



# Performance Modeling of Finite-Source Cognitive Radio Networks Using Simulation

Thesis for the Degree of Doctor of Philosophy (PhD)

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# Performance Modeling of Finite-Source Cognitive Radio Networks Using Simulation

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*Hereby I confirm that Hamza Nemouchi. candidate conducted his studies with my supervision within the Information Technology Systems and Networks Doctoral Program of the Doctoral School of Informatics between 2014 and 2020. The independent studies and research work of the candidate significantly contributed to the results published in the thesis.*

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# 1

## Introduction

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*This first chapter introduces the retrial queueing model for the cognitive radio networks and highlights the motivation of the research conducted in the dissertation*

Wireless systems are enduring some fundamental service problems with regards to certain appropriate spectrum bands to satisfy future requests. Furthermore, the radio spectrum is essentially allocated to various services, applications, and users. Observation reveals that the use of the spectrum is remarkably low. The massive growth in wireless communications leads to frequency spectrum depletion and the available radio spectrum is a scarce essential resource that is packed day by day. Many of the pre-allocated frequency bands are unsurprisingly underused and consequently, the resources are wasted. This considers the reserved spectrum is underutilized because of the static spectrum allocation. The reliable approach to manage the spectrum is unbending. In a certain frequency band, each wireless operator is assigned a single license to operate. It is hard to find available bands to deliver new services and improve existing ones. To surmount the situation, we need better spectrum usage that will offer opportunities for Dynamic Spectrum Access DSA. The use of "Cognitive Radio System" is a possible alternative, which acquires the ability to sense and be cognizant of its operating condition and it can modify its functioning parameters. This approach seems like a promising method for efficiently utilize the available spectrum on the frequency band. Cognitive radio is considered to be a completely reconfigurable radio system that is capable of adapting itself "cognitively" to the communications requirements of its user, to the radio frequency environment in which it operates, and to the different network and regulatory policies applicable to it.

The Cognitive radio responds to the environmental conditions by evaluating and makes use of this information for future assessments. There are mainly two tiers of users in the cognitive radio model. Primary Users (PU) are approved users who have the exclusive right to use certain licensed frequency bands. Secondary Users (SU) are allowed to access 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.

This thesis presents a short synopsis of cognitive radio systems and their architecture. The aim is to develop a simulation program for modelling a cognitive radio network with the help of the queueing theory. Then, we investigate the efficiency of cognitive radio techniques in servicing a given population.

Queueing theory has its origins in the seminal work of Erlang in the context of early telephone exchange networks. Since then, its implementation in various contexts, such as operations research, telecommunications, data networks, industrial engineering. Nowadays cognitive radio networks have fueled interest in queueing theory. The Retrial queueing system in the cognitive radio network

consists of a system with two non-independent frequency bands servicing two classes of users, which are considered: Primary Users (PUs) and Secondary Users (SUs). PUs have preemptive priority over SUs at the licensed spectrum, while SUs are served at the normal spectrum containing an orbit for the retrial users. To model cognitive radio network, queueing theoretical methods have been used in several works such as in [3], by setting retrial queueing systems containing two finite sources of PUs and SUs, respectively. A multidimensional Markov chain was introduced since the assumption of all inter-event times were exponentially distributed. As a result, the mean values of the important performance measures were calculated and then illustrated.

As a natural generalization the model used in [3], the same system is investigated in this thesis by allowing non-exponentially distributed request generation, service, retrial, failure and repair times. In order to evaluate the performance of our system, a stochastic simulation approach is used to obtain estimations for the most important characteristics of it and several case studies illustrate the impact of these general distributions.

Among different approaches, which are useful to evaluate different alternatives, simulation has proven its high capability in modelling and evaluating such complex systems. Every simulation study consists of at least the followings:

- Translating a system's definition into a formal abstraction that specifically allows all interactions in logic and mathematics.
- Identifying all parameters of the abstraction that require numerical values as input.
- Identifying all measures of performance whose values require estimation.
- Estimating the values of all unknown input parameters from available data.
- Converting the logical abstraction to executable code in a simulation programming language.
- Perform a series of sampling experiments by repeatedly running the code, at least once for each set of input-parameter values.
- For each measure of performance, evaluating how well its time average approximates its unknown long-run average.
- Comparing corresponding sample time averages for each performance measure across experiments.

One of the advantages of the simulation is that we can give estimations for the variances. The investigation of the distribution of the sojourn time is usually very complicated and in most cases, its Laplace transform is given. The calculation of the variance is not a simple problem, it can be evaluated by the help of numerical and algorithmic approaches. Therefore, We have built a simulation program to model the finite-source cognitive radio network and analyze the effect 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 study cases that we mention:

- 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.

This dissertation consists of 5 chapters. Chapter 1 introduced the background of the subject area and justified the significance of the research study. Chapter 2 provides an overview of the cognitive radio networks. It is important to understand firstly the cognitive radio communication than to be able to create a network by using this technology. This chapter includes also the architecture of the network and various spectrum sensing techniques. Chapter 3 contains the conception of our work. Firstly, an overview is given about the basic random processes, as well as, some basics on discrete-event simulation modeling. Afterward, All measures of performance whose values require estimation are identified and illustrated by the help of flowcharts the simulation model used to evaluate the suggested system model. Chapter 4 presents all the results collected during the performance evaluation of the various case studies on the system model. Several examples with comparisons were made and different figures illustrate the above-mentioned analysis. Finally, Chapter 5 summarizes all the achieved work and research findings of the dissertation.

# 2

## The cognitive radio network

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*This chapter describes the cognitive radio networks, it is an overview on their architecture, paradigms and spectrum sensing techniques*

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**2.1****Introduction**

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Nowadays, the evolution of the new wireless technologies is bounded by the scarcity of the available radio spectrum. These new technologies are becoming continually bandwidth critical due to their higher proportion requirement. Cognitive radio networks and spectrum-sensing techniques are a topic of great interest and hold much promise as a natural way that will play an essential role to grant these new technologies to be deployed. The term cognitive radio was introduced by Mitola and Maguire in 1999 [40] in an article where they have defined a cognitive radio as a smart radio that understands the context in which it finds itself and accordingly adjusts the communication process. Since then, the term cognitive radio has grown and enlarged and has tended to be used in many ways.

As defined in [57], one of the most outstanding features of the cognitive radio networks is the capability to switch between the radio access technologies and transmitting in several parts of the radio spectrum when frequency channel slots (portions) appear. Usually, the cognitive radio networks are called or named secondary networks, they need to coexist with licensed ones which are the primary networks, and they have the right to their spectrum slot without causing interference. This technique is called dynamic spectrum access.

Dynamic spectrum access introduces a variation in wireless communication and it is the mainstay of the cognitive radio networks. It is one of the essential requirements for the transmitters to adapt to variant qualities of the frequency band, network congestion, interference, and service requirements. Cognitive radio influences the concept of the dynamic spectrum access to permit the secondary network users to use the primary channel in an opportunistic manner, by meaning to avoid interferences with the primary users.

As a new technology, cognitive radio networks introduce numerous novel research challenges such as spectrum sensing, spectrum handoff, resource allocation, Medium access control, etc. This chapter gives an overview of the cognitive radio communication, the network architecture, and spectrum sensing techniques.

**2.2****Cognitive Radio Communication**

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The two basic resources for wireless communication are bandwidth and energy. These resources are becoming scarce, which is associated with a limited in-

crease in service quality and channel capacity in wireless networks. Therefore, researchers are currently focusing on new communication and network models that can use these resources in an accurate and methodical way.

### 2.2.1

### Cognitive radio characteristics

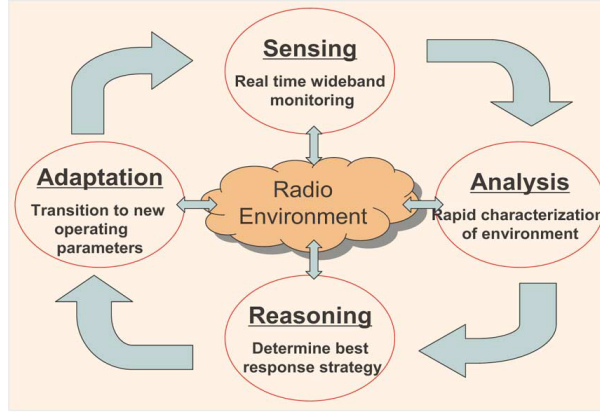
Cognitive radio (CR) is an essential technology for future communications and networking. It makes more efficient use of limited resources. It differs from traditional communication paradigms where radios devices can define their operating parameters, such as transmission power, frequency, modulation type, etc., from the variations of the surrounding radio environment as published in [17]. In 2005, Simon Haykin published an article [27] in which he defined what is known as cognitive capability and reconfigurability. These characteristics relate to the modification of the operating mode and the collection of the necessary information by the CRs. First of all, the cognitive capability which allows cognitive devices to be informed about the transmitted waveform, the radio frequency spectrum, the communication network, geographical information, locally available resources and services, user needs, etc. Finally, by collecting the information from the environment, the nodes of CR can dynamically change their transmission parameters according to the variations of the environment they detect and achieve optimal performance.

### 2.2.2

### Cognitive radio functions

A typical work cycle of CR, as illustrated in 2.1 includes detecting free spectrum space, selecting the best frequency channel, coordinating spectrum access with other users and vacating the frequency when a primary user appears. Such a cognitive cycle is supported by the following functions:

- *Spectrum sensing and analysis*: Detecting unused spectrum and sharing the spectrum without harmful interference with other users.
- *Spectrum management and handoff*: Capturing the best available spectrum to meet user communication requirements.
- *Spectrum allocation and sharing*: Maintaining seamless communication requirements during the transition to better spectrum and providing the fair spectrum scheduling method among coexisting cognitive users.



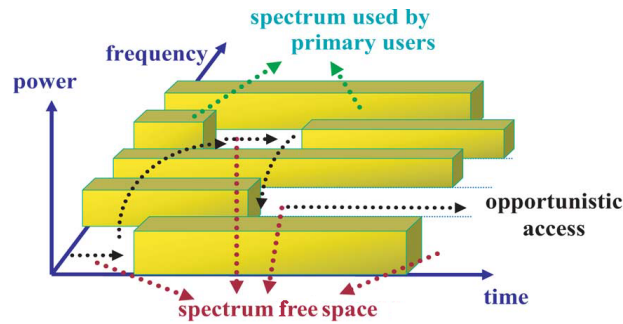
**Figure 2.1:** Cognitive cycle

During spectrum sensing and analysis, CR can identify the portion of the frequency band not used by primary users, as shown in 2.2, and access the spectrum. If, on the other hand, the primary users start using the licensed spectrum again, CR can identify their activity by sensing, so that no harmful interference is caused by the transmission of the secondary.

After recognizing the spectrum free space or white space [2] by sensing, spectrum management and handoff function of CR allow cognitive users to select the best frequency channel and then hop among multiple bands according to the channel characteristics to meet various Quality of Service (QoS) requirements. For example, if a primary user reclaims his frequency band, the secondary user using the licensed band can redirect his transmission to other available frequencies, depending on the channel capacity determined by noise and interference levels, path loss, channel error rate, holding time, etc.

Dynamic spectrum access allows a secondary user to share spectrum resources with primary users, other secondary users, or both. A good spectrum allocation and sharing mechanism is therefore essential to achieve high spectrum efficiency. Since primary users own the spectrum rights, where secondary users coexist with primary users in a licensed band, the interference level caused by to secondary spectrum usage should be limited by a certain threshold. Where multiple secondary users share a frequency band, their access should be coordinated in order to mitigate collisions and interference.





**Figure 2.2:** Illustration of spectrum free space

## 2.3

## Cognitive Radio Network Architecture

Cognitive radio is designed to sense available networks and communication systems around it to complete network functions beyond the use of spectrum white space at the link level as we described above. Therefore, CRN are not simply another network of interconnected cognitive radios. They are composed of various types of coexisting multi-radio communication systems, including cognitive radio systems as mentioned in [57]. CRNs can be considered as a kind of heterogeneous network, consisting of different communication systems. Heterogeneity exists in wireless access technologies, networks, user terminals, applications, service providers, etc. [1].

### 2.3.1

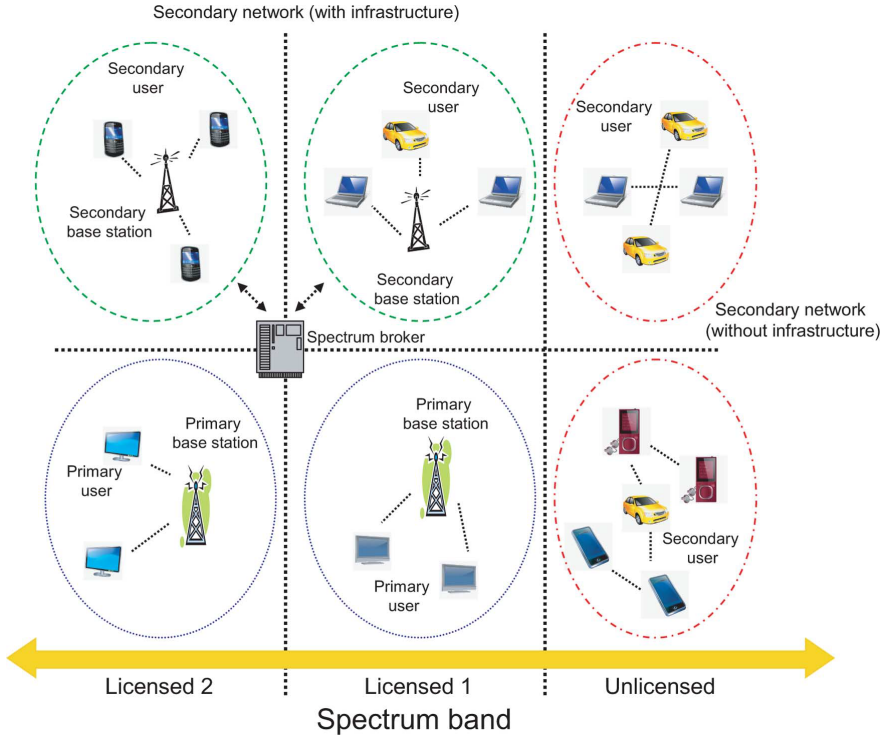
### Network Architecture

The components of the cognitive network architecture, as shown in 2.3, can be divided in two subsystems: the primary network and the secondary network (cognitive network). The main elements of the two groups of the system are defined as follows:

#### 2.3.1.1

#### Primary Network

An existing network infrastructure is generally referred to as a primary network which has been granted licensing rights for a particular frequency band, e.g.



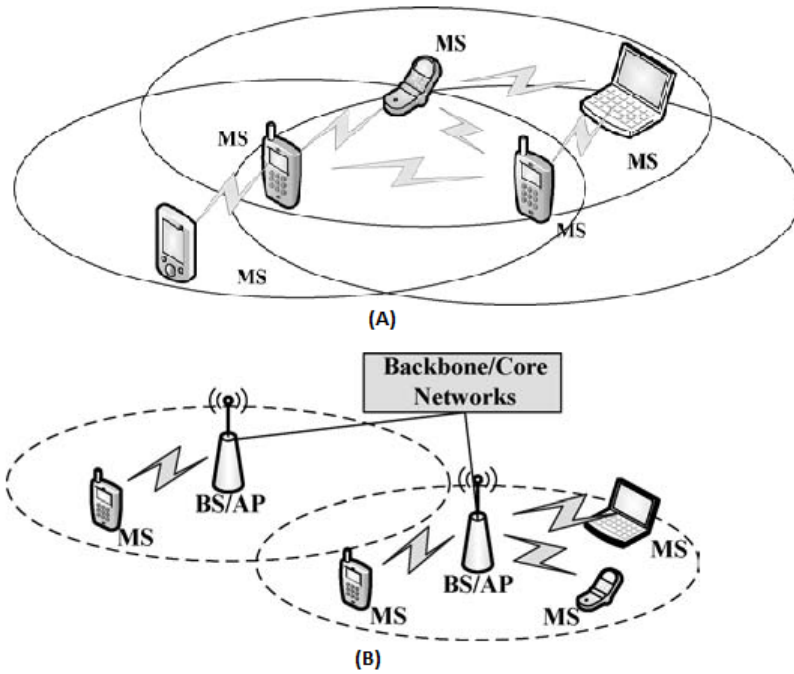
**Figure 2.3:** Cognitive radio network architecture

the common cellular and TV broadcasting networks. The basic components of the primary network are:

- *Primary user (PU)*: or licensed user has the exclusive right to operate in some spectrum band. This access can only be controlled by the primary base-station and should not be affected by the operations of other unlicensed (secondary) users. Primary users do not require any modifications or additional functions for coexistence with secondary base-stations and cognitive users.
- *Primary Channel Service (PCS)*: or Primary base-station (licensed base-station) is a fixed infrastructure network component that has a spectrum license, such as the base-station transceiver system (BTS) in a cellular system. In principle, the primary base-station has no cognitive capability to share spectrum with secondary users. However, it may be required that the primary base-station has both legacy and cognitive protocols for primary network access by secondary users, as explained below.

### 2.3.1.2 Secondary Network

The secondary network (or cognitive radio network, Dynamic Spectrum Access network, unlicensed network) is not licensed to operate in the selected band. Therefore, the spectrum access is only allowed in an opportunistic manner. Cognitive networks can be deployed both as an infrastructure network and as an ad-hoc network, as shown in 2.4. The main elements of a secondary network are the following:



**Figure 2.4:** (A) Ad-hoc architecture/(B) Infrastructure architecture

- *Secondary user (SU)*: or cognitive user has no frequency band license. Hence, additional functionalities are required to share the licensed spectrum band.
- *Secondary Channel Service (SCS)*: or Cognitive (secondary) base-station is a fixed infrastructure component with cognitive capabilities. SCS provides a single-hop connection for secondary users without a spectrum access license. This connection allows a secondary user to access other networks.
- *Spectrum broker*: takes place when several secondary networks share a

**Table 2.1:** Summary of links in the CRN

Rx\Tx	SU	SCS	PU	PCS
<b>SU</b>	•	•	•	•
<b>SCS</b>	•	•	•	
<b>PU</b>	•	•	•	•
<b>PCS</b>	•		•	•

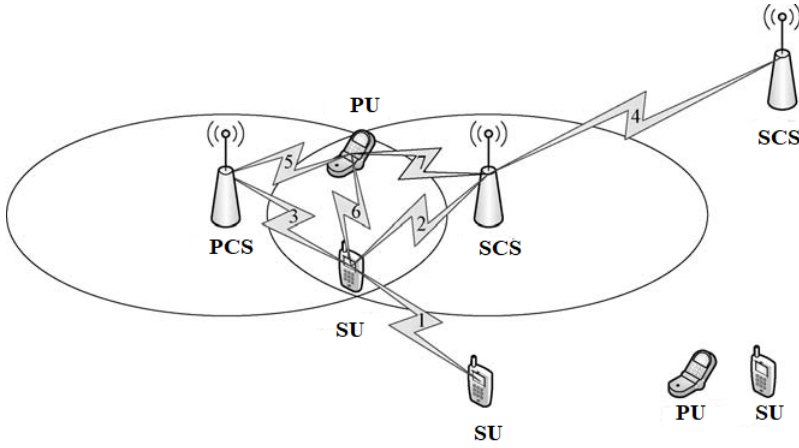
common spectrum band. In this case, spectrum usage may be coordinated by a central network unit called a spectrum broker. It can be connected to each network and can serve as a spectrum information manager to enable coexistence of multiple cognitive networks [10, 32, 55].

### 2.3.2

### Links in CRN

Two types of wireless communication systems can be reminded in CRNs: Primary systems (PS) and cognitive radio (CR) systems, which are categorized on frequency bands according to their priorities. A primary system is known as an existing system operating in one or more fixed frequency bands. Different types of primary systems operate in either licensed or unlicensed bands, either in the same geographical location or in the same frequency band. There is no privilege for a cognitive radio system to access certain frequency bands. CR system entities must interact with each other by using dynamically spectrum gaps (holes) and opportunistic access. Since the CR system can provide interoperability among different communication systems, some inter-system connections should be enabled. the connection's possibilities are listed and illustrated in table 3.1 and in figure 2.5

- **SU  $\Rightarrow$  SU:** SU can interact directly with other SUs. They can cooperatively sense and use spectrum holes in separate frequency bands that can be licensed or unlicensed as their working frequency band.
- **SU  $\Rightarrow$  SCS:** SCS can dynamically sense a frequency band around it, collect other sensing outcomes from Mobile Stations, and provide one-hop access to SU under its coverage area. This may require the method of collaborative sensing. The SU can either access backbone networks or interact with other communications systems under the coordination of SCS.



**Figure 2.5:** Links in CRNs

- **SU  $\Rightarrow$  PCS:** If there is a need for a SU to connect to a PCS, it will reconfigure itself and become one part of the primary system. In this case, it will become a primary user on that band.
- **SCS  $\Rightarrow$  SCS:** They can form a mesh wireless backbone network while allowing direct wireless connections between SCSs. They can dynamically choose an operating frequency band and communicate with each other because of their cognitive radio capability.
- **PU  $\Rightarrow$  PCS:** It is the typical one-hop connection between users and channel services. The PCS is responsible for coordinating communications in its coverage and providing backbone network access to the PU. This link is bi-directional all the time, which is fundamentally different from other links.
- **PU  $\Rightarrow$  SU:** In order to provide interoperability between different communication systems, this kind of link may be necessary. In this case, the SU shall reconfigure itself to be one part of the primary system.
- **PU  $\Rightarrow$  SCS:** In order to provide interoperability between different communication systems, this kind of link may be necessary. Only if the SCS can run the protocol of primary system, it can provide access service to the PU.
- **PU  $\Rightarrow$  PU:** This type of communication in wireless networking systems can occur in the primary system as a kind of ad-hoc network. In some systems, however, it may also be banned under infrastructure mode.

These linking possibilities in cognitive radio networks were described by Kwang Cheng Cheng and Ramjee Prasad in [14], where it was noted that a special feature of CR Links in the above list. With the exception of the link between PUs and PCS, which guarantees a bi-directional connexion, each of the other seven types of links is only available in one direction, during an opportunity of spectrum access.

## 2.4

## Spectrum Sensing in Cognitive Radio Networks

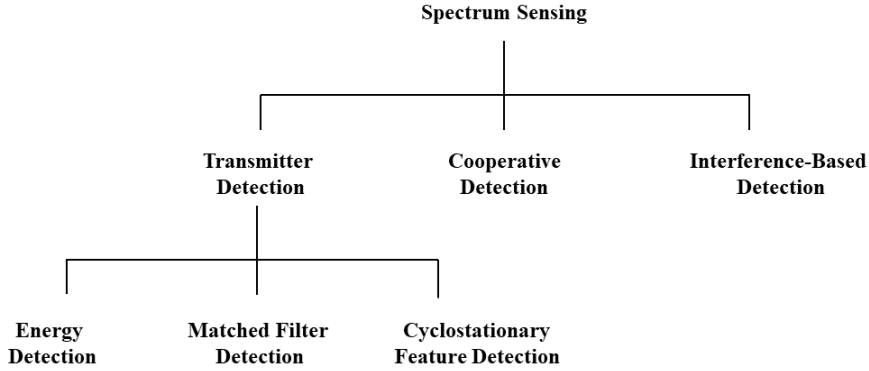
The design principle for cognitive radio (CR) networks considers the cognitive radio users as visitors in the spectrum they occupy. This requires effective spectrum management functions to occupy unused channels without interfering with primary users and to leave these channels when user activity is detected. The successful operation of these principles depends on the CR users ability to be aware of their environment, which is achieved through spectrum sensing solutions. In fact, it is difficult for a cognitive radio to directly measure a channel between a primary receiver and a transmitter.

