Short thesis for the degree of doctor of philosophy
(PhD)

Performance Modeling of Finite-Source Cognitive Radio Networks Using Simulation

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1 Introduction

Wireless systems are enduring some fundamental service problems with regard to some appropriate spectrum bands in order to satisfy future requests. The expression cognitive radio was presented for the first time in 1999 by Mitola in [18], demonstrating that this technology is conscious of the surrounding environment where performers have the ability to adjust its own parameters to improve customers performance. Many studies and researches reveal that often many parts of the channels are unused in time and space. The Cognitive radio evaluates the environmental conditions and makes use of this information for future evaluations. The cognitive radio model mainly features two levels of users. Primary Users (PU) are approved users who have the exclusive right to use certain licensed communications frequency bands. Secondary Users (SU) are allowed to use the frequency spectra only for the moment they do not conflict with the PU. The ability to detect an unused spectrum and the ability to use a spectrum temporarily without interfering with primary users are therefore two essential components necessary for the success of cognitive radios. For more details on the characteristics, architectures and spectrum sensing techniques; we refer the following books [4, 8, 24, 25].

Nowadays cognitive radio networks has taken an interest in queueing theory. Retrial queueing system in cognitive radio network contains a system with two non-independent frequency channels servicing two groups of customers that we have described above. In [1], Queueing theoretical methods have been utilized to model cognitive radio network by setting retrial queueing systems that contain two finite PU and SU sources, respectively. A multidimensional Markov chain has been implemented as all the inter-event periods have been distributed exponentially by definition. The mean values of the major performance measurements were evaluated and then illustrated.

As a natural generalization the model used in [1], the same system is analyzed in this thesis allowing non-exponentially distributed request generation, service, retrial, failure and repair times. To evaluate our system's performance, stochastic simulation approach is used to obtain estimates for its most important characteristic and different case studies illustrate the influence of these general distributions.

During communication sessions, customers (users) generally compete over resources because of the scarcity of frequency bands or communication channels. In many situations there is a serious possibility of collision. Several sources that launch uncoordinated requests can cause conflicts that conduct to the trasmission loss and, therefore, the need for retransmission. it is very significant to study the impact of the collision on communication network's quality of service and build up efficient procedures to prevent these conflicts. Some recent results on this phenomenon in [17, 19].

Usually in the literature, the service units are typically supposed to be available constantly in these types of communication networks. However, these suppositions do not reflect the real life situations where errors and power disruption may occur at any time. For instance, the wireless communication systems are very exposed to the transmission failure because of the wireless frequency bands. Therefore, it is very important to study these cases due to their great influence on the network characteristic and performance measure. previous authors have treated the non-reliability of the servers on several retrial queueing systems. For example in [2, 13, 15, 16, 21]

We have built a simulation program to model the finite-source cognitive radio network and investigate the influence of the inter-request time distribution on the mean, variance of the response time for PUs and SUs and the utilization of the primary and secondary servers. We have combined several case studies, for instance:

- Finite-source retrial queuing system for cognitive radio network.
- Finite-source cognitive radio network with non-reliable services.
- Servers subject to breakdown and repair in finite-source cognitive radio network.
- Finite-source cognitive radio network with collision.
- combined collision and non-reliability of the servers in the same network.

2 The aim of the research

The work of this thesis revolves around a cognitive radio network simulation. A finite-source retrial queueing system is used to model a system based on cognitive paradigms. the model introduced in this thesis considers primary and secondary (cognitive) users, both are assigned to two interconnected, not independent frequency band. The first channel is attached to preemtive priority queue and the second one to an orbit. These units are built in order to treat the retrial demands of the primary and secondary users that find the service units busy upon arrivals. In this thesis, a simulation program is developed to investigate the performance of such a system, considering several scenarios that reflects different troubles in the radio network communication.

Previously in [1], the authors have modeled a cognitive radio network by the help of retrial queueing systems. They have introduced a multidimensional Markov chain since by assumption all the inter-event times were exponentially distributed. By the use of queueing theoretical methods, they have investigated the effect of the distribution parameters on the performance measures of the system. Hence, as a natural generalization of that model, we assume in this thesis a general distributions for the inter-event times to analyze and compare the impact of these distribution on the mean and variance response times of the primary and secondary users. Several scenarios take place at this point such as a non-reliability of the services, non-reliability of the servers and collision. The aim of this work is to investigate the effects of the general distributions as well as the impact of the mentioned phenomenon on the performance measures of the system.

Several papers from the literature have treated queueing systems by the help of an asymptotic methods, for instance [17, 19]. Assuming exponentially distributed inter-event time, the mean and variance of the performance measures could be calculated. However, solving the underlying steady-state equations by assuming non-exponential distributed inter-event times is almost impossible. Hence, the novelty in this work is that we build a simulation program for performance modelisation of a finite-source cognitive radio network with the help of a retrial queueing systems. The most important advantage of this simulation is to give estimations for the distribution's variances.

Overall, a queueing systems with two finite sources is introduced to model the performance of cognitive radio networks. Different scenarios are taken in consideration such as systems with non-reliable services, non-reliable servers as well as collision. The aim is to investigate the impact of the inter-event times distributions on the expectation and variance of the sojourn time of the primary and secondary customers. Using simulation, several sample examples for the above mention problems are illustrated in different figures.

3 Methodology

The investigation of the inter-time distribution is usually very complicated, and in most situations its Laplace-transform is given. Variance estimation isn't a simple problem, it can be calculated using numerical and algorithmic approaches. in many practical cases, the described Markov Chain state space is very big, to evaluate the system measures using analytical methods to solve steady-state equations is almost impossible. To simplify this process, numerous numerical and algorithm approaches have been developed that are capable of defining and evaluating complex systems but are constrained in terms of handling only exponentially distributed random variables or their memory consumption is too high. However, a simulation program based on the use of SimPack [11], which is a series of C/C++ libraries and computer simulation executable programmes. Various simulation models including discrete event simulation, continuous simulation and hybrid simulation are provided in this collection of algorithms. In order to aimed the required performance measures, a statistic module is provided and developed by [12]. this module is a statistical analysis tool that contains the routines dealing with the statistical aspects of a simulation run. It is able of evaluating a quantitative estimation of the mean and variance for the observed variables.

In order to estimate the mean and variance values and set up its confidence interval, the batch means method is used

which consists on the division of the observations collected in consecutive blocks of data, so called batches. and then treats the means obtained from these batches as if they were independent. It is the most popular confidence interval technique for the output analysis of a steady-state simulation. The batch means method has been used and described in [5, 7, 10, 23]. The statistical class applies this method to collect a series of independent batch means by aggregating n successive random variables of a steady state simulation. The batch size should be long enough to ensure the sample averages are approximately independent.
Several simulation runs have been performed to investigate the performance measures of the retrial queue cognitive radio network with finite number of sources using the following input parameters in the statistical module:

- Relative half-width of the confidence interval required to stop the simulation run is 0.05 (The run is stopped when all the analyzed processes achieve the selected accuracy level).
- Minimum number of observations to be collected before to check the initial transient closing condition is 5000.
- Maximum number of treatable observations = 10000000
- Size of the batch used to check the initial transient duration is 30
- Number of the transient batch means used to check the initial transient closing condition is 10

- Accuracy level required to close the initial transient detection is 0.99
- Initial size of a batch used during the stationary analysis is 10000 (If the number of collected batch means exceeds the available dedicated memory space, the means are coupled and the batch size doubles).
- the confidence level = 95%

The main simulation program is based on a set of routines for the events. The most important actions during the simulation run are:

- Arrival of a customer to the system.
- Request the primary service unit.
- Request the secondary service unit.
- Release the primary server.
- Release the secondary server.
- Arrival from the orbit.
- Primary server breaks down.
- Secondary server breaks down.

