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

Performance Investigation of a Modelled Finite-source Cognitive Radio Network

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1 Introduction

Constant service issues in wireless systems arise from the struggle to find appropriate frequency bands. In 1999, Mitola introduced the term "Cognitive Radio" to describe a technology that can detect its surroundings and adjust its own settings to optimize wireless system performance for users. Research indicates that a significant number of channels have sizable portions that remain unused. Cognitive radio technology, which analyzes environmental conditions, is a well-known solution to this issue and utilizes this information to improve performance.

The cognitive radio paradigm involves two main user tiers: Primary Users (PU), who have been authorized to use specific licensed communication frequency bands, and Secondary Users (SU), who can only access the frequency spectrum without interfering with the primary users. The success of cognitive radios depends on two key factors: the ability to detect unused spectrum and the ability to use the spectrum temporarily without disrupting authorized users. We suggest referring to the following books to gain a better understanding of the characteristics, designs, and techniques used in spectrum sensing [4, 8, 21, 22].

In today's queuing theory world, cognitive radio networks are a highly significant subject that has attracted the attention of many researchers. The retrial queuing system for this network comprises two non-independent frequency channels catering to the two customer groups previously mentioned. A retrial queuing system with two finite sources, one for Primary Users (PU) and one for Secondary Users (SU), has been developed using queuing theoretical approaches in [1]. As all inter-event times are exponentially distributed by definition, a multidimensional Markov chain has been established. The primary performance measures of the system are computed and illustrated.

This thesis focuses on the same naturally generalized model utilized in [1], but also accounts for non-exponentially distributed request generations, including service, retrial, failure, and repair times. The key characteristics of the system are evaluated using a stochastic simulation technique, and several case studies demonstrate how these general distributions impact these evaluations.

Given the limited availability of frequency bands or communication channels, users frequently compete for resources during communication sessions. Several risks, such as server failures, customer impatience and discouragement, and uncoordinated requests from different sources, can lead to communication or customer loss, requiring retransmission. Investigating how these risks affect communication network quality of service and devising effective preventive measures is critical. Recent findings in this area are presented in [17, 18].

Communication networks often assume that service units are continuously accessible, but this doesn't accurately reflect real-world scenarios, as failures and power outages can happen at any time. Wireless communication systems, in particular, are prone to transmission failures due to their use of wireless frequency bands. It's crucial to examine these scenarios as they significantly impact network characteristics and performance measures. Previous research, such as [2, 13, 15, 16, 19], has addressed the unreliability of servers in various retry queueing methods.

To investigate the impact of the inter-request time distribution on the mean, variance, and utilization of the primary and secondary service units, we developed a simulation program to model the finite-source cognitive radio network. We conducted several case studies, including the following:

- Unreliability analysis of finite-source Cognitive Radio Networks.
- Performance evaluation of Cognitive Radio Network with with unreliability and abandonment. Analysis of finite-source cognitive radio network with balking and reneging.

2 The research's objective

This thesis centers on simulating a finite-source cognitive radio network system using a retrial queueing system based on cognitive paradigms. The system comprises primary and secondary (cognitive) users assigned to two interconnected frequency bands, with the first channel linked to a priority queue and the second to an orbit. These units handle the retrial needs of primary and secondary customers who might encounter busy service units. The simulation program developed in this thesis assesses the system's effectiveness under various communication challenges that can arise in radio networks.

In a previous study [1], a retrial queueing system was used to model a cognitive radio network. Researchers assumed that all inter-event periods are exponentially distributed and developed a multidimensional Markov chain to analyze the effects of distribution parameters on performance measures using queueing theoretical methods. In contrast, this thesis uses a natural generalization of the model that allows for non-exponential distributions for inter-event times. Additionally, the thesis examines events such as server failures, user abandonment and reneging, and their impact on the system's performance metrics. The aim of these studies is to compare the impacts of the general distributions and these events on the mean and variance response times of the two types of users.

There have been previous studies on queueing systems that use asymptotic techniques, such as [17, 18]. Assuming that inter-event time is exponentially distributed, performance measures' mean and variance can be determined. However, solving the underlying steady-state equations becomes very challenging, if not impossible, when inter-event intervals are non-exponentially distributed. Our study is unique in that we use retrial queueing systems to develop a simulation program for modeling the performance of a finite-source cognitive radio network. The key advantage of this simulation is that it provides estimates for the mean and variances of the distributions.

We establish a queueing system with two finite sources to describe the functioning of our cognitive radio network, taking into account various scenarios, including server failure and customer impatience. Our aim is to investigate how the inter-event time distributions affect the sojourn time expectations and variations of the primary and secondary customers. We present several sample instances of these scenarios using simulations and visualize them in various figures.

3 Methodology

Often, investigating the distribution of inter-event times can be challenging, and the Laplace transform may be used instead. While estimating the variance is not an easy task, algorithmic and numerical methods can be used to compute it. Due to the vast state space of the Markov Chain, analytic techniques for solving steady-state equations are almost impossible. Various numerical and algorithmic solutions have been developed to simplify this process, but they are limited by memory consumption or the ability to handle only specific random variables.

However, our simulation employs SimPack [11], which is a collection of C/C++ libraries and executable simulation programs. This collection includes various simulation models, such as discrete event, continuous, and hybrid simulations. The [12] statistic module was created to obtain the necessary performance measures. The module's algorithms for managing the statistical components of a simulation run are located in a statistical analysis tool that can compute the mean and variance for the observed variables.

The batch means approach, which divides the gathered observations into sequential blocks or "batches", is commonly used to estimate the mean and variance values and develop the confidence interval by treating the means derived from these batches independently. This approach is the most widely used confidence interval approach for analyzing the output of a steady-state simulation. Various citations, such as [5, 7, 10, 20], have employed and discussed the batch means method. The statistical class uses this method to combine n consecutive random variables from a steady-state simulation to provide a series of independent batch means. The batch size must be sufficient to ensure that the sample averages are roughly independent.

The statistics module has been used in many simulation runs with the following input settings to examine the performance metrics of our cognitive radio network with a retrial queueing system:

- The confidence interval's relative half-width must be at least 0.05 to terminate the simulation (The run is stopped when all the analyzed processes achieve the selected accuracy level).
- A minimum of 5000 observations must be gathered before the first transitory shutting condition may be verified.
- 10000000 is the maximum number of treated observations.
- 30 batches were utilized to test the first transient duration.
- The first transient closure condition is checked using 10 transient batches.
- It takes a 0.99 accuracy level to terminate the first transient detection.
- The batch size employed initially for the stationary analysis is 10,000. (If the number of collected batch means exceeds the available dedicated memory space, the means are coupled and the batch size doubles).

- 95% is the confidence level.

The main simulation is built around a series of events. The following are the simulation run′s most crucial actions:

- The user′s entry into the system.
- Inquire for the primary server.
- Inquire for the secondary server.
- Release the primary service unit.
- Release the secondary service unit.
- Activate the backup server.
- Arrival from the orbit.
- Breaks down in the primary server.
- Breaks down in the secondary server.

