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Performance of Joint Interference and Data Buffer Management for Cognitive Radio

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Master of Science in Electronics
Submission date: June 2010
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Problem Description

Resource and noise control within Cognitive Network based on network sensing. The student will evaluate algorithms for system optimalization using Matlab.

Assignment given: 01. February 2010
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Abstract

Cognitive Radio is a technology where Software Defined Radio functionality is augmented in order to permit a radio system where its operations will be adjusted depending on the environment. This capability offers a variety of benefits, first of all to solve the problem of spectrum scarcity.

This Master's thesis proposes a solution based on sensing interference and data queue back-pressure. For this purpose, a Matlab simulator has been done to simulate some scenarios and prove the theory in a practical way. The thesis has shown how sensors can be used to listen to the mutual interference between Primary System and a Secondary System. The results show how sensors are important for two such different systems to be working at the same time in the same frequency.

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Chapter 1

Problem Description

1.1 Introduction

This first chapter of the Master Thesis provides an overview of the importance of the radio spectrum in communication systems. It begins by explaining in basic terms what is a radio spectrum, the scarcity of the spectrum for new applications, which factors have done the scarcity and which the possible solutions are.

The radio spectrum is what makes possible wireless communication of all sorts. It is used for a wide range of economic, social, scientific and developmental purposes and services.

Unlike oil or water, the spectrum will never run out, it will always be the same, although it may become increasingly congested. In fact, because the spectrum has so many uses, them in cases of shortage, can be difficult.

Historically, accessing and using radio spectrum has been highly regulated in order to prevent interference among various users in adjacent frequency band. There is now a growing consensus that the past and current regulatory practices have delayed the introduction and growth of beneficial technologies and it caused what is known as a “spectrum drought”.

As new technologies that depend on the radio spectrum continue to be developed and used more widely, the need of managing the spectrum has grown increasingly notoriously. The radio spectrum can become congested if too many users operate on it, in an uncoordinated manner.

Spectrum management is an extremely important part of telecommunications policy and regulation. The spectrum is allocated for a particular users and specific technical and services rules, developed by spectrum managers who govern those allocations. In addition, spectrum has no geographical boundaries, the domestic management is close tied to international agreements on spectrum use. Therefore, the radio spectrum must be carefully managed, both on international and national levels to meet the needs of a constantly increasing variety of services and users.

1.2 Background

From [10, 1, 4]papers, it can be said that the spectrum is:

From an economic point of view, the spectrum is a resource used by a wide range of entities, including public services such as defence or emergency services. Using a large number of applications, including narrow and broadband mobile telecommunications, broadcasting, aeronautical and marine communications and scientific applications such as radio astronomy and environmental sensing.

From a technical point of view, the radio spectrum is the portion of the electromagnetic spectrum that carries radio waves. The boundaries of the radio spectrum are defined by the frequencies of the transmitted signals, and are usually considered to be in a range from 9 kHz to 3000 GHz.

The key characteristics of the spectrum are the propagation features and the amount of information which signals can carry. In general, signals sent using higher frequencies reach shorter distances but have a higher information-carrying capacity. These physical characteristics of the spectrum limit are currently identified in a range of applications for which any particular frequency band is suitable.

Although the radio spectrum spans nearly 300 billion frequencies, 90 percent of its use is concentrated in the 1 percent of frequencies that are below 3.1GHz. The fact that this region is used most intensely is (crowding in this region has occurred) because these frequencies have properties that are suitable for many important wireless technologies, such as phones, radios and TV broadcasting.

As a resource, from [10] the spectrum has both economic and technical dimensions:

- Economically, efficient use of the spectrum, as a starting point, means the maximization of the value of outputs produced from available spectrum. This includes the valuation of public outputs provided by the government or other public authorities.
- Technically, efficient use of the spectrum, at a basic level, implies the fullest possible use of all available spectrum. Two measures of technical efficiency are occupancy and data rate. Time, for example, can be used as a measure of technical efficiency, in the sense of how constant or how heavy the usage of the spectrum is over time. Data rate means how much data and information can be transmitted for a given amount of spectrum capacity.

The process known as Spectrum allocation has been adopted, both domestically and internationally, as by means of apportioning frequencies among the various types of uses and users of wireless services and for preventing radio congestion, which could lead to interference. Interference occurs when a radio signal of two or more users interact in a manner that disrupts the transmission and reception of messages, Spectrum allocation involves segmenting the radio spectrum into bands of frequencies that are designated for use by particular types of radio services or classes of users, such as broadcast TV and satellites.

Over the years, the US has designated hundreds of frequency bands of numerous types of wireless. Within these bands, governments, commercial, scientific, and amateur users receive specific frequency assignments or licenses for their wireless operations. The equipment they used is designed to operate on these frequencies.

During the last 50 years, developments in wireless technology have opened up additional usable frequencies, reduced the potential for interference, and improved the efficiency of transmission through various techniques, such as reducing the amount of spectrum needed to send information.

While this has helped limit congestion within the radio spectrum, there is still a great competition for additional spectrum (remains high). Wireless services have become a criticall situation, due to the extraordinary growth of the consumers market for wireless services.

1.3 Spectrum Allocations

Since nearly all of the usable radio spectrum has been allocated already, accommodating more services and users often involves redefining spectrum allocations.

One method, spectrum “Sharing”, enables others than the user to transmit radio signals on the same frequency band. In a shared allocation, a distinction is made to which user has “primary” or priority use of a frequency, and which user has “secondary” status, meaning it must defer to the primary user. Users may also be designated as “co-primary” in which the first operators obtain authority to use the spectrum has priority to use the frequency over another primary operator.

Another method to accommodate new users and technologies is “band-clearing” or re-classifying a band of spectrum from one set of radio services and users to another. This requires moving previously authorized users to a different band. Band clearing decisions affecting either non-federal or federal users are managed within FCC or NTIA respectively, albeit sometimes with difficulty. However, band clearing decisions that involve radio services of both types of users, present a great challenge.[10]

Chapter 2

Cognitive Radio “as a solution”

2.1 Defining “Cognitive Radio Concept”

The term “Cognitive Radio” appeared for the first time in 1999 defined by Josep Mitola III in “Cognitive Radio for Flexible Multimedia Communications” as “A radio that employs model based reasoning to achieve a specified level of competence in radio-related domains”.