CR can obtain necessary information about its radio environment through spectrum sensing, such as the presence of primary customers and the occurrence of spectrum holes. Only with this information, CR can adjust its transmission and reception parameters, such as transmission power, frequency, modulation schemes, ect., to achieve effective use of the spectrum. The most efficient way to detect spectrum holes is to identify the primary users who receive data within the communication range of a secondary user. However, having a direct measurement of a channel between a primary receiver and a transmitter is hard for a cognitive radio. Therefore, recent research focuses on the detection of primary transmitters based on local observations of secondary user. In general, spectrum sensing techniques can be classified into three groups: transmitter detection, cooperative detection and interference-based management, as described in 2.6.

### 2.4.1

### Transmitter detection (non-cooperative detection)

Since CR users are generally presumed to have no real-time communication with primary transmitters and receivers, they are unable to understand the exact information about current transmissions within primary networks. In order to distinguish between used and unused frequency bands in transmitter detection, users of CR only detect the signal from a primary transmitter through the



**Figure 2.6:** Classification of spectrum sensing techniques

local observations of users of CR. The users of CR should therefore be able to determine whether a signal from the primary transmitter is locally present in a particular spectrum. The basic hypothesis model for transmitter detection can be defined as follows [25] :

$$x(t) = \begin{cases} n(t) & H_0 \\ hs(t) + n(t) & H_1 \end{cases} \quad (2.1)$$

where  $x(t)$  is the signal received by the CR user,  $s(t)$  is the transmitted signal of the primary user,  $n(t)$  is a zero-mean additive white Gaussian noise (AWGN), and  $h$  is the amplitude gain of the channel.  $H_0$  is a null hypothesis, which states that there is no licensed user signal in a certain spectrum band. On the other hand,  $H_1$  is an alternative hypothesis, which indicates that there exists some primary user signal [21]. Three schemes are generally used for the transmitter detection: matched filter detection, energy detection, and feature detection. Defined and explained as follow in [52, 44, 54].

- **Matched filter detection:** When the information of the primary user signal is known to the CR user, the optimal detector in stationary Gaussian noise is the matched filter for maximizing the signal-to-noise ratio (SNR) in the presence of additive stochastic noise. This detection method requires only  $O(1/SNR)$  samples to achieve a detection error probability constraint.
- **Energy detection:** If the receiver cannot gather enough information about the primary user signal, e.g. the receiver only knows the power of random Gaussian noise, the optimal detector is an energy detector. In the energy detection scheme, CR users sense the presence/absence of

the primary users through the energy of the received primary signal. To measure the energy of the received primary signal, the received signal is squared and integrated over the observation interval. Finally, the output of the integrator is compared with a threshold value to decide whether a primary user is present or not.

- **Feature detection:** An alternative detection method is cyclostationary feature detection. Modulated signals are generally coupled with sine wave carriers, pulse trains, repetitive spreads, hopping sequences, or cyclic prefixes that result in a built-in periodicity. These modulated signals are characterized as cyclostationarity since their mean value and autocorrelation have periodicity. These features are determined by the analysis of a spectral correlation function.

#### 2.4.2

#### Cooperative detection:

Due to the lack of communication between primary users and CR users, transmitters detection strategies depend only on the weak signals of the primary transmitters. Therefore, transmitter detection techniques cannot avoid interference with primary receivers simply because of the lack of primary receiver information. In addition, the problem of hidden terminal cannot be avoided by transmitter detection models. A CR transmitter may have a favourable line-of-sight for a CR receiver, but the primary transmitter may not be identified due to shadowing. For more accurate primary transmitter detection, it is necessary to gather information from other users; this is called cooperative detection. Cooperative detection is potentially more effective because it reduces the uncertainty in identifying a single user. In addition, multi-path fading and shadowing effects can be mitigated, improving the probability of detection in a heavily shaded environment.

#### 2.4.3

#### Interference-based detection:

Interference is generally regulated on a transmitter-centric basis, which means that interference at the transmitter can be managed via the radiated power, out-of-band emissions, and individual transmitter positions. In fact, interference occurs at the receivers. Consequently, the FCC [17] recently introduced a new standard for calculating interference, called the interference temperature. The interference temperature model treats interference at the receiver using the interference temperature limit, unlike the traditional transmitter-centered



method, is defined by the amount of new interference that the receiver can handle. In other words, interference temperature model takes into account the combined RF energy from multiple transmissions and sets their overall level to a maximum upper limit. As long as cognitive users do not exceed this limit through their communication, they can use the spectrum band.

**2.5****Conclusion**

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Cognitive networks are being developed to resolve current wireless network issues resulting from the limited spectrum availability and inefficient use of spectrum by using the existing wireless spectrum in an opportunistic way. This chapter has provided an overview of their main functionalities, architectures and spectrum sensing techniques. In the next chapter our system model is presented and the simulation modeling of a cognitive radio network with a finite number of sources using queuing theory is described in detail.



# 3

## Simulation modeling of cognitive radio network

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*This chapter describes the theoretical, experimental methodologies used throughout this scientific research*

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## 3.1

## Review of random processes

In this section, we review some of the processes and distributions from the theory of random processes that are needed in the study of the queueing system introduced in this thesis. We will discuss the exponential and its related distributions which play a key role in the analysis results of this thesis.

## 3.1.1

## Distributions related to the exponential distribution

Certain concepts and approaches from the theory of stochastic processes are basic in the study of elementary queueing systems. Perhaps the most important of these are the properties of the exponential distribution and the Poisson process. Much of the literature and results in stochastic analysis are based on the assumption that exponential distributions provide the times between events in the stochastic processes under study. Therefore, this section will give an overview of these distributions properties. The exponential distributions regardless its related distributions have the memoryless property, which is defined as follows:

**Definition 3.1.1** *A random variable  $\bar{x}$  is said to be memoryless if, and only if, for every  $\alpha, \beta \geq 0$ ,*

$$P\{\bar{x} > \alpha + \beta \mid \bar{x} > \beta\} = P\{\bar{x} > \alpha\} \quad (3.1)$$

The implication of the memoryless property is that the lifetime of the process in question begins all over again at every single point in time. Thus, if for example  $\bar{x}$ , represents the lifetime of a battery, and  $\bar{x}$  is memoryless, then at every single point in time, the battery is as good as new.

**Definition 3.1.2** *A random variable  $X$  is said to have an exponential distribution with parameter  $\lambda$  where  $\lambda > 0$  ( $X \in \text{Exp}(\lambda)$ ) only if its density function is given by*

$$f(x) = \begin{cases} 0, & \text{if } x < 0. \\ \lambda e^{-\lambda x}, & \text{if } x \geq 0. \end{cases} \quad (3.2)$$

and it's density function is

$$F(x) = \begin{cases} 0, & \text{if } x < 0. \\ 1 - e^{-\lambda x}, & \text{if } x \geq 0. \end{cases} \quad (3.3)$$

Thus, the mean, the variance and the square coefficient of variation of  $X$  are:

**Lemma 3.1.1**

$$E(X) = \frac{1}{\lambda}, \quad Var(X) = \frac{1}{\lambda^2}, \quad C_x^2 = 1. \quad (3.4)$$

#### 3.1.1.1

#### The hypoexponential distribution

The hypoexponential distribution and the hyperexponential distribution are special cases of phase-type distributions that are useful in queuing theory. These distributions are models for inter-arrival times or service times in queuing systems. They are obtained by breaking down the total time into a number of phases, each having an exponential distribution, where the parameters of the exponential distributions may be identical or may be different.

**Definition 3.1.3** Suppose that  $X_i \in Exp(\lambda_i)$  ( $i = 1, \dots, n$ ) be independent exponentially distributed random variables. The random variable  $Y_n = X_1 + \dots + X_n$  is said to have a hypoexponential distribution when its density function is given by:

$$f_{Y_n}(x) = \begin{cases} 0, & \text{if } x < 0. \\ (-1)^{n-1} [\prod_{i=0}^n \lambda_i] \sum_{j=0}^n \frac{e^{-\lambda_j x}}{\prod_{k=1, k \neq j}^n (\lambda_j - \lambda_k)}, & \text{if } x \geq 0. \end{cases} \quad (3.5)$$

Thus, the main characteristic of the hypoexponential distribution are:

**Lemma 3.1.2**

$$E(Y_n) = \sum_{i=1}^n \frac{1}{\lambda_i} \quad \text{and} \quad Var(Y_n) = \sum_{i=1}^n \frac{1}{\lambda_i^2} \quad (3.6)$$

And for the squared coefficient of variation we have:

**Lemma 3.1.3**

$$C_{Y_n}^2 = \frac{\sum_{i=1}^n (\frac{1}{\lambda_i})^2}{(\sum_{i=1}^n \frac{1}{\lambda_i})^2} \leq 1. \quad (3.7)$$

**3.1.1.2****The hyperexponential distribution**

The hyperexponential distribution is the mixture of a set of independent exponential distributions. Its density function is given as the following:

**Definition 3.1.4** Let  $X_i \in \text{Exp}(\lambda_i)$  ( $i = 1, \dots, n$ ) and  $p_1, \dots, p_n$  be distributions. The random variable  $Y_n$  is said to have a hypoexponential distribution when its density function is given by:

$$f_{Y_n}(x) = \begin{cases} 0, & \text{if } x < 0. \\ \sum_{i=1}^n p_i \lambda_i e^{-\lambda_i x}, & \text{if } x \geq 0. \end{cases} \quad (3.8)$$

It is easy to see that

**Lemma 3.1.4**

$$E(Y_n) = \sum_{i=1}^n \frac{p_i}{\lambda_i} \quad \text{and} \quad \text{Var}(Y_n) = 2 \sum_{i=1}^n \frac{p_i}{\lambda_i^2} \quad (3.9)$$

It can be shown that:

**Lemma 3.1.5**

$$C_{Y_n}^2 = \frac{2 \sum_{i=1}^n (\frac{1}{\lambda_i})^2 - (\sum_{i=1}^n \frac{1}{\lambda_i})^2}{(\sum_{i=1}^n \frac{1}{\lambda_i})^2} \geq 1. \quad (3.10)$$

**3.1.2****The lognormal distribution**

Let  $Y \in N(m, \sigma)$ , then the random variable  $X = e^Y$  is said to have lognormal distribution with parameters  $(m, \sigma)$ ,  $X \in LN(m, \sigma)$

$$F_x(x) = \phi\left(\frac{\ln x - m}{\sigma}\right), x > 0 \quad (3.11)$$

$$f_x(x) = \phi'(\frac{\ln x - m}{\sigma}) = \frac{1}{\sigma x} \phi(\frac{\ln x - m}{\sigma}), x > 0 \quad (3.12)$$

It can be proved that

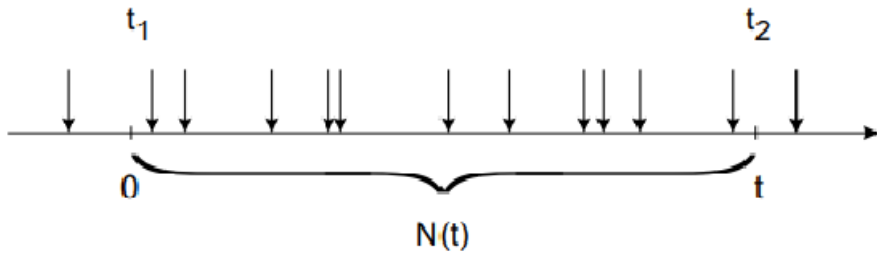
### Lemma 3.1.6

$$E(X) = e^{m + \frac{\sigma^2}{2}}, \quad Var(X) = e^{2m + \sigma^2} (e^{\sigma^2} - 1) \quad \text{and} \quad C_X^2 = e^{\sigma^2} - 1 \quad (3.13)$$

#### 3.1.3

#### Poisson process

A Poisson process is often used as a model for counting events occurring one at a time, such as the number of births in a hospital, the number of arrivals at a service facility, the number of calls made... etc. it is one of the most important models used in queueing theory where the arrival process of customers can be described by a Poisson process. In teletraffic theory the “customers” may be calls or packets. Poisson process is applicable model when the calls or packets originate from a large population of independent users.



**Figure 3.1:** number of arrivals in the interval  $(0, t)$

Mathematically the process is described by the so called counter process  $N(t)$ . The counter tells the number of arrivals that have occurred in the interval  $(0, t)$ , or more generally, in the interval  $(t_1, t_2)$ .

The Poisson process can be characterized as a pure birth process with arrival intensity  $\lambda$  and the inter-arrival times are independent and obey the  $Exp\zeta\lambda$  where  $Pinterarrivaltime > t = e^{-\lambda t}$ .

## 3.1.4

## Properties of the Poisson process

- Conditioning on the number of arrivals :  
Given that in the interval  $(0, t)$  the number of arrivals is  $N(t) = n$ , these  $n$  arrivals are independently and uniformly distributed in the interval. One way to generate a Poisson process in the interval  $(0, t)$  is as follows:
  - draw the total number of arrivals  $n$  from the  $Poisson(\lambda t)$  distribution.
  - for each arrival draw its position in the interval  $(0, t)$  from the uniform distribution, independently of the others
- Superposition:  
The superposition of two Poisson processes with intensities  $\lambda_1$  and  $\lambda_2$  is a Poisson process with intensity  $\lambda = \lambda_1 + \lambda_2$ .
- Random selection  
If a random selection is made from a Poisson process with intensity  $\lambda$  such that each arrival is selected with probability  $p$ , independently of the others, the resulting process is a Poisson process with intensity  $p\lambda$ .
- Random split:  
If a Poisson process with intensity  $\lambda$  is randomly split into two subprocesses with probabilities  $p_1$  and  $p_2$ , where  $p_1 + p_2 = 1$ , then the resulting processes are independent Poisson processes with intensities  $p_1\lambda$  and  $p_2\lambda$ . (This result allows an straight forward generalization to a split into more than two subprocesses).
- PASTA:  
The Poisson process has the so called PASTA property (Poisson Arrivals See Time Averages): for instance, customers with Poisson arrivals see the system as if they came into the system at a random instant of time (despite they induce the evolution of the system).

## 3.2

## Some basics on simulation modeling

Computational modeling and simulation has grown to be one of the most powerful design tools available in industry now, particularly when used for analyzing and controlling dynamic systems. It is one of the most commonly used, if not the most widely used, methods in operations-research and management-science.



One indication of this, is the Winter Simulation Conference, which attracts 600 to 800 people every year. However, there are several other conferences on simulation that often have more than 100 participants per year. Perspectives on the historical evolution of simulation modeling may be found in Nance and Sargent (2002).

**3.2.1****Discrete-event simulation**

Discrete-event simulation is about modeling a system as it progresses over time through a representation in which the state variables change instantly at separate time points. These points in time are the ones at which an event occurs, where an event is described as an immediate phenomenon that can modify the state of the system.

Although simulation has been applied to a wide variety of real-world systems, discrete-event simulation models all share a number of common components, and for these components there is a rational organization that promotes scripting, testing, and eventual modification of the computer program of a simulation model. In particular, using the next-event time-advance method programmed in a general-purpose language, the following components will be found in most models of discrete-event simulation:

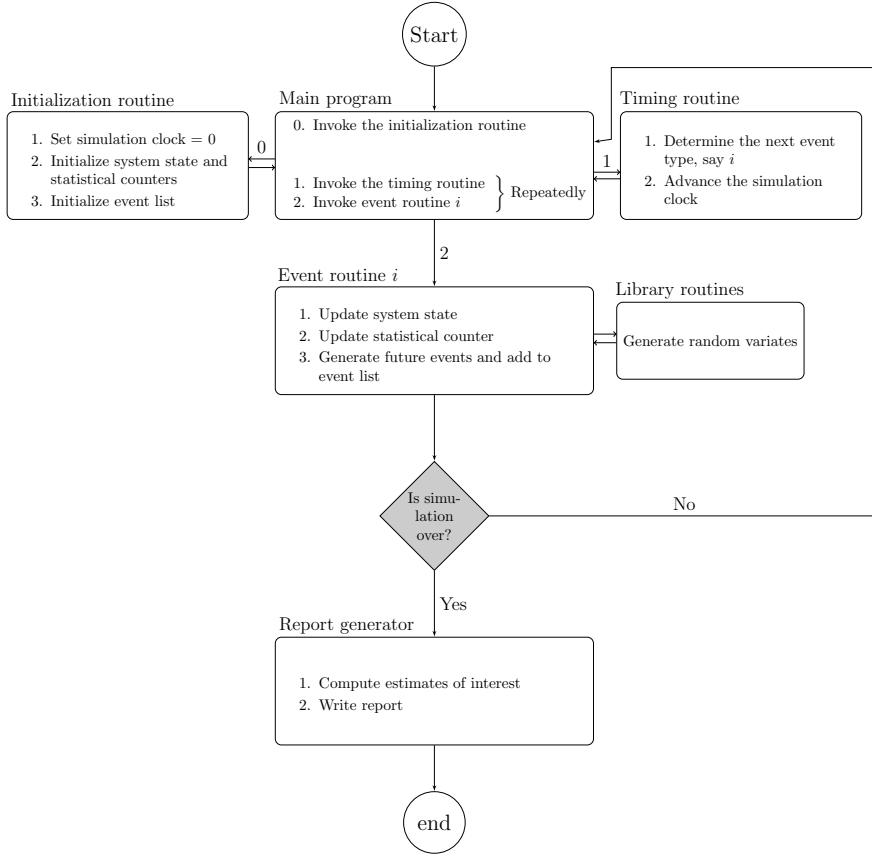
- **System state:** Set of state variables needed to describe the system at a given time.
- **Simulation clock:** A variable that gives simulated time's current value
- **Event list:** A list containing the next time when each type of event will occur.
- **Statistical counters:** Variables used to store numerical system performance data.
- **Initialization routine:** A sub-program to initialize the simulation model at time 0.
- **Timing routine:** A sub-program that selects the next event from the list of events and then moves the simulation clock to the time when the event will occur.
- **Event routine:** A sub-program that updates the system state when a particular type of event occurs.

- **Library routines:** A collection of sub-programs used to generate random observations from probability distributions as part of the simulation model.
- **Report Generator:** A sub-program that calculates the estimates of the required performance measures (from the numerical counters) and generates a report when the simulation ends.
- **Main program:** A sub-program that invokes the timing routine to evaluate the next event and then transfers control to the relevant event routine to adequately update the system state. The main program can also test for termination and invoke the report generator when the simulation is over.

The flow of chart among these components are illustrated in the 3.2. At time 0, the simulation begins with the main program running the initialization routine, where the simulation clock is set to zero, the system state and the statistical counters are initialized, and the event list is initialized. After control has been restored to the main program, it invokes the timing routine to identify which type of event is most probable. If a type  $i$  event will occur next, the simulation clock is extended to the time that type  $i$  event will occur and control is returned to the main program.

The main program then invokes event routine  $i$  where usually three types of activities occur: The first one is updating the system state to account for the occurrence of a type  $i$  event. The second is gathering information about system performance by updating the statistical counters and finally, calculating the occurrence times of future events, and adding this information to the event list. Often, in order to define these future event times or inter-event times it is necessary to generate random variables (observation) from probability distributions. After completion of all processing, either in the event routine  $i$  or in the main program, a test is typically performed to decide whether the simulation should now be terminated. If the simulation is to be terminated, the report generator will be called from the main program to calculate estimates (from the statistical counters) of the desired performance measures and write a report. If it is not time to terminate the simulation, a control cycle is repeated between all the components until the stopping condition of the simulation is eventually satisfied.

Before starting the next subsection which will detailed the modeling of the finite source retrial queueing system for cognitive radio network (see section 3.2.2) using simulation, a few additional words about the system state may be in order. As well-known, a is defined by a collection of entities. Entities are defined by data values called attributes, and for a discrete-event simulation model, these attributes are part of the system state. There is a record in



**Figure 3.2:** Flow of control for the next-event time-advance approach

the list of the entity's attributes for each entity, and the order in which the records are inserted in the list depends on a given rule. Also, the structure and operation of a discrete-event simulation program using the next-event time-advance method is quite typical while programming such simulations in a general-purpose programming language such as C. It is called: *event scheduling approach* to simulation modeling.

### 3.3

## Retrial queueing models in cognitive radio networks

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 modeling magnetic disk memory systems [42], cellular mobile networks [50], computer networks [29], and local-area networks with non-persistent CSMA/CD protocols [30], with star topology [34, 39]. Further recent results with finite-source of primary requests can be found in [4, 5, 6, 15]. In this section we introduce the finite-source retrial queue used to model the cognitive radio network, on which the analysis is based on this thesis.

### 3.3.1

### Literature review

The common queueing models used for cognitive radio networks are the priority queueing models, where higher-priority calls can preempt the service of lower-priority calls, and breakdown/repair models, where a server can go down and stop providing service for some period. These are convenient models for the CRN paradigm, where PUs can preempt the transmissions of SUs. 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. Many researchers have made an extraction of some performance measures regarding the extreme complexity of such models because of the presence of many interacting factors that have an impact on the queueing analysis for CRNs, such as: homogeneous channels, PU/SU homogeneity, perfect spectrum sensing, negligible spectrum sensing and channel connection time, etc.

Let us consider some specific queueing models from the literature where the continuous time models have been applied in the context of the CRNs.

In [12], Chang and Jang calculate the spectrum occupancy, delay and performance of two CRN queues (preemptive priority PU  $M/M/1$  queue and a retrial SU  $M/M/1$  queue), both being served by the same server (when a PU/SU is serviced, the whole radio channel is assigned to them). Arriving SUs' customers which find the spectrum busy exit the serving channel (going to the orbit), from where it retries the request at the SU queue with a specific retrial rate. The steady-state probabilities and the mean number of customers in the system and average delay are obtained based on results from [26].

The authors in [16] propose and analyze a priority retrial queue model for CRN. Different types of PUs are supposed having different service time distributions (all types have same priority of access). There is only one type of SU and a SU can be serviced by a sub-channel. PU requires the whole channel. Arrivals of both PUs and SUs is modeled using a marked Markovian arrival process (MMAP). Service time distributions of PUs are modeled by phase-type distributions, while SU service times are exponentially distributed. PUs which find the server busy are lost (PUs have preemptive priority over SUs), while SUs which find the sub-channel busy, move into a queue list modeled by an orbit, from which they randomly retry to access the system (with exponential distribution of inter-retrial times), or permanently exit the orbit due to impatience (with exponentially distributed leave time). SUs interrupted by arriving PUs also go to the orbit. Modeled as a continuous-time Markov chain, whose states include: number of SUs in orbit, number of PU customers in service, number of SU customers in service, state of underlying MMAP, number of servers at a particular phase for PU customers.

Heo et al. [28] investigate the SU flow performance in a priority preemption system. The system is settled with a number of frequency service bands that are provided for the SUs via a distributor. The authors also determined the blocking and forced termination probabilities of the SUs.

The worked published by Liu et al. in [37] evaluate a CRN while considering the traffic pattern of the PU. The interest is that the ON-OFF behaviour is commonly considered inadequate. Fading is presumed, and a general Gaussian distribution is imposed for the channel capacity. The researchers suggest self-similar traffic and analyzed system performance subject to fractional Brownian motion processes. Service decomposition is utilized for the queueing evaluation with priorities assigned to the customers in the system. The highest priority part contains the PU while the SU part is the lowest priority. The network is modeled by the help of a simple single-server single-queue model.

The waiting time distribution of the SUs in an interweave CRN was examined by Suliman and Lehtomäki in [46]. SUs execute spectrum detection of all channels at the starting of each time frame, to determine their accessibility.. The system is modeled as an  $M/D/1$  queue with the service rate equal to size of the time frame. In the theoretical analysis, the Pollaczek-Khintchine formula is implemented. It leads to the derivation of the waiting time for both PU and SU queues. Monte Carlo experiments are carried out to test the outcomes for the optimal and incomplete sensing cases.

In [9], Bassoo and Khedun evaluate the preemptive and non-preemptive priority queue waiting times for PUs and SUs where a PU delay is modeled (arriving PU packets wait a finite delay before attempting to access the channel). The motivation for such a delay is to prevent SU starvation due to PU activity. In non-preemptive case, a PU which finds the channel occupied by a SU cannot preempt it after its delay, whereas in the preemptive case, it can. Modeled as an  $M/D/1$  queue for both PUs and SUs, being served by a single server.