Our investigation results will be discussed in the next section.

4 Results of the simulation and discussions

4.1 Finite-source cognitive radio network

Cognitive Radio (CR) is a potential solution to provide dynamic spectrum access and boost the effectiveness of a mostly unused spectrum. In cognitive radio networks, if no high priority activity (the primary user's task) are detected, the unlicensed customers (Secondary Users) are provided an opportunistically access to the licensed bands. If a primary customer shows up in this period, secondary users must respond in a cooperative manner and release the service unit. See [4, 21] for a comprehensive review of the cognitive radio networks.

Retrial queues are defined by the following characteristics: a query that finds all server unit busy upon arrival, leaves the service facility but retries to seek service after a random period of time. For the performance evaluation of communication systems and computers, queuing models are often utilized. Retrial queues may be used in performance modelling for a variety of real-world systems, including call centers, wireless communication systems, computer networks, telephone switching systems, and telecommunication networks. Priority queuing models have been employed in cognitive radio networks, where requests with higher priorities may be served before those with lower priorities, as well as in breakdown/repair models, where a server may be down for a while and cease to function. Primary servers, under certain circumstances, may be utilized opportunistically and dynamically by SUs. The two types of requests (PUs and SUs) are data packets, sessions, or connections, they are queued if the targeted units are not immediately available. We list a few earlier studies that used retrial queuing systems to simulate cognitive radio networks [1, 3, 6, 9, 14]

4.1.1 System model of basic CRN

It should be noted that several distributions, either exponential or general distributions (Hypo-Exponential, Hyper-Exponential, Gamma and Log-normal) will be used for all inter-events times of our system. The mentioned above distributions were combined in several case scenarios depending on the investigation we are conducting. We will be referring to Hypo, Hyper, Gamma and Log-normal distributions with "general distributions" and specifying which distribution is used for each inter-event time in the relevant section. The following assumptions describe the basic model of a cognitive radio network. Assuming that our model uses a queuing mechanism with a finite number of sources for PUs and SUs, defined N_1 and N_2, respectively, we deal with two independent sub-networks for PUs and SUs calls.

Furthermore, licensed requests will be generated from N_1 each inter-request time with parameter λ_1. The produced requests are sent via a preemptive priority queue to the Primary Channel Service, or PCS. The service time is a random distrusted variable with parameter μ_1.

In the second subsystem which is dedicated for the SUs, requests generated by N_2, the inter-request times and service times of this single server unit (Secondary Channel Service - SCS) are having the parameters λ_2 and μ_2, respectively.

A high priority packet is created and sent to the main service unit, if is not in use, the packet's service starts right away. The packet enters the preemptive priority queue if the server is engaged with a high priority request. However, if the user occupying the unit is secondary, its service is interrupted and the low priority job is routed back to its subsystem, in which, the latter is sent to either the server or the orbit, depending on the status of the secondary channel. Now, taking in consideration SUs requests, their service begins if the SCS is vacant; otherwise, the packet tries to seek service opportunistically in the PCS, if the SCS is occupied. Supposing that the PCS is idle, the low priority packet is served at the high priority channel (PCS). The packet is sent to orbit if the PCS is busy. SUs attempt again to be served after a randomly distributed duration, having a retrial rate ν.

The below notations are introduced to form a stochastic process that describes the behaviour of the system.

- $k_1(t)$ refers to the number of licensed sources at time t,
- $k_2(t)$ denotes the number of unlicensed sources at time t,

- $q(t)$ is the number of licensed requests in the FIFO queue at time t,
- $o(t)$ is the number of requests in the orbit at time t,
- $y(t) = 0$ in case the PCS is free, $y(t) = 1$ in case the PCS is busy with a job coming from the high priority class, $y(t) = 2$ when the PCS unit is dealing with a job coming from the secondary class at time t,
- $c(t) = 0$ when the SCS is idle and $c(t) = 1$, when the SCS is busy at time t.

Consequently, we can deduce

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

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

The input parameters are gathered in Table 4.1 for ease of comprehension.

4.2 Unreliability analysis in CRN

In this section, we take in consideration servers unreliability on the system described above. The originality of this study lies in its examination of the effect of failures (in busy or idle status) and repairs times (generally distributed) of the SCS on the system behaviour overall.

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

Thesis 1 (J1) [1] *(Section 4.2). We have analyzed the performance measures of a finite-source cognitive radio network with secondary server subject to breakdowns and repairs, where all the inter-event times were exponentially distributed random variables, except failure and repair times, which were generally distrusted having the following parameters (Primary failure rate: γ_1, Secondary failure rate: γ_2, Repair rate of the primary server: σ_1, Repair rate of the secondary server: σ_2) with the same mean but different variances. The goal was to determine how these distributions can affect our system's primary key measures. The failure and repair time distributions have shown a significant impact on the performance of the system, according to the given results. This behaviour is influenced mainly by the distribution's squared coefficient of variance.*

Although there are numerous potential case combinations, we only take into account the following example results

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

TABLE 4.2: Numerical values of model parameters

N_1	N_2	λ_1	λ_2 / N_2	μ_1	μ_2	ν / N_2	θ_2	γ_2	σ_2
10	10	0.01	x-axis	1	1	0.01	0.1	0.1	1

TABLE 4.3: Numerical values of model parameters

Paramater	Definition
N_1	Primary number of sources
N_2	Secondary number of sources
λ_1	Primary arrival
λ_2	Secondary arrival
μ_1	Primary service
μ_2	Secondary service
ν / N_2	Retrial from orbit
σ_2	Repair rate
θ_2	Failure while idle
γ_2	Failure while busy

which demonstrate the effect the repair time distributions (while the squared coefficient of variation is greater or less than one) on the behaviour of the secondary sub-system.
In Table 4.2 we introduce the numerical values of the model's parameters and their indication in Table 4.3.

4.2.1 New results

Our initial objective was to determine how the repair time distributions influence the system's performance, with identical means and different variances. According to the square coefficient of variation C_x^2 when greater or less than

TABLE 4.4: Parameters of the distributions

Distribution		Hyper	Hypo	Gamma	Pareto	Lognormal
Fig 5,6,7	Mean	N/A	1	1	1	1
	Var	N/A	0.68	0.68	0.68	0.68
	Para.	N/A	λ_1=1.25 λ_2=5	α=1.470 β=1.470	α=2.751 K=0.611	m=0.720 σ=-0.259
Fig 2,3,4	Mean	1	N/A	1	1	1
	Var	2.56	N / A	2.56	2.56	2.56
	Para.	λ_1=0.661 λ_2=1.3380 p=0.330	N/A	α=0.3906 β=0.390	α=2.179 K=0.541	m=1.126 σ=-0.634

one, we chose to divide this evaluation into two subsections. Table 4.4 displays the input variables for the distributions of the repair times.

Repair time is generally distributed with $C_x^2 > 1$ Figures 4.1, 4.2 and 4.3 show, respectively, the effects of the server's repair time distribution on the mean response time, overall server utilization, and the total mean service time of secondary users. These results were obtained in relation to the secondary arrival intensity.