The Federal Communication Commission, as the entity that regulates the operations of transmitters, has defined cognitive radio as “A radio that can change its transmitters parameters based on interaction with the environment in which it operates”.

From the international spectrum regulatory community in the context of the ITU Wp8A document, defines cognitive radio as “A radio or system that senses and is aware of its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly”.

The IEEE USA defined cognitive radio as “A radio frequency transmitter/receiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use, and jump into the temporally-unused spectrum very rapidly, without interfering with the transmissions of the other authorized users”.

There are several general points or capabilities from the definitions that can be extracted for the Cognitive Radio concept:

1. Observation – Cognitive Radio system can acquire information of the environment where it is operating.
2. Adaptability – Cognitive Radio system can change its parameters automatically, depending of the environment.

3. Intelligence – Cognitive Radio has enough intelligence to make decisions in a certain moment.

2.2 Introduction

Nowadays there is many research and investigation by many industrial organizations and national administrations on the closely related topics of dynamic spectrum management, flexible spectrum use, dynamic channel assignment, and opportunistic spectrum management.

Cognitive radio and the closely related technologies of policy-based adaptive radio, software defined radio, software controlled radio and reconfigurable radio enabling technologies to implement these new spectrum management and usage paradigms.

A more efficient use of the spectrum has a benefit associated with C. R. and the closely related technologies, like policy-based adaptive radio. To be able to achieve this benefit, it is necessary for these advanced radios to be controlled in such a way that underutilized portions of the spectrum can be utilized more efficiently. This has been called opportunistic spectrum management.

The methods of control needed to achieve opportunistic spectrum management are a network issue as well as a radio issue. Network control of these advanced radios includes control of the configuration of the radio, the RF operating parameters, and also regulatory policies. [3]

2.3 The Cognitive Domain

The cognitive domain is based on what is called a Cognitive Engine, which controls the Software Defined Radio (SDR) and receives feedback from it. The Cognitive Engine works according to a series of rules, these consist in monitoring diverse aspects of its environment, making decisions about what changes have to be made and evaluating the results. Since this is the main part, it has been placed in the centre of the schematic but noting that the model that is shown is functional, and has no relation to the physical modularity of the system.

The main purpose of the radio system is to achieve a certain goal, set or mission. The characteristics of those missions are shown in the box labelled “Mission/Goals/Objectives”. In box marked as “Operations”, all of the technical capabilities and state information about the equipment and the operating environment are placed. Further considerations about the system have to be acknowledged and therefore are placed in the box labelled “Imposed Constrains”.

Connected directly to the Cognitive Engine is the Software Defined Radio (SDR), due to the need of controlling the SDR to be able to optimize all the values and operations. All of these elements together build up to what is called the Cognitive Radio, and will be explained in the following sections. [7]

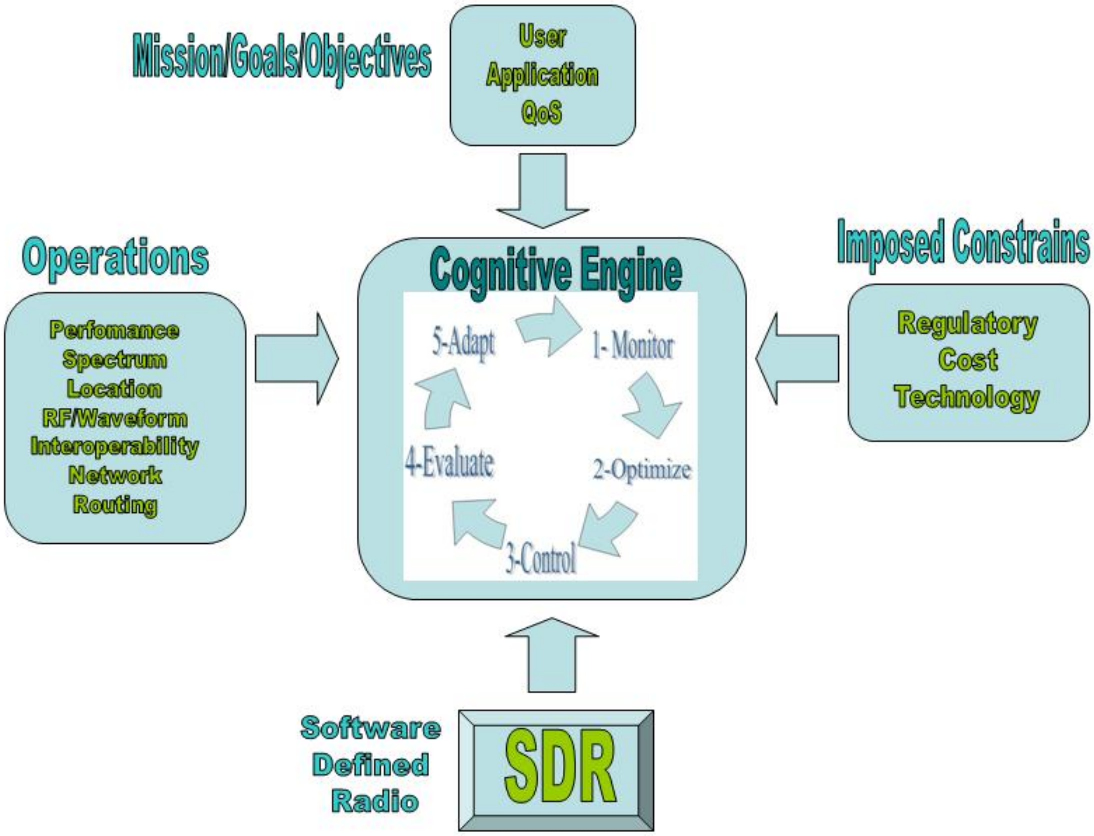

Figure 2.1: Cognitive Domain

2.3.1 Operations

The contents of the operation box are parameters that use both, the characteristics of the radio and the architecture of the system.