Zhang et al. [56] They determine the performance of a CRN network with an SU queue of two levels. The aim is to improve performance by erasing SU packets without transmission which will remain in the network for too long. The CRN is in interweave mode, with the ability to resume priority preemption. There are two components to the queue, a delay component and a discard component. When no channel is available, following FCFS-based politic, SUs will join the delay portion of the queue. A threshold specifies how many SUs are allowed in the delay queue, the remainder will join the discard part. Packets are created by SUs while in queue. At the SU, the generated packets in the delay queue are saved in a buffer. When a band becomes idle, the SUs will be reconnected on a FCFS basis. Those in the discard queue will not be saved and will be lost. By using a two-dimensional continuous-time Markov chain (CTMC), the authors then theoretically evaluate the ratio, packets generated over packets lost from an SU. Performance is measured by the help of statistical analysis, and analyzed by differing the queue threshold and the inactive times of the PUs and SUs in the network.

Oklander and Sidi [43] aim to model the dynamics of the system within an interweaving CRN. Geometric analysis of the matrix is used to determine a CTMC's stationary probabilities. Methods of Matrix geometric analysis offer a simple method for determining the stationary probabilities from transition matrix. Estimation of channel state is also embedded into the component of decision making.

Jang and Chang [33] model a queue  $M/M/1$  based on differing transmission rates. The system is a fading Nakagami-m band with Doppler switches. Analytically, the transmission rate is calculated using average fade length and integrating the Doppler shift. The rate of transmission is then compared to the exponential operating rate. The general equations of delay and throughput for a priority queue in  $M/M/1$  are derived.

Azarfar et al. [7] study the server interruption effect in both single and multiple channel CRNs. The system is modeled by the help of queue  $M/G/1$ . Scenarios of incomplete transmission (resume transmission) and retransmission are considered following a transmission disruption. Analytical probability is used to study the behavior of the queue and to deduce parameters of the queue performance. In another paper, Azarfar et al. [8] study the impacts of various queue priority disciplines on performance.

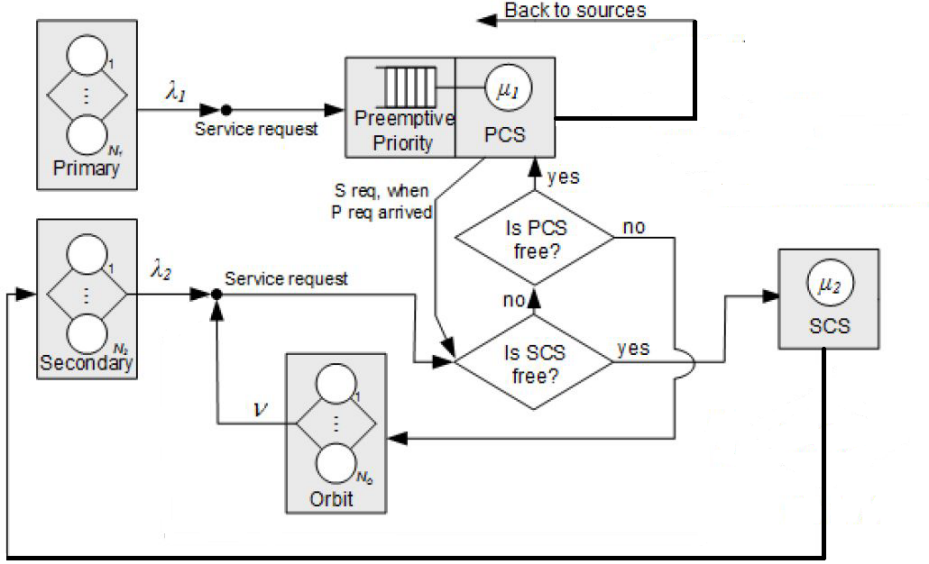
In [3], Almási B. and Sztrik J., analyze the main characteristic of a finite-source queueing model with two (non independent) frequency channels. the users are classified into two classes: the Primary Users (PUs) and the Secondary Users (SUs). If the channel of the SUs is occupied then a newly arriving SU request may use the band of the PUs in a cognitive way: the licensed channel must be released by the SU if a PU request appears. The channel of the PUs is modeled by a queue, where the requests from the PUs' class has preemptive priority over the SUs' request. The band of the SUs is described by a retrial queue: if the band is free when the request arrives then it is transmitted. Otherwise the request goes to the Orbit if both bands are busy. MOSEL tool was used in order to evaluate the main performance measures.

### 3.3.2

### System Model

Let us consider the following retrial queueing system with finite number of sources used to model a cognitive radio network. The system is divided into two non-independent sub-systems. One part is for the primary customers (users) PUs where the number of sources is denoted by  $N_1$  and the second part is for the secondary users SUs where the number of sources is denoted by  $N_2$ . These sources generate primary and secondary requests modeled by a Poisson process. Connections of the PUs arrive with rate  $\lambda_1$  and connections of SUs arrive with rate  $\lambda_2$ . The system has got two service facilities, the Primary Channel Service (PCS) shared between PUs and SUs with PUs having high priority over SUs and Secondary Channel Service (SCS) dedicated for the SUs only. If the PCS is not occupied, the PUs can access the channel immediately and leave the service after an exponentially distributed service time with a rate  $\mu_1$ . In case the PCS is busy with a high priority request (PU), the PUs join a preemptive priority queue. Otherwise, if the PCS is engaged with a low priority request (SU), the service at the PCS level is interrupted and the interrupted low priority request is sent back to sense the SCS. At the second part of the system, the generated requests from the SUs sense the SCS. If the SCS is idle, the customers join

the service channel and leave it after an exponentially distributed time with a rate  $\mu_2$ . If the SCS is occupied, the SUs sense the PCS, if it is free, the service of the SUs begins at the high priority channel. If the PCS is busy, the requests join a retrial queue modeled by an orbit where the users retries their demands after an exponentially retrial time with a rate  $\nu$ . The functionality of the system can be seen on 3.3.



**Figure 3.3:** A retrial queue model for the cognitive radio network

Different case studies have been derived from this system models, in what follow, we mention the different scenarios analyzed in this thesis.

- In order to support the imperfect sensing, we assume that the transmission within the channels is non-reliable. An error may occur during a transmission of a request and the service will fail with a probability  $p_1$  or  $p_2$  for the PUs and the SUs, respectively.
- After detection of an incoming PU, SUs keep sensing both channels after a random retrial time without abandoning the system until getting served from one of the service facilities. The PUs retry following a FIFO discipline from the queue.
- The interrupted secondary calls at the high priority will sense the SCS, depending on its state, if it is free the SUs will restart its service from the beginning.
- The primary and secondary service units may not be reliable. Each service unit may go on "vacation", sleep or breakdown after a random



distributed time with rates  $\gamma_1$  and  $\gamma_2$  for the PCS and SCS, respectively. The repair time is also randomly distributed with rates  $\omega_1$  and  $\omega_2$  for the PCS and SCS, respectively. The users under service while the servers go down join their appropriate queue (preemptive queue or orbit). Different study cases are taken in consideration from this scenario. Continuous and non-continuous cases where the breakdown of the server blocks the system, or keeps generating new calls. Intelligent and non-intelligent cases where the customers resumes its service after the interruption, or repeat the service from the beginning.

- The incoming SUs may go into collision with the request under service while sensing. In this case, sensing the channel involves collision in the system and both tasks (under service, new arrival) will join the orbit and retries their demands after a random distributed time.

### 3.4

## Simulation of the finite source cognitive radio network

This subsection shows how to build a simulation program to model retrial queueing cognitive radio network system with finite number of sources illustrated in 3.3.

### 3.4.1

## Problem statement

Consider a retrial queueing system with primary and secondary servers (PCS, SCS) for which the inter-arrival times  $A_{11}, A_{12}, \dots, A_{1n_1}$  and  $A_{21}, A_{22}, \dots, A_{2n_2}$  are independent and identically distributed random variables (same probability distribution) for the primary and secondary customers, respectively. A customer who arrives and finds its appropriate server idle enters the service instantaneously, and the service times  $S_{11}, S_{12}, \dots, S_{1n_1}$  and  $S_{21}, S_{22}, \dots, S_{2n_2}$  of the successive primary and secondary customers are independent and identically distributed random variables. A primary customer who arrives and finds the primary server busy, will join the end of the primary service unit (Queue). Upon completing the primary service, the unit chooses a client from the queue in a FIFO manner. The secondary customers who finds both channels occupied joins the orbit and the retrial times  $R_1, R_2, \dots$  are also independent and identically random distributed variables.

The simulation will begin in the "empty/idle" state (no customers in the system and idle servers). at time 0, we will begin generating the random

arrival times for each primary and secondary customers  $A_{11}, A_{12}, \dots, A_{1n_1}, A_{21}, A_{22}, \dots, A_{2n_2}$  with  $n_1 = \text{Primary number of sources}$  and  $n_2 = \text{Secondary number of sources}$  while scheduling the "Arrival event" after each generation. The first arrival event will occur after the smallest inter-arrival time  $\min(A_{11}, A_{12}, \dots, A_{1n_1}, A_{21}, A_{22}, \dots, A_{2n_2})$ . We wish to simulate this system until  $N$  number of customers have completed their service. The simulation will stop when the  $n$ th customer enters the service.

#### 3.4.2

#### Program organisation and logic

In this section we set up the necessary ingredients for the program to simulate the retrieval queueing cognitive radio system. The developed simulation is based on the use of SimPack, which is a collection of C and C++ libraries and executable programs for computer simulation. Several specific simulation algorithms are provided in this set, including discrete event simulation, continuous and combined (multimodal) simulation. It was introduced by Paul A. Fishwick on 1992 in [19]. We construct a simulation model to measure the characteristics of the studied system for several values of its input parameters. However, performance measures are difficult and complicated in some situations to determine or provide precise equations. In some cases where all inter-event times are exponentially distributed, the operation of the systems can be described by the help of a continuous-time Markov chain and the main stationary performance measures can be calculated. otherwise the state space of the describing Markov chain is very large, in which calculating the system measures using the asymptotic methods and solving the steady-state equations is impossible. Therefore, simulation of system model can be the best alternative to approximate these complex measurements. To simplify this procedure, several software packages have been developed that are capable of describing and evaluating complex systems based only on exponentially distributions, such as in [22, 23, 24, 31]. The most essential step in developing a system simulation model is to define the basic events and adjust the system status every time an event occurs. The state of the system remains unchanged during the period spanning between two consecutive events. To integrate the basic events into the simulation model, each event is correlated with timer information that will keep a record of the time at which event occurs. After the processing of an event, the simulation model rejoins all possible events that will arise in the future and chooses the one with the smallest clock value. These simulation components and its relationship are described in subsection 3.2.1 and illustrated in figure 3.2.

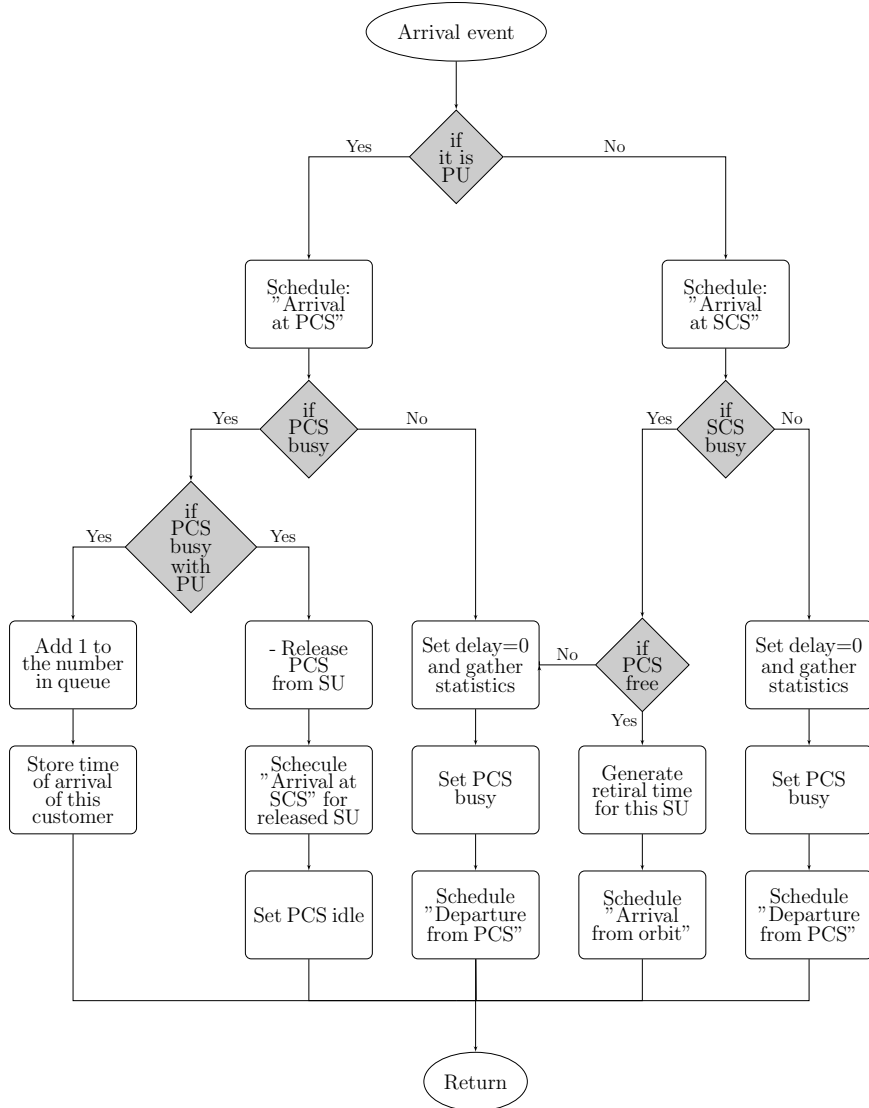
In our simulation environment, we applied random number generator of several distributions according to exponential, hyper-exponential, hypo-exponential

and lognormal distribution. This set of routines was inspired by both Herb Schwetman in [45] and M. H. MacDougall in [38]. In addition of the random number generator and main program, the simulation program includes routines for initialization, timing and report generation. The most important action, however, takes place in the routines for the events, which we number as follows:

- Arrival of a customer to the system:  
This event is always scheduled each time an arrival of primary (PU) or secondary (SU) user occurs.
- User's arrival at the primary channel service (PCS):  
This event occurs when the arriving customer (primary or secondary) finds the primary service unit (PCS) idle and the service is not interrupted by another arrival (cognitive user arrival), service failure or server's breakdown. Because of the cognitive radio channels, secondary customers can come either from the orbit in multiple times or the primary users from the source.
- User's arrival at the secondary channel service (SCS):  
This event is triggered when the arriving secondary user finds the secondary service unit (SCS) idle and the service is not interrupted by another arrival, service failure or server's breakdown. Because of the collision in some situations, secondary customers can come either from the orbit in multiple times or from the source.
- Departure of a customer after completion from the PCS:  
This event takes place when a primary or secondary complete its service at the PCS level.
- Departure of a customer after completion from the SCS:  
This event takes place when a secondary complete its service at the SCS level.
- Arrival from the orbit:  
This event is scheduled immediately when an arriving secondary user (SU) finds both secondary (SCS) and primary (PCS) service units busy. In the special cases, this event occurs when arriving customer and customer under service involve collision or the secondary service unit breaks down during service.

Usually, clocks are represented by real numbers in simulation. Hence it is not possible to have simultaneous events taking place. we have implemented the above network models and scheduling algorithms into the simulation program where the principle routines arrival and departure of customers are described

the figures bellow.



**Figure 3.4:** Flowchart for arrival routine

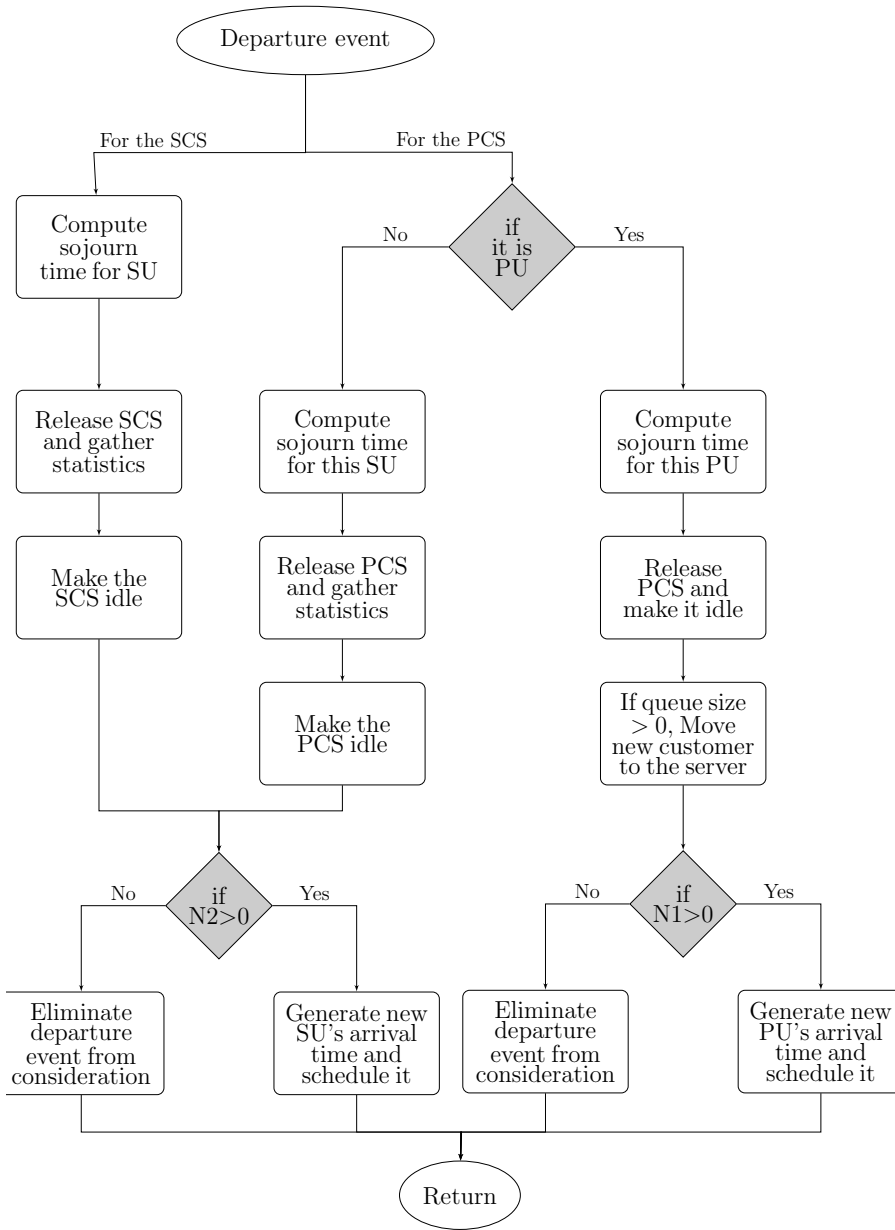
Figure 3.4 includes a flowchart for the arrival routine. First, future time of all next arrivals is generated and inserted in the list of events according to the primary and secondary number of sources. A check is then performed to establish whether the arriving customer is primary. If so, a second check is

**Table 3.1:** Event description in the simulation program

Events	Event defined as
Arrival of customer	1
Arrival from the orbit	2
Request PCS	3
Request SCS	4
Departure of customer:	
- Departure from PCS	5
- Departure from SCS	6

made to determine if the PCS is busy or idle. While the arriving primary user senses the licensed channel, the primary server interrupts its service in case it is servicing a secondary customer. this latter must release the PCS and schedule a new arrival at SCS event. The primary server is idle at the moment and the PU starts its job. the PCS must be made busy and the time of departure from service of the arriving PU is scheduled into the event list. In case another PU is under service at the primary service unit. The arrival time of the arriving PU is stored and the customer is put at the end of the preemptive queue. On the other hand, arriving SU senses the secondary channel whether it is busy. If so, another sensing of the PCS is made by the SU. If one of the both service units is idle. The arriving secondary customer starts the service. Departure from SCS is scheduled after a generated random service time. Else if both servers are busy, a new retrial time is generated for the arriving SU and arrival from orbit event is scheduled and placed into the event list.

The departure event (departure from PCS and departure from SCS) is depicted in the flowchart of figure 3.5. Recall that this routine is invoked when a service completion at PCS or SCS level occurs. If the departing primary customer leaves no other customers behind in queue, the server is idled. Otherwise, If one or more users are left behind by the departing customer, the first user in queue leaves the queue and enters service. Hence, the queue length is reduced by 1 and that customer's waiting time is calculated and recorded in the appropriate statistical counter. If a secondary job is interrupted by a PU's arrival at the PCS level. Departure from PCS event for the interrupted job is no longer taken in consideration. On the other hand, departure from SCS occurs when a secondary customer finishes its service. The secondary server is idled and the time spent in the orbit by that customer is computed and registered as its waiting time in an appropriate statistical counter. In both cases, a new primary or secondary arrival time is generated and added to the event list if and only if the primary or secondary number of sources ( $N_1$ ,  $N_2$ ), respectively,



$N_1$ : Primary number of sources

$N_2$ : Secondary number of sources

**Figure 3.5:** Flowchart for departure routine

is greater than 0.

## 3.4.3

## Confidence interval, estimation of the mean and variance

In this subsection, we show some basic formulas useful in order to estimate the mean and the variance during the simulation modeling. For instance, let us take the example shown in [36].

Suppose that  $X_1, X_2, \dots, X_n$  are independent random observations with finite source mean  $\mu$  and variance  $\sigma^2$ ; The sample mean is given by:

$$\bar{X}(n) = \frac{\sum_{i=1}^n X_i}{n} \quad (3.14)$$

it is an impartial estimator of  $\mu$ . If we perform a very large number of independent experiments each resulting in an  $\bar{X}(n)$ . the average of  $\bar{X}(n)$  will be  $\mu$ . Similarly the sample variance is given by:

$$S^2(n) = \frac{\sum_{i=1}^n [X_i - \bar{X}(n)]^2}{n-1} \quad (3.15)$$

it is an impartial estimator of  $\sigma^2$ , since  $E[S^2(n)] = \sigma^2$ .

The difficulty with using  $\bar{X}(n)$  as an estimator of  $\mu$  without any additional information is that we have no way of assessing how close  $\bar{X}(n)$  is to  $\mu$ . Because  $\bar{X}(n)$  is a random variable with variance  $Var[\bar{X}(n)]$ , on one experiment  $\bar{X}(n)$  may be close to  $\mu$  while on another  $\bar{X}(n)$  may differ from  $\mu$  by a large amount. The usual way to assess the precision of  $\bar{X}(n)$  as an estimator of  $\mu$  is to construct a confidence interval.

Let  $X_1, X_2, \dots, X_n$  be random variables with finite mean  $\mu$  and finite variance  $\sigma^2$ . In order to construct the confidence interval for  $\mu$ , we begin with the classical central limit theorem.

Let  $Z_n$  be the random variable  $[\bar{X}(n) - \mu]/\sqrt{\sigma^2/n}$  and let  $F_n(z) = P(Z_n \leq z)$  be the distribution function of  $Z_n$  for a sample size of  $n$ .