In the next section, we will discuss the obtained results in this work and refer each one to its appropriate publication.

4 Simulation results and discussions

4.1 Finite-source cognitive radio network

The Cognitive Radio (CR) technology has emerged as a promising technology to realize dynamic spectrum access and increase the efficiency of a largely underutilized spectrum. In cognitive radio networks, the unused licensed bands which is for the licensed customers (Primary Users) are granted for the unlicensed customers (Secodary Users) for a strategically access if no high priority activities (Primary user's job) are detected. In this situation secondary users must react in a cooperative way if a primary customer arrives. For a detailed overview of the cognitive radio networks, see [4, 24].

Retrial queues are defined by the following feature: a query that find all servers busy during arrival leaves the service facility but after a random time repeats his request. Queueing models are often used for the performance analysis of computer and communication systems. In case of many real-life systems, retrial queues can be applied in the performance modeling, for example, in telephone switching systems, telecommunication networks, computer networks and computer systems, call centers, wireless communication systems, etc. The prioriy queueing models have been used for the cognitive radio networks, where higher-priority requests can preempt the service of lower-priority ones, and breakdown/repair models, where a server can go down and stop providing service for some period. The servers are the PUs channels, which can be opportunistically and dynamically used by SUs under determined conditions. The requests are PUs and SUs data packets, sessions or connections, which are queued if they cannot immediately access to the required channel. We mention some of previous works that have been applied retrial queueing systems to model cognitive radio network: [1, 3, 6, 9, 14]

4.1.1 System model

Let us consider a queueing system with finite number of sources is utilized for the modelisation cognitive radio network. The queueing model consists of two associated, not independent sub-networks. The first part is for the PUs calls. The number of sources is defined by N_1. In order to investigate the impact of the distribution, these sources generate high priority requests with hypo-exponentially, hyper-exponentially and lognormally distributed inter-request times with the same rate λ_1 or with the same mean $1/\lambda_1$. The generated requests are sent to a single server unit (Primary Channel Service - PCS) with preemptive priority queue. The service times are supposed to be also hypo-exponentially, hyper-exponentially and lognormally distributed with the same rate μ_1 or with the same mean $1/\mu_1$.

The second part is for the requests of the SUs. There are N_2 sources, the inter-request times and service times of the single server unit (Secondary Channel Service - SCS) are assumed to be hypo-exponentially, hyper-exponentially and lognormally distributed random variables with rate λ_2 and μ_2, 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 secondary channel the interrupted job is directed to either the server or the orbit. The transmission through the radio channel may produce errors, which can be discovered after the service. In the model this case has a probability p, and the failed packet is sent back to the appropriate service unit. When the submission, is successful (probability *1-p*), the requests goes back to the source.

In case of requests from SUs. If the SCS is idle, the service starts, if the SCS is busy, the packet looks for the PCS. In 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 with parameter ν. The same transmission failure with the same probability can occur as in the PCS segment.

The present model is a generalization of a system treated in [1]. The probability of service failure is assumed to be a constant in order to only analyze the impact of the inter-event times distribution on the mean and variance sojourn time of the PUs and SUs, then, compare with the above mentioned paper.

Thesis 1 (J1)[1] *(Section 4.2) We have analyzed the performance measures of a finite-source cognitive radio network where the inter-event times were generally distributed random variables with the same mean but different variance. The objective was to investigate the impact of these distributions on the mean and variance of the response time. The results have shown a considerable effect of the service time distribution on the performance measures. this effect depends on the squared coefficient of variation of the distribution.*

To create a stochastic process describing the behaviour of the system, the following notations are introduced

- $k_1(t)$ is the number of high priority sources at time t,
- $k_2(t)$ is the number of low priority 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, $y(t) = 1$ if the PCS unit is busy with a job coming from the high priority class, $y(t) = 2$ 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

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[1] "J" denotes Journal papers, "C" denotes Conference papers

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

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

4.1.2 New results

For the sake of easier understanding, the input parameters are collected in Table 4.1.

TABLE 4.1: 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 priority queue	N_1 - 1	$q(t)$
Requests in orbit	N_2 - 1	$o(t)$
Primary service rate		μ_1
Secondary service rate		μ_2
Retrial rate		ν
Error probability		p

Table 4.2 gives the confidence interval of the given point of observation from the simulation runs. Table 4.3 shows the exact values of the service time distribution for the secondary customers. The squared coefficient of variation of lognormal distribution is less than one.

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[2] Square coefficient of variation

TABLE 4.2: Confidence interval for scenarios in case 1

Figures	Distributions	Mean	Variance	Confidence interval	
				Lower bound	Upper bound
4.2	Hyperexp. Hypoexp. Lognormal	8.1593	70.3942	7.7333	8.4666
4.4	Hyperexp.	7.1265	49.8092	6.8106	7.4293
	Hypoexp.	9.2543	89.1245	8.8360	9.6639
	Lognormal	9.5024	91.2480	9.0816	9.9183
4.6	Hyperexp.	2.5014	7.8410	2.317	2.6826
	Hypoexp.	2.2303	5.0162	2.0839	2.3763
	Lognormal	2.0189	4.8694	1.8667	2.1532

TABLE 4.3: Parameter of service times distribution of secondary customers

Distributions	Hyper-exponential	Hypo-exponential	Lognormal
Parameters	p = 0.45 $\mu_1 = 0.228$ $\mu_2 = 0.195$	$\mu_1 = 1.3$ $\mu_2 = 4.3335$	$m = -0.2488$ $\sigma = 0.7055$
Mean	1	1	1
Variance	15	0.6449708	0.6449708
SCV [2]	15	0.6449708	0.6449708

The sample numerical results are treated to illustrate graphically the influence of the inter-event time distributions on the SUs expectation and variance sojourn time. The system input parameters of the following figures are given in Table 4.4.

Figure 4.1 show that the distribution of the inter-arrival

TABLE 4.4: Numerical values of model parameters

No.	N_1	N_2	λ_1	λ_2	μ_1	μ_2	ν	p
Fig 4.1	10	50	x - axis	0.03	1	1	20	0.1
Fig 4.2 and Fig 4.3	10	50	x - axis	0.03	1	1	20	0.1
Fig 4.4 and Fig 4.5	10	50	0.02	x - axis	1	1	20	0.1
Fig 4.6	10	50	0.02	0.03	1	1	x - axis	0.1
Fig 4.7	10	50	0.02	x - axis	1	1	20	0.1

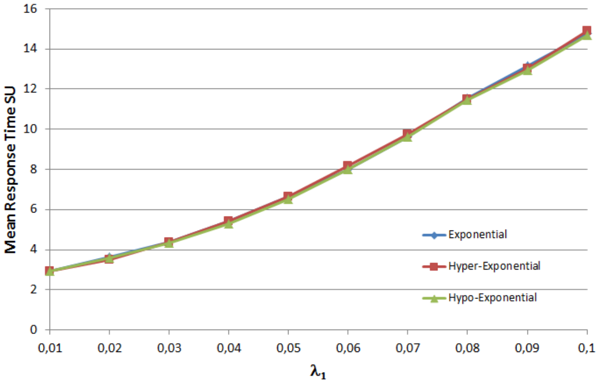

FIGURE 4.1: The effect of inter-request time distribution of the PUs on the mean response time of SUs vs λ_1

time of the primary packets with the same mean has no effect on the mean response time of the secondary users, they depend only on their mean supposing that the inter-request time of the SUs and the service time of both servers units are exponentially distributed. It is the consequence of [20] in which it was proved that the steady-state distribution is insensitive to the distribution of