Performance

The performance parameter takes into account the equipment capabilities and current operating variables, like battery condition and buffer availability. The Cognitive Engine uses the information of these characteristics for optimizing system performance. For example, a status of low battery might lead to a decision to operate slower to keep critical data flowing longer. The performance levels have to be known by the system to be able to adjust its operation parameters such as power and buffer size, and also optimize that performance.

Spectrum

To improve spectrum utilization is one of the most promising capabilities of Cognitive Radio. Unused spectrum has proven to be a good treat due to fixed and inflexible allocations. Cognitive Radio offers the potential to monitor spectrum and also to configure the radio to make use of available spectrum, avoiding interference with others systems or services, and accessing when it is needed by higher priority traffic. There are several rules applied to licensed channels and unlicensed spectrum, and these rules permit Cognitive Radio to operate in either.

Location

A different feature of Cognitive Radio is maintaining information about where the system is located. Location is known by terrestrial applications in relation to other communication nodes or networks, and keeping in mind political considerations of the country of operation, local jurisdictions, and relevant regulatory authority.

Interoperability

Communications systems in the previous time were a number of incompatible radio systems, because they were designed for specific requirements or user communities. SDR's on the other hand, offer the possibility of joining two incompatible radio systems with different waveforms to be able to operate together, as a bridge across them. Cognitive Radios have the capability of making decisions about the operating details of interoperability, and to diffuse information needed for secure operation between different systems.

Network routing

There is a new capability that permits a group of radio systems to organize themselves into ad-hoc networks and optimize the flow of information between network members. The Cognitive Engine plays an important role in organizing the communication needed to maintain good performance, capacity optimization, and assured connectivity in these systems.[7]

2.3.2 Mission/Goals/Objectives

The goal of a radio system is to achieve some objective or service which radio system is set to work on.

This element of the Cognitive Radio domain considers the objective or mission aspect of Cognitive Engine utilization.

User

Users are both sources and sinks from the information point of view. Source data varies from voice communication to the state of a fireman's breathing gas supply. Sink behaviour of the user ranges from passive television watching to issuance of military orders during combat. User needs are constantly changing, in other words dynamic; therefore they may change rapidly during operation.

Cognitive Radio has the purpose to support the user by instantiating connectivity and by providing certain levels of flexibility and functionality so that the user interface ends up being easier to use. It should provide the information needed by the user in a timely fashion and a noncomplex to use form, therefore the user interface is of primal concern. In normal operation the user interface is unobtrusive, but it can give feedback to the user regarding the actual state of the system. The user can also conveniently request to receive more or less information, or to be regularly updated on the state of a particular parameter or variable of special interest.

Application The application is the context within which the Cognitive

Radio understands what the user wants and needs, and operates to develop and present needed information. There are mainly two aspects of Cognitive Radio operation: One of them is functionality, which is associated with the operation of the radio itself, and the other one is the execution of the application programs to provide support desired by the user. Multiple applications will frequently coexist in a Cognitive Radio. The radio responds to both the input from the user and changes in the environment to activate applications.

QoS If several application programs are in operation, the Cognitive Radio

will often lead to a mixture of data with needs of all sorts. Voice and streaming video need to have continuity of service with consistent information flow. If it's too slow it will lead to gaps in the picture, while too much speed could lead to buffer overflow. Data transfer has a small need for a consistent rate of transferring in which case it can often be prioritized and some elements postponed if circuits are too busy.

To reserve capacity is needed to handle peak loads and maintain response time. The Cognitive Engine requires knowing the operating mix and how much operating margin exists. It can also choose alternative routing if the case of overloading and congestion are encountered. [7]

2.3.3 Imposed Constrains

Some constraints are established by the external environment, regulatory considerations, financial factors, technological limits, and decisions made during the system design.

Regulatory

To maintain order in the use of spectrum, any emitted RF energy is subject to restrictions that are imposed by government agencies. This operation could require a license. Usually the operation is subject to radiated power restrictions. The rule base contains information derived from currently imposed operational constraints.

Cost Radio systems are built taking into account costs that may limit the

performance of the unit. During the design period, tradeoffs are made between the range of available reactions and system cost. The need of controlling equipment cost may result in choices that compromise certain aspects of performance or functionality.

Cognitive Radio systems also frequently interact with other networks, commercial services for instance, that oblige other charges for traffic. The total cost of alternative routings can be included as part of the optimization criteria.

Technology

Something to keep in mind at the time a design is finalized is the technological evolution. The design cannot easily be modified in the field for a particular radio model, but will almost surely be different for the following generations. In occasions design modularity can be used to make storage for technological developments, and the rate of appearance of new technology often influences when engineering for a new version is carried out.[7]

2.3.4 The Cognitive Engine

The Cognitive Engine is the core of this Cognitive Radio model. During system initiation it starts with current Operations information, Constraints, and Objectives uses that information to update the Rule database. During operation mode, the Engine iterates frequently through its cycle, and generates control information to change the state of the radio.

Monitor

The Cognitive Engine gathers information from the radio, auxiliary transducers, environment, and the user. It keeps information of the current state, and is also aware of state changes.

Optimize

At standard intervals, or when activated by a state change, the Cognitive Engine develops updated solutions for radio configuration. At this point it tests to verify if the objective function values can be improved. The solution is done within the rules available in the Rules database, and at each iteration some of the data stored there may change.

Control

Taking the differences between current radio state and the new optimization as a starting line, the Cognitive Engine creates control data to advance in the direction of the desired state. Control data is then taken in its broadest sense; it may include information shown to the user through the user interface, changes in SDR performance, notification to a remote authority of status changes, or input to operational application programs.

Evaluate The influence of the control information is evaluated as an intrinsic

part of each iteration, and could involve additional state evaluation or changes to the rule base to gain knowledge. The concepts of control theory are called upon to maintain constant radio operation and avoid hunting, inappropriate feedback, or other pathological behaviour.

Adapt/learn Possible changes to the rule base are made in a rather slower

manner than the main control loop to be able to avoid unreliable behaviour. Response from the user is very important in learning; especially user interface feedback that indicates what information elements the user does or does not want to receive.