The figures illustrates how the characteristics are significantly impacted by the distributions of the repair time. For instance, the gamma distribution in Figure 4.1 offers the shortest value of the mean response time, whereas the lognormal distribution offers a higher value of the mean.

Furthermore, the server recovers more rapidly because the gamma distribution results in low numbers when the previously presented input parameters are used. Consequently, Figure 4.2 shows a higher value of utilization.

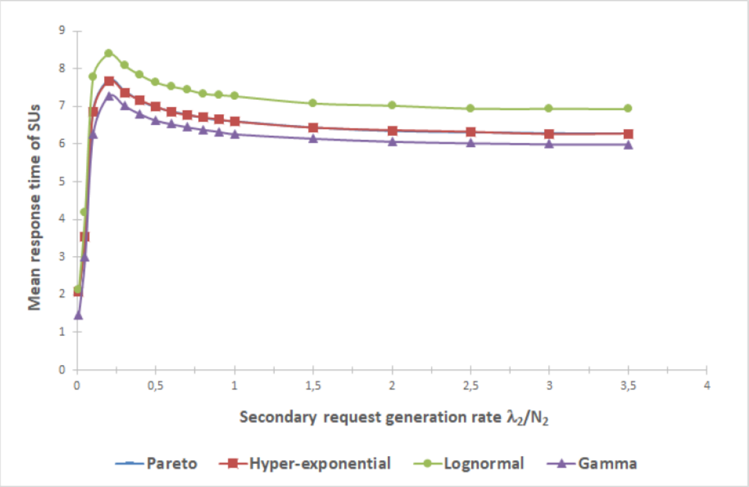

FIGURE 4.1: The effect of repair time distributions on the mean sojourn time of cognitive users vs secondary arrival rate

Since the system is frequently in operating mode, the gamma distribution in Figure 4.3 results the highest value of the mean service time, similar to Figure 4.2.

The interpretation of our results may be affected by the observed random variable.

The value of the mean sum of primary and secondary service time will change, for instance, if the distribution's mean and variance are modified.

By modelling the performance measures of such a system, we are capable of investigating characteristics that are almost impossible to analyse analytically. However, we provide the following explanation for the outcomes:

Figure 4.1 displays the distribution of repair time, with the

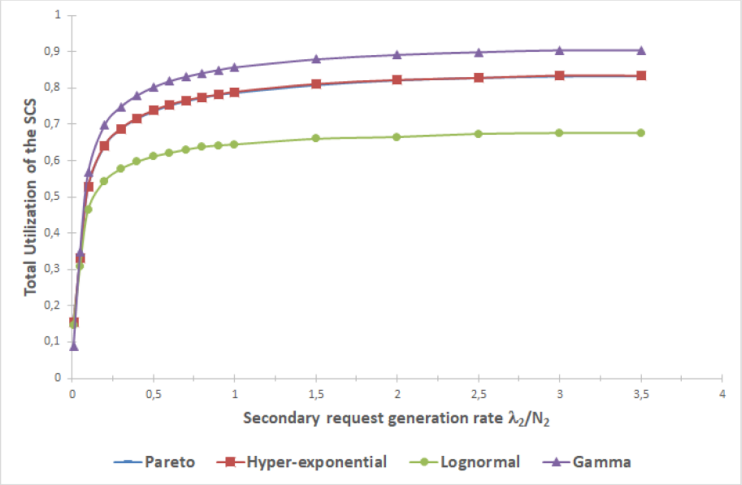

FIGURE 4.2: The effect of repair time distributions on total utilization of the secondary server vs secondary arrival rate

log-normal distribution exhibiting a higher relative probability of the random variable x (repair time) than the gamma distribution. This suggests that repair time is more likely to take longer when distributed log-normally, as evident from the Probability Density Function graph. As a result, prompt response to requests is crucial for users since server repairs take a longer time. Conversely, Figure 4.2 shows that when the repair time is distributed log-normally, server utilization is lower than when it is distributed gamma, as the server is frequently down and unoccupied.

Repair time is generally distributed with $C_x^2 < 1$ This subsection examines and compares the effect of repair

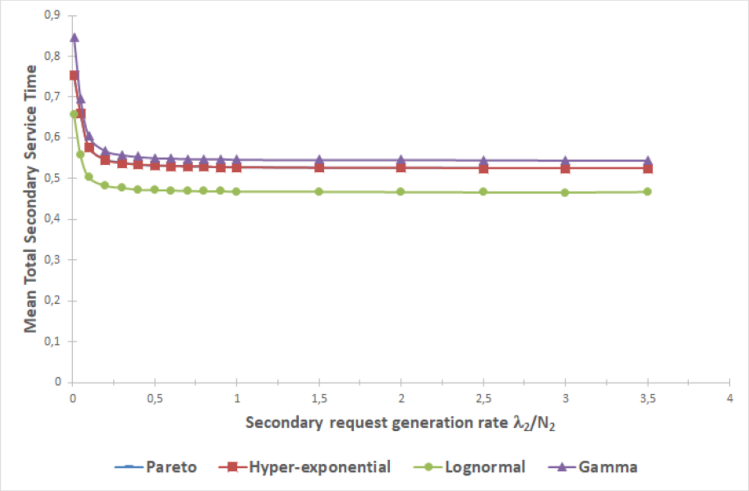

FIGURE 4.3: The effect of repair time distributions on total utilization of the secondary server vs secondary arrival rate.

time distribution on the selected features, but with hypo-exponential distribution instead of hyper-exponential distribution. The new parameters are set such that their coefficient of variation is less than one, as illustrated in Table 4.4. Figures 4.4, 4.5, and 4.6 present analogous results on the average response time/service time of secondary requests and the use of SCS vs secondary inter-arrival rate. The performance metrics differ for the two sets of distributions when the distribution's C_x^2 is less than 1. Estimates from hypo-exponential and Pareto distributions show comparable values, which are higher than those produced by log-normal and gamma distributions. The displayed influence of the distributions follows the same pattern as in the case of $C_x^2 > 1$. The anticipated phenomenon of having a

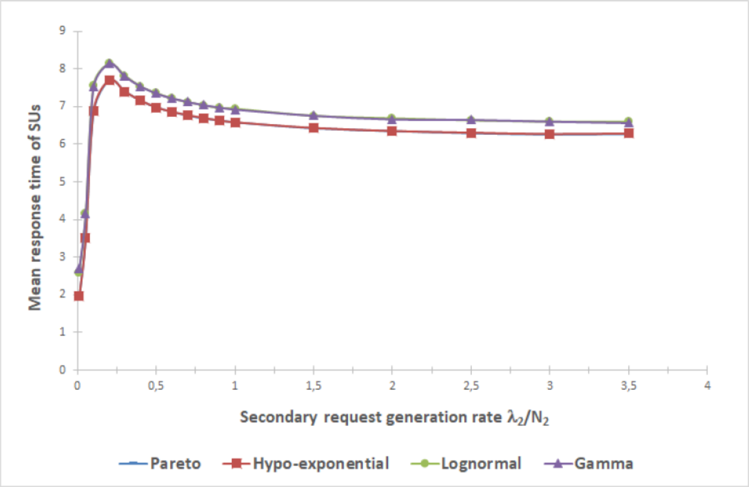

FIGURE 4.4: The impact of repair time distributions on the mean response time of SUS vs λ_2/N_2

maximum mean value was observed in this case, and as the arrival intensity increases, the server is utilized more frequently, leading to a decrease in the mean service time.