The theorem says, in effect, that if  $n$  is sufficiently large, the random variable  $Z_n$  will be approximately distributed as a standard normal random variable, regardless of the distribution of  $X_i$ 's. It can also be shown for large  $n$  that the sample mean  $\bar{X}(n)$  is approximately distributed as a normal random variable with mean  $\mu$  and variance  $\sigma^2/n$ . However, since the sample variance  $S^2(n)$  converges to  $\sigma^2$  as  $n$  gets large, it remains true if we replace  $\sigma^2$  by  $S^2(n)$  in the expression for  $Z_n$ . With this change, the theorem says that

if  $n$  is sufficiently large, the random variable  $t_n = [\bar{X}(n) - \mu]/\sqrt{S^2(n)/n}$  is approximately distributed as a standard normal random variable. It follows for large  $n$  that:

$$\begin{aligned}
 P(-z_{1-\alpha/2} \leq \frac{\bar{X}(n) - \mu}{\sqrt{S^2(n)/n}} \leq z_{1-\alpha/2}) \\
 = P[\bar{X}(n) - z_{1-\alpha/2}\sqrt{\frac{S^2(n)}{n}} \leq \mu \leq \bar{X}(n) + z_{1-\alpha/2}\sqrt{\frac{S^2(n)}{n}}] \\
 \approx 1 - \alpha
 \end{aligned} \tag{3.16}$$

Where  $z_{1-\alpha/2}$  (for  $0 < \alpha < 1$ ) is the upper  $1 - \alpha/2$  critical point for a standard normal random variable. Therefore, if  $n$  is sufficiently large, an approximate  $100(1 - \alpha)$  percent confidence interval for  $\mu$  is given by:

$$\bar{X}(n) \pm z_{1-\alpha/2}\sqrt{\frac{S^2(n)}{n}} \tag{3.17}$$

where for a given set of data  $X_1, X_2, \dots, X_n$  the lower confidence interval endpoint is  $\bar{X}(n) - z_{1-\alpha/2}\sqrt{S^2(n)/n}$  and the upper confidence interval endpoint is  $\bar{X}(n) + z_{1-\alpha/2}\sqrt{S^2(n)/n}$ .

#### 3.4.4

#### The batch mean method

The statistical module class comes from an adaptation of the statistics package published in 1994 by Andrea Francini [20]. The statistic class is a statistical analysis method capable of carrying out a quantitative approximation of the mean and variance values of the observed variables. The difficulty of using an estimator of the mean without any additional information is that we have no approach to determine how close the estimator is to the mean. The approximation may be adjacent to the mean on one analysis while it may diverge by a large difference on another. The common method used in the simulation to evaluate the precision of the estimator for the mean is to construct the confidence interval for this latter. The estimation of the mean value of a generic variable  $X$  is given in equation 3.14 and the concept of the confidence interval and the confidence level is expressed in mathematical terms in subsection 3.4.3.

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. For more details of this method see [53, 11, 13, 18].

The statistical estimation of a stochastic process can only be applied when the process has already reached the statistic stationary condition. The observations collected during the initial transitional period must be dismissed, since they can considerably deviate from the correct estimate values. This period is called "the warm-up period". See [51].

For instance, let the length of simulation be  $M$  and  $K$  is the number of observation in the beginning of simulation (warm-up period). The useful run (of length  $M - k$ ) is divided into  $N$  batches, thus in each batch there are  $n = \frac{M-K}{N}$  observations.

Andrea Francini proposes two methods for calculating the initial transient:

- A method which involves assigning three parameters  $n_0$ ,  $N$  and  $\sigma$ . Given a series of averages  $\bar{X}_1(n_0), \bar{X}_2(n_0), \dots$ , relating to batches of consecutive data, the warm-up period can be considered as exhausted after  $N_0$  batches, if the last  $k$  averages have an accuracy of  $\sigma$ .
- Given a series of consecutive batches of data, the averages relating to them  $\bar{X}_1(m), \bar{X}_2(m), \dots$ , are used as secondary output data in the statistical analysis of the simulation results.

The final estimator for the expectation  $\bar{\bar{X}}$  is given as:

$$\bar{\bar{X}}(N, n) = \frac{1}{N} \sum_{i=1}^N \bar{X}_i(n) = \frac{1}{nN} \sum_{i=1}^N \sum_{j=1}^n X_{ij}(n) \quad (3.18)$$

where  $N$  is the number of batches and  $n$  is the size of batches (number of observation in a single batch).

Their sample variance then provides an estimate for the variance of a single  $\bar{X}_i$ :

$$S^2 = \frac{1}{N-1} \sum_{i=1}^N (\bar{X}_i(n) - \bar{\bar{X}}(n))^2 \quad (3.19)$$

The difficulty in using equation 3.17 in subsection 3.4.3 to give the lower and upper confidence-interval endpoint for  $\bar{\bar{X}}$  is in knowing what "n sufficiently large" means. If  $n$  is chosen too small, the coverage of a

desired  $100(1 - \alpha)$  percent confidence interval will generally be less than  $1 - \alpha$ . This is why the confidence interval given by 3.17 is stated to be only approximate. Instead, an alternative expression of the confidence interval for the mean  $\bar{X}$  (at confidence level  $1 - \alpha$ ) is given by:

$$\bar{X}(N, n) \pm t_{N-1, 1-\alpha/2} \frac{S}{\sqrt{N}} \quad (3.20)$$

where  $t_N$  has a student t distribution with  $N-1$  degrees of freedom (df).

In light of the above discussions, we performed several simulation runs in order to investigate the performance measures of the retrial queue cognitive radio network with finite number of sources using the following parameters:

- 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%

### 3.5

#### Simulation of non-reliable servers is finite source cognitive radio network with collision

In this subsection we introduce another scenario of the system modeled in the previous subsection of finite source retrial queuing system. In this case, we focus on the non-reliability of the servers and the collision on the second part of our system model. The primary and secondary servers are subject to breakdown and repair according to a random distributed time. The collision is introduced at the

ht

**Table 3.2:** Event description in the simulation program for non-reliable servers

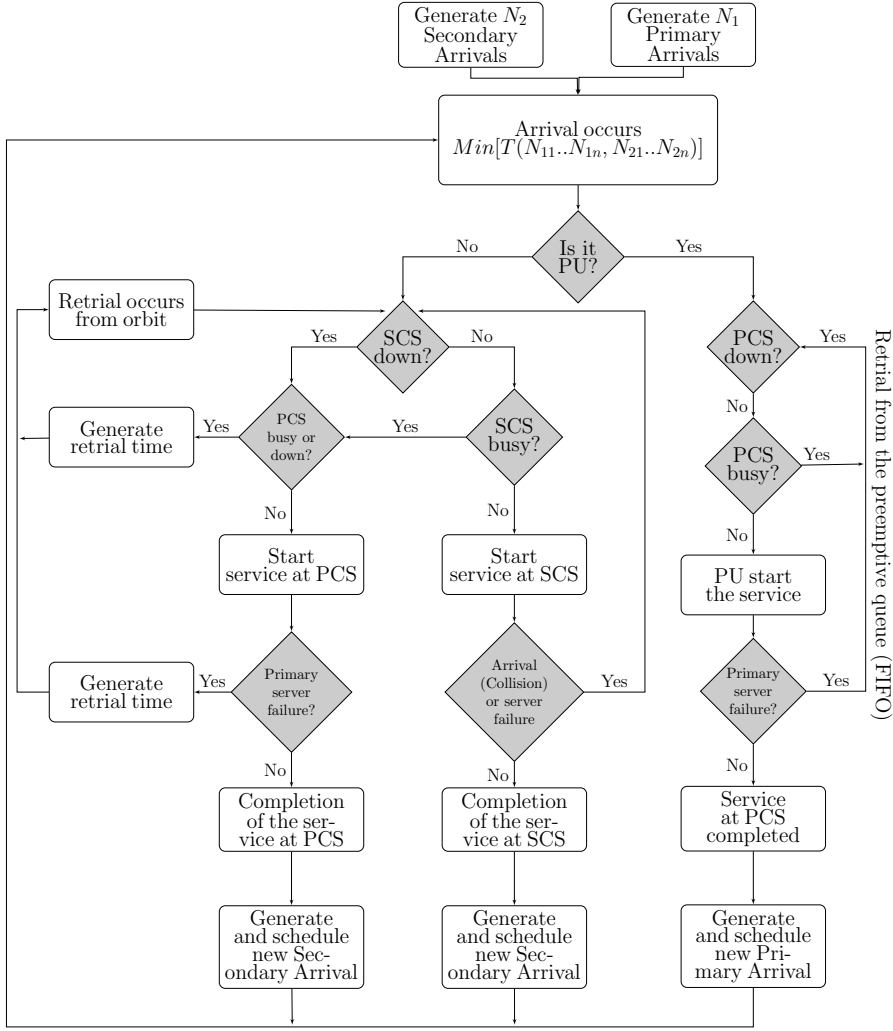
Events	Event defined as
Primary server breaks down	7
Secondary server breaks down	8
Primary server operates	9
Secondary server operates	10

retrial part of the cognitive radio network. This conflict invokes the interruption of a servicing packet when a new arriving call requests the secondary server unit. In order to analyze the performance of this system model using simulation, new routines for the events take place into the simulation program.

In addition of the events described in subsection 3.4.2 and table 3.1. The following new routines may occur during the simulation run:

1. Primary server breaks down: In this event, we generate the time when the primary server will be repaired and will become operational.
2. Secondary server breaks down: Similarly, we generate the time for when the secondary server will be repaired.
3. Primary server operates: When this event is called, a random time is generated when the primary server will breakdown in the future. During this time, the server works.
4. Secondary server operates: Also, a random time is generated when the secondary server will breakdown in the future.

The figure 3.6 illustrates the simulation model of finite source retrial queueing model with non reliable servers and collision on the retrial part of the system. After the initialization routine which assigns the parameter values of the program. The simulation starts by generating  $N_1$  and  $N_2$  number of random times for the arriving customers and store its in the list of event. Afterwards, Arrival of customer event occurs (Customer with smaller arrival time). Check will then take place in order to determine whether the customer is primary. If so, the user must sense the channel to verify if the PCS whether is busy or down. In this case, the customer joins the preemptive queue. If the PCS is neither down nor busy, the service starts at the primary unit. On the other hand, if the customer is secondary, a check happens in order to know if the SCS is down or busy. If so, as cognitive radio allows it, the secondary client senses the PCS as well. If the PCS is busy, similarly to the previous model, retrial events occurs from the orbit. Otherwise, if the SCS is idle, the service



**Figure 3.6:** Simulation model of non-reliable servers with collision

starts. During the service time, the service may be interrupted due to a new secondary arrival. This new event invokes a collision at the SCS and both customers join the orbit. It should be noticed that in both sub-systems (PCS and SCS), the service units may breakdown during a service time. In this case, the customer will retry its service from the orbit or the queue. Asymptotic analysis of similar retrial queue systems with collision was dealt by A. Kvach and A. Nazarov in [35, 41].

**3.6****Conclusion**

To understand the simulation modeling of our cognitive radio network using queuing theory, this chapter was divided into three main subsections. It is a network with two service facilities. The first is a primary sub-network that has a licensed frequency band that does not suffer from congestion and is connected to a preemptive queue. The second part is a retrial queueing sub-network with a frequency band that suffers from overloading. The queue in the second part is modeled by an orbit from where the packets retries their requests according to a distributed random time. The two subsystems are non-independent and the secondary packets can sense cognitively the primary channels while their service unit is occupied. Firstly, this chapter gives an overview on the random processes and distributions related to our work. Then, the second part of the chapter introduces the related works where theoretical queueing methods were used to model the cognitive radio networks from the literature. Therefore, in the last part of the chapter we have shown our simulation modeling and its most important functionalities and parameters. In the next chapter the results obtained from the simulation program are illustrated



# 4

## Performance evaluation and analysis

*This chapter illustrates the several simulation results obtained on this research work by the help of figures*

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## 4.1

## Introduction

In this chapter we introduce a finite-source queueing model with two (non independent) frequency channels, see 3.3. According to the CRN modeling the users are divided into two types: the Primary Users (PUs) have got a licensed frequency, which does not suffer from overloading feature. The Secondary Users (SUs) have got a frequency band too, but suffers from overloading. A newly arriving SU request can use the band of PUs (which is not licensed for SUs) if the band of SUs is engaged, in the cognitive way: the non-licensed frequency must be released by the SU when a PU request appears. In our environment the band of the PUs is modeled by a queue where the requests has preemptive priority over the SUs requests.

It should be noted that in the several proposed study cases of the created model we analyze the effect of distribution of inter-event times on the mean and variance of the response time of the PUs and SUs. In several combinations of the distribution of the involved random variables and using simulation we compare the effect of their distribution on the first and second moments of the response times illustrating in different figures.

The validated new test results illustrated in this chapter are published in the following journal and conference papers [J1<sup>i</sup>, J2, J3, J4, C3<sup>ii</sup>].

## 4.2

## Finite-source cognitive radio network

## 4.2.1

## System model

The Figure 4.1 illustrates a finite source queueing system which is used to model the considered cognitive radio network. The queueing system contains two interconnected, not independent sub-systems. The first part is for the requests of the PUs. The number of sources is denoted by  $N_1$ . In order to analyze the effect of the distribution, these sources generate high priority requests with hypo-exponentially, hyper-exponentially and lognormally distributed inter-request times with the same rate  $\lambda_1$  or with the same mean  $1/\lambda_1$ . The generated requests are sent to a single server

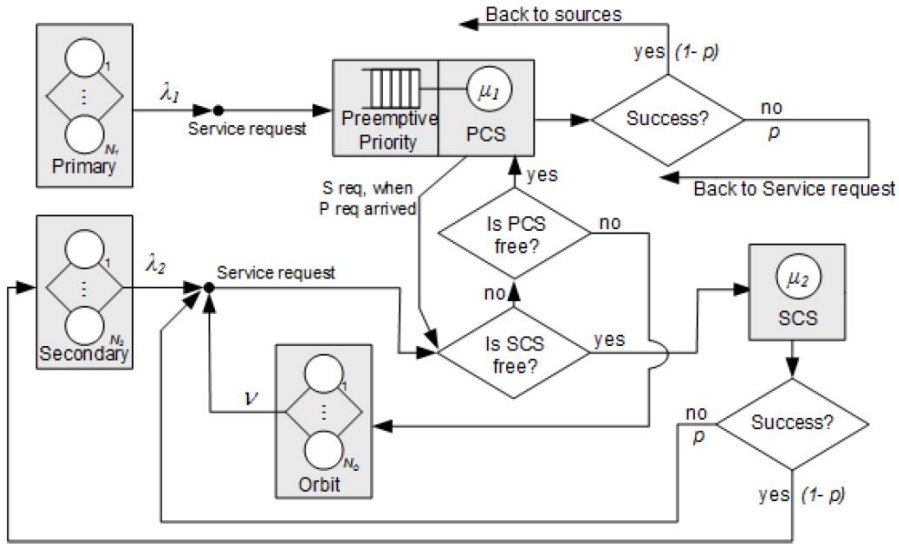
<sup>i</sup>"J" denotes Journal papers

<sup>ii</sup>"C" denotes Conference papers



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  $\mu_1$  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  $\lambda_2$  and  $\mu_2$ , respectively.



**Figure 4.1:** A priority and a retrial queue with components

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  $\nu$ . The same transmission failure with the same probability can occur as in the PCS segment.

**New results in (J1)** *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

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

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

## 4.2.2

## Validation of results

In the case of exponentially distributed inter-event time a continuous-time Markov chain can be constructed and the main steady-state performance measures can be obtained, as it was carried out in [3]. The numerical result obtained in this case were the test result validated by C language based on SimPack [19], for the simulation outputs.

However, we deal with more general situation allowing non-exponentially distributed times. 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		$\lambda_1$
Secondary generation rate		$\lambda_2$
Requests in priority queue	$N_1 - 1$	$q(t)$
Requests in orbit	$N_2 - 1$	$o(t)$
Primary service rate		$\mu_1$
Secondary service rate		$\mu_2$
Retrial rate		$\nu$
Error probability		$p$

The figures in this section illustrates the results related to the effect of the inter-events times distribution on the mean and variance response time for the primary and secondary customers. Therefore, 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.

## 4.2.3

## Numerical results

In this subsection some sample numerical results are treated to illustrate graphically the influence of the inter-event time distributions on the mean response time  $E[T]$  and on the variance of the response time of the secondary

**Table 4.2:** Confidence interval for scenarios in case 1

Figure	Distributions	Mean	Variance	Confidence interval	
				Lower bound	Upper bound
4.2	Hyperexponential	8.1593	70.3942	7.7333	8.4666
	Hypoexponential				
	Lognormal				
4.4	Hyperexponential	7.1265	49.8092	6.8106	7.4293
	Hypoexponential	9.2543	89.1245	8.8360	9.6639
	Lognormal	9.5024	91.2480	9.0816	9.9183
Figure 4.6	Hyperexponential	2.5014	7.8410	2.317	2.6826
	Hypoexponential	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
Square coefficient of variation	15	0.6449708	0.6449708

customers. The system input parameters of the following figures are collected in Table 4.4.

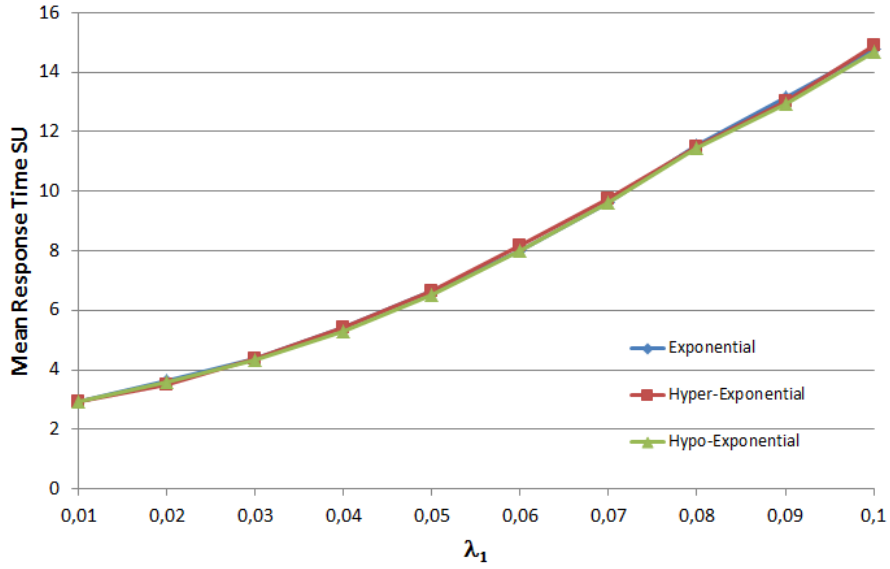
**Table 4.4:** Numerical values of model parameters

Figure	$N_1$	$N_2$	$\lambda_1$	$\lambda_2$	$\mu_1$	$\mu_2$	$\nu$	$p$
4.2 and Fig 4.3	10	50	x - axis	0.03	1	1	20	0.1
4.4 and Fig 4.5	10	50	x - axis	0.03	1	1	20	0.1
4.6 and Fig 4.7	10	50	0.02	x - axis	1	1	20	0.1
4.8	10	50	0.02	0.03	1	1	x - axis	0.1
4.9	10	50	0.02	x - axis	1	1	20	0.1

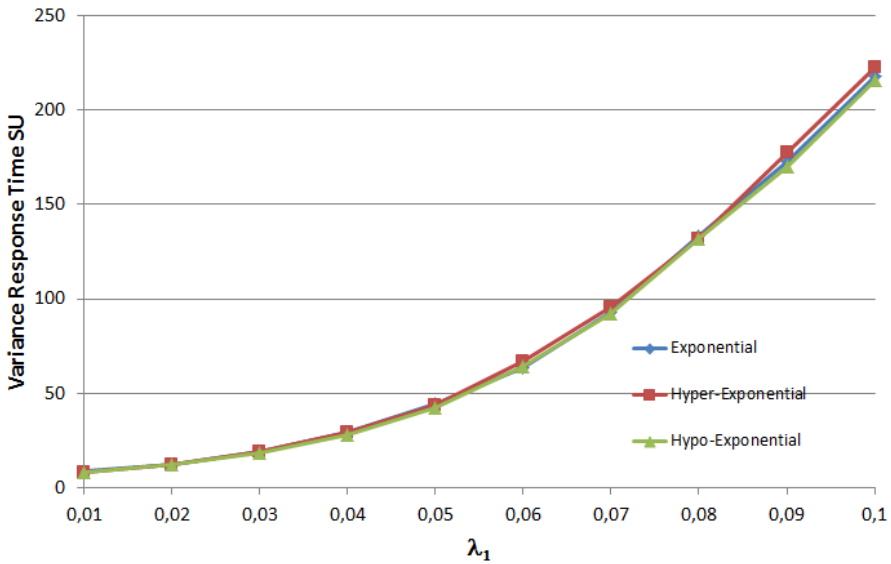
### 4.2.3

### Comments

Figure 4.2 and Figure 4.3 show that the distribution of the inter-arrival time of the primary packets with the same mean has no effect on the mean and

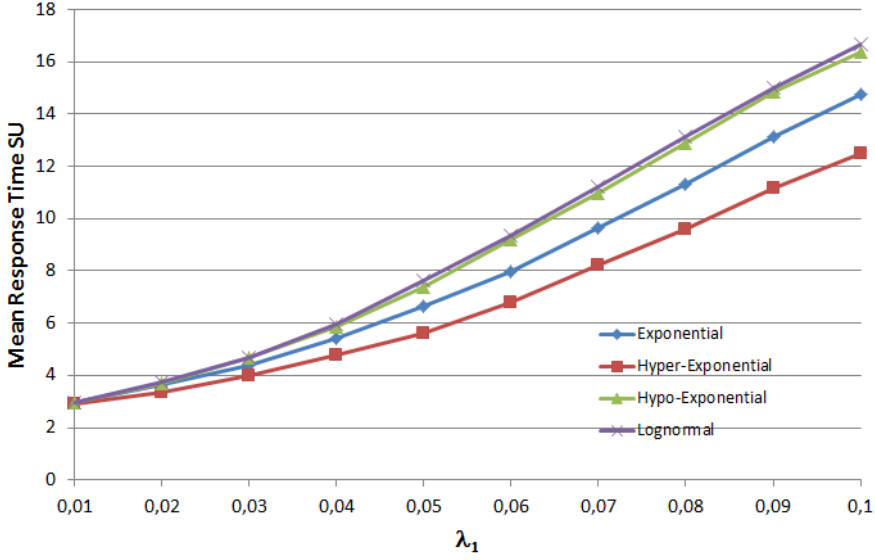


**Figure 4.2:** The effect of inter-request time distribution of the PUs on the mean response time of SUs vs  $\lambda_1$