Cognitive Operation

By performing the iteration through the five steps of this loop, the Cognitive Engine is now ready for generating controls for the Software Defined Radio to optimize its performance, improve execution of the user's application objectives, and to fine-tune its own operation. In this stance, the reach of the cognitive mission is not limited to any subset of the benefits set forth in the list in before mentioned sections. It can be applied to any part of the domain. If, however, the Cognitive Engine is not involved with the RF performance of the associated Software Defined Radio, then the term Cognitive Radio is probably not the best suited, it should be, in any case, a cognitive system.[7]

2.4 Cognitive Radio Elements

2.4.1 Sensors

A cognitive radio requires current information regarding its awareness of its environment, its internal state, node capabilities, and current needs of its user. Environmental sensing may be local and self contained in a radio or remotely performed elsewhere in the network. In collaborative sensing for example, some other device or system collects information about a radios environment and that information may be relayed to the user's radio.

Spectrum sensing refers to the action of a wireless device measuring characteristics of received signals, which may include RF energy levels as part of the process of determining if a particular section of spectrum is occupied. Sensing in the spectrum domain is the detection of some signal features indicating the presence (or absence) of other users/services. These can include signal energy, periodic features (pilots, preambles, chip rates), likely identity of the other users/services, estimation of interference-tolerance capabilities and estimation of the duration of spectrum occupancy.[5]

2.4.2 Primary Users (PU)

Primary users are defined as an entity that legally owns some frequency band (F-Band). Primary users are not cognitive radio aware. There are no ways to exchange information between Primary and Secondary users provided by a primary system. Especially, Primary users do not provide special signalling in order to acces their frequency.[6]

2.4.3 Secondary Users (SU)

Secondary users are defined as an entity that wants to acquire unused spectrum of license owners (PUs) for its communication. These Secondary users have the Cognitive Radio techniques. Cognitive unaware Secondary users are treated as noise by the Primary user system.[6]

2.5 Cognitive Radio Benefits

From [5], the following list indicates functional advances enabled by Cognitive Radio:

- Find spectrum that is currently available for use
- Decide what waveform to instantiate
- Broker for service among competing suppliers
- Monitor the local area and the radio's own operation for regulatory compliance
- Adapt radio operation for radio state and environmental conditions
- Learn from actions taken in the current context to adapt and improve future operation
- Provide location awareness
- Avoid contention with known licensed users in a given geographical area

- Adapt radio operation to provide interoperability with other radio systems
- Develop actions necessary to bridge between incompatible systems
- Interact with central authority to obtain authentication materials to permit secure operation

Chapter 3

COGNITIVE RADIO SOLUTION "A Possible Cognitive Radio Solution Based on Sensing the Interference and Data Queue Back-Pressure Approach"

3.1 Introduction

First of all, the radio spectrum problem has been explained in Chapter 1, and Cognitive Radio has been presented as a solution in Chapter 2. Now, an approach based on sensing interference and data queue back-pressure for Cognitive Radio is going to be explained in this chapter.

This approach is based on the studu of back-pressure framework to solve the problem which is explained in [Kimmo Papers]. For that purpose, a Matlab simulator program has been implemented, which tries to recreate several scenarios, and study how this approach can help to solve the radio spectrum problem in a real situation. This simulator is based on several equations and expressions that will be explained in the nexts points, and its functionality and code can be found in Appendix A.

Some assumptions have been considered for doing the simulator which simplifies the problem and tries to help to understand in which context the simulator is going to work.

In addition, to understand how the simulator works, a Simple Model is presented, where its functionality and expected results are explained, too. Then another model is shown, a General Model, where the interaction between a real system and Secondary System is studied. Some questions are presented to see the behavior of the design simulator.

Finally, the functions and equations that follow the system are explained.

3.2 Assumptions

There are various assumptions made in this report:

General Assumptions:

- The System uses Time Division Multiple Access (TDMA-FDD).
- The system is thought to work in a Narrow Band, but the algorithms are implemented to work in Broad band, as well.
- A control channel is considered for signalling between the secondary system elements.
- There will be as many communication channels as then number of frequencies considered in the system.

Propagation environment:

- The channel is located in a high density area, where there are a lot of objects creating many paths (multipath) from the transmitter to the receiver, without any line of sight (LOS) between them. Rayleigh fading distribution is assumed for these channels.
- AWGN channels are considered.
- "Time Correlation": the system has a frame of work, composed by two function models, Silent Period and Busy Period, that is repeated in every iteration of the system.
  - There are two types of measurement of the propagation environment in a particular frame:
    - During "Silent Period measure", the time of measurement is considered short, so the path loss, long term fading and short term fading are assumed constant.
    - During "Busy Period measure", the path loss, long term fading will be constant, but the short term fading will change.
- "Frequency Correlation": it is assumed that channels with different frequencies are uncorrelated.

- “Spatial Correlation”: it is assumed that users placements are big enough to consider spatial uncorrelated channels.

Primary System:

- It is assumed that there will be just one receiver per cell. It means that will be just one primary system per cell, composed by one receiver and several transmitters.
- Unicast communication is considered at the primary system, between the primary transmitters and the primary receiver.
- Transmit power at the Primary transmitters are constant.

Secondary System:

- It is assumed that there will be just one receiver per cell. This means that there will be just only one secondary system per cell, composed by one receiver and several transmitters.
- Unicast communication is considered at the secondary system, between the secondary transmitters and the secondary receiver.
- Adaptive methods are considered for allocated power at the secondary transmitters, depending on the environment.
- Secondary transmitters will know the communication channel between themselves and the secondary receiver.
- Data buffers are implemented in the different transmitters. With a constant maximum size.

Sensors:

- Sensors only have to measure the power of the received signal. A focus in this project is not looking for new holes of frequency, because the frequencies that are going to be used in the Secondary System are the same as those the Primary System uses.
- No additional signal processing is considered by the Sensors.

Positions:

- Movements are not considered by the elements, i.e. the elements will be fixed during the whole simulation.
- The primary receiver is set in the middle of the cell, so the rest of the elements use its position as a reference point.
- Several methods are implemented in order to place the elements at the scenario as fixed, random, and cellular distribution.

3.3 Simple Model

The Simple Model that is considered, it is shown in the figure 3.1. Where there are several elements, such as a transmitter-receiver pair of a Primary System, two transmitters and a receiver of a Secondary System, a Sensor and the Fusion Center.