4.3 Performance evaluation with unreliability and abandonment

The system model discussed in the preceding section, which focused on system unreliability, is expanded to include the abandonment behaviour of SUs. This refers to the situation where secondary customers are required to exit the system once their cumulative waiting time reaches a

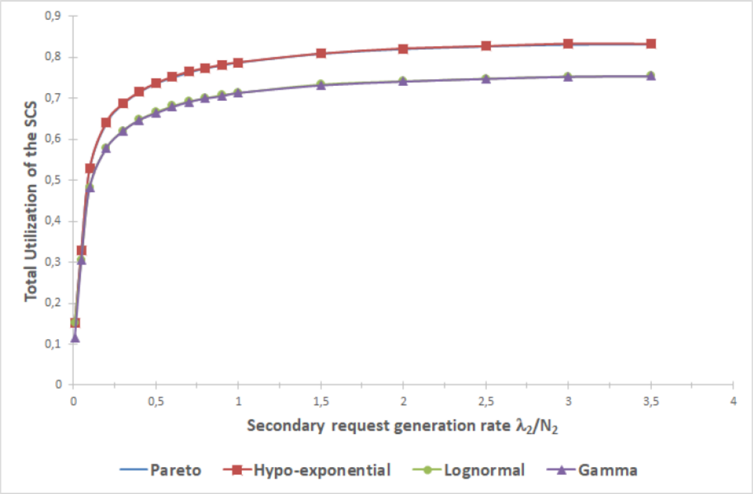

FIGURE 4.5: The impact of repair time distributions on the total utilization of secondary server vs λ_2 / N_2

predetermined random abandonment time, thus reflecting the case scenario of the current study.

> **Thesis 2 (J3)** *(Section 4.3) We considered abandonment time as a set of random variables generally distributed with the same mean but non-identical variances to examine the performance measures of a finite-source cognitive radio network that experiences unreliability and abandonment. The main objective was to analyze the effects of secondary server unreliability and abandonment on several network performance measures, including the probability of abandonment, mean sojourn time of users, etc. Our results indicate that the abandonment time distributions has a substantial impact on performance metrics.*

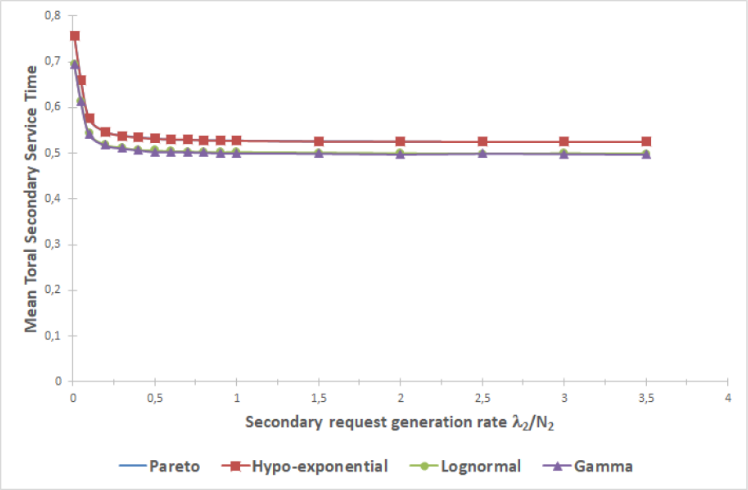

FIGURE 4.6: The impact of repair time distributions on the mean total secondary service time vs λ_2/N_2

For this investigation, a queuing system with two interconnected and non-independent subsystems was used. The first subsystem, which caters to primary requests, consists of N_1 sources that generate high-priority requests with exponentially distributed inter-request times, using the λ_1 parameter. All the requests generated by the primary sources, are directed to a single PCS server, which is connected to a pre-emptive FIFO queue. The service times for PU jobs are also exponentially distributed with a rate of μ_1.

The second subsystem handles low priority requests, and the inter-arrival and service times are assumed to be exponentially distributed with parameters N/λ_2 and μ_2, respectively, where N_2 represents the number of sources. The servers can either be in an idle or busy status. The primary packets are directed to either the FIFO queue (if a PU is in the PCS) or the primary server based on the server′s situation. If a secondary request is being handled in the PCS, it is interrupted and redirected to the secondary unit, allowing PUs to start service in their dedicated unit. The aborted task is then sent to either the secondary server or the retrial queue (orbit), depending on the availability of the secondary unit. The task is retried after an exponentially distributed period with a parameter ν / N_2.

Requests from Secondary Users are handled by the SCS. If the SCS is available, the service starts; otherwise, if the PCS is idle, the unlicensed process will be able to sense it, and the service may start opportunistically in the high-priority channel. If the PCS is busy, the request is sent to the orbit. It should be noted that SUs in the orbit are required to leave the system if their cumulative waiting time exceeds a random time that is generated using one of the following distributions: Hyper, Hypo, Gamma, Log-normal, and Pareto, with a rate of τ. The secondary service unit may experience random failures in both its busy and idle states after an exponentially distributed random period with parameters γ_1 and γ_2, respectively. The repair time is also an exponential random variable with σ as a parameter.

4.3.1 New results

In this study, we were able to deal with multiple scenarios using simulation to allow for comparisons of different observations within a single run. Performance is evaluated for two categories of cognitive customers (SUs): those who receive successful service and those who abandon the system due to waiting time exceeding a predefined threshold. Furthermore, a distinction is made between secondary users who successfully received service from the primary channel and those who leave the system due to primary customers' priority over them. To estimate the performance measures for these categories, we use the batch mean approach [7] in the simulation. Several results were generated by dividing cognitive users into two categories: Successful and Abandon. This investigation is structured according to the following scenarios:

- **Scenario 1**: The users' impatience time is exponentially distributed.
- **Scenario 2**: Impatience time is generally distributed using the Hyper-Exponential, Gamma, Lognormal, and Pareto distributions, with $C_x^2 > 1$.
- **Scenario 3**: impatience time is generally distributed using the Hypo-Exponential, Gamma, Lognormal, and Pareto distributions with $C_x^2 < 1$.

It is assumed that if the secondary service in the SCS is disrupted due to the arrival of PUs or server failure, it will restart from the beginning without any intelligence. Moreover, if a service unit fails, it will not cause the system to be blocked, and the available sources will continue to generate new requests. We present in this section of the thesis only the results of **Scenario 1** (The secondary users' impatience time is exponentially distributed).

