time distribution is hypo-exponentially than hyper-exponentially.

Figure 10 illustrates the effect of the primary failure distribution on the variance of the sojourn time. There is no effect on the value of the variance and, as expected, increase of failure intensity involves longer sojourn time.

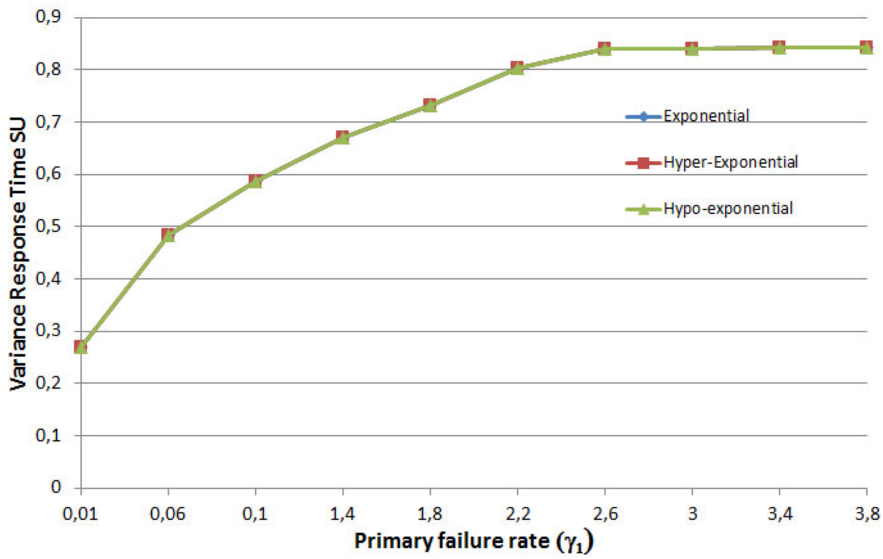

Fig. 10. The effect of the failure time distribution on the variance response time of the SUs vs γ_1.

4. Conclusion

In this paper, we presented a finite-source retrial queueing system with two non-independent sub-systems to model cognitive radio networks with primary and secondary service units subject to breakdowns and repairs. The high-priority tasks have preemtive priority over the low-priority packets in servicing at primary server. For the secondary sub-system an orbit was established for the low-priority jobs finding the servers busy upon arrival. With the help of the stochastic simulation method, an estimate of the mean and variances of the response times of the secondary users showed the effect of the distribution of the failure and repair times.

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