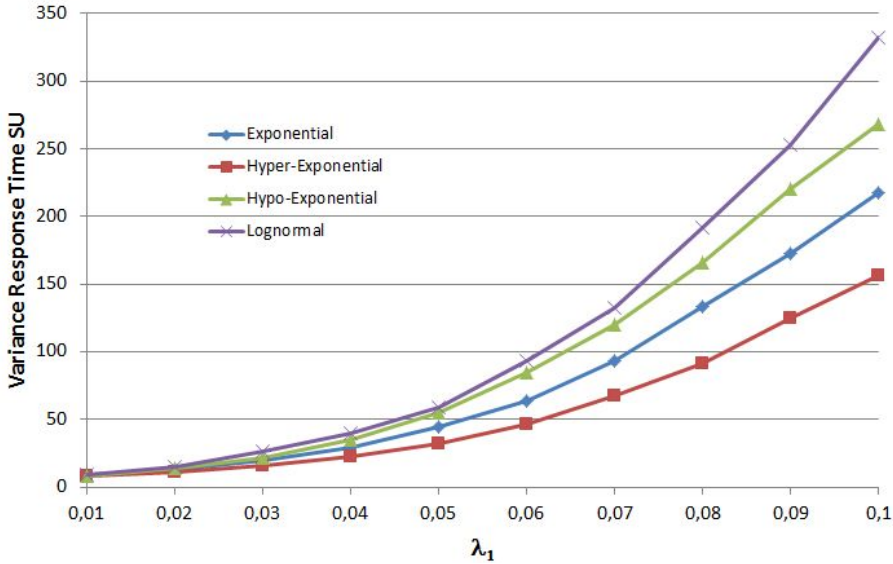


**Figure 4.3:** The effect of inter-request time distribution of the PUs on the variance of response time of SUs vs  $\lambda_1$

variance of 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

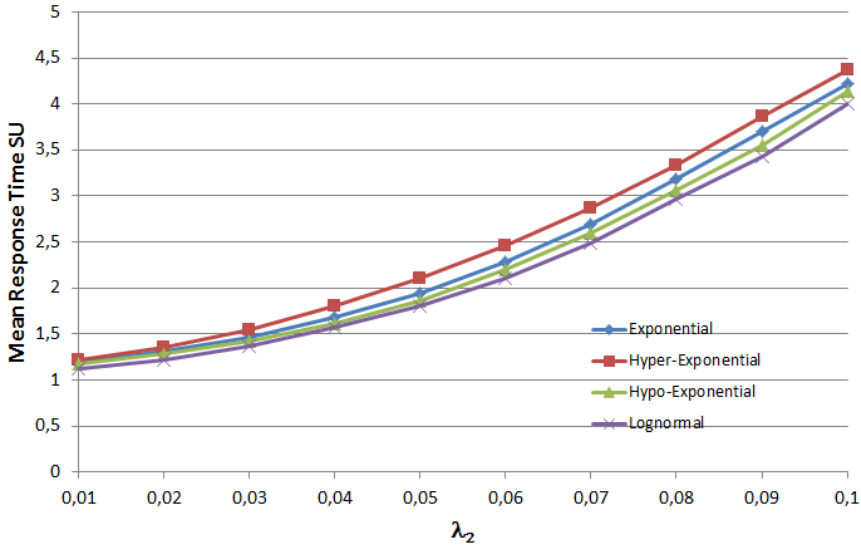


**Figure 4.4:** The effect of service time distribution of the PUs on the mean response time of SUs vs  $\lambda_1$

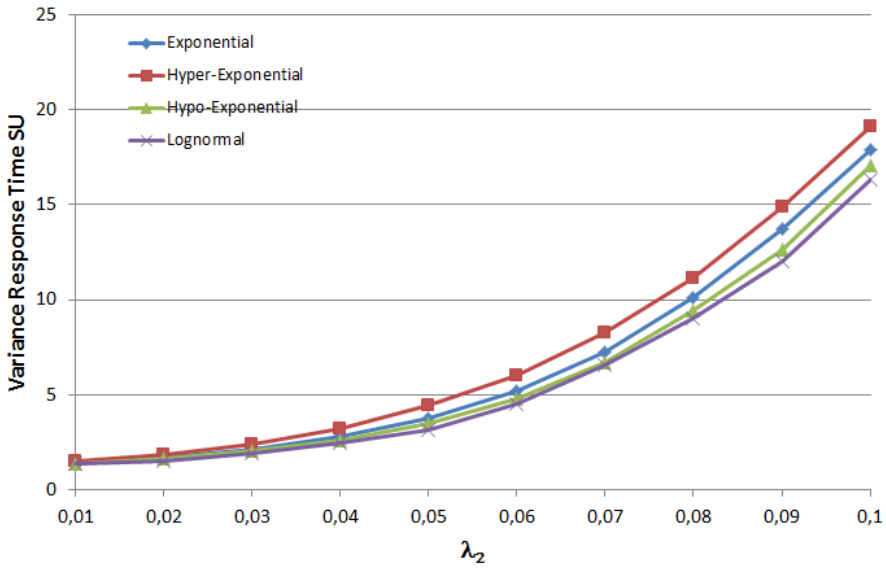


**Figure 4.5:** The effect of service time distribution of the PUs on the variance of response time of SUs vs  $\lambda_1$

both servers units are exponentially distributed. It is the consequence of [47] in which it was proved that the steady-state distribution is insensitive to the



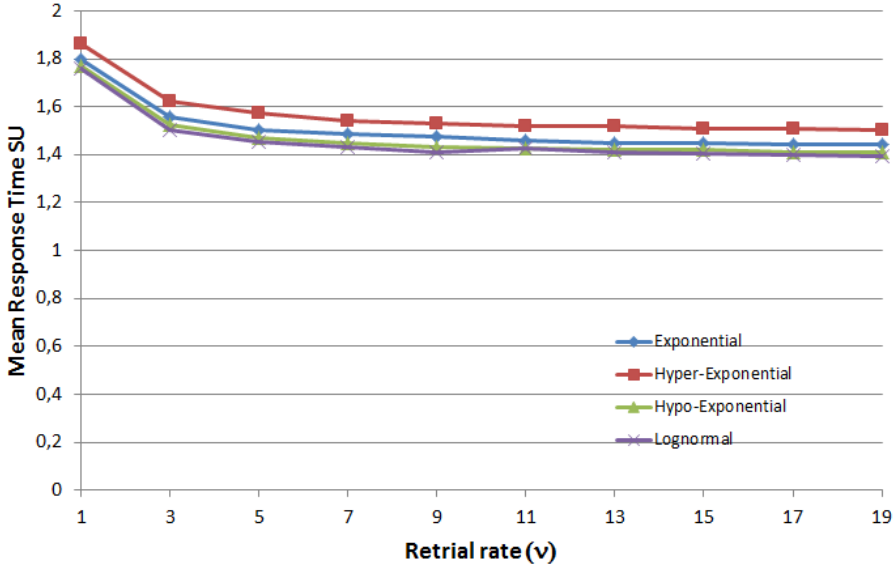
**Figure 4.6:** The effect of service time distribution of the SUs on the mean response time of SUs vs  $\lambda_2$



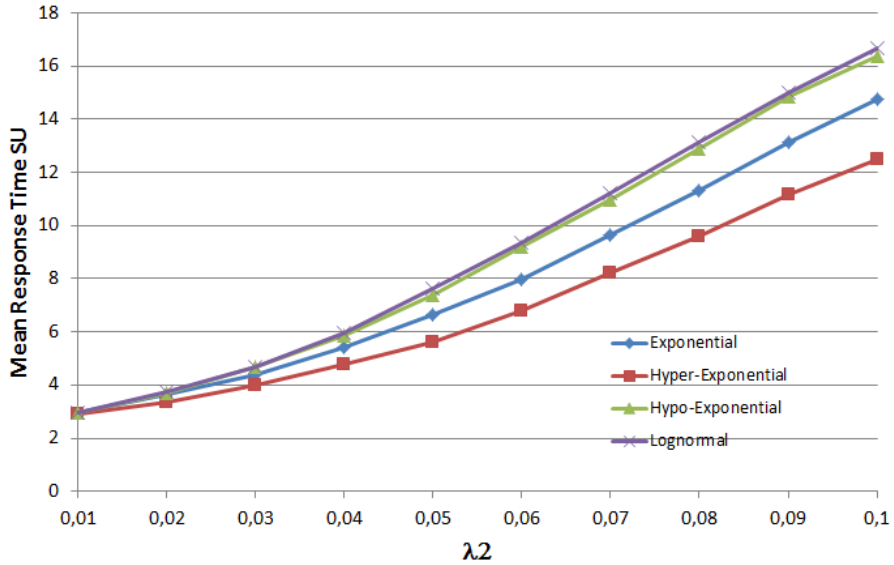
**Figure 4.7:** The effect of service time distribution of the SUs on the variance of response time of SUs vs  $\lambda_2$

distribution of the source times, depending only on their means.

The other operation mode is where the service time at the primary server is



**Figure 4.8:** The effect of service time distribution of the SUs on the mean response time of SUs vs the retrial rate  $\nu$



**Figure 4.9:** The effect of service time distribution of the PUs on the mean response time of SUs vs  $\lambda_2$

hyper-exponentially, hypo-exponentially and lognormally distributed 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 4.4 and Figure 4.5 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 4.6 and Figure 4.7, 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 4.8 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 4.9, 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.

### **4.3**

## **Finite-source cognitive radio networks with non-reliable services**

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In addition to the system model illustrated in Figure 4.1. We introduce in this section, similar model of finite-source queueing model with two (non

independent) frequency channels. Alike, the cognitive radio architecture of this model consists of two main networks: The Primary Channel Service (PCS) and Secondary Channel Service (SCS). In [3], the authors have applied the queueing theoretical methods on a finite-source cognitive radio network in order to analyze the main performance of the system by the help of tool supported approach. Therefore by the help of a discrete-event simulation, on the model illustrated in Figure 4.1 we have investigated the impact of the source and service time's distribution, where the probability of service failure remained a constant. Hence, 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.

#### 4.3.1

#### System model

As in Figure 4.1, we propose similarly a finite source queueing system which is used to model the considered cognitive radio network. The queueing system contains two interconnected, not independent sub-systems. The first part is for the requests of the PUs. The number of sources is denoted by  $N_1$ . These sources generate high priority requests with an exponentially distributed inter-request times with the parameter  $\lambda_1$  or with the 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 exponentially, hypo-exponentially and hyper-exponentially distributed with the same rate  $\mu_1$  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-arrival times are exponentially distributed random variables with parameter  $\lambda_2$  and the service times of the single server unit (Secondary Channel Service - SCS) is assumed to be exponentially, hypo-exponentially and hyper-exponentially distributed random variables with the same mean  $1/\mu_2$ .

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 and starts again its service from the beginning. The transmission through the radio channel may produce errors, which can be detected after the service and produce a failure. In the model, this case has a probability  $p_1$ , and the failed packet is sent back to the appropriate service unit. When the

Figure	$N_1, N_2$	$\lambda_1$	$\lambda_2$	$\mu_1, \mu_2$	$\nu$	$p_1$	$p_2$
4.10, Fig 4.11	10	0.02	0.03	1	20	x - axis	0.1
4.12, Fig 4.13	10	0.02	0.03	1	20	x - axis	0.1
4.14, Fig 4.15	10, 50	0.02	0.03	1	20	x - axis	0.1
4.16, Fig 4.17	10	x - axis	0.03	1	20	0.3, 0.6	0.3, 0.6
4.18, Fig 4.19	10	x - axis	0.03	1	20	0.3, 0.6	0.3, 0.6
4.20, Fig 4.21	10	0.02, 0.06	0.03	1	20	x - axis	0.1
4.22	10	0.02	0.03	1	20	0.1	x - axis

**Table 4.5:** Numerical values of simulation parameters

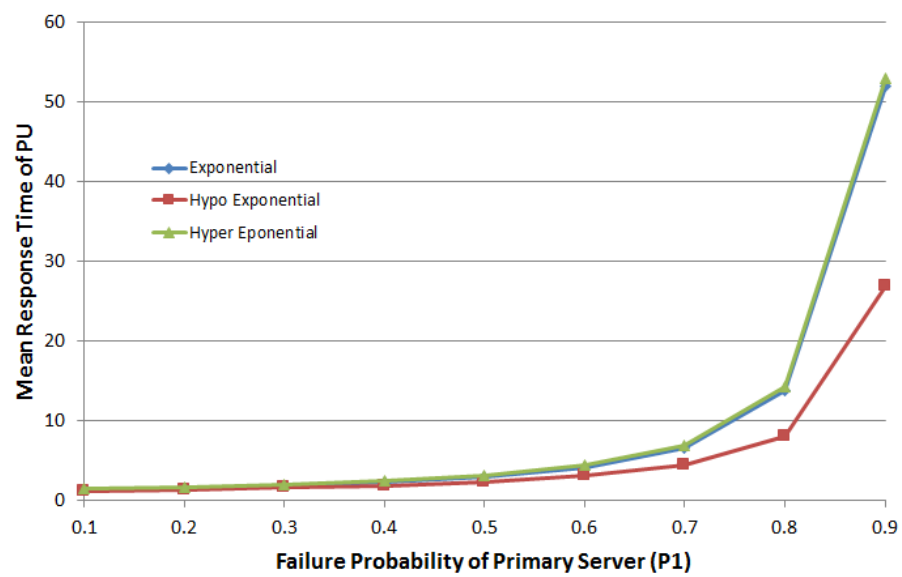
submission, is successful (probabilities  $1 - p_1$ ), the requests goes back to the source. In case of requests from SUs. If the SCS is idle, the service starts, if the SCS is busy, the packet senses the PCS. In case of an idle PCS, the service of the low priority packet begins at the high priority 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  $\nu$ . The same transmission failure with the probability  $p_2$  may occur as in the PCS segment.

**New results in (J3)** *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.*

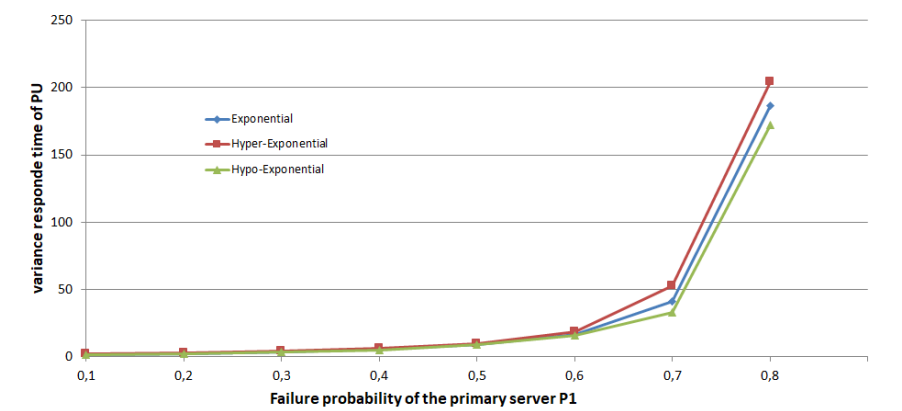
### 4.3.2

### Numerical results

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



**Figure 4.10:** The effect of the failure probability of the PCS on the mean response time of the PUs

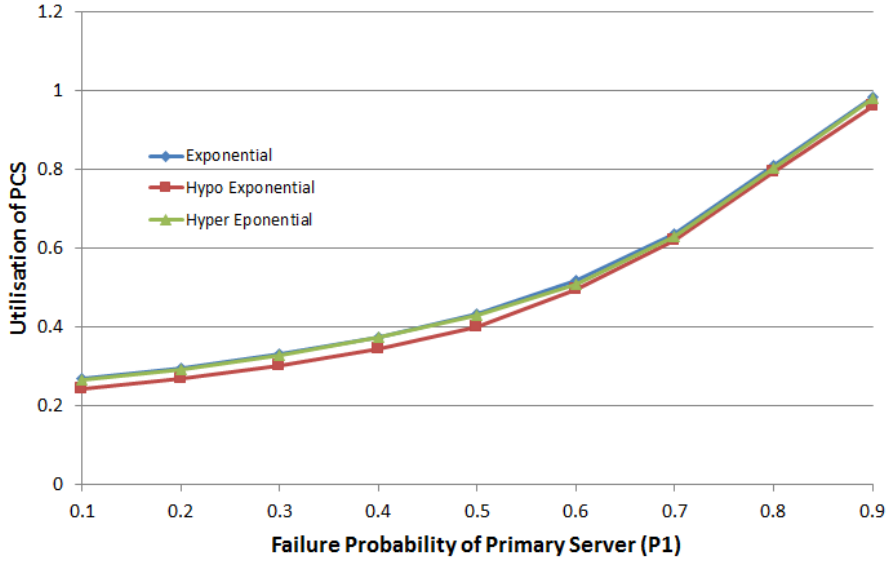


**Figure 4.11:** The effect of the failure probability of the PCS on the variance response time of the PUs

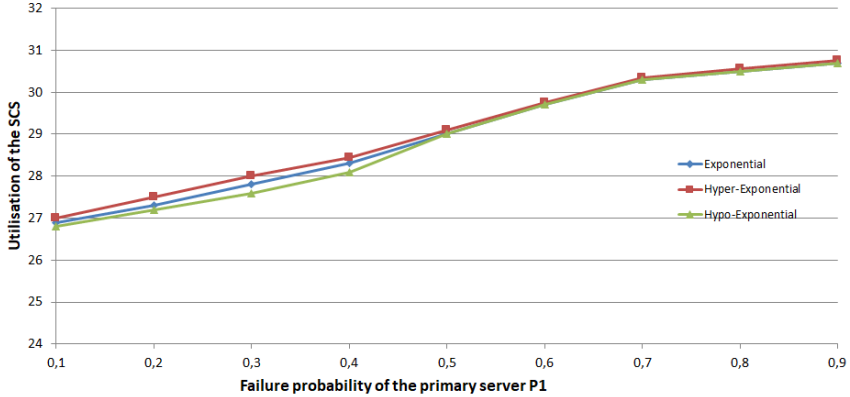
4.3.2

Comments

Figure 4.10 and Figure 4.11 illustrate the effect of the failure probability of the PCS on the mean and the variance response time while the transmission in the primary channel may occur errors more often. In this simulation case,

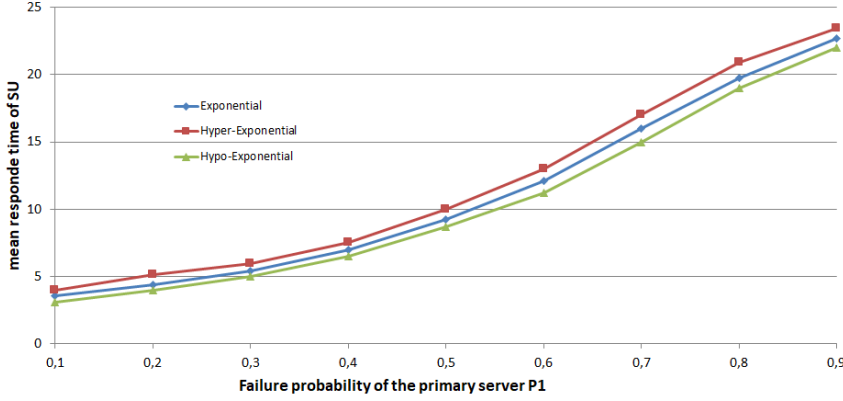


**Figure 4.12:** The impact of the failure probability of the PCS on the Utilization of the PCS

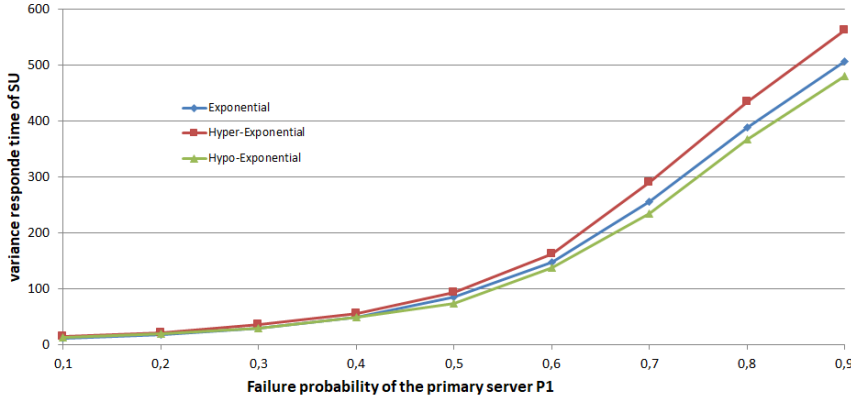


**Figure 4.13:** The impact of the failure probability of the PCS on the Utilization of the SCS

the distribution of the inter-request time of SUs and the service time of the secondary service unit are exponentially distributed random variable, however, the service time of the primary server is exponentially, hypo-exponentially and hyper-exponentially distributed random variable. The Figures show that increasing the failure probability of the services involves longer response time of the users. Similarly, the value of variance is Also rising while the failure probability increases.



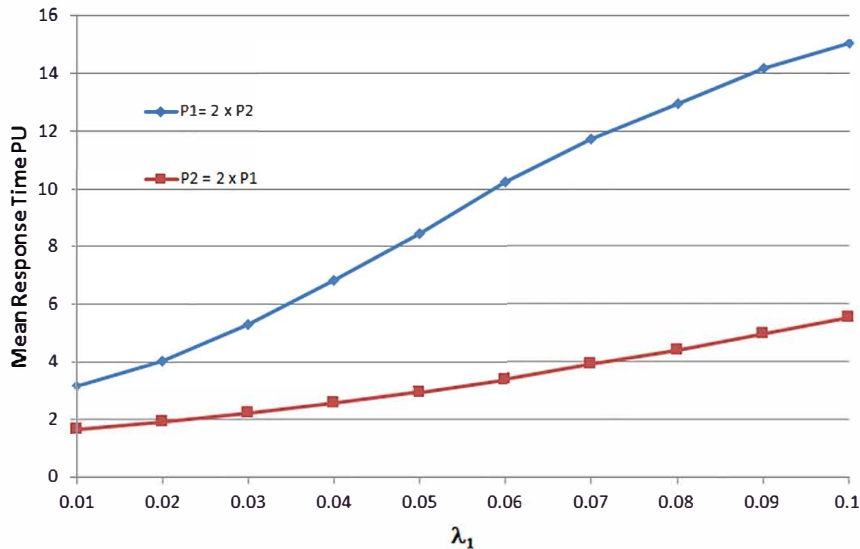
**Figure 4.14:** The impact of the failure probability of the PCS on the mean response time of the SUs



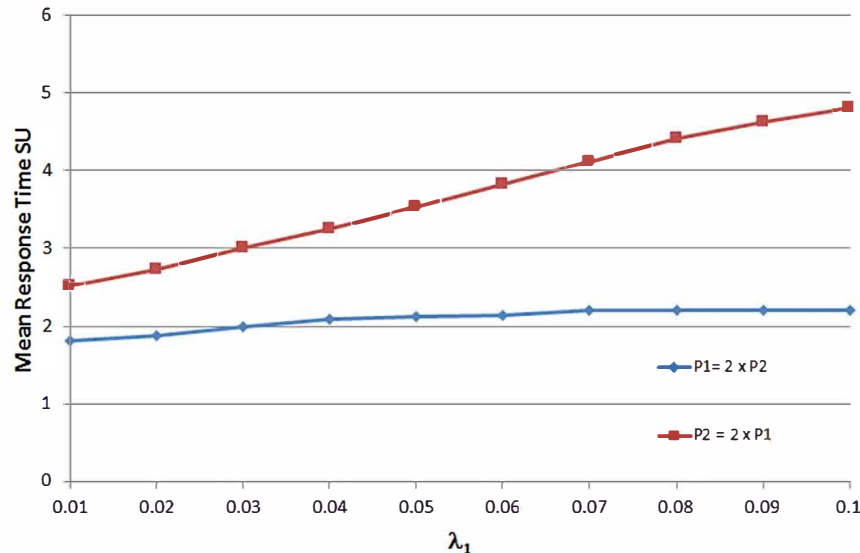
**Figure 4.15:** The impact of the failure probability of the PCS on the variance response time of the SUs

Likewise, the Figure 4.12 and Figure 4.13 show how the utilizations of the primary and secondary service channel are larger when the probability of the services failures is increasing on this part of system.