Impatience time is exponentially distributed Assuming that all the random inter-event times (including SU impatience) follow an exponential distribution, our focus was on analysing the critical features of the system by increasing τ.

TABLE 4.5: Different impatience rates

	N_2	λ_2/N_2	ν/N_2	γ_1	γ_2	σ	μ_1, μ_2	τ
Case 1	100	0.01	0.1	0.1	0.1	1	1	0.000001
Case 2	100	0.01	0.1	0.1	0.1	1	1	0.0001
Case 3	100	0.01	0.1	0.1	0.1	1	1	0.001
Case 4	100	0.01	0.1	0.1	0.1	1	1	0.01
Case 5	100	0.01	0.1	0.1	0.1	1	1	0.1
Case 6	100	0.01	0.1	0.1	0.1	1	1	1

The parameter values specified in Table 4.5 were employed to generate the outcomes.

The simulation allowed us to present accurate estimates for two types of cognitive users: those successfully serviced and those abandoned. The following sections contain tables with specific system characteristics, denoted in Table 4.10, such as the estimated means and variances of the measurements. Tables 4.6, 4.7, 4.8, and 4.9 present the results. The observations are based on two sub-scenarios:

- **Scenario A**: there are only a few sources, specifically $N_1 = 10$, and a low volume of primary customers arriving with a rate of $\lambda_1 = 0.01$.
- **Scenario B**: involves a significantly greater number of sources, with $N_1 = 100$, and a heavier incoming traffic with a rate of $\lambda_1 = 0.1$.

In this section, we present Tables 4.7 and 4.6 which display the variances and expectations for different categories of cognitive users. These results were obtained by setting $\lambda_1 = 0.01$ and $N_1 = 10$. The tables identify instances where

TABLE 4.6: Estimation of the expectations for scenario A

	E(T S)	E(W S)	E(T)	E(W)	E(N S)	E(T A)	P_a
Case 1	14.0437	13.8001	14.04	13.8001	48.59	0.0000	0.0000
Case 2	14.0525	13.8165	14.05	13.8284	44.64	15.0001	0.001
Case 3	13.8333	13.5979	13.59	13.0235	38.17	15.226	0.012
Case 4	12.3461	12.1107	12.48	12.27	28.33	13.5472	0.15
Case 5	5.5598	5.3241	6.0853	5.9801	12.21	6.4914	0.56
Case 6	0.8258	0.5908	0.9654	0.3491	0.9772	0.9772	0.9217

TABLE 4.7: Estimation of the variances for scenario A

	Var(T S)	Var(W S)	Var(T)	Var(W)	Var(T A)
Case 1	197.227	190.66	197.227	197.227	0.0000
Case 2	197.473	190.897	197.47	190.87	185.249
Case 3	191.36	184.902	191.35	181.35	185.652
Case 4	152.42	146.67	152.48	146.66	183.52
Case 5	30.9119	28.3471	30.91	28.43	42.13
Case 6	0.6818	0.3491	0.6820	0.3491	0.955

the impatience rate τ increases, and show that as the probability of abandonment increases, the mean and variance values of response and waiting times decrease for all users. Interestingly, we also observed that the mean and variance values of impatient users became unstable as the abandonment rate increased. This can be explained by the fact that when the impatience rate is extremely low, customers tend to stay in the system for a long time, making it difficult to accurately estimate the expectation with a small number of observations, resulting in wider confidence intervals.

Tables 4.8 and 4.9 address the same aspects as in the previous section, but with more intensive primary traffic, where $N_1 = 100$ and $\lambda_1 = 0.01$. Comparing these tables to Tables 4.6 and 4.7, the efficiency of cognitive technology is evident. In scenario A, with a very low impatience rate ($\tau = 0.000001$), Table 4.6, row 1, shows a probability of abandonment of 0 due to the lack of primary users at the licensed service channel.

Despite higher mean and variance values in scenario B, we perform the same analysis to explain the expectation and variance of waiting time for impatient users, as shown in Table 4.10.

We obtained different results in scenarios 2 and 3 compared to when exponential distribution was used, as the repair time was generally distributed with a squared coefficient of variation greater than and less than one, respectively. Notably, we observed a higher sensitivity to the distribution when using a Hyper-exponential distribution. These results confirm that $C_x^2 > 1$ has a significant impact on such a complex system.

TABLE 4.8: Estimation of the expectations for scenario B

	E(T S)	*E(W S)*	*E(T)*	*E(W)*	*E(N S)*	*E(T A)*	P_a
Case 1	25.0657	24.8343	25.0651	24.8338	57.28	29.5803	0.000023
Case 2	24.9055	24.66	24.8423	24.6119	57.28	26.5792	0.002
Case 3	24.2940	24.0632	24.3561	24.1307	52.26	26.9554	0.02
Case 4	20.0967	19.8643	20.4913	20.3042	30.15	22.118	0.194
Case 5	6.5178	6.2909	7.2363	7.1664	6.07	7.5563	0.61
Case 6	0.8242	0.6068	0.9743	0.3682	0.9598	0.9834	0.943

TABLE 4.9: Estimation of the variances for scenario B

	Var(T S)	*Var(W S)*	*Var(T)*	*Var(W)*	*Var(T A)*
Case 1	628.037	616.75	628.29	616.57	726.24
Case 2	620.037	608.519	608.59	606.84	724.40
Case 3	590.201	579.04	590.2013	579.03	726.65
Case 4	403.8815	394.591	403.8813	394.5913	489.2139
Case 5	42.4828	39.5766	0.6794	39.4741	57.0989
Case 6	0.6771	0.3682	0.6794	0.3682	0.9671

TABLE 4.10: Expectations and variances notations

Notation	Definition
E(T S), Var(T S)	Mean and variance response time of successful SU
E(W S), Var(W S)	Mean and variance wating time of successful SU
E(T), Var(T)	Mean and variance response time of arbitrary SU
E(W), Var(W)	Mean and variance waiting time of arbitrary SU
E(N S)	Mean number of secondary customers in the system
E(T A), Var(T A)	Mean and variance waiting time of impatient customers
P_a	Probability of abandonment

4.4 Analysis of balking and reneging

This thesis covers the theories of balking (refusing to join the queue) and reneging (leaving the system after joining) as they relate to cognitive radio networks. These behaviours, which users may exhibit while waiting in queues, are among the most well-known. As the system gets more crowded, new arriving customers may be discouraged from joining, while impatient users will exit after entering once their waiting time exceeds a maximum value.

> **Thesis 3 (J4)** *(Section 4.3) We model the reneging (leaving the system after joining) time of secondary users (SU) as a set of random variables that follow an exponential distribution, and the secondary service time as generally distributed with the same mean but non-identical variances. Newly arriving secondary customers may balk (refuse to join the server) with a probability of n/N_2, where n is the number of customers in the system and N_2 is the number of secondary sources. We intended to investigate the impact of service time distributions, cognitive technology, and impatience behavior of SU on the key performance measures of the system.*

Assuming that our system possesses the fundamental characteristics of a cognitive radio network, we consider two subsystems that are interconnected. In the first subsystem, the primary server receives requests from a limited number of sources N_1 over an exponentially distributed period of time with a mean of $1/\lambda_1$. The service starts when the unit is available; otherwise, the request is placed in a preemptive priority queue. The service time for primary customers is a random variable with an exponential distribution and the parameter μ_1.