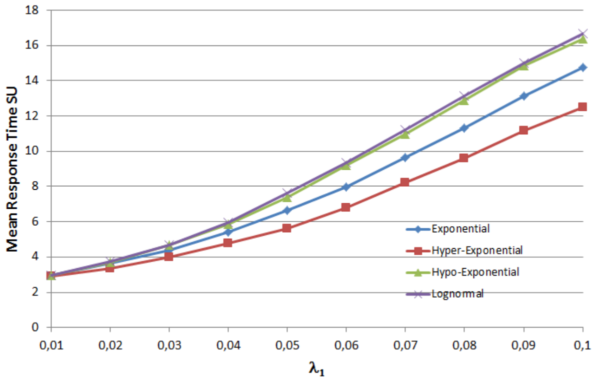

FIGURE 4.2: The effect of service time distribution of the PUs on the mean response time of SUs vs λ_1

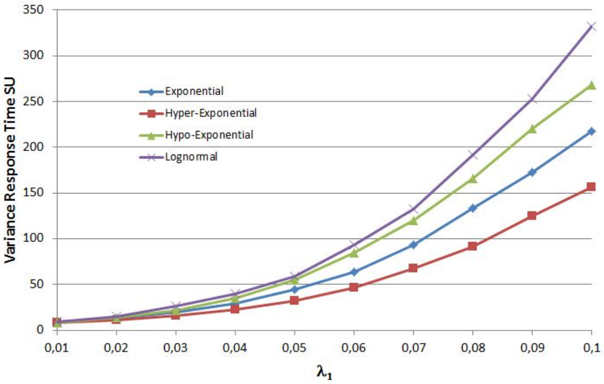

FIGURE 4.3: The effect of service time distribution of the PUs on the variance of response time of SUs vs λ_1

the source times, depending only on their means.

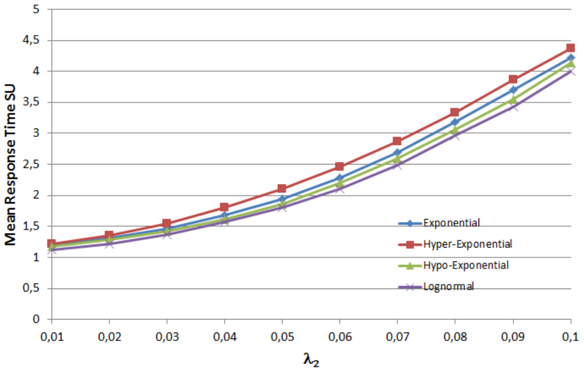

FIGURE 4.4: The effect of service time distribution of the SUs on the mean response time of SUs vs λ_2

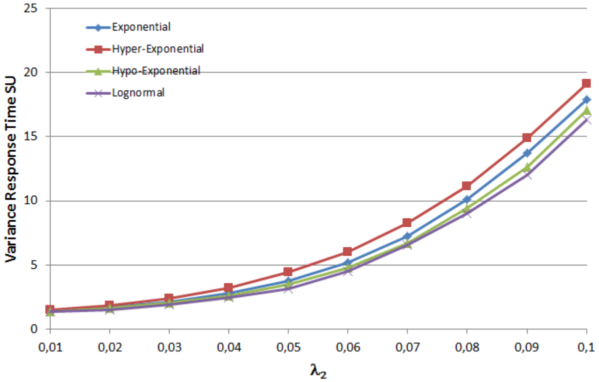

FIGURE 4.5: The effect of service time distribution of the SUs on the variance of response time of SUs vs λ_2

In the other operation mode, the service time at the primary

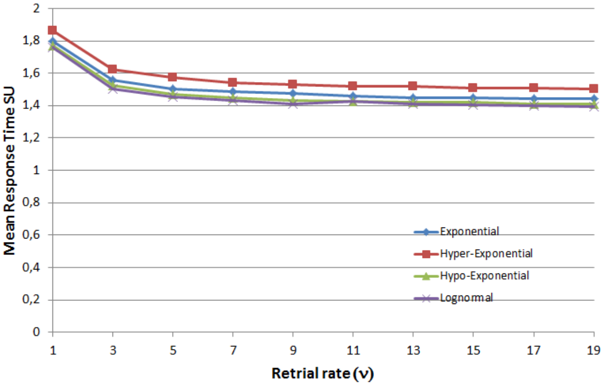

FIGURE 4.6: The effect of service time distribution of the SUs on the mean response time of SUs vs the retrial rate ν

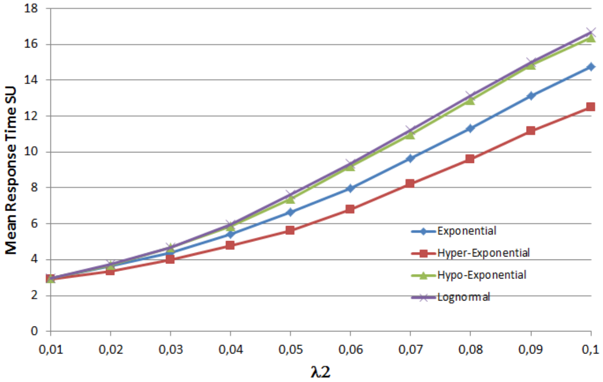

FIGURE 4.7: The effect of service time distribution of the PUs on the mean response time of SUs vs λ_2

server is hyper-exponentially, hypo-exponentially and log-normally distri-buted with the same mean supposing that the inter-arrival time of PUs and SUs, and the service time of the secondary server are exponentially distributed. Figure 4.2 and Figure 4.3 show that the value of the mean response time and variance is greater when the service time is hypo-exponentially distributed, also the mean response time of the secondary users. In the case the service time is lognormally distributed is approximately the same when it is hypo-exponentially distributed.

In Figure 4.4 and Figure 4.5, the inter-request time for the PUs and SUs is exponentially distributed. In this cases, Figures show the effect of the SU's inter-request arrival time on the mean and variance response time of the SUs knowing that the service time of SCS is exponentially, hypo-exponentially, hyper-exponentially and lognormally distributed with the same mean. The value of the squared coefficient of variation for the hypo-exponentially distribution is always less than one and for the hyper-exponentially is always greater than one, therefore the mean and variance of response time of SUs when the service time is hyper-exponentially is greater than the mean response time of SUs when the service time is hypo-exponentially distributed.

On Figure 4.6 the service time distribution of SCS is exponentially, hypo-exponentially, hyper-exponentially and lognormally distributed with the same mean. The service time of PCS and the inter-arrival time of both PUs, SUs are exponentially distributed. Figure shows the effect of the time spent in orbit on the mean response time of the SUs, it was modeled by a variable retrial rate. The result confirms the expectation that is increasing retrial rate involves shorter response times.