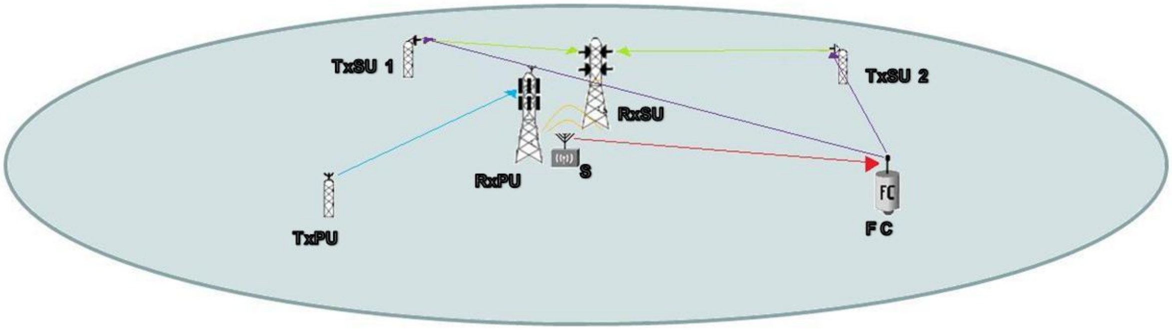

Figure 3.1: Simple Model Scenario

According to Radio Cognitive system, the primary system uses its own licensed frequency. Primary users are not cognitive-aware, i.e. There are no ways to exchange information between primary and secondary users provided by a primary system. On the other hand, the secondary system is an entity that wants to acquire unused spectrum of licensed owners (Primary users) for its communication, but in this case, the secondary system uses the same spectrum as primary users..

Also, instead of these two systems, primary and secondary, another entity appears, the sensor. The sensor has the responsibility of managing the measurement of the interference produced by the secondary system in the Primary receiver user. For that purpose, the sensor has to be close enough to the primary receiver, so it can be assumed that the sensor and the primary receiver have the same statistics on the propagation environment, and it can be said they have the same signal strength, and the measured interference might be the same as at the primary receiver.

Moreover, the entity that has to manage the secondary system and its interference is the Fusion Center (FC), as a centralized system.

With the interference measurement values given by the sensor, the FC has the function to allocate the best suitable power for the secondary transmitter, for avoiding interferences, or being less interferent to the primary system.

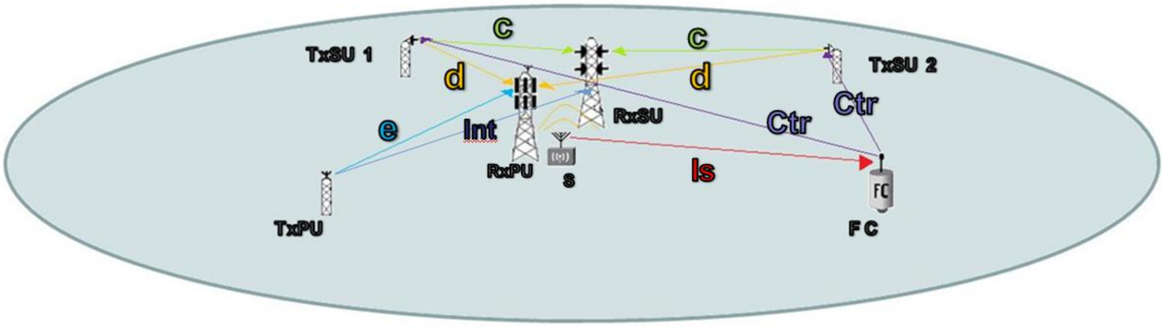

Figure 3.2: Simple Model Channels

In addition to the elements, there are several channels of communication between the elements, as:

- Channel "c", is the channel between the transmitter-receiver pair of the Secondary System. Through this channel, the secondary transmitter will send the data information to the secondary receiver.
- Channel "e", is the channel between the transmitter-receiver pair of the Primary System. This channel tries to model the communication channel between "TxPU-RxPU".
- "Int" and "d" are the interference channels. The first one is the interference channel between "TxPU-RxSU" and the other interference channel is between "TxSU-RxPU".
- There are also two more channels; the channel between the Sensor and Fusion Center, "Is", and the channel between Fusion Center and TxSU, "Ctr".

Once the elements set in the figure are known, their function has to be explained.

Sensors

As explained in "Spectrum Sensing", the sensors are wireless devices that focus on measuring the characteristics of the received signals, look for new holes in frequency where is possible to see a Cognitive channel communication, and detect the presence of users/services in the frequency that is being used at the moment of the transmission.

In this simple model, the functionality of the sensors is as basic as possible. Sensors only have to measure the power of the received signal. A focus in this project is not looking for new holes of frequency, because the frequencies that are going to be used in the Secondary System, are the same as those the Primary System uses.

To determine the interference level in the system at each moment, there has been implemented two periods of work in the program.

Figure 3.3: SP-BP Timing

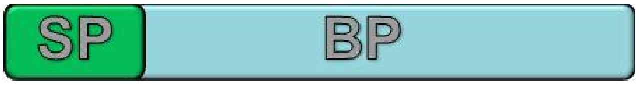

Figure 3.4: SP-BP Frame

The first one will be the “Silent Period”; in this period the primary system will be studied, i.e. the sensor will measure the level of power that is received from the primary transmitter. As it has been said, the sensor and RxPU are close enough, so they have the same statistics on the propagation channel.