In the secondary subsystem, N_2 represents the number of sources. Each source generates low-priority tasks based on an exponentially distributed time with the parameter λ_2/N_2. The service time for SUs, with a rate of μ_2, is generally distributed with the same mean but different variances using hypo-exponential, hyper-exponential, and gamma distributions. It is assumed that the retrial time for the secondary customer is exponentially distributed with a parameter of ν.

When newly arriving secondary customers join the server, they may balk (refuse to join the server) with a probability of n/N_2, where n is the total number of sources and N_2 is the total number of users in the system. Additionally, if the service has not begun by a certain random time, which is exponentially distributed with a parameter of τ, they may renege (leave the server).

4.4.1 New results

A stochastic simulation program was developed using C language and SimPack [11], assuming that all random variables in the system, except for secondary services, are exponentially distributions. The simulation outputs were validated, and the numerical obtained results are displayed below. The main class input parameter values used in the simulation are listed in Table 4.12, and the parameters of the distributions are shown in Table 4.11.

Service times are generally distributed Figure 4.7 depicts the impact of primary and secondary service time distributions on the mean sojourn time of SUs vs secondary inter-arrival time. The gamma distribution with a $C_x^2 > 1$ displays a notable sensitivity to the distribution. The effect

TABLE 4.11: Parameters of the general distributions

Distribution	Gamma $C_x^2 < 1$	Hyper	Hypo	Gamma $C_x^2 > 1$
Para.	α=1,7857 β=1,7857	p = 0,3309 λ_1 = 0,66198 λ_2 = 1,33803	λ_1= 1,4854 λ_2= 3,06	α= 0,3906 β= 0,3906
Mean	1	1	1	1
Var	0.56	2.56	0.56	2.56
C_x^2	0.56	2.56	0.56	2.56

TABLE 4.12: Simulation input parameters

N_1	N_2	λ_1	λ_2/N_2	μ_1	μ_2	ν	τ
20	50	0.1	x-axis	1	1	0.1	0.1

of primary and secondary service times distribution on the mean reneging time of SUs versus secondary request time generation is shown in Figure 4.8, with the gamma distribution with a $C_x^2 > 1$ greater than one indicating the same sensitivity observed in previous results. As expected, a substantial number of users abandon the system due to the increased arrival rate of SUs, especially in the hypoexponential case. Table 4.11 provides the parameters of the general distributions. The simulation program was developed using SimPack [11] in C language, with all random variables in the system, except services, being exponentially distributed, and the numerical outputs were validated. The primary input parameter values for the simulation are presented in Table 4.12.

Figure 4.9 demonstrates how the average balking rate is affected by the distribution of service times in the primary and secondary subsystems, as well as the secondary arrival

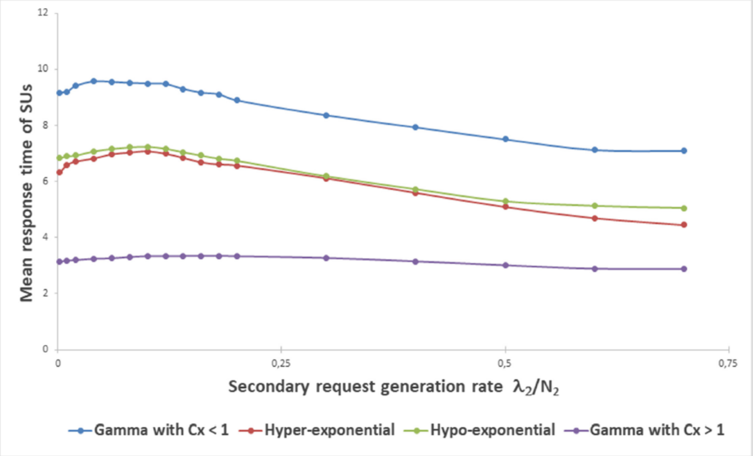

FIGURE 4.7: The impact of primary and secondary service times distribution on the mean residence time of SUs vs secondary request time generation

rate. As the secondary arrival rate increases, the discouragement for newly arriving secondary users also increases, especially when using the Gamma distribution. It is well-known that the Gamma distribution produces high random service times when $C_x^2 > 1$, leading to system overload.

The impact of the service times distribution in the primary and secondary subsystems on the average response time of

TABLE 4.13: Simulation input parameters for Figures 4.10 and 4.11

N_1	N_2	λ_1	λ_2/N_2	μ_1	μ_2	ν	τ
20	50	x-axis	0.14	1	1	0.1	0.1

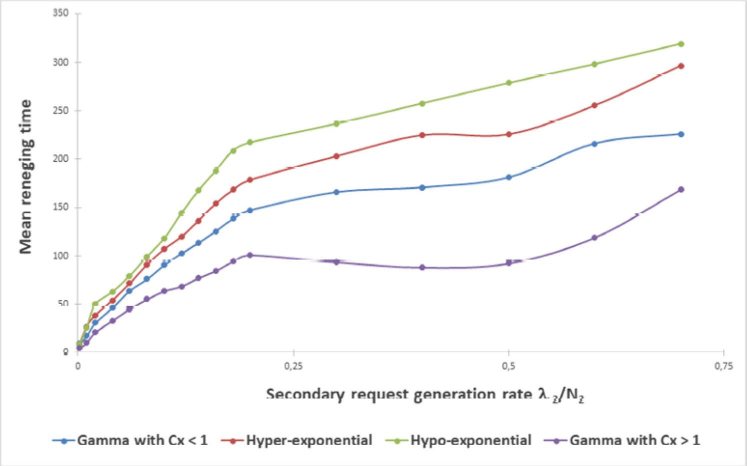

FIGURE 4.8: The impact of primary and secondary service times distribution on the mean reneging time of SUs vs secondary request time generation

SUs compared to primary request time generation is illustrated in Figure 4.10. This figure clearly shows the effect, especially when the squared coefficient of variation is greater than one.

To investigate the effects of primary and secondary service times distribution on the mean SU reneging time vs primary request time generation, we generated Figure 4.11. Using the Gamma distribution, which has a squared coefficient of variation less than one, did not result in a high mean reneging rate compared to the other distributions. However, increasing the main request generation rate does result in a higher mean reneging time.