On the last Figure 4.7, we assume that the service time of the PCS is exponentially, hypo-exponentially, hyper-exponentially and lognormally distributed with the same mean. The service time of the SCS and the inter-request time of PUs and SUs are exponentially distributed. The Figure shows the effect of the inter-request time of the SUs on the mean response time of SUs. Here again we get what we expected that is increasing arrival intensity involves longer response times.

4.1.3 Results of the model with non-reliable services

Similarly to the model described above, let us now consider the non-reliability of the services. The novelty of analysis is to evaluate the effect of the failure probability on the mean and the variance response time of the PUs and SUs, and on the utilization of the PCS and SCS. It should be known that the service times in this model are generally distributed random variables, as we have previously shown that the steady-state distribution is insensitive to the distribution of the source times.

> **Thesis 2 (J3)** *(Section 4.3) We have investigate the main characteristic of a finite-source cognitive radio network with non-reliable services. The service times were generally distributed random variables with the same mean but different variance. The objective was to study the reliability of service channel transmission. The results have shown the impact of the service failure probability the performance*

measures. The Figures illustrate the importance of the primary service channel reliability for the PUs and SUs in cognitive radio networks.

There are many possible combinations of the cases, We consider only the following sample results showing the effect of the services failure probability on the mean response time of PUs, SUs and the utilisation of PCS and SCS. For the easier understanding the numerical values of parameters are collected in table 4.5.

No.	N_1,N_2	λ_1	λ_2	μ_1,μ_2	ν	p_1	p_2
Fig 4.8, Fig 4.9	10	x - axis	0.03	1	20	0.3, 0.6	0.3, 0.6
Fig 4.10, Fig 4.11	10	x - axis	0.03	1	20	0.3, 0.6	0.3, 0.6

TABLE 4.5: Numerical values of simulation parameters

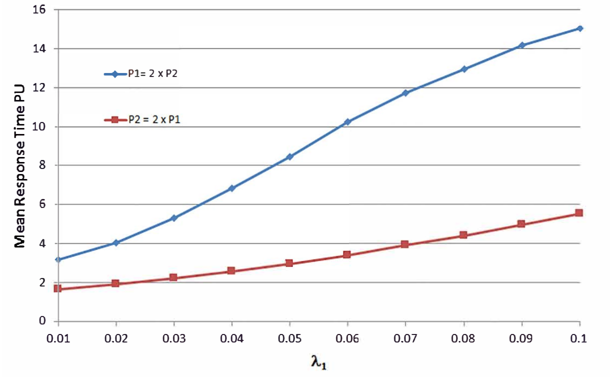

FIGURE 4.8: The effect of the failure probability of the services on the mean response time of the PUs vs λ_1

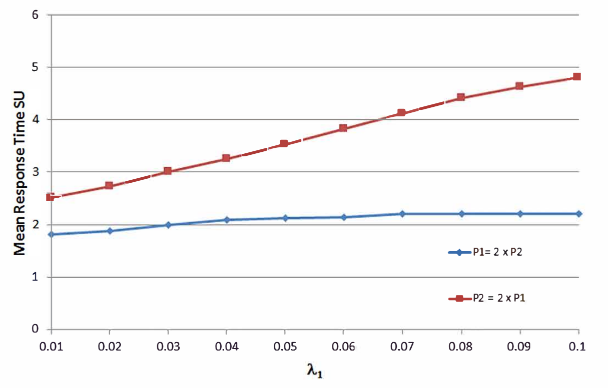

FIGURE 4.9: The effect of the failure probability of the services on the mean response time of the SUs vs λ_1

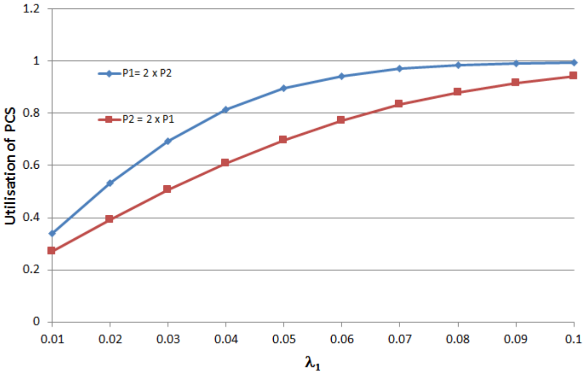

FIGURE 4.10: The effect of the failure probability of the services on the utilization of the PCS vs λ_1

In this scenario, we have treated the cases where the Primary Service Channel (PCS) is less reliable than the Secondary Service Channel (SCS) and where the PCS is more

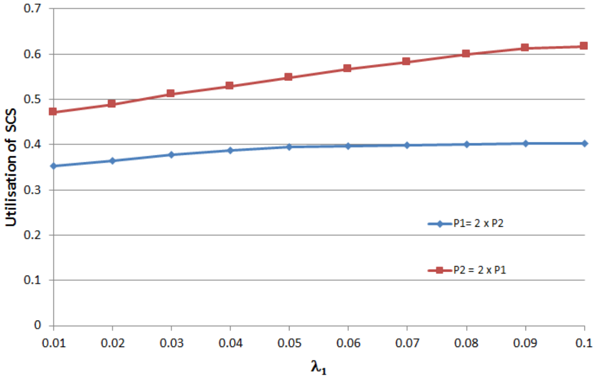

FIGURE 4.11: The effect of the failure probability of the services on the utilization of the SCS vs λ_1

reliable than the SCS, supposing that the inter-request times are exponentially distributed random variable and the service times are hyper-exponentially distributed random variables.

The Figure 4.8 and Figure 4.9 illustrate the effect of the failure probability of the servers on the mean response time of the users in terms of the primary inter-request rate (λ_1). The Figure 4.8 demonstrates the difference on the mean response time of the PUs where the PCS is less reliable than the SCS and the contrary case. The Figure 4.9 shows the effect of the failure probability of the servers on the mean response time of the SUs. As it was expected in the cognitive radio networks, when the PCS is not reliable and increasing the primary arrival intensity (λ_1), the mean response time of the SUs becomes a constant.

The Figure 4.10 and Figure 4.11 illustrate the effect of the failure probability of the servers (p_1 and p_2) on the utilization of the servers in terms of the primary inter-request rate (λ_1). In the Figure 4.10, when increasing λ_1 the utilization of the PCS is almost the same when the PCS is less reliable than the SCS, similarly in the opposite case, when the SCS is less reliable than the PCS. Hence, in the Figure 4.11, the utilisation of the SCS becomes a constant when the PCS is less reliable than the SCS and when the arrival intensity higher.

4.2 Finite-source cognitive radio network with servers subject to breakdowns and repairs

In this case, we deal with the performance evaluation of a cognitive radio network by the help of a queueing model with servers subject to breakdown and repair. Since in real life some components of the systems are subject to random breakdowns, it is important to study the reliability of queueing systems with non-reliable servers because of limited ability of repairs and heavy influence of the breakdowns on the performance measures of the system.