Therefore, the impact of the primary service failure probability on the mean and variance response time of the secondary users (SUs) is displayed in the Figure 4.14 and Figure 4.15. In this case of the simulation, The inter-arrival times of the customers and the service time of the Primary server are exponentially distributed random variable, as for the service time of the secondary server is generally distributed random variable (Hypo-exponential and Hyper-exponential distributions). Regarding the opportunistic use of the primary service channel (PCS) by the secondary customers (SUs) in the cognitive radio

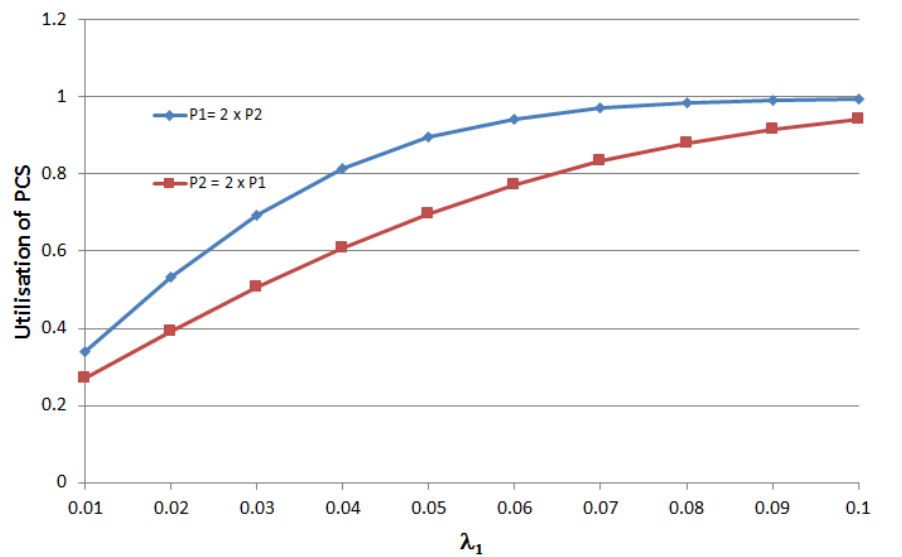


**Figure 4.16:** The effect of the failure probability of the services on the mean response time of the PUs vs  $\lambda_1$

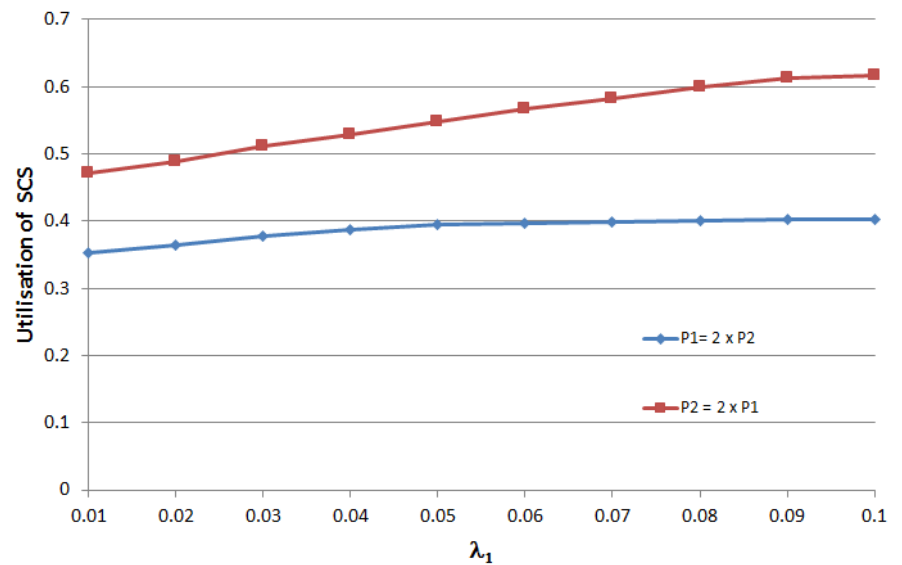


**Figure 4.17:** The effect of the failure probability of the services on the mean response time of the SUs vs  $\lambda_1$

networks, the failure of the services at the PCS level causes longer waiting time for the secondary calls. Hence, a high probability of primary service failure affects the mean and the variance response time of the secondary users (SUs)



**Figure 4.18:** The effect of the failure probability of the services on the utilization of the PCS vs  $\lambda_1$

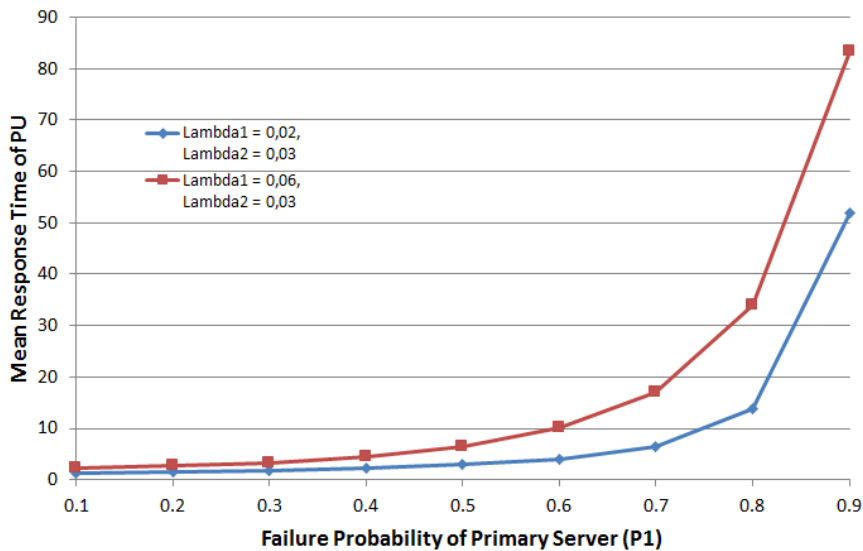


**Figure 4.19:** The effect of the failure probability of the services on the utilization of the SCS vs  $\lambda_1$

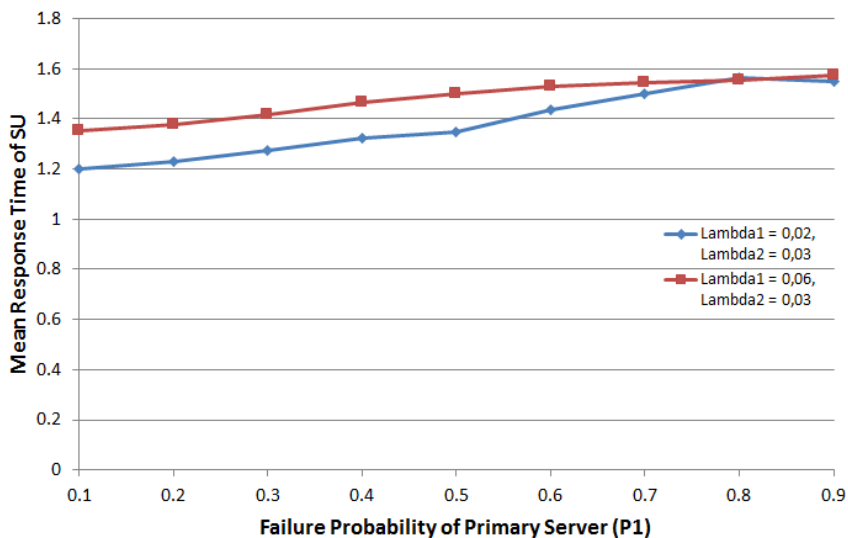
by involving longer response time for the customers.

Recap, the previous Figures show the effect of the distribution of the service





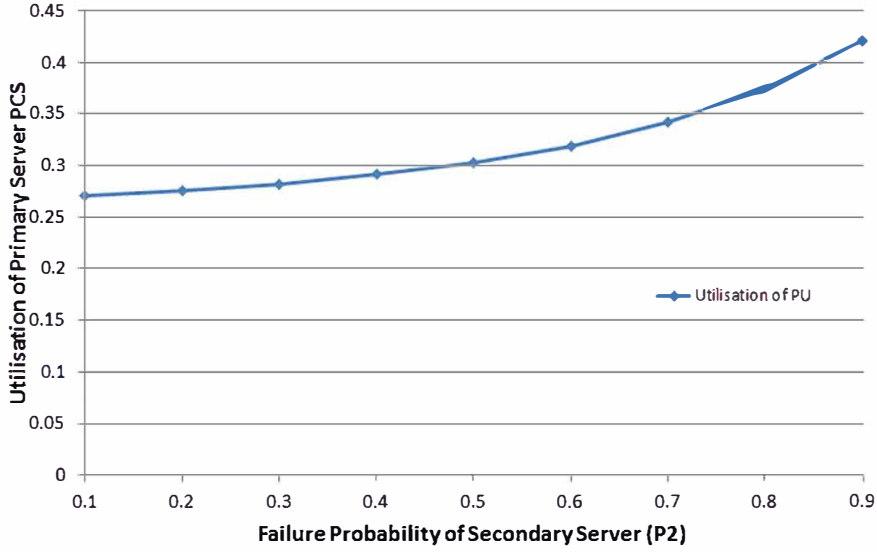
**Figure 4.20:** The effect of the inter-request rate on the mean response time of the PUs vs  $p_1$



**Figure 4.21:** The effect of the inter-request rate on the mean response time of the SUs vs  $p_1$

time on the mean, variance response time and the utilization of service units.

The other case of simulation is where the Primary Service Channel (PCS) is less



**Figure 4.22:** The effect of the failure probability of the SCS on the Utilization of the PCS

reliable than the Secondary Service Channel (SCS) and where the PCS is more 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 4.16 and Figure 4.17 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 ( $\lambda_1$ ). The Figure 4.16 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 4.17 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 ( $\lambda_1$ ), the mean response time of the SUs becomes a constant.

The Figure 4.18 and Figure 4.19 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 ( $\lambda_1$ ). In the Figure 4.18, when increasing  $\lambda_1$  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 4.19, the utilisation of the SCS becomes a constant when the PCS is less reliable than the SCS and when the arrival intensity higher.

The other results of the several cases of the simulation are illustrated in the

Figures that show the effect of the inter-request times on the mean response time of the customers and the utilization of the servers in terms of the failure probability of the primary services ( $p_1$ ).

The Figure 4.20 shows the effect of the primary arrival rate ( $\lambda_1$ ) on the mean response time of the PUs. Here also as it was expected, increasing the primary failure probability ( $p_1$ ) involves longer response time of the PUs. Otherwise, the Figure 4.21 shows that the mean response time of the SUs is insensitive to the primary arrival rate ( $\lambda_1$ ) when the primary failure probability ( $p_1$ ) is high.

In the Figure 4.22, according to the cognitive radio networks paradigms and as shown in the previous Figures, we see that the utilization of the PCS depends on the failure probability of the SCS ( $p_2$ ). It shows that more the SCS is not reliable, more the utilization of the PCS increase.

#### 4.4

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

In this investigation, each server is subject to random breakdowns in which case the interrupted request is sent to the queue or orbit, respectively. The operating and repair times of the servers are 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.

**New results in (J4)** *(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 sent 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.)*

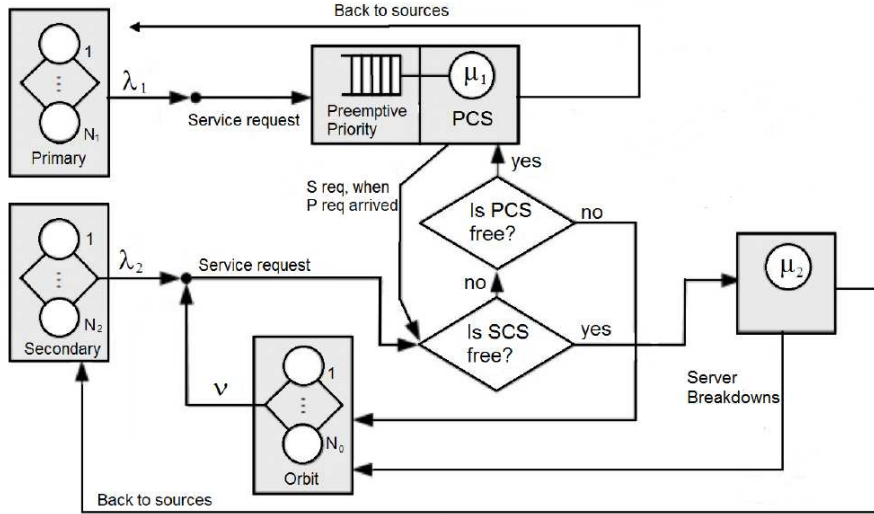
#### 4.4.1

#### System model

The finite source retrial queueing system which is used to model the considered cognitive radio network is illustrated in Figure 4.23. The queueing system contains two interacting, not independent sub-systems. The first sub-system of the network is for the calls of the PUs. The number of sources is finite and denoted by  $N_1$ . Each source generates high priority requests according to an exponentially distributed inter-request times with the parameter  $\lambda_1$ . 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  $\mu_1$ .

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  $\lambda_2$  and  $\mu_2$ , 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.



**Figure 4.23:** Finite-source retrial queueing system: Modeling the Cognitive Radio Network with non-reliable servers

When the unit is servicing a customer from SUs, the service is interrupted and the interrupted low priority task joins the SCS. Depending on the state of secondary channel the interrupted job is directed to either the server or the orbit. The primary server can breakdown during an idle or busy state according to exponentially, hypo-exponentially and hyper-exponentially distributed time with the same rate  $\gamma_1$ . 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  $\sigma_1$ .

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  $\nu$ . 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  $\gamma_2$ . The repair time of the secondary service unit is also exponentially, hypo-exponentially and hyper-exponentially distributed random variable with the same intensity  $\sigma_2$ .

## 4.4.2

## Validation of 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.

**Table 4.6:** Confidence interval for scenarios in case 3

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

## 4.4.3

## Numerical results

This subsection presents several graphs illustrating some sample examples which show the effect of the failure and repair time distributions having the same mean but different variance. It 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

**Table 4.7:** Parameters of repair times distributions of secondary customers

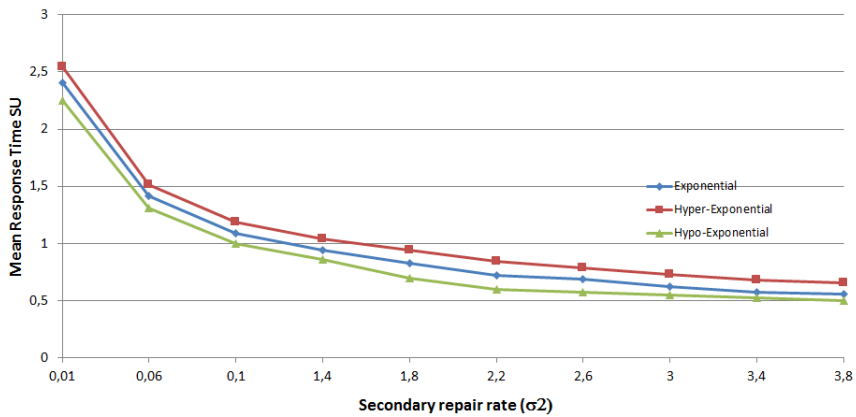
Distributions	Hyper-exponential	Hypo-exponential	Exponential
Parameters	$p = 0.45$ $\sigma_1 = 1.358$ $\sigma_2 = 0.865$	$\sigma_1 = 3.386$ $\sigma_2 = 11.2053$	$\sigma_1 = 2.6$
Mean	0.3846	0.3846	0.3846
Variance	0.2491	0.0952	0.1479
Square coefficient of variation	1.6842	0.6449	1

**Table 4.8:** Numerical values of the parameters

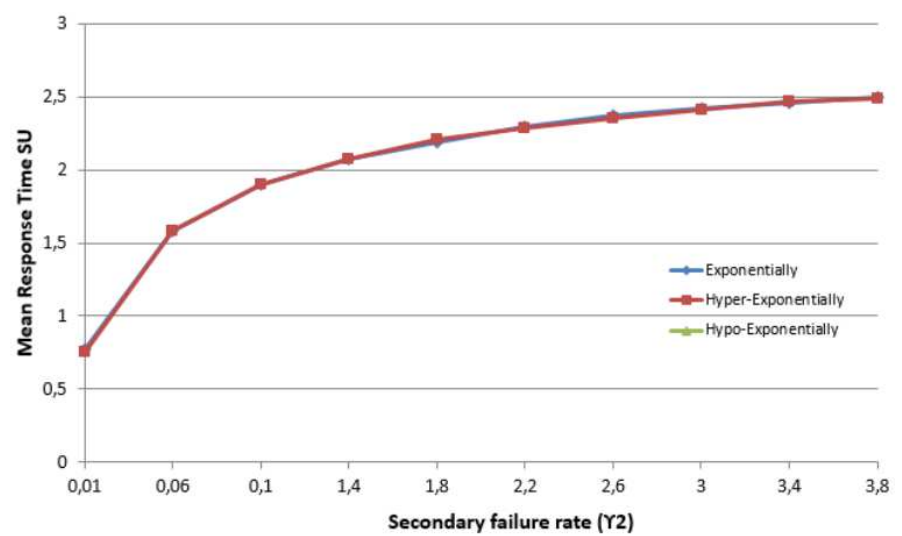
Figure	$N_1, N_2$	$\lambda_1, \lambda_2$	$\mu_1, \mu_2$	$\nu$	$\gamma_1$	$\gamma_2$	$\sigma_1$	$\sigma_2$
4.24	10	0.1	4	0.4	0	0.05	0	x-axis
4.25	10	0.1	4	0.4	0	x-axis	0	0.05
4.26	10	0.1	4	0.4	x-axis	0	0.05	0
4.27	10	0.1	4	0.4	0.05	0	x-axis	0
4.28	10	0.1	4	0.4	0,0.05	0.05,0	0,x - axis	x - axis, 0
4.29	10	0.1	4	0.4	0,x - axis	x - axis, 0	0,0.05	0.05,0
4.30	10	0.1	4	0.4	0	0.05	0	x-axis
4.31	10	0.1	4	0.4	0.05	0	x-axis	0
4.32	10	0.1	4	0.4	x-axis	0	0.05	0

simulation program, an estimation of the mean and variance of the sojourn time of the PUs and SUs could be obtained.

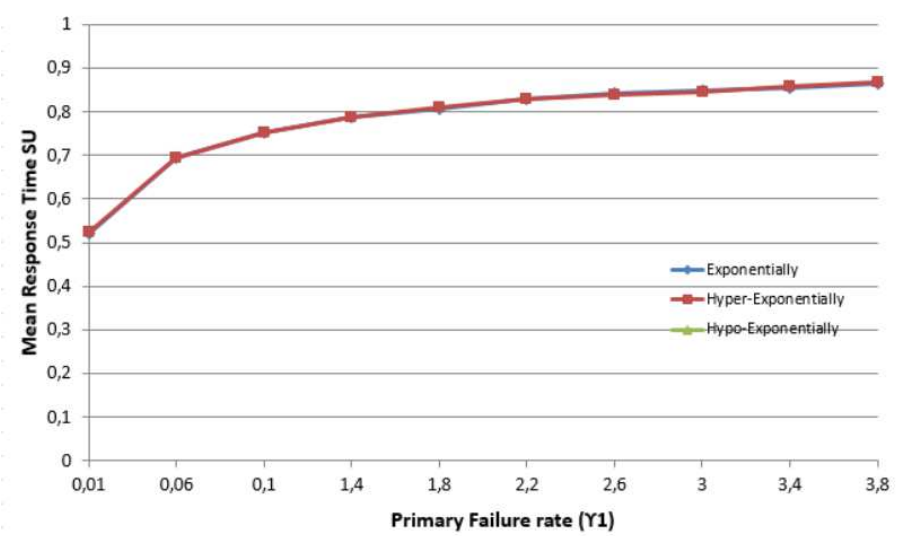
For the numerical values of the input parameters see 4.12.



**Figure 4.24:** The impact of the secondary repair time distribution on the expectation of the sojourn time of the SUs vs  $\sigma_2$



**Figure 4.25:** The effect of the secondary failure time distribution on the mean response time of the SUs vs  $\gamma_2$



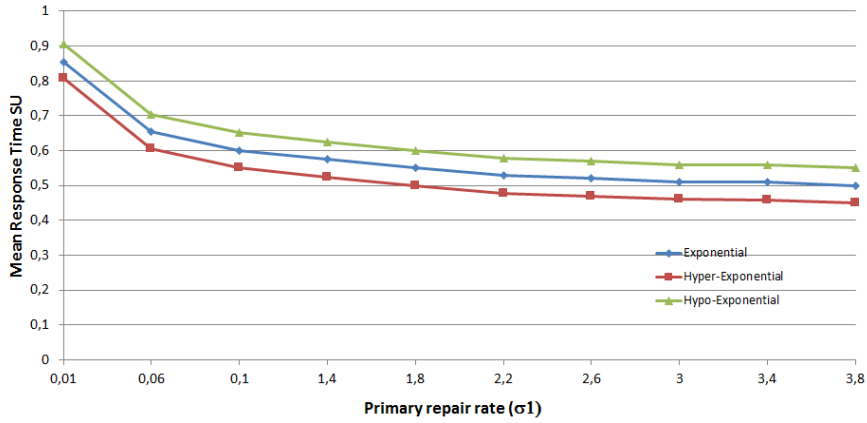
**Figure 4.26:** The effect of the failure time distribution on the mean response time of the SUs vs  $\gamma_1$

4.4.3

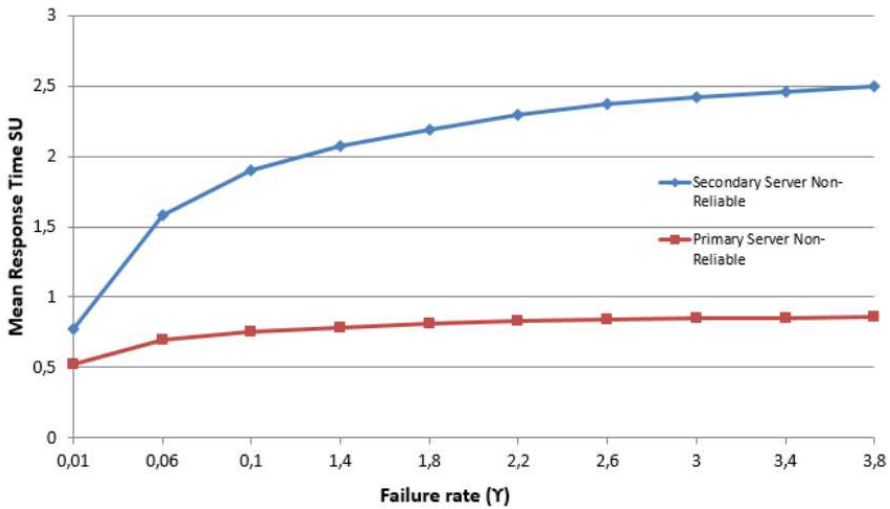
Comments

In Figures 4.24 and 4.25, we assume that the primary server is reliable, thus,  $\gamma_1 = 0$  and  $\sigma_1 = 0$ . Therefore, we concentrate on the second sub-system of the





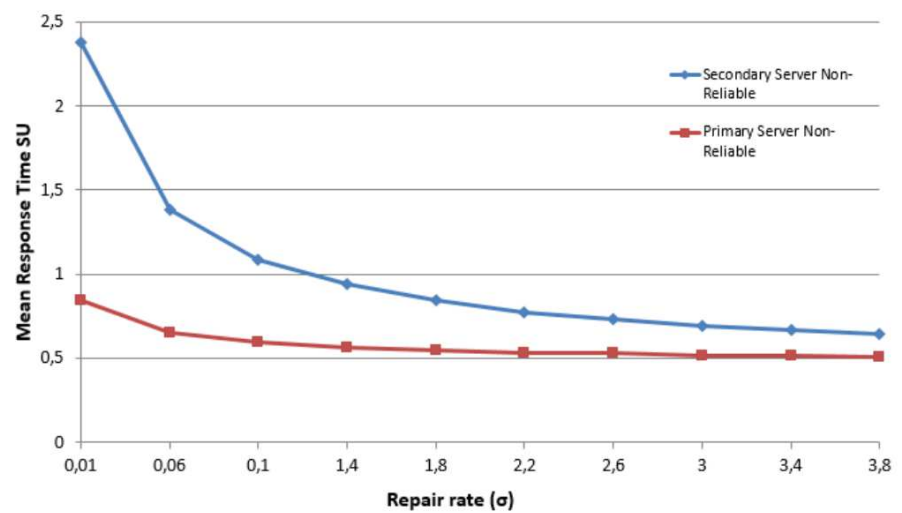
**Figure 4.27:** The impact of the primary repair distribution on the expectation of the sojourn time of the SUs vs  $\sigma_1$



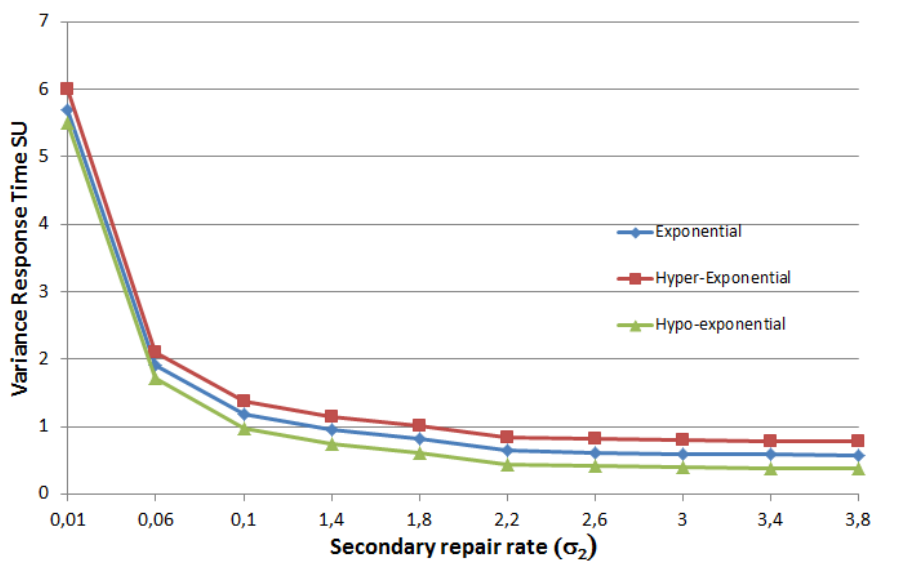
**Figure 4.28:** The impact of the non-reliability of the server on the mean response time of the SUs vs failure rate ( $\gamma$ )

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 ( $\gamma_2, \sigma_2$ ), respectively.