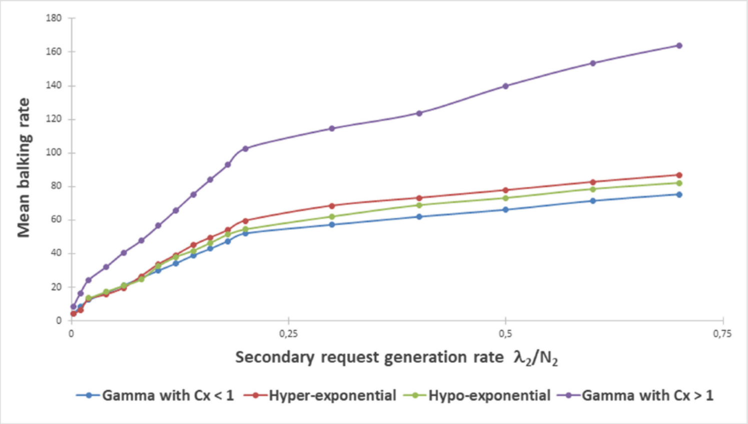

FIGURE 4.9: The impact of primary and secondary service times distribution on the mean balking rate of SUs vs secondary request time generation

All Inter-event times are exponentially distributed In this subsection, we make the assumption that inter-event times follow an exponential distribution. The input parameters listed in Table 4.12 are used, with a constant value of $\lambda_2 = 0.5$. Our aim is to investigate the impact of cognitive technology on the system's characteristics.

The average response time of low-priority users is affected by the primary inter-arrival rate and N_2, as shown in Figure 4.12. The figure reveals that the average SU sojourn duration is lower when $\lambda_1 = \lambda_2/2$ compared to when $\lambda_1 = \lambda_2 * 2$. However, N_2 has no impact, and the intensity of the main sub-traffic subsystem increases as N_2 increases. When the number of primary sources is greater, Figure 4.13 demonstrates a distinct effect because more secondary users

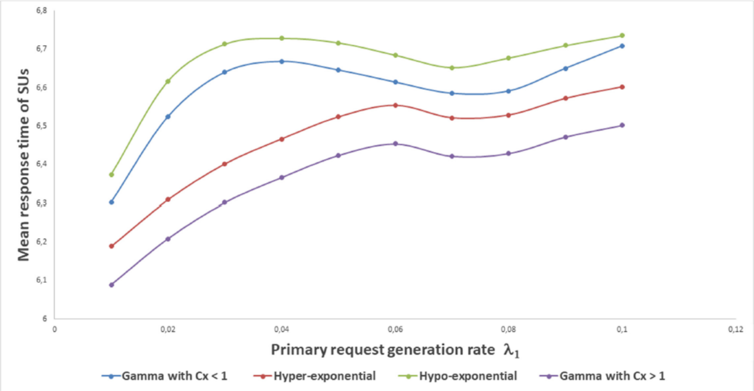

FIGURE 4.10: The impact of primary and secondary service times distribution on the mean residence time of SUs vs primary request time generation

leave the system. The impact of the primary arrival rate being half of the secondary's can only be seen in Figure 4.14 when there are only a few primary sources, which is due to the primary network characteristics. This is because fewer users balk due to the opportunistic use of PCS by SUs.

Figure 4.15 demonstrates how the primary subsystem rates affect the average residency duration of cognitive users, in contrast to the secondary number of sources. As N_2 increases, the use of the secondary system also increases, but there is a limit where the server becomes fully utilized. A distinct difference can be observed when the primary arrival rate is at its highest or lowest, with $\lambda_1 = \lambda_2 * 2$ and $\lambda_1 = \lambda_2/2$, respectively.

Figure 4.16 shows an impact when there are only a few sources, with $N_1 = 20$ and $N_2 = 10$. The main network characteristics may influence the average response time of

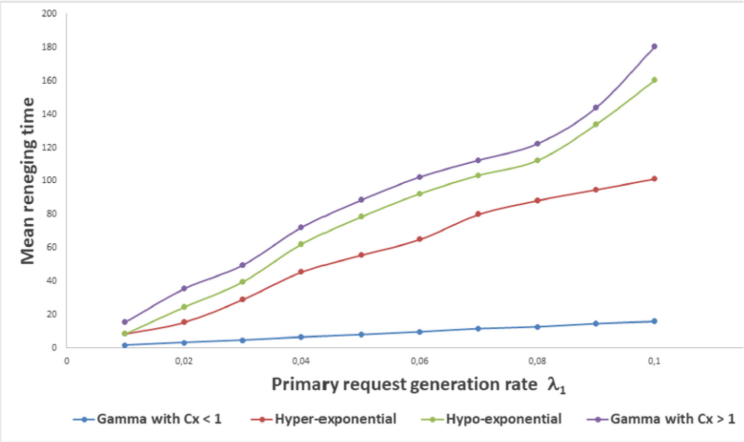

FIGURE 4.11: The impact of primary and secondary service times distribution on the mean reneging time of SUs vs primary request time generation

SUs relative to N_2, as shown in this graph.

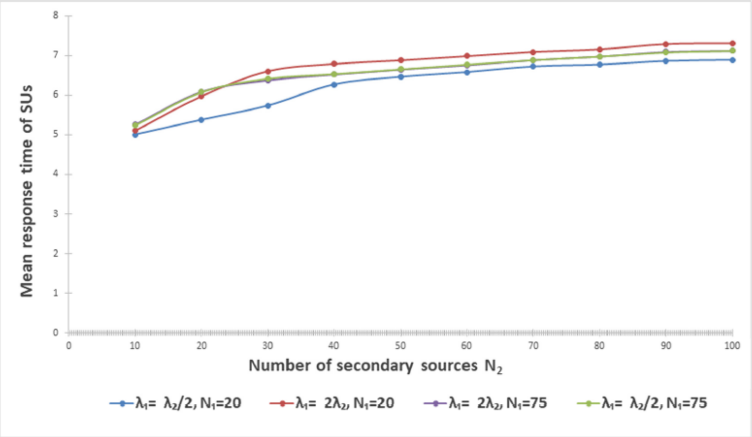

FIGURE 4.12: The effect of the primary network parameters on the mean response time of SUs vs N_2

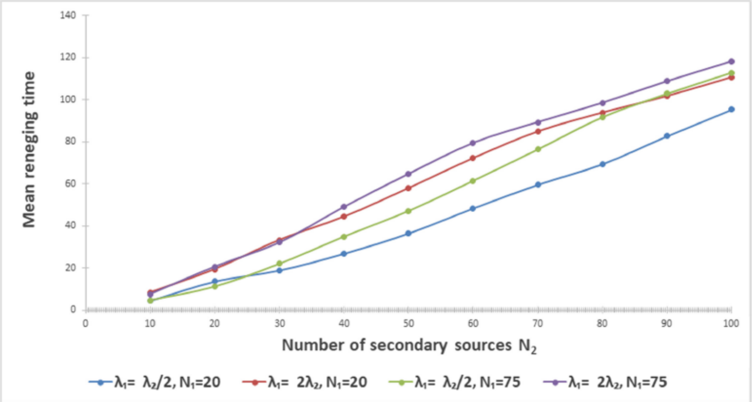

FIGURE 4.13: The effect of the primary network parameters on the mean reneging time of SUs vs N_2