> **Thesis 3 (J4)** *(Section 4.4) We have evaluated the performance measures of a finite-source cognitive radio network with non-reliable servers (Breakdown and repair). In this investigation, each server is subject to random breakdowns in which case the interrupted request is send to the queue or orbit, respectively. The operating and repair times of the servers are supposed to be generally distributed. Finally, all the random times included in the model construction are assumed to be independent of each other. Our aim is to analyze the effect of the non-reliability of the servers on*

> *the mean and variance of the response time for the SUs by using simulation. The results have shown a considerable effect of the repair time distribution while the failure time distribution has no effect on the mean sojourn time.*

The finite source retrial queueing system which is used to model the considered cognitive radio network contains two interacting, not independent sub-systems. The first subsystem of the network is for the calls of the PUs. The number of sources is finite and denoted by $N1$. Each source generates high priority requests according to an exponentially distributed inter-request times 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 sub-system 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 supposed 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 request is sent to the preemptive priority queue. When the unit is servicing a costumer 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 breakdown 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 busy state, the service is stopped, and the interrupted task joins the preemptive priority queue or the SCS, depending on request's type. The repair time is also supposed to be exponentially, hypo-exponentially and hyper-exponentially distributed random variable with the same rate σ_1.

In 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 exponentially, hypo-exponentially and hyper-exponentially distributed random variable with the same intensity σ_2.

4.2.1 New results

The numerical results obtained in this case were the test result of the simulation program to investigate the impact of the failure and repair times distributions on the mean and variance response time of mainly secondary users. Table 4.6 and table 4.7 shows the exact confidence interval for the estimation of the means response times and the values of the repair times distributions parameters for the secondary users.

The following graphs illustrates some sample examples which show the effect of the failure and repair time distributions having the same mean but different variance. It

TABLE 4.6: Confidence interval for scenarios in case 3

Figures	Distributions	Mean	Variance	Confidence interval	
				Lower bound	Upper bound
4.24	Hypoexp.	1.0271	1.9810	0.9654	1.0887
	Exponential	1.2031	2.018	1.1408	1.2653
	Hyperexp.	1.2823	2.8911	1.2066	1.3579
4.47	Hypoexp.	0.6803	2.8137	0.5705	0.79
	Exponential	0.6012	2.4017	0.4998	0.7025
	Hyperexp.	0.5502	2.0017	0.4576	0.6427

TABLE 4.7: Parameters of repair times distributions of secondary customers

Distributions	Hyper-exponential	Hypo-exponential	Exponential
Parameters	$p = 0.45$ $\sigma_1 = 1.358$ $\sigma_2 = 0.865$	$\sigma_1 = 3.386$ $\sigma_2 = 11.2053$	$\sigma_1 = 2.6$
Mean	0.3846	0.3846	0.3846
Variance	0.2491	0.0952	0.1479
SCV	1.6842	0.6449	1

is done by the help of the hypo-exponentially and hyper-exponentially distributions and comparing to the results of the exponential distribution. By using the batch mean method within stochastic simulation program, an estimation of the mean and variance of the sojourn time of the PUs and SUs could be obtained.

For the numerical values of the input parameters see 4.12.

In Figure 4.12 and 4.13, we assume that the primary server

TABLE 4.8: 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 4.12	10	0.1	4	0.4	0	0.05	0	x-axis
Fig 4.13	10	0.1	4	0.4	0	x-axis	0	0.05
Fig 4.14	10	0.1	4	0.4	x-axis	0	0.05	0
Fig 4.15	10	0.1	4	0.4	0.05	0	x-axis	0

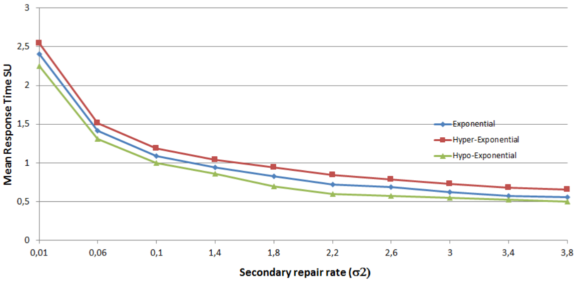

FIGURE 4.12: The impact of the secondary repair time distribution on the expectation of the sojourn time of the SUs vs σ_2

is reliable, thus, $\gamma_1 = 0$ and $\sigma_1 = 0$. Therefore, we concentrate on the second sub-system of the network and we would like to see the impact of the secondary breakdown and repair times distribution on the mean response time of the secondary costumers when the failure's and repair's intensity is increasing (γ_2,σ_2), respectively.

Figure 4.12 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 [22], the same

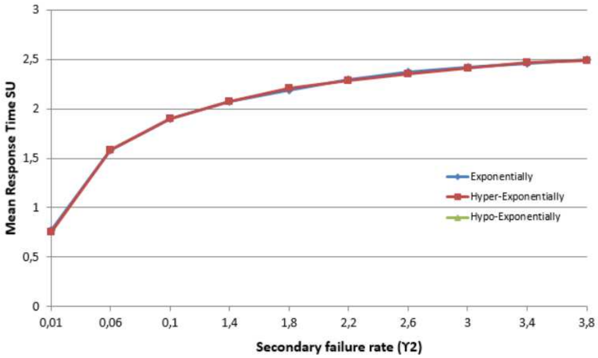

FIGURE 4.13: The effect of the secondary failure time distribution on the mean response time of the SUs vs γ_2

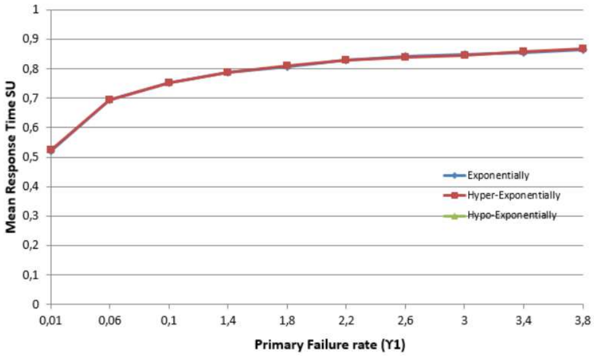

FIGURE 4.14: The effect of the failure time distribution on the mean response time of the SUs vs γ_1

results of the impact of the secondary service time distribution was illustrated. As known already, the squared coefficient of variation of the hyper-exponential distribution is always greater than 1, contrary to the hypo-exponential

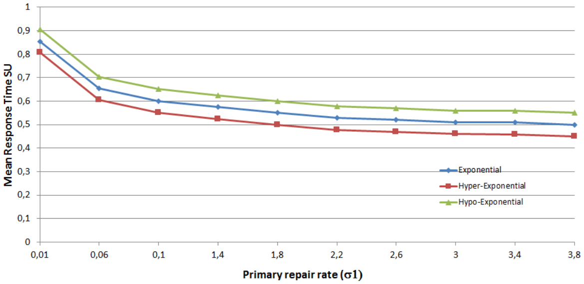

FIGURE 4.15: The impact of the primary repair distribution on the expectation of the sojourn time of the SUs vs σ_1

distribution which is always less than 1.
However, Figure 4.13 shows that under the present parameter setup the distribution of the secondary failure time has no any effect on the expectation of the sojourn time of the secondary users.

In Figures 4.14 and 4.15, we suppose 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 investigat e the effect of the primary breakdown and repair time distribution on the mean response time of the secondary calls when the failure and repair rate are increasing (γ_1,σ_1), respectively.
Figure 4.14 illustrates that the distribution of the primary failure rate has no effect on the expectation of the sojourn time of the SUs. Similarly to Figure 3, we have got the same response time of the costumers whether the distribution of the primary or secondary breakdown time is exponentially, hypo-exponentially or hyper-exponentially.
Also, in Figure 4.15 as in Figure 4.12, the distribution of

the primary repair has an effect on the mean response time of the SUs. Contrary to Figure 4.12, here we have got 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 it was mentioned earlier, secondary customers must release the primary server unit when a high priority packet requests the server unit.