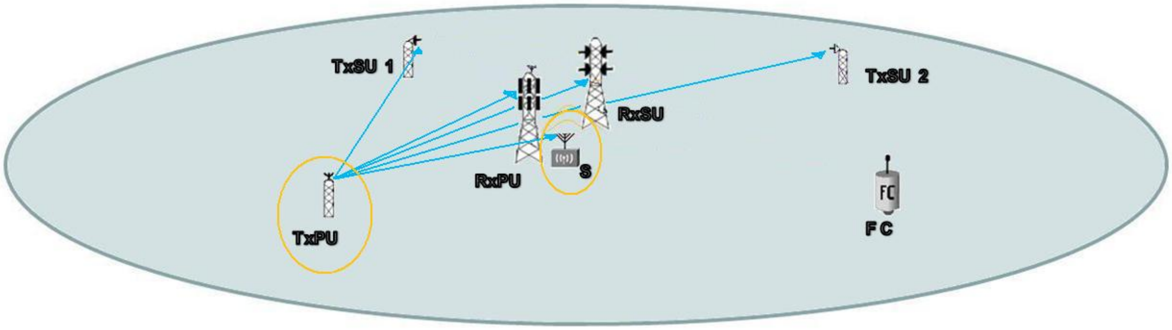

Figure 3.5: Silent Period Scenario

On the other hand the second period will be the “Busy Period”. In this period, the sensors listens the whole system, i.e. the sensor will measure the level of power that is received from the primary and secondary transmitter, once the fusion center has allocated the power to the secondary transmitter. The difference between the BP and SP power measurement will be the level of interference power. The sensor will send this value to the fusion center for forward assignments.

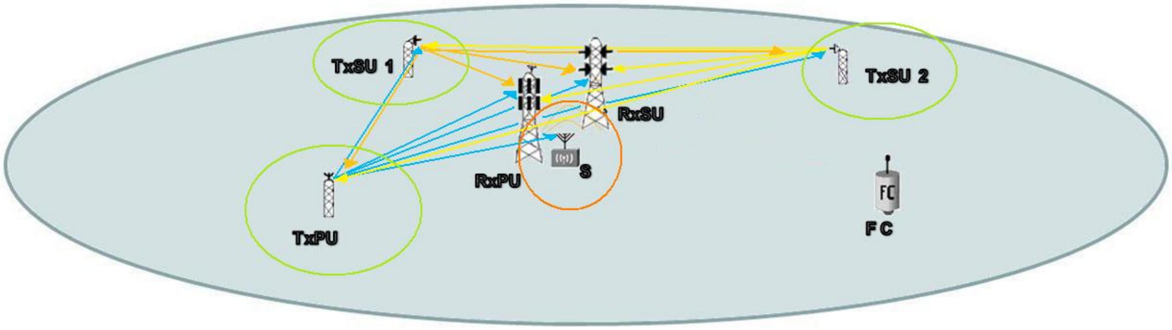

Figure 3.6: Busy Period Scenario

Secondary Transmitter

As it is a unicast communication system, the secondary transmitter will send its packets when the Fusion Center chooses to send them. The secondary transmitters generate data packets with a length and arrival probability establishment, as the initial settings of the system, which tries to recreate a typical behavior of a real transmitter.

As the real transmitter, secondary transmitters have a data queue with a particular length, “V”. An admission protocol has to be implemented if the data queue is full, and no more packets can be stored. The admission protocol that is implemented is “dropping packets”; it means that if the data queue is full no more packets are admitted, so these packets are lost.

Internally, the transmitters know its channel estimation “c”, and the factor “No+Int” that the receiver receives. This is an important assumption in this thesis, because as it is a unicast communication, there is non-exchange information between the transmitter and receiver. But there are several techniques that try to estimate the channel between the transmitter and receiver. With this information the transmitter can obtain its SNR. These two values, the data queue length and the SNR, have to be sent to the Fusion Center through the control channel

As a System close to the reality, quantification methods have been implemented to send the data queue length signal. It is important to emphasize that the more bits allocates, the most closen is the measure to the real value. As it is not allowed to send an infinitive number of bits, the proper number of bits it has to be known to the property performance of the system, depending on the data queue’s length.

Fusion Center

The Fusion Center (FC), as the brain of the system, will have several parameters, such as input parameters, pre-establish parameters as initial settings, and output parameters. As said previously, the input parameters will be the value of the system interference. For this simple case, it will be only one value, because there is only one sensor, monitoring the system, but if the system grows, more sensors will be needed and the fusion center will receive the interference measurements as the sensors do.

With these values, the fusion center will create an interference memory where all the measurements will be stored according the number of secondary transmitters. As the fusion center knows which secondary transmitter is transmitting, the FC will know the interference this transmitter is producing (i.e. Monitoring the System).

In addition to the interference values, communication between TxSU and FC is needed. The Fusion Center has to know if the transmitters have data to send, as a centralized model, and has to know all the parameters in every moment to manage the system. For that reason, the Transmitter will send the data queue value and the channel estimation "c" between the Transmitter and the Receiver. The Fusion Center will use these values in the best user selection process, which will be explained later (i.e. Control the system).

The initial settings are those parameters that the system needs for its correct function ability. It will be needed before the simulation, such as "X_{av}" for the interference queues, number of primary and secondary transmitters, number of Sensors, peak power constraint, etc.

With all these parameters, the FC will decide which user is the best suitable to transmit each moment at, and also the best suitable power for transmission. The user selection Process is a process that takes into account the channel state, the length of the data queue and the interferences that each user produces. It will be explained in the point #,# (i.e. Evaluate).

When the fusion center chooses the best user, FC will send the transmit order to the select user and the power that it has to utilize. If there are more than one user, and they do not receive the transmit order, they will continue to send its parameters in the property time.

Once the transmitter is selected and its power is allocated, the secondary transmitter will have all the busy period to transmit its data. The time of the Busy Period is an estimation of time, and depends on the syste. This time is known for the whole Secondary System.

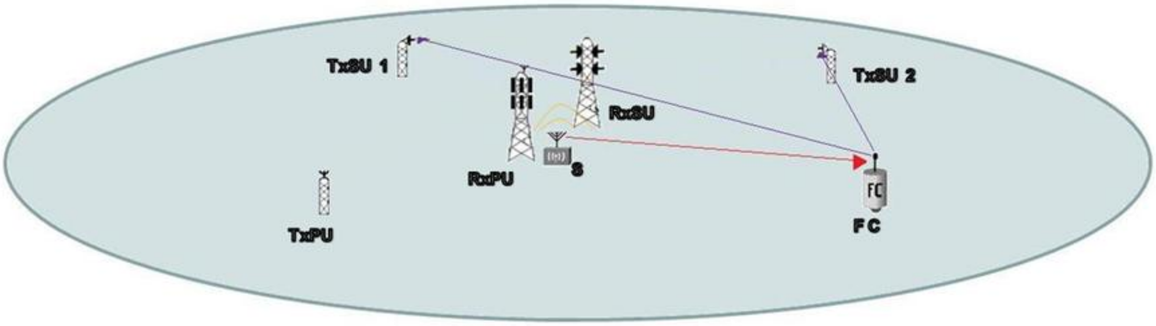

Figure 3.7: Fusion Center Signally

Secondary Receiver

The secondary receiver will be an entity that receives the data information from the secondary transmitter. No futher functionality has been implemented for them.