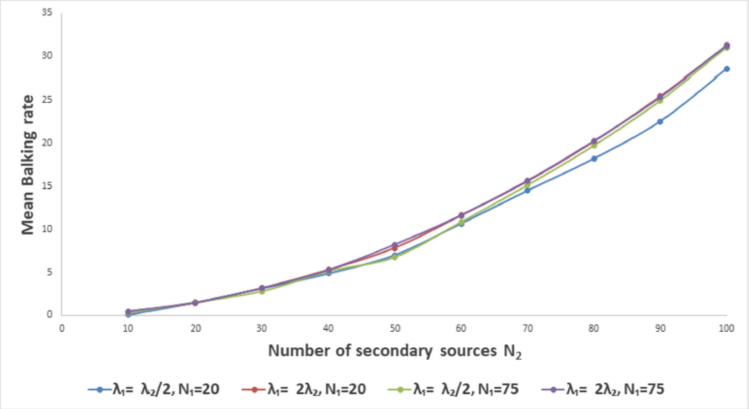

FIGURE 4.14: The effect of the primary network parameters on the mean balking rate of SUs vs N_2

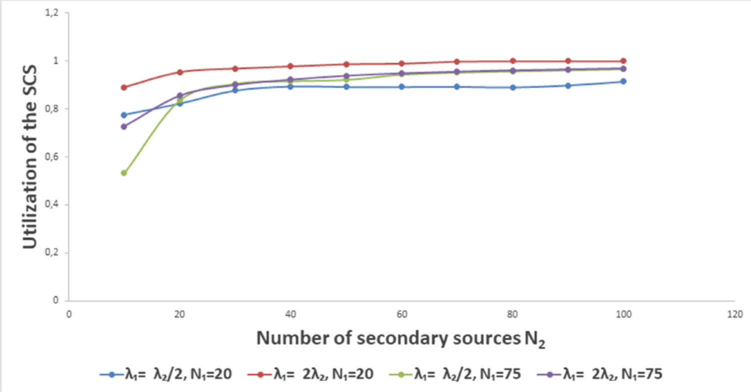

FIGURE 4.15: The effect of the primary network parameters on the utilization of SCS vs N_2

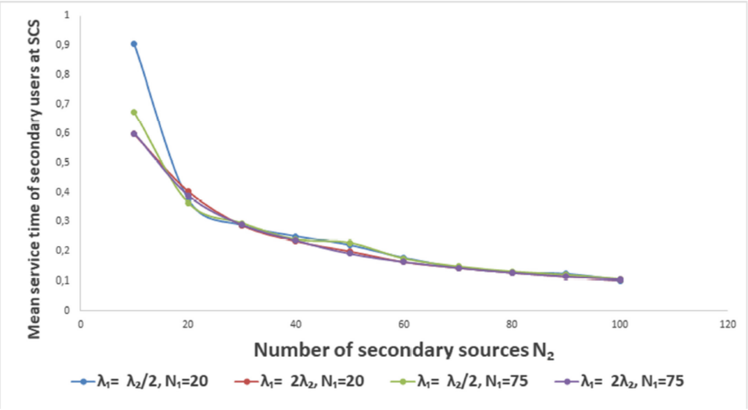

FIGURE 4.16: The effect of the primary network parameters on the mean service time of SUs vs N_2

5 Application of the results

The upcoming generations of wireless systems and networks are expected to benefit significantly from Cognitive Radio (CR) technology. One of the most significant issues in wireless systems is the underutilization of licensed spectrum, which can be resolved by employing CR. In this thesis, we aimed to investigate the performance of cognitive networks using a simulation retrial queuing system. The models developed in this study can be used to validate more complex simulation models in various scenarios, including incorporating additional distributions, secondary server facilities, and outgoing calls. Our study also addressed several issues that arise in actual network connections, such as server failures, customer impatience, reneging, and balking. The model is adaptable to handle more real-world instances such as catastrophic breakdowns, system blocking, and higher service quality.

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List of Publications

List of Papers [J]:

J1 Zaghouani, M.H., Sztrik, J., and Uka A.,
Simulation of the performance of Cognitive Radio Networks with unreliable servers,
Ann. Math. Inform. 52, 255-265, 2020. ISSN: 1787-5021.

J2 Nemouchi, H., Zaghouani, M.H., and Sztrik, J.,
Analysis of Cognitive Radio Networks with Balking and Reneging,
Distributed Computer and Communication Networks: Control, Computation, Communications / Vishnevskiy Vladimir M, Springer International Publishing Ag, Cham, 3-13, 2021. ISBN: 9783030925062

J3 Zaghouani, M. H., Nemouchi, H., Sztrik, J.,
Reliability analysis of Cognitive Radio Networks with balking and reneging,
The International Conference on Digital Technologies (IDT 2021), IEEE, [s.l.], 212-215, 2021. ISBN: 9781665436922.

J4 Nemouchi, H., Zaghouani, M.H., and Sztrik, J.,
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J5 Zaghouani, M. H., Sztrik, J., Uka, A.,
Reliability Analysis of Cognitive Radio Networks,
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List of Conference Proceedings [C]:

C1 Zaghouani, M. H., Nemouchi, H., Sztrik, J.,
Performance investigation of reverse balking in cognitive radio networks using simulation,
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C2 Zaghouani, M. H., Nemouchi, H., Sztrik, J.,
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2022 IEEE 2nd Conference on Information Technology

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C4 Nemouchi, H., Zaghouani M.H., and Sztrik,
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C5 Zaghouani, M. H., Sztrik, J.,
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Ann. Math. Inform. 51, 89-99, 2020. ISSN: 1787-5021. DOI: http://dx.doi.org/10.33039/ami.2020.07.004.

C6 Zaghouani, M. H., Sztrik, J., Melikov, A.,
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Subject: PhD Publication List

Candidate: Mohamed Hedi Zaghouani
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List of publications related to the dissertation

Foreign language scientific articles in Hungarian journals (2)

1. **Zaghouani, M. H.**, Sztrik, J.: Performance evaluation of finite-source Cognitive Radio Networks with impatient customers.
   Ann. Math. Inform. 51, 89-99, 2020. ISSN: 1787-5021.
   DOI: http://dx.doi.org/10.33039/ami.2020.07.004
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   Ann. Math. Inform. 52, 255-265, 2020. ISSN: 1787-5021.
   DOI: http://dx.doi.org/10.33039/ami.2020.01.002

Foreign language conference proceedings (5)

3. Nemouchi, H., **Zaghouani, M. H.**, Sztrik, J.: Analysis of Cognitive Radio Networks with Balking and Reneging.
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List of other publications

Foreign language conference proceedings (4)

8. **Zaghouani, M. H.**, Nemouchi, H., Sztrik, J.: Performance investigation of reverse balking in cognitive radio networks using simulation. In: Informational technologies and mathematical modelling (ITMM-2021): Proceedings of the 20th International Conference named after A. F. Terpugov (2021 December, 1-5) / Nazarov, A. A., Moiseeva, S. P., Moiseev, A. N, Tomsk State University Publishing, Tomsk, 145-149, 2022. ISBN: 9785907572201

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