Figure 4.24 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 [48], the same results of the impact of the secondary service time distribution was illustrated. As known already, the squared coefficient of variation of



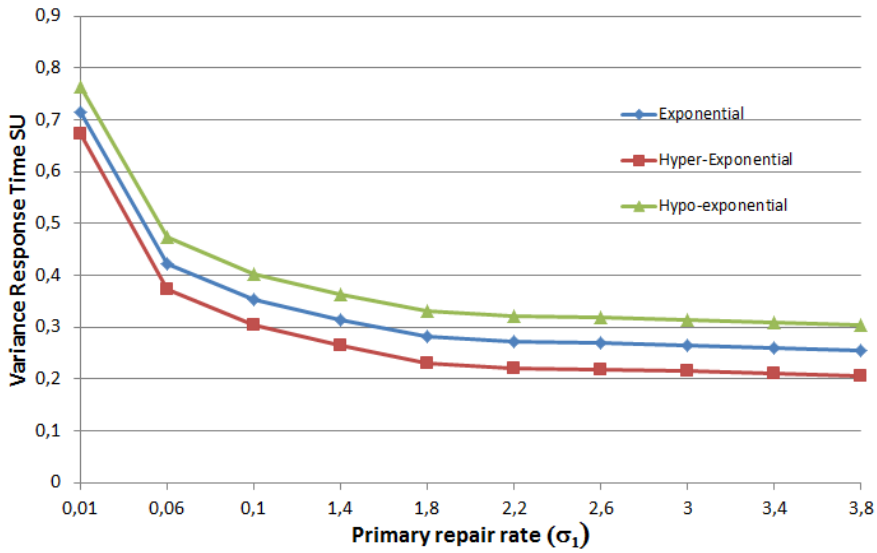
**Figure 4.29:** The effect of the non-reliability of the server on the mean response time of the SUs vs repair rate ( $\sigma$ )



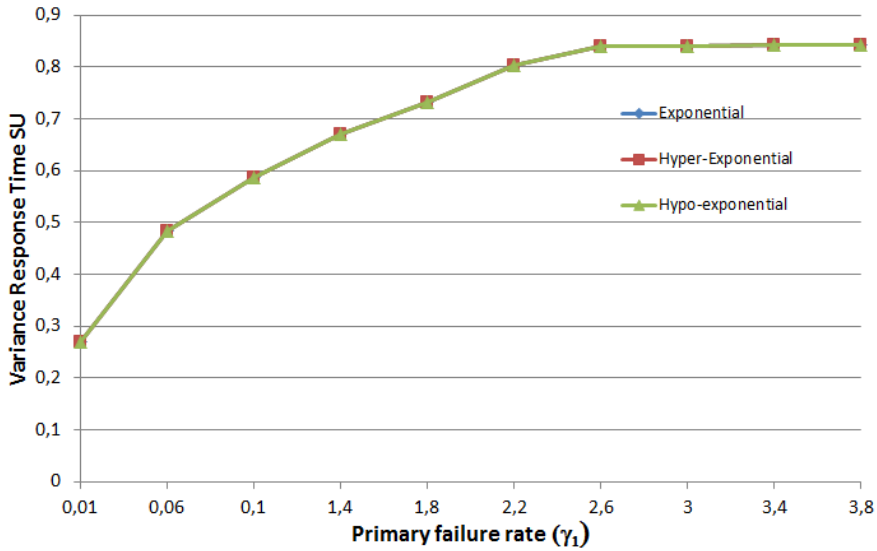
**Figure 4.30:** The impact of the secondary repair time distribution on the variance of the response time of the SUs vs  $\sigma_2$

the hyper-exponential distribution is always greater than 1, contrary to the hypo-exponential distribution which is always less than 1.

However, Figure 4.25 shows that under the present parameter setup the



**Figure 4.31:** The impact of the primary repair time distribution on the variance of the sojourn time of the SUs vs  $\sigma_1$



**Figure 4.32:** The effect of the failure time distribution on the variance response time of the SUs vs  $\gamma_1$

distribution of the secondary failure time has no any effect on the expectation of the sojourn time of the secondary users.

In Figures 4.26 and 4.27, 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 investigate the effect of the primary breakdown and repair time distribution on the mean response time of the secondary calls when the failure and repair rate are increasing  $(\gamma_1, \sigma_1)$ , respectively.

Figure 4.26 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 4.27 as in Figure 4.24, the distribution of the primary repair has an effect on the mean response time of the SUs. Contrary to Figure 4.24, 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.

Figure 4.28 illustrates the effect of the non-reliability of the server on the expectation of the response time when the failure intensity is increasing  $(\gamma)$ . We compare two cases, namely when the secondary server is non-reliable and when the primary server is non-reliable. As it was expected, increasing the secondary failure intensity causes longer response time for the secondary users. Also, by increasing the primary failure intensity, the secondary costumers can not access the primary channel service which involves a constant values of the sojourn time.

Figure 4.29 shows the impact of the non-reliability of the server unit on the mean sojourn time of the SUs. It illustrates the difference on the value of the mean response time while the repair intensity is increasing  $(\sigma)$ . As shown in this Figure, in the cognitive radio networks having a reliable servers causes shorter response time and the difference on the values is small.

In Figure 4.30 and Figure 4.31, we are investigating in the effect of the repair times distribution on the variance of the response time of the SUs.

Figure 4.30 shows the same behaviour of the variance as the average of the response time. It should be known that in the case, the primary service unit is reliable. The value of the variance is greater than the value of the mean response time and the distribution of the secondary repair time has an impact on the second moment of the response time of the SUs.

Similarly, in Figure 4.31 as in Figure 4.26, when the secondary service unit is reliable the distribution of the primary repair time has an effect on the variance of the response time of secondary customers. In this case the value of the variance is smaller than the value of the expectation. Similarly, the variance's value is greater when the repair time distribution is hypo-exponentially than hyper-exponentially.

Figure 4.32 illustrates the effect of the primary failure distribution on the variance of the sojourn time. There is no effect on the value of the variance and as expected increase of failure intensity involves longer sojourn time.

## 4.5

### Finite-source cognitive radio networks with collision

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. 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. For illustration, various sample examples are derived and figures are generated for better understanding.

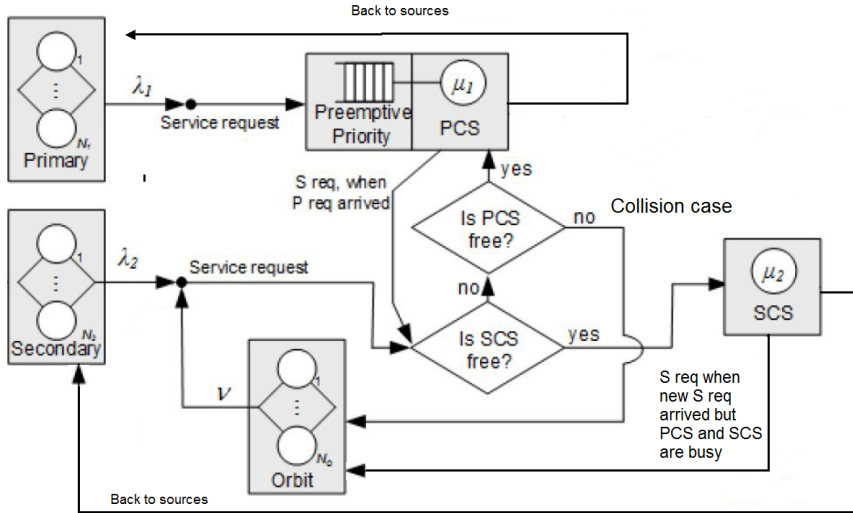
**New results in (C3)** *We have dealt with performance measures of a finite-source cognitive radio network with collision at the retrial part of the system. We have established a simulation program to model the queueing system and to obtain estimation for the basic performance measures. Since individual 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.*

#### 4.5.1

#### System model

The queueing system proposed in this section and illustrated in Figure 4.33 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  $\lambda_1$ . Whereas, during simulation the service times are assumed to be exponentially, hypo-exponentially and hyper-exponentially distributed random variables with the same intensity  $\mu_1$ . 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  $\lambda_2$ . 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  $\mu_2$ .



**Figure 4.33:** A finite source retrial queueing system with collision

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  $\nu$ .

## 4.5.2

## Validation of 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

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

**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
Square coefficient of variation	1.6842	0.8456	1

## 4.5.3

## Numerical results

In this section we would like to show some examples to illustrate the impact of distribution having the same mean but different variance.

Table 4.11 shows the numerical values of the input parameters.

Table 4.11: Numerical values of the parameters

No.	$N_1$	$N_2$	$\lambda_1$	$\lambda_2$	$\mu_1$	$\mu_2$	$\nu$
Fig 4.34	20	50	x axis	0.1	1	1	20
Fig 4.35	20	50	x axis	0.1	1	1	20
Fig 4.36	20	50	x axis	0.1	1	1	20
Fig 4.37	20	50	0.1	x axis	1	1	20
Fig 4.38	20	50	0.1	x axis	1	1	20
Fig 4.39	20	50	0.1	x axis	1	1	20
Fig 4.40	50	50	0.1	x axis	1	1	20
Fig 4.41	50	50	0.1	x axis	1	1	20

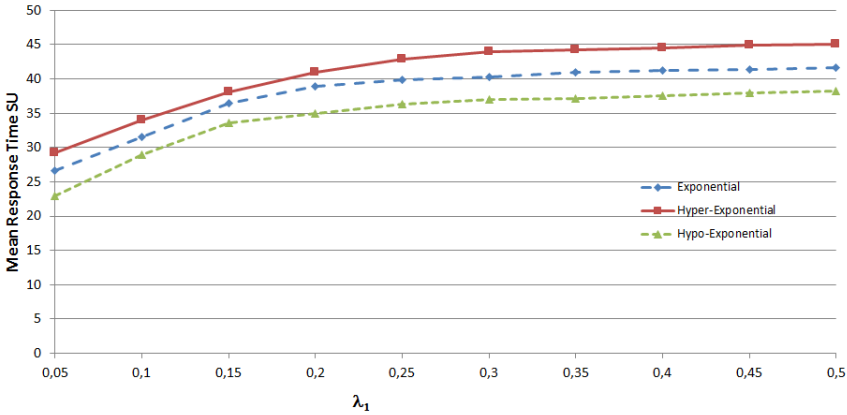


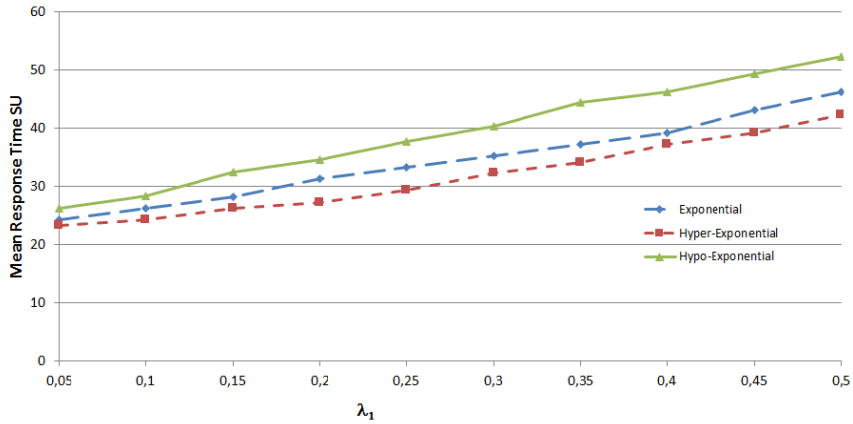
Figure 4.34: The effect of the secondary service time distribution of the SUs on the mean response time of the SUs vs  $\lambda_1$

4.5.3

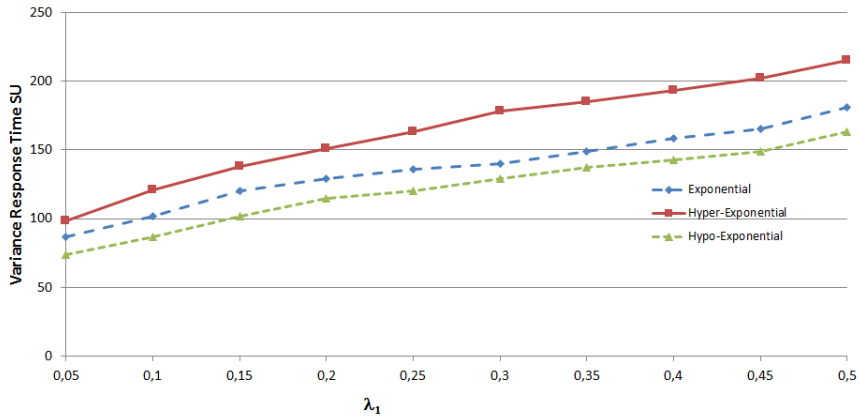
Comments

Figure 4.35 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





**Figure 4.35:** The effect of the primary service time distribution of the SUs on the mean response time of the SUs vs  $\lambda_1$

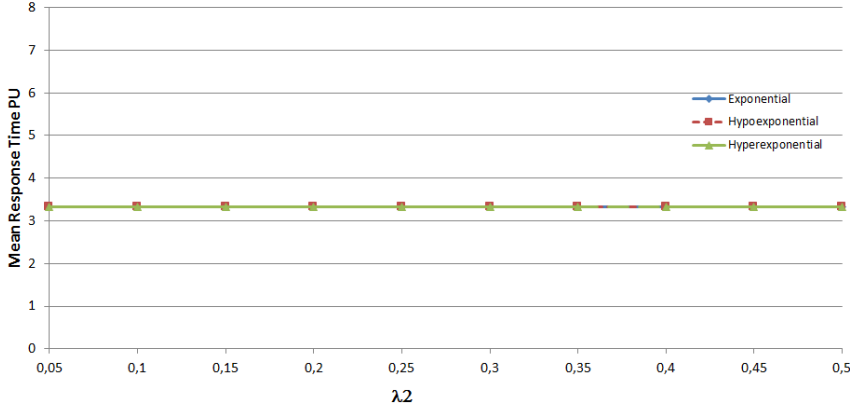


**Figure 4.36:** The effect of the secondary service time distribution of the SUs on the variance of the response time of the SUs vs  $\lambda_1$

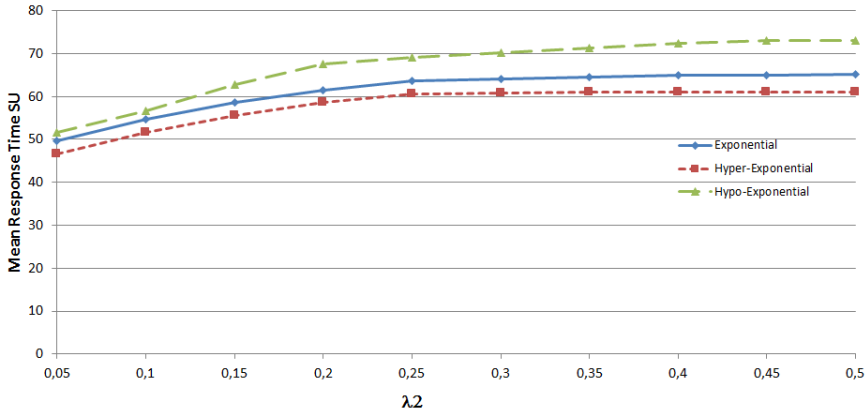
variables. The collision at the retrial part of the system involves longer sojourn times as it was expected. Customer spends more time in the system comparing to the finite-source cognitive radio networks without collision (Section 4.1).

Figures 4.36 and 4.37 show the impact of the distribution of the primary service time on the average and the variance of sojourn time of the secondary users, respectively, 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.

Figure 4.37 illustrates the impact of the secondary arrival rate on the average



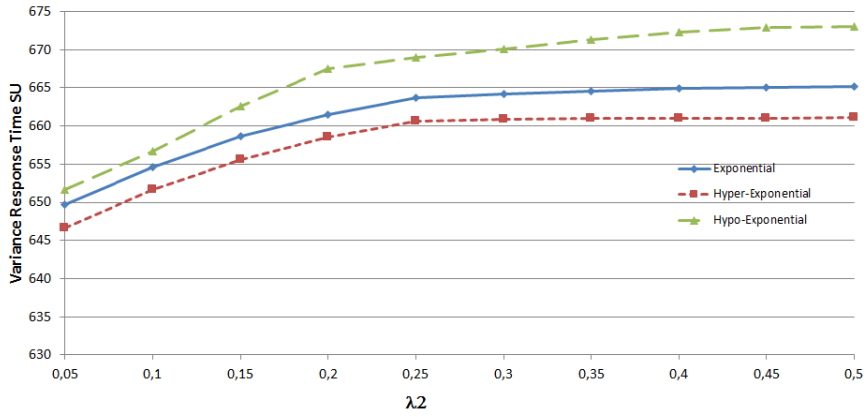
**Figure 4.37:** The effect of the secondary arrival rate ( $\lambda_2$ ) on the the mean response time of the PUs



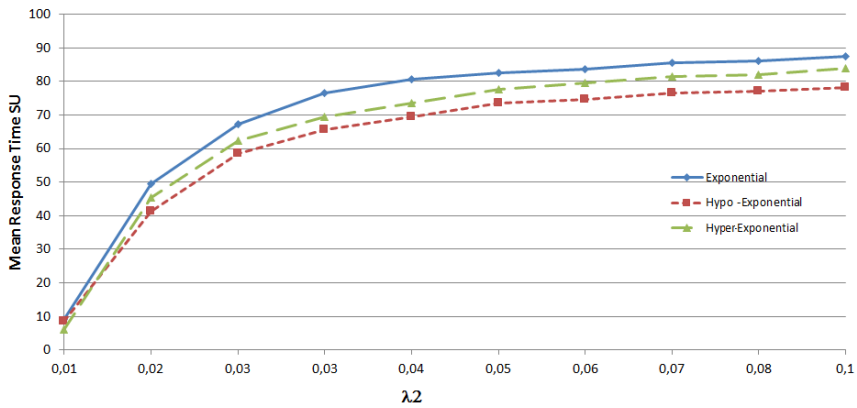
**Figure 4.38:** The effect of the secondary service time distribution of the SUs on the mean response time of the SUs vs  $\lambda_2$

sojourn time of PUs where the secondary service time is non-exponentially distributed. As the primary users have got a high priority over the secondary users, the average sojourn time of the primary users is insensitive to the generation rate of the SUs, secondary service distribution and the collision in the retrial part of the system. This Figure verifies that the simulation program operates correctly. Hence, the average time is constant as it was expected.

In Figures 4.38 and 4.39, the service time of PUs is supposed to be exponentially distributed random variable. Figures 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



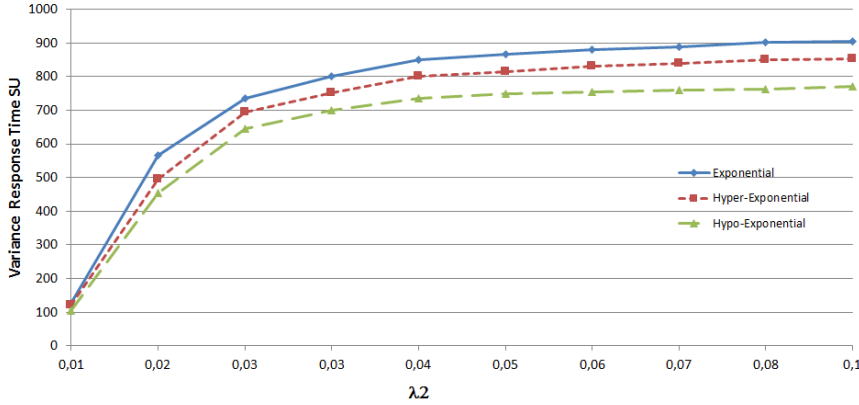
**Figure 4.39:** The effect of the secondary service time distribution of the SUs on the variance of the response time of the SUs vs  $\lambda_2$



**Figure 4.40:** The effect of the retrial time distribution on the mean response time of the SUs vs  $\lambda_2$

longer sojourn time and the value of its average changes where the distribution of the service time changes.

Figure 4.40 and Figure 4.41 illustrate the effect of the distribution of the retrial time on the average and the variance of the sojourn time of the secondary requests when the secondary arriving rate is increasing. In this case, all the other inter-events time are supposed to exponentially distributed. Due to the collision or finding the server busy, when the customers retry to be served after a hypo-exponentially or a hyper-exponentially distributed time, there the average response time will be shorter than retrying after an exponentially distributed time.



**Figure 4.41:** The effect of the retrial time distribution on the variance of the response time of the SUs vs  $\lambda_2$

## 4.6

### Non-reliable servers of finite-source cognitive radio networks with collision

This section introduces a finite-source retrial queueing system which models cognitive radio networks. 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.

In this case, we focus on the non-reliability of the servers and the collisions at the secondary servers. The primary and secondary servers are subject to random breakdowns and repairs. A collision is introduced at the retrial part of the cognitive radio network. This conflict invokes the interruption of a servicing packet when a new arriving call requests the server unit. The investigation is the non-reliability of servers and the inclusion of conflicts at the secondary server. Hence, we analyze the effect of the non-reliability of the servers on the mean response time of the secondary users.

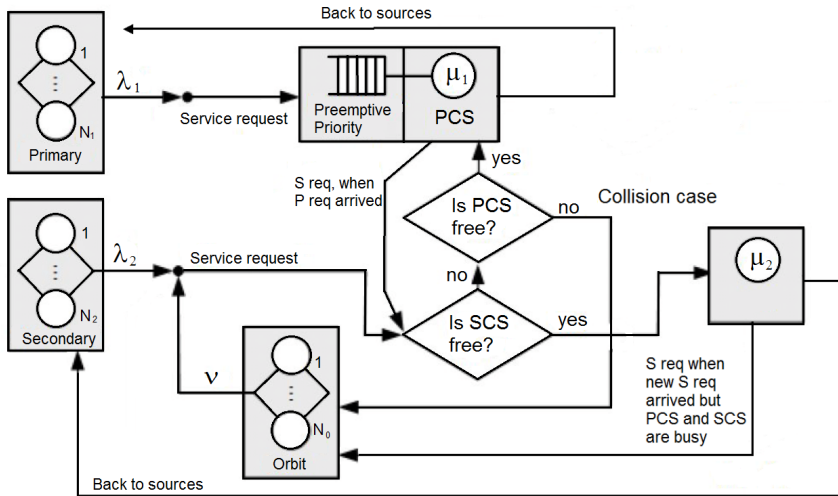
**New results in (J2)** *In this paper, we have combined the two studied models in [C3] and [J4]. A finite-source cognitive radio network with non-reliable servers and collision at the retrial part of the system. Mainly, we have focused on these two phenomenon. Hence, we analyze the effect of the non-reliability 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.*

#### 4.6.1 System model

Figure 4.42 illustrates a finite source queueing system which is used to model the considered cognitive radio network. The queueing system contains two interconnected, not independent sub-systems. The first part is for the requests of the PUs. The number of sources is denoted by  $N_1$ . These sources generate high priority requests with an exponentially distributed inter-request times with the parameter  $\lambda_1$ . The generated requests are sent to a single server unit (Primary Channel Service - PCS). The service times are supposed to be also exponentially distributed with the parameter  $\mu_1$ .