Control Channel

All the siganlling will send in other channel that will be called "Control Channel". Iit will be different from the channel that is used for sending data packets, i.e. different frequency.

Finally, with this short description, it can be shown that the system fulfill all the points mentioned in 2.4. Where FC monitors, optimizes, evalues, and adapts the system.

3.4 General Model

The second model that is considered, is the General Model. The General model is going to be used for studying how the system can be implemented in a real situation, i.e. in a system where there is a primary system working with several primary transmitters.

As it is desirable to be close to the reality, the primary receiverçs place is going to be used to set the secondary receiver. Once the receiver is placed, the sensor network has to be placed around the primary receiver as a mesh and in the same place of the primary receiver base station. One example scenario that is considered is:

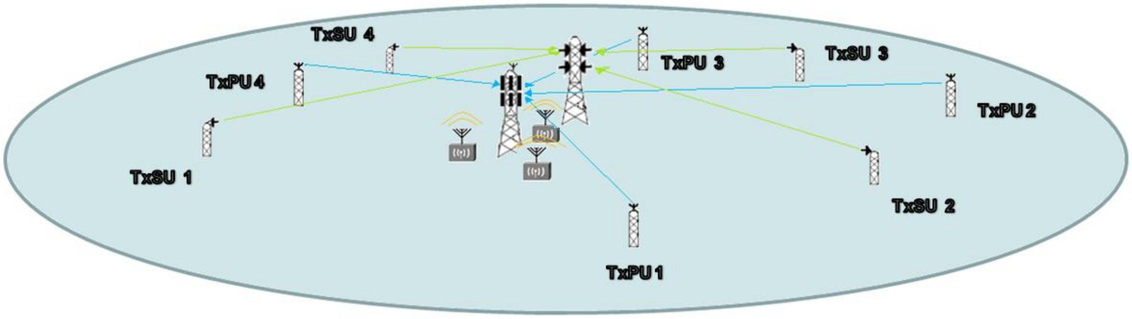

Figure 3.8: Real Scenario

The sensor network is placed as a mesh, because it is the best way to have knowledge and monitor the interference of the system. The functionality of the sensor, in this case, is to measure the power that the sensor receives in the different periods, silent and busy periods, for obtaining the interference value. But it is thought that the sensor could have other applications, and could be more intelligent in future developments.

The functionality of this second model is similar to the simple model, but there are several innovations that have been considered. One of them is the possibility of using more than one frequency in order to transmit data information at the same time. These frequencies are used by the primary system as well, but it can be used to increase the number of secondary transmitters users and be more close to the reality. The Fusion center will decide who the best user is at each moment for each frequency, but no one can transmit in more than one frequency at the same time. For that reason, each user has to send his data queue value to the fusion center, and the channel estimation for each frequency that are available to be sent. The sensor will send the interference value for each frequency as well.

In order to recreate a real scenario, the different parameters are going to be changed to see the different effects and its behavior, and they will be compared with the simple model results.

There are some questions, like:

- Which is the power that is going to be allocated depending of the number of users?
- How is the behavior of the system depending on the data queue length, bit per packet, or probability?
- How is the behavior of the system depending on the number of quantification bits in the data queue?

- How many secondary transmitters can support the system with one frequency? And with more frequencies?
- How can the number of primary transmitters affect the system, and its position at the scenario?

3.5 Channel Characterization

In this subsection, the propagation mechanisms are going to be explained.

The wireless radio channel has a severe challenge as a way of reliable high-speed communication. It is susceptible of noise, interference, and other channel impediments which can also change over time in unpredictable ways, because of users' movement or environment dynamics.

Signal propagation can be described by three mechanisms, differentiated by the considered path length (spatial scale).

For large distances, the propagation is characterized by the loss equation, where the average power received falls exponentially when the distance increases.

For several hundred wave lengths distances, the average power is not constant, rather, it is distributed as a log-normal law. It is known as Long-term fading or Shadowing.

For tens wave lengths distances, the received signal envelope goes through rapid changes around the local media. It is known as Short-term fading or Fast fading.

The basic characterization of a mobile channel that is considered can be obtained through the path loss, the short term fading, and long term fading.

$$L = P + S + F(dB\text{'}s)$$

Where,

- L = Path losses
- P = Plane earth losses
- S = Long term fading
- F = Short term fading

For the simulations, it is considered that the path lost and long-term fading are going to be constant during the simulation of the scenario. However, the Short-term fading will change every time instant during the simulation. And the elements at the scenario are fixed, i.e. there are no movements for the elements.

From [?] defines the following propagation mechanism as:

3.5.1 Path loss

The path loss between a pair of antennas is the ratio of the transmitted power to the received power, usually expressed in decibels. It includes all of the elements of loss associated to the interactions between the propagating wave and all the objects between the transmitted and the received antennas.

In order to define the path loss properly, the losses and gains in the system have to be considered. The elements of a simple wireless link are shown in the next equation. The power appearing at the receiver input terminals, *Pr*, can be expressed as

$$Pr = \frac{P_T \cdot G_T G_R}{L_T \cdot L \cdot L_R}$$

Where the parameters are showed in the next diagram: 1.