4.3 Finite-source cognitive radio networks with collision at the retrial part

The present section deals with a finite-source retrial queueing system to model cognitive radio networks as previously. The novelty in this model is that we introduce the server with conflict in the retrial part of the cognitive radio network. Therefore, the arriving secondary customers involve into collision with the secondary customers under service in the SCS, and both joins the orbit.

> **Thesis 4 (C3)** *(Section 4.5) We have dealt with performance measures of a finite-source cognitive radio network with collision at the retrial part of the system. We have established a simulation program to model the queueing system and to obtain estimation for the basic performance measures. Since individual users mostly interested in their sojourn time in the system, we analyze the impact of the service time distribution (s.t.d) on the expectation and variance of sojourn time of the PUs and SUs, respectively. Various sample examples are derived and Figures are generated for better understanding.*

The queueing system proposed contains two interacting sub-systems. The first block is for PUs having a single server unit (Primary Channel Service - PCS) with preemptive priority queue, and N_1 sources. Each source generates a high priority requests according to an exponential distribution with parameter λ_1. Whereas, during simulation the service times are assumed to be exponentially, hypo-exponentially and hyper-exponentially distributed random variables with the same intensity μ_1. The second block is for the SUs, where there are N_2 sources, the request generation times of the SUs are supposed to be exponentially distributed random variables with rate λ_2. Here SUs are served in a single server unit (Secondary Channel Service - SCS) according to an exponential, hypo-exponential and hyper-exponential distribution with the same rate μ_2. A generated PU goes to the PCS and if the unit is idle the service of the packet begins immediately. If the server is busy with a PU the packet joins the preemptive priority queue. When the server is busy by a SU, the service process is interrupted and the interrupted task is directed to the SCS. If it is busy, the interrupted job involves into collision with customer under service and both moves into the orbit. For SUs we have the following operation rules. If at the arrival the SCS is idle the service begins immediately, otherwise the packet senses the PCS. If it is idle the service begins otherwise the packet involves into collision with other SU and both go to the orbit. Retrial customers repeat their demands for service after an exponentially distributed time with parameter ν.

4.3.1 New results

The numerical results obtained in this case shows the impact of the service times distributions on the mean and variance response time of mainly secondary users as well as the effect of the collision on the retrial part of the system. Table 4.9 and table 4.10 shows the exact confidence interval for the estimation of the means response times and the values of the service times distributions parameters for the secondary users.

TABLE 4.9: Confidence interval for scenarios in case 4

Figures	Distributions	Mean	Variance	Confidence interval	
				Lower bound	Upper bound
4.38	Hypoexp.	68.0128	667.0891	67.8808	69.1447
	Exponential	61.8901	661.3619	60.7630	62.0171
	Hyperxp.	59.0298	658.0184	58.9055	60.1540
4.40	Hypoexp.	70.0139	700.1073	69.2834	71.7443
	Exponential	81.0089	870.0318	80.0798	82.9375
	Hyperexp.	74.4380	800.8	74.5872	76.2887

Table 4.11 shows the numerical values of the input parameters.

Figure 4.16 shows that the distribution of the service time of the secondary packets has an impact on the average sojourn time of the SUs, where the value is greater when the service time is hyper-exponentially distributed, knowing that the service time of the high priority packet is exponentially distributed random variables. The collision at the retrial part of the system involves longer sojourn times as it was

TABLE 4.10: Parameters of the service times distributions of secondary customers

Distributions	Hyper-exponential	Hypo-exponential	Exponential
Parameters	$p = 0.45$ $\sigma_1 = 0.303$ $\sigma_2 = 1.067$	$\sigma_1 = 0.456$ $\sigma_2 = 5.93$	$\sigma = 0.5$
Mean	2	2	2
Variance	5.3824	3.3824	4
SCV	1.6842	0.8456	1

TABLE 4.11: Numerical values of the parameters

No.	N_1	N_2	λ_1	λ_2	μ_1	μ_2	ν
Fig 4.16	20	50	x - axis	0.1	1	1	20
Fig 4.17	20	50	x - axis	0.1	1	1	20
Fig 4.18	20	50	x - axis	0.1	1	1	20
Fig 4.19	20	50	0.1	x - axis	1	1	20
Fig 4.20	20	50	0.1	x - axis	1	1	20

expected. Customer spends more time in the system comparing to the finite-source cognitive radio networks without collision (Section 4.1).

Figures 4.17 and 4.18 show the impact of the distribution of the primary service time on the average sojourn time of the secondary users and the secondary service time on the variance sojourn time of the secondary users, respectively,

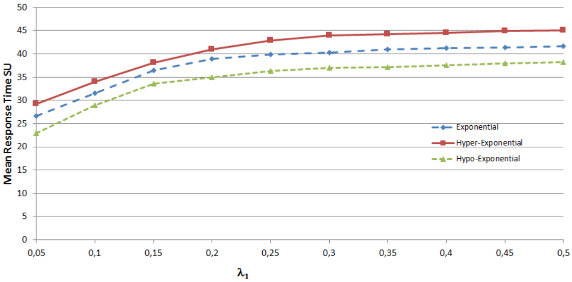

FIGURE 4.16: The effect of the secondary service time distribution of the SUs on the mean response time of the SUs vs λ_1

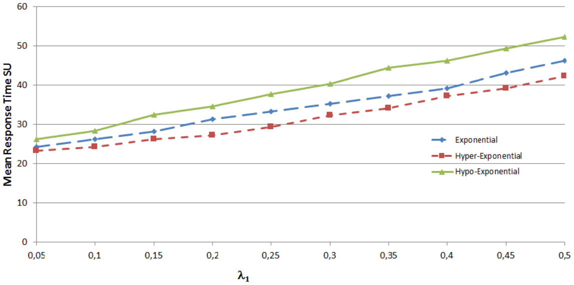

FIGURE 4.17: The effect of the primary service time distribution of the SUs on the mean response time of the SUs vs λ_1

where the primary arrival rate is increasing. The distribution has an impact on the average and variance of the sojourn time as it was expected and the collision on the secondary part involves longer sojourn time.

In Figures 4.19 and 4.20, the service time of PUs is supposed to be exponentially distributed random variable. Figures

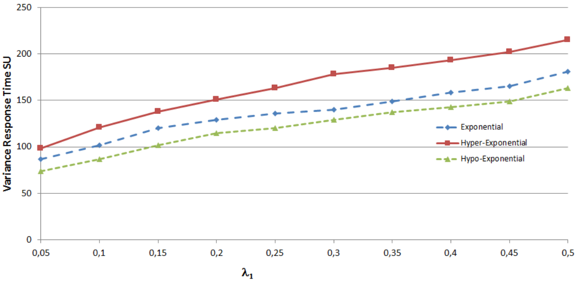

FIGURE 4.18: The effect of the secondary service time distribution of the SUs on the variance of the response time of the SUs vs λ_1

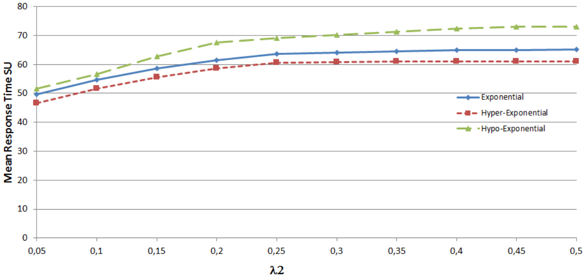

FIGURE 4.19: The effect of the secondary service time distribution of the SUs on the mean response time of the SUs vs λ_2

show that the average sojourn time of the secondary requests depends on the s.t.d of the low priority packets. As shown previously, increasing the arriving intensity of the secondary calls causes longer sojourn time and the value of its average changes where the distribution of the service time changes.