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 exponentially distributed random variables with rate  $\lambda_2$  and  $\mu_2$ , respectively.



**Figure 4.42:** A priority and a retrial queue with collision

The servers can be in three states: idle, busy and failed. For the primary server unit, if it is idle, the service of the generated high priority packet starts 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 server unit can fail during an idle or busy state according to an exponentially distributed time with parameter  $\gamma_1$ . If the server fails in busy state, the service is interrupted and the interrupted request joins the preemptive priority queue. The repair time is exponentially distributed random variable with a parameter  $\sigma_1$ .

In case of requests from SUs. If the SCS is idle, the service starts. If it 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 involves into collision with the low priority servicing packet and both goes to the orbit. the same failure state can occur at the secondary server unit according to an exponentially distributed time with parameter  $\gamma_2$ , the repair time is exponentially distributed with the parameter  $\sigma_2$ . The interrupted packet also goes to the orbit. From the orbit it retries to be served after an exponentially distributed time with parameter  $\nu$ . All the random variables involved in the model construction are supposed to be independent of each other.

#### 4.6.2

#### Numerical 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.

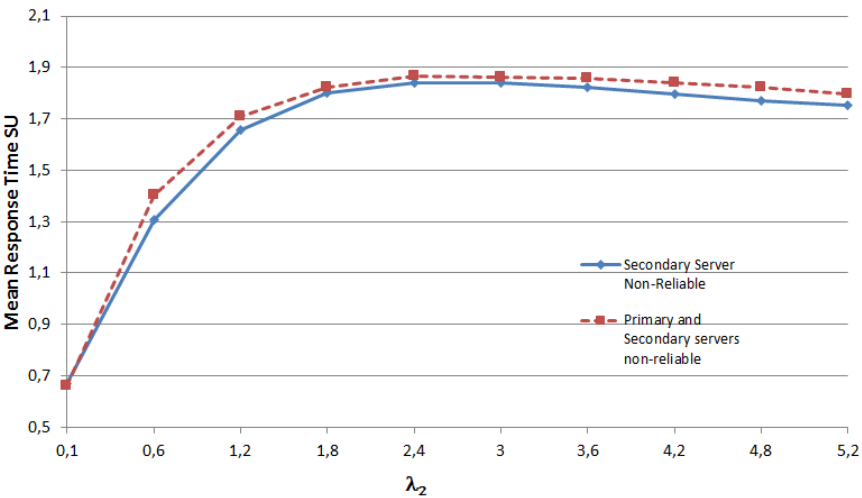
#### 4.6.2

#### Comments

Figure 4.43 shows 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, where the Figure 4.44 shows the same effect in the two cases of non-reliability with collision in the retrial part of the system. Figures show the phenomenon of having a maximum value of the mean response time which was noticed in [49]. The collision involves longer response time for the users as it was expected.

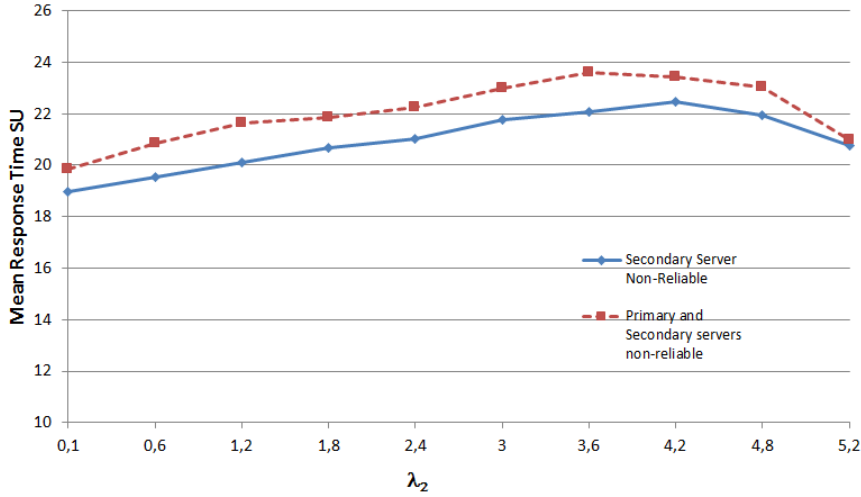
**Table 4.12:** Numerical values of model parameters

Figure No.	$N_1$	$N_2$	$\lambda_1$	$\lambda_2$	$\mu_1$	$\mu_2$	$\sigma_1$	$\sigma_2$	$\gamma_1$	$\gamma_2$	$\nu$
4.43	6	6	0.6	x - axis	4	4	1	1	0.05	0.05	0.4
4.44	6	6	0.6	x - axis	4	4	1	1	0.05	0.05	0.4
4.45	6	6	0.6	0.6	4	4	1	1	0.05	0.05	x - axis
4.46	6	6	0.6	0.6	4	4	1	1	0.05	0.05	x - axis
4.47	6	6	0.6	0.6	x - axis	4	1	1	0.05	0.05	0.4
4.48	6	6	0.6	0.6	x - axis	4	1	1	0.05	0.05	0.4
4.49	10	10	0.1	0.1	4	4	x - axis	x - axis	0.05	0.05	0.4
4.50	10	10	0.1	0.1	4	4	0.05	0.05	x - axis	x - axis	0.4
4.51	10	10	0.1	0.1	4	4	0	x - axis	0	0.05	0.4

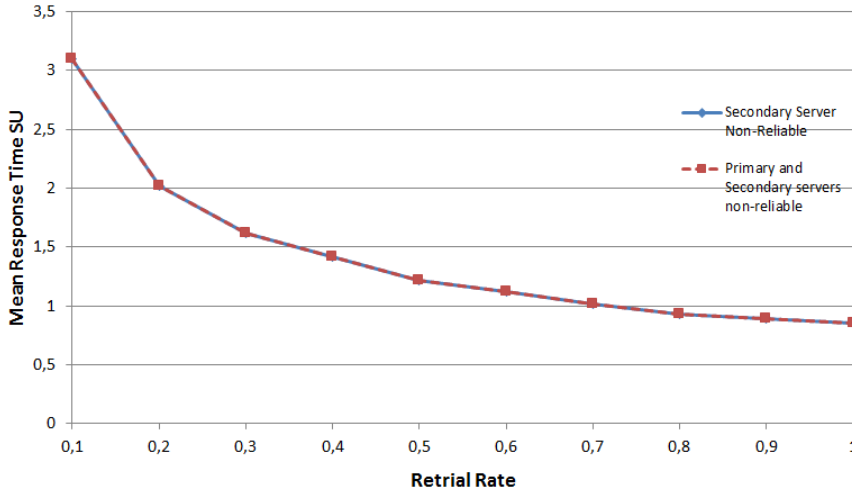


**Figure 4.43:** The effect of servers non-reliability on the mean response time of secondary users vs  $\lambda_2$

Figure 4.45 and Figure 4.46 shows the effect of the retrial rate on the mean response time of the secondary users. In Figure 4.45, the non-reliability of the primary server unit does not have any effect on the mean response



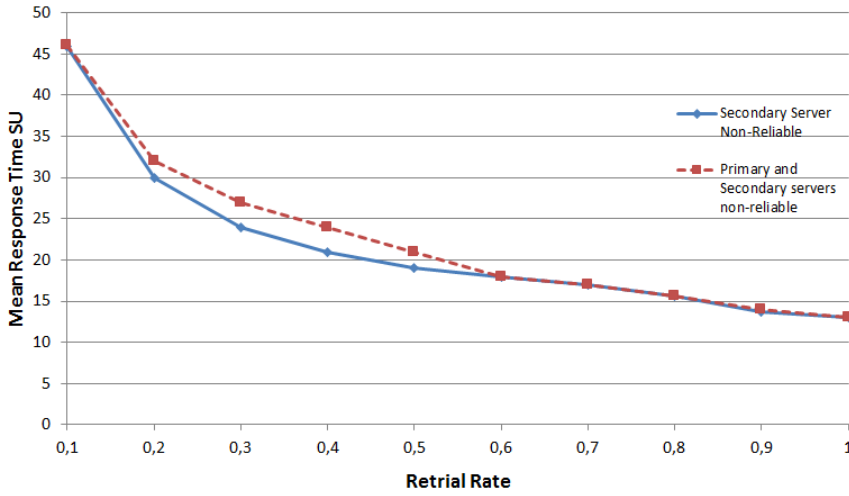
**Figure 4.44:** The effect of servers non-reliability with collision on the mean response time of secondary users vs  $\lambda_2$



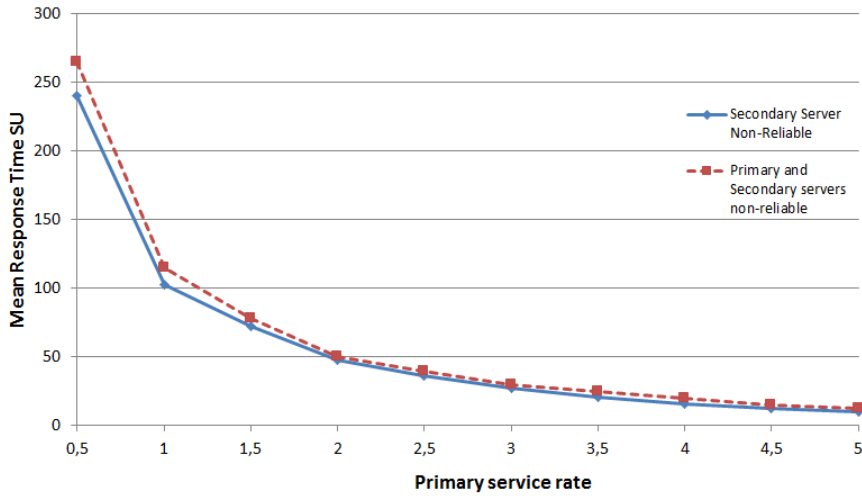
**Figure 4.45:** The effect of servers non-reliability on the mean response time of secondary users vs the retrieval rate  $\nu$

time of secondary users where the retrieval rate is increasing. However, the non-reliability of the primary server has an effect on the mean response time which can be shown on the Figure 4.46. It means that in the cognitive radio networks, having a reliable primary server involves shortest mean response time of secondary users where there is a collision in the retrieval part of the system.



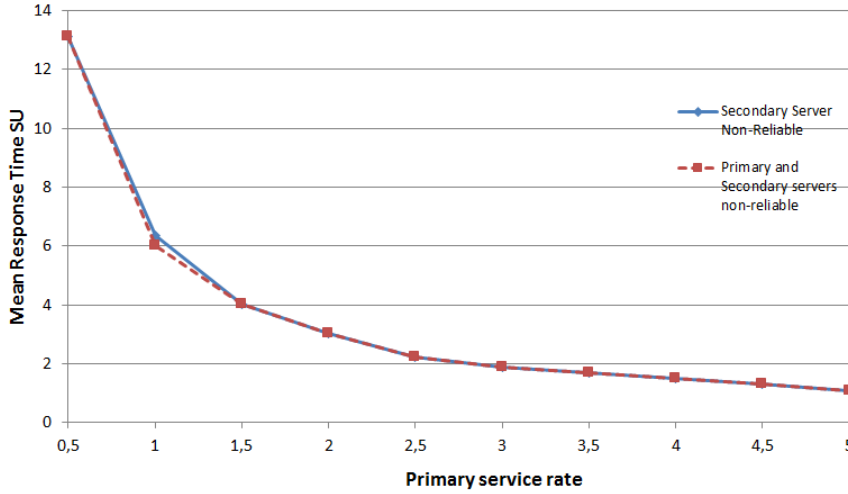


**Figure 4.46:** The effect of servers non-reliability with collision on the mean response time of secondary users vs the retrial rate  $\nu$

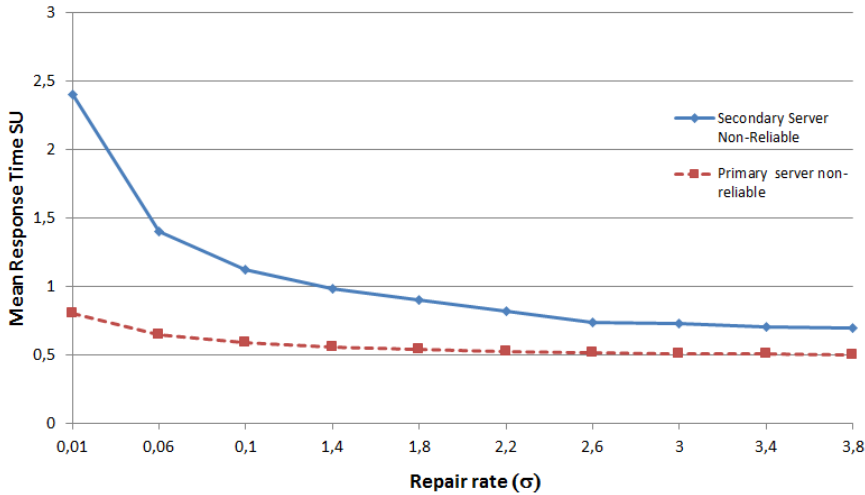


**Figure 4.47:** The effect of servers non-reliability with collision on the mean response time of secondary users vs Primary service rate  $\mu_1$

Figure 4.47 and Figure 4.48 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.

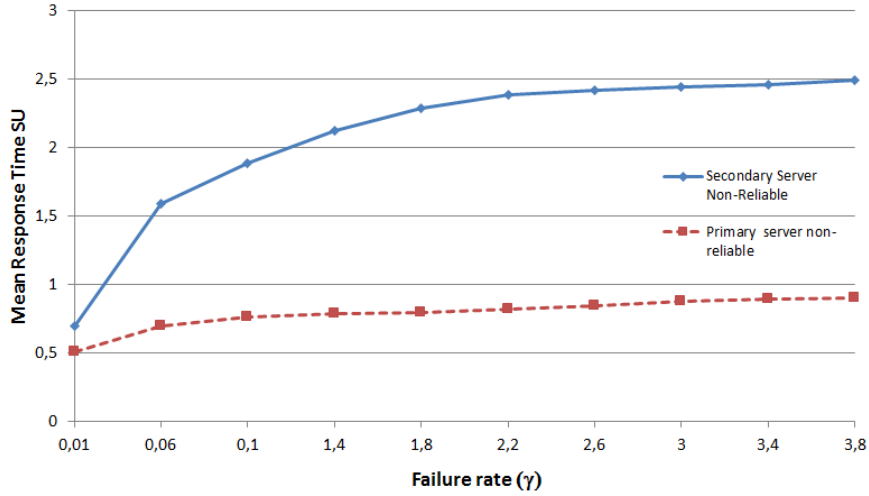


**Figure 4.48:** The effect of servers non-reliability on the mean response time of secondary users vs Primary service rate  $\mu_1$

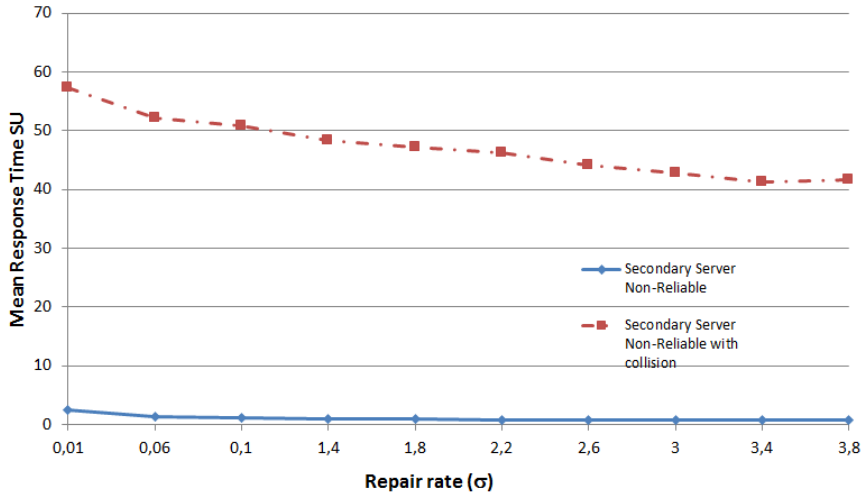


**Figure 4.49:** The effect of servers non-reliability on the mean response time of secondary users vs the repair rate  $\sigma$

Figure 4.49 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



**Figure 4.50:** The effect of servers non-reliability on the mean response time of secondary users vs the failure rate  $\gamma$



**Figure 4.51:** The effect of servers non-reliability and collision on the mean response time of secondary users vs the repair rate  $\sigma$

primary repair rate ( $\sigma_1$ ) 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 ( $\sigma_2$ ) is increasing.

Figure 4.50 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).

The last Figure 4.51 shows the effect of the collision on the mean response time of the secondary users. The conflict on a non-reliable secondary server causes a very long response time.

# 5

## Conclusion

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*This chapter conclude and summarize the work of this dissertation*

This thesis presents a work focused on developing simulation program based on SimPack [19] in order to create simulation models. Specifically, discrete event simulation standing on several algorithms was developed to examine the performance of finite source retrial queueing cognitive radio network.

The cognitive radio network is one of the candidate sectors, where cognitive techniques can be used for opportunistic spectrum access. Research in this field is still in its infancy, but it is making a rapid progress. The aim of chapter 2 is to give a state of the art on cognitive radio networks. They are the center of interest in this thesis, while they are based on two sub-networks, primary and secondary. Beside the introduction and conclusion, this chapter is divided into three main sections. First section describe and define the cognitive radio communications, their characteristics and functions. It is necessary to understand the idea of cognitive radio communication in order to set up a network based on this latter. Afterwards, the next section detailed and illustrate in some figures the architecture of a cognitive radio system. As mentioned in that section: CRN is composed of several types of co-existing multi-radio communication systems, including cognitive radio systems. They can be viewed as some sort of heterogeneous networks formulated of several communication systems. Furthermore, they shall sense available networks and communications systems around its to complete networking functions beyond utilization of available spectrum. Therefore, spectrum sensing techniques are presented in the third section of this chapter. As there are several spectrum techniques, some figures illustrate their classification.

In chapter 3, an overview on some of the processes and distributions from the theory of random processes was given in the first part of the chapter. The main distribution functions used in the simulation program are also presented in this section by highlighting exponential, hypo-exponential, hyper-exponential and lognormal distributions. In the second section, some basics on simulation modeling were given in order to understand the most important components of the discrete-event simulation. Section 3 initiates from the literature the related work that introduce the retrial queueing system to the cognitive radio communication.

The proposed model contains two bands servicing primary and secondary users in a cognitive way. Primary users have preemptive priority over the secondary ones in servicing at licensed channel. At the secondary channel, an orbit is installed for the secondary packets finding a busy server upon arrival. Therefore, the aim of this chapter is to collect the main parameters and formulas in order to build a simulation program to model our system. Consequently, section 4

demonstrates the program organization and its logic by the help of figures, which illustrates flowcharts that describe the program logic.

By the help of the developed simulation program in this thesis, we analyze the impact of the inter-event time distributions on the first and the second moment of the response time for the primary and secondary users in the system. Moreover, in some cases we evaluate the utilization of the primary and secondary channel services. This estimation of the average and variance of the response time can be obtain by using statistical class in the simulation program created by Andrea Francini in [20]. In a particular case when all times are exponentially distributed, the operation of the system can be described by the help of a continuous-time Markov chain and the most important stationary performance characteristics could be calculated. However, in our work we generalize the model assuming non-exponentially distributed inter-event time. Therefore, In section 3.4.3 we gave the functionality of the batch mean methods, the main routine of the statistical class which gives the estimation of the mean and the variance. It consists to divide the simulation run into several blocks of observations and give an estimation of the mean for each block after a "warm-up" period. This latter is the first test performed at the beginning of the simulation which is needed to construct the confidence interval for the mean, in order to assess how the estimate is close to the final expectation. it should be noticed that the batch mean method is the most popular confidence interval technique for the output analysis of a steady-state simulation. In section 4.5, we introduce the system model that take in consideration the non-reliability of the service units and the collision of the customers at the retrial part of the system. The Figure illustrates the simulation model of the retrial queueing cognitive radio network with non-reliable servers and collision.

In chapter 4, we have shown samples examples to illustrate the impact of distribution on the mean and variance of the response time for the primary and secondary users. Also, utilization of the servers. It was done by the help of hypo-exponential, hyper-exponential and lognormal distributions comparing to the basic exponentially distribution. The performance measures of several combined system models has been done and the obtained results are depicted in this chapter. The following study cases were mentioned:

- The impact of the inter-request and service times distributions on the mean and variance of the primary and secondary users for a finite-source cognitive radio network. It is a model with two interacting blocks to model the operation of cognitive radio system. Primary users have got licensed frequency channel and have preemptive priority over the secondary ones in servicing this licensed band. The secondary channel suffers from overloading. Thus, an orbit was constructed for the secondary

packets that find both servers busy upon arrival. The results of [47] were validated by knowing that the squared coefficient of variation of the hyper-exponential distribution is greater than one and the hypo-exponential is less than one. It is shown that the distribution of the service times has an important impact on the mean and variance of the response time.

- The effect of the non-reliable services on the finite-source cognitive radio networks. Similarly, the components and functionality of this model does not change. Nevertheless, the transmitting channels are not reliable and the transmissions in both channels may produce error and the failed packet is sent back to the appropriate service unit. This error may occur with a probability  $p_1$  and  $p_2$  in the licensed and unlicensed channels, respectively. The investigation of the failure probability on mean, variance of the response time and utilization of the servers will show as expected, because the two interconnected sub-systems are not independent. Increasing the probability of the primary service channel will increase the overloading of the secondary channel service.
- Performance measure of non-reliable servers in finite-source cognitive radio network. As we analyzed previously the effect of the inter-request time on the characteristic of the system model. In this section, the non-reliability of the service is introduced and the impact of the failure and repair times distributions on the first and second moment of the sojourn time is investigated. By the help of simulation results depicted in figures, it is shown that the steady-state distribution is insensitive to the failure time distribution. In contrast, the repair time distribution has an effect on the mean and variance of the response time.
- In section 4.5, we present the simulation results within figures that illustrate the effect of the service time distribution on the expectation and variance of the sojourn time. In this case, we introduced the collision in the retrial part of the system. This conflict occurs often in radio communication systems. Therefore, we evaluated the performance of our finite-source cognitive radio network while collision take place in the secondary sub-network.
- In the last section of chapter 4, we combined the system with servers subject to breakdowns and repairs and the system with collision. The investigation is the non-reliability of the servers and the inclusion of conflicts at the secondary server. Hence, we analyze the impact of the servers failure on the main characteristic of the performance measures.

In conclusion, the aim of this thesis is to interconnect two type of retrial queueing systems with regards to the cognitive radio technology. This was inspired from previous related works that evaluate the performance of this



kind of systems by using theoretical methods. A simulation program was built that allowed us to analyze the performance of the system dealing with general situation by allowing the non-exponential distribution. By the help of SimPack and simulation program, several sample examples were obtained by illustrating the effect of the distribution of the inter-events times on the first and second moments of the response times.



# 6

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# MY PUBLICATIONS

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## 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,  
(**2016**), pp. 64-73, 2016.
- J2 Nemouchi, H., and Sztrik, J.,  
*Performance Simulation of Non-reliable Servers in Finite-Source Cognitive Radio Networks with Collision,*  
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- 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, (**2019**), pp. 702-711.

Software developed during PhD:

- *Simulation programs*: Based on SimPack with C/C++ language

# MY PUBLICATIONS

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- C1 Sztrik, J., Bérczes, T., Nemouchi, H., and Melikov A.Z.,  
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