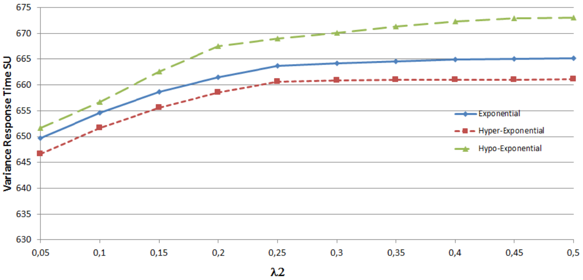

FIGURE 4.20: The effect of the secondary service time distribution of the SUs on the variance of the response time of the SUs vs λ_2

4.4 Non-reliable servers in finite-source cognitive radio networks with collision

This section introduces a finite-source retrial queueing system which models cognitive radio networks. Similarly, we assume two non-independent frequency bands servicing two classes of users: Primary Users (PUs) and Secondary Users (SUs). A service unit with a priority queue and another service unit with an orbit are assigned to the PUs and SUs, respectively.

Thesis 5 (J2) *(In this thesis, we have combined the two studied models in thesis 3 and thesis 4. A finite-source cognitive radio network with non-reliable servers and collision at the retrial part of the system. Mainly, we have focused on these two phenomenon. Hence, we analyze the effect of the non-reliability of the servers on the mean response time*

> *of the secondary users. It should be mentioned that we applied the non-intelligent continues scenario which means: During server failure, the generation process continue and after the repair time, the failed job repeats the service from the beginning. The main stationary performance and reliability measures were given by the help of the developed simulation program.*

Let us consider the same system model described earlier in the previous section and combined it to the system model described in Section 4.2 of this thesis. The resulting model is a finite-source cognitive radio network with collision and servers subject to breakdown and repairs. The number of sources is denoted by N_1 and N_2 for the primary and secondary users, respectively. All the inter-event times are exponentially distributed random variables. The distribution's parameters of these variables for the primary and secondary are denoted as follows:

- Inter-request time λ_1, λ_2
- Service time μ_1, μ_2
- Failure time γ_1, γ_2
- Repair time σ_1, σ_2, respectively.
- Secondary retrial rate ν

4.4.1 New results

In this subsection some sample numerical results are considered to illustrate graphically the influence of the non-reliable server on the mean response time E[T] of the response time at the secondary users level.

For the easier understanding the numerical value of parameters are collected in 4.12.

TABLE 4.12: Numerical values of model parameters

No.	N_1	N_2	λ_1	λ_2	μ_1	μ_2	σ_1	σ_2	γ_1	γ_2	ν
Fig 4.21	6	6	0.6	x - axis	4	4	1	1	0.05	0.05	0.4
Fig 4.22	6	6	0.6	0.6	x - axis	4	1	1	0.05	0.05	0.4
Fig 4.23	6	6	0.6	0.6	x - axis	4	1	1	0.05	0.05	0.4
Fig 4.24	10	10	0.1	0.1	4	4	x - axis	x - axis	0.05	0.05	0.4
Fig 4.25	10	10	0.1	0.1	4	4	0.05	0.05	x - axis	x - axis	0.4

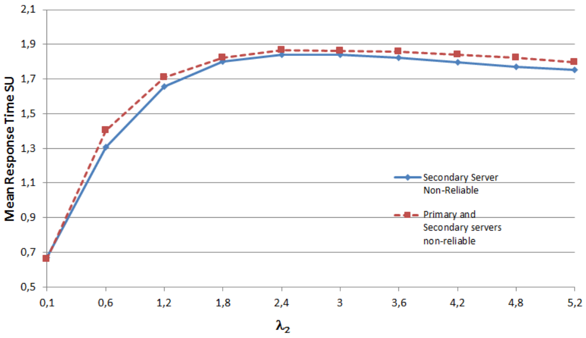

FIGURE 4.21: The effect of servers non-reliability on the mean response time of secondary users vs λ_2

Figure 4.21 compares the effect of the request generation rate on the mean response time of the secondary users in the two cases: Secondary server unit non-reliable and both servers non-reliable. Figure shows the phenomenon of having a maximum value of the mean response time which was

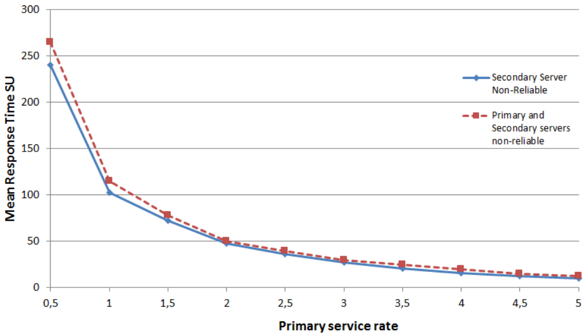

FIGURE 4.22: The effect of servers non-reliability with collision on the mean response time of secondary users vs Primary service rate μ_1

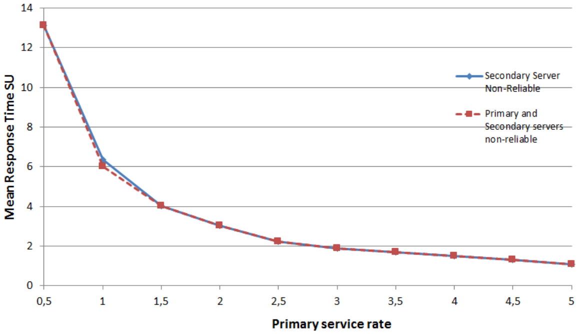

FIGURE 4.23: The effect of servers non-reliability on the mean response time of secondary users vs Primary service rate μ_1

noticed in [21]. The collision involves longer response time for the users as it was expected.

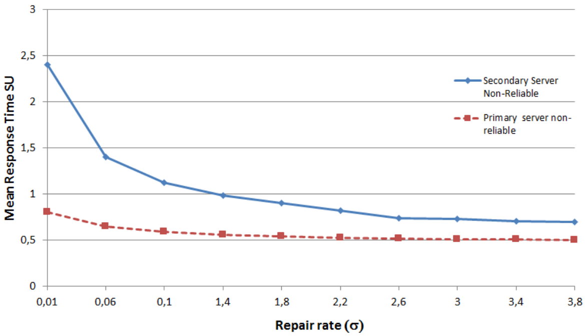

FIGURE 4.24: The effect of servers non-reliability on the mean response time of secondary users vs the repair rate σ

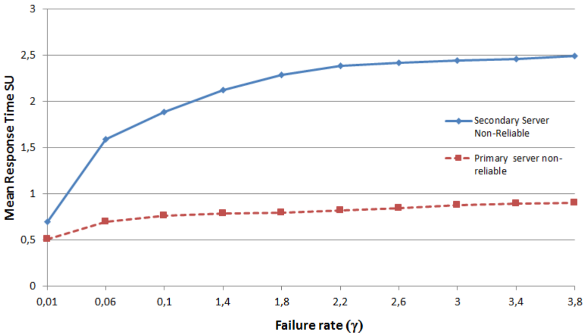

FIGURE 4.25: The effect of servers non-reliability on the mean response time of secondary users vs the failure rate γ

Figure 4.22 and Figure 4.23 illustrate the effect of the primary service rate on the mean response time of the secondary users. The non-reliability of the primary server has an effect on the mean response time of the secondary users in the case of the collision where the primary service rate is increasing. A longer response time can be seen in the case of the collision in the retrial part, as it was expected.

Figure 4.24 shows the effect of the non-reliability of the servers on the mean response time of the secondary users where the repair rate is increasing. The first case is where the primary server is non-reliable, in this case the value of the mean response time of the secondary users becomes a constant when the primary repair rate (σ_1) is higher. The second case is where the secondary server is non-reliable, in this case, the value of the mean response time of the secondary users is decreasing when the secondary repair rate (σ_2) is increasing.

Figure 4.25 illustrates the effect of the non-reliability of the servers on the mean response time of the secondary users where the failure rate is increasing. As it was expected, increasing the failure rate involves longer response time in the both cases (primary server non-reliable and secondary server non-reliable).

5 Application of the results

Cognitive Radio (CR) intends to use licensed but currently unused spectrum to enhance spectrum utilization. This will have a major impact on the next generation of wireless systems and networks. In this thesis we conducted a cognitive network for a performance analysis by the help of retrial queueing systems using simulation program. The models created and studied in this work can be applied for the validation of more complex simulation models including more distributions, more secondary server facilities or the impatience of customers who abandon the service request due to a high waiting time. In addition, we have treated some of real-life network communication problems such as servers failure, transmission failure and collision. The model can treat more real-life scenarios for a better quality of service such as systems with out going calls.

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List of Publications

List of Papers [J]:

J1 Sztrik, J., Bérczes, T., Nemouchi, H., and Melikov A.Z., "Performance modeling of finite-source cognitive radio networks using simulation," *Communications in Computer and Information Science. Springer*, Vol.678, pp. 64-73, 2016.

J2 Nemouchi, H., and Sztrik, J., "Performance Simulation of Non-reliable Servers in Finite-Source Cognitive Radio Networks with Collision," *Information Technologies and Mathematical Modelling - Queueing Theory and Applications, Communications in Computer and Information Science*, Vol.800, pp. 194-203, 2017.

J3 Nemouchi, H., and Sztrik, J., "Performance evaluation of finite-source cognitive radio networks with non-reliable services using simulation," *Annales Mathematicae et Informaticae*, Vol.49, pp. 109-122, 2018.

J4 Nemouchi, H., and Sztrik, J., "Performance simulation of finite-source cognitive radio networks with servers subject to breakdowns and repairs," *Journal of Mathematical Sciences*, Vol.237, pp. 702-711, 2019.

List of Conference Proceedings [C]:

C1 Sztrik, J., Bérczes, T., Nemouchi, H., and Melikov A.Z., "Performance modeling of finite-source cognitive radio networks using simulation," *Proceedings of the 19th International Scientific Conference on Distributed Computer and Communication Networks: Control, Computation, Communications (DCCN-2016), Volume 1: Architecture, Methods of Control, Modeling and Design of Computer Networks, Moscow, Russia*, pp. 162-165, October 2016.

C2 Nemouchi, H., and Sztrik, J., "Performance evaluation of finite-source cognitive radio networks with non-reliable services using simulation," *Proceedings of the 10th International Conference on Applied Informatics, Eger, Hungary*, pp. 225-234, January 2017.

C3 Nemouchi, H., and Sztrik, J., "Performance Evaluation of Finite-Source Cognitive Radio Networks with Collision Using Simulation," *Proceedings of 8th IEEE International Conference on Cognitive Infocommunications (CogInfoCom-2017), Debrecen, Hungary*, pp. 127-131, September 2017.

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Registry number:	DEENK/285/2020.PL
Subject:	PhD Publication List

Candidate: Hamza Nemouchi
Doctoral School: Doctoral School of Informatics
MTMT ID: 10071632

List of publications related to the dissertation

Foreign language scientific articles in Hungarian journals (1)

1. **Nemouchi, H.**, Sztrik, J.: Performance evaluation of finite-source cognitive radio networks with non-reliable services using simulation.
   Ann. Math. Inform. 49, 109-122, 2018. ISSN: 1787-5021.
   DOI: http://dx.doi.org/10.33039/ami.2018.12.001

Foreign language scientific articles in international journals (1)

2. **Nemouchi, H.**, Sztrik, J.: Performance Simulation of Finite-Source Cognitive Radio Networks with Servers Subjects to Breakdowns and Repairs.
   J. Math. Sci. 237 (5), 702-711, 2019. ISSN: 1072-3374.
   DOI: http://dx.doi.org/10.1007/s10958-019-04196-y

Foreign language conference proceedings (2)

3. **Nemouchi, H.**, Sztrik, J.: Performance simulation of non-reliable servers in finite-source cognitive radio networks with collision.
   In: Information technologies and mathematical modelling : Queueing theory and applications. Eds.: Alexander Dudin, Anatoly Nazarov, Alexander Kirpichnikov, Springer, Cham, 194-203, 2017, (Communications in Computer and Information Science, ISSN 1865-0929 ; 800.) ISBN: 9783319680682

4. Sztrik, J., Bérczes, T., **Nemouchi, H.**, Melikov, A.: Performance modeling of finite-source cognitive radio networks using simulation.
   In: Distributed Computer and Communication Networks : 19th International Conference, DCCN 2016, Moscow, Russia, November 21-25, 2016, Revised Selected Papers. Eds.: Vladimir M. Vishnevskiy, Konstantin E. Samouylov, Dmitry V. Kozyrev, Springer, Cham, 64-73, 2016, (Communications in Computer and Information Science, ISSN 1865-0929 ; 678.) ISBN: 9783319519166

List of other publications

Foreign language conference proceedings (2)

5. **Nemouchi, H.**, Sztrik, J.: Performance evaluation of finite-source cognitive Radio networks with collision using simulation.
   In: 8th IEEE International Conference on Cognitive Infocommunications: CogInfoCom 2017 : Proceedings : September 11-14, 2017 Debrecen, Hungary, IEEE Computer Society, Piscataway, 127-131, 2017. ISBN: 9781538612644

6. Sztrik, J., Bérczes, T., **Nemouchi, H.**, Melikov, A.: Performance modeling of finite-source cognitive radio networks using simulation.
   In: Distributed Computer and Communication Networks : Control, Computation, Communications (DCCN-2016) : Proceedings of the Nineteenth International Scientific Conference Russia, Moscow, 21-25 November 2016 : Volume 1 : Architecture, Methods of Control, Modeling and Design of Computer Networks. Eds.: V. M. Vishnevskiy, K. E. Samouylov, RUDN, Moscow, 162-165, 2016. ISBN: 9785209076667

Foreign language abstracts (1)

7. **Nemouchi, H.**, Sztrik, J.: Performance simulation of finite-source cognitive radio networks with servers subject to breakdowns and repairs.
   In: XXXIV. International Seminar on Stability Problems for Stochastic Models 25-29 August 2017 Debrecen, Hungary : Book of abstracts, Debreceni Egyetem Informatikai Kar, Debrecen, 71, 2017.

The Candidate's publication data submitted to the iDEa Tudóstér have been validated by DEENK on the basis of the Journal Citation Report (Impact Factor) database.

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