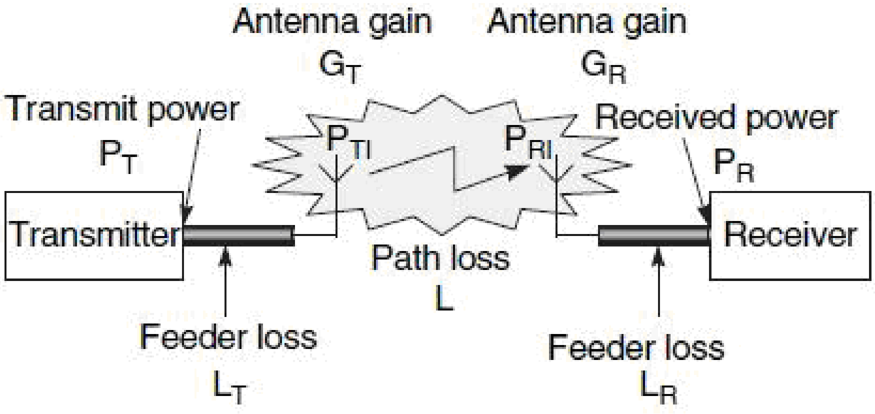

Figure 3.9: Path Loss diagram[9]

The antenna gains are expressed with reference to an isotropic antenna, which radiates the power equally in all directions. The effective isotropic radiated power (*EIRP*) and the effective isotropic received power (P_{RI}) are given by these formulas:

$$EIRP = \frac{P_T \cdot G_T}{L_T \cdot} = P_{TI}$$

$$P_{RI} = \frac{P_R \cdot L_R}{G_R}$$

The advantages of expressing the power un terms of *EIRP* is that the path loss, L, can then be expressed independently of systems parameters by defining it as the radio between the transmitted and the received *EIRP*:

$$Path\,Loss,\ L = \frac{P_{TI}}{P_{RI}} = \frac{P_T{\cdot}G_TG_R}{P_R{\cdot}L_TL_R}$$

3.5.1.1 Plane earth path loss

The propagation model that is considered is the Plane earth loss, and it is illustrated in the figure above. Here, the base and the mobile station antennas are situated above a flat reflecting ground (plane earth), at heights hb and hm, respectively.

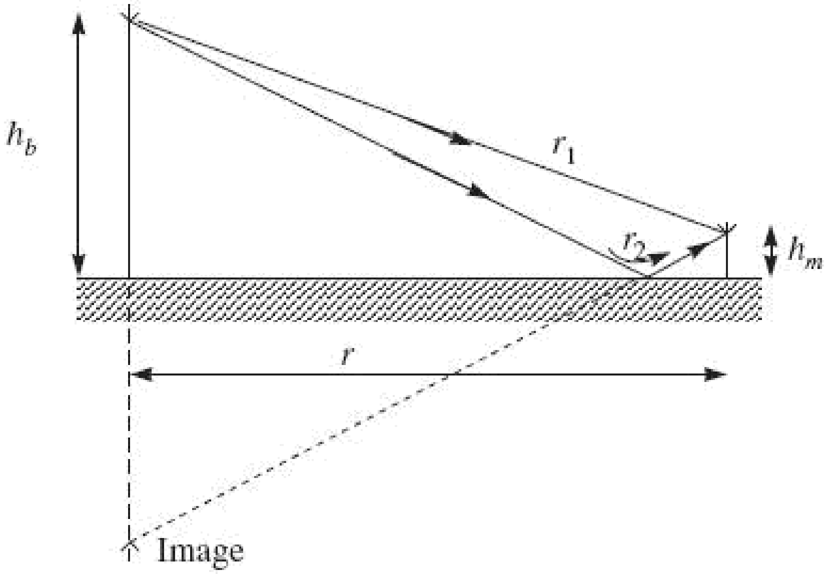

Figure 3.10: Plane Earth Loss diagram[9]

The two-ray model is used when a single ground reflection dominates the multipath effect. The received signal consists of two components: the LOS component or ray, which is just the transmitted signal propagating, thought the space, and a reflect component or ray, which is the transmitted signal reflected off the ground. These two paths sum at the receiver with a phase difference related to the difference in length between the two paths.

A simple way to analyze the situation is to make use of image theory, which considers the reflected ray as coming from an image of the transmitter in the ground, just as if the ground was a mirror. The different paths are given by The path length difference is then

$$(r_2 - r_1) = r\cdot \left[\sqrt{\left(\frac{h_m+h_b}{r}\right)^2 + 1} - \sqrt{\left(\frac{h_m+h_b}{r}\right)^2 + 1}\right]$$

Assuming the antenna heights are small compared with the total path length (hb,hm<<r), applying the binomial theorem, e the next approximation as a result is:

$$(r_2 - r_1) \approx \frac{2\cdot h_m\cdot h_b}{r}$$

Since the path length is large compared with the antenna heights, the arriving amplitudes of the waves are identical apart from the reflection loss, R. The overall amplitude of the result is then,

$$A_{total} = A_{direct} + A_{reflected} = A_{direct}\cdot \left|1 + R\cdot exp(j\cdot k\cdot \frac{2\cdot h_m\cdot h_b}{r})\right|$$

where k is the free space wave number.

Since the power is proportional to the amplitude squared, the next formula where P_{r} is the received power, can be written as,

$$\frac{P_r}{P_{direct}} = \left(\frac{A_{total}}{A_{direct}}\right)^2 = \left|1 + R\cdot exp(j\cdot k\cdot \frac{2\cdot h_m\cdot h_b}{r})\right|^2$$

The direct path is itself subjected to free space loss, so it can be expressed in terms of transmitted power, so the path loss can be expressed as

$$P_{direct} = P_T\cdot \left(\frac{\lambda}{4\pi r}\right)^2$$

$$\frac{Pr}{P_T} = \left(\frac{\lambda}{4\pi r}\right)^2 \cdot \left|1 + R\cdot exp(j\cdot k\cdot \frac{2\cdot h_m\cdot h_b}{r})\right|^2$$

Since the angle of incidence with the ground is close to grazing, the magnitude of the reflection coefficient will be close to one, whatever its conductivity or roughness.

It is further assumed that the signal always undergoes a phase change of 180, then R≈-1 and the result can be expressed as

$$\frac{Pr}{P_T} = 2\cdot \left(\frac{\lambda}{4\pi r}\right)^2 \left[1 - cos(k\cdot \frac{2\cdot h_m\cdot h_b}{r})\right]$$

3.5.2 Shadowing

Shadowing causes considerable variability about the mean power predicted by path loss. Because of the physical size of the obstacle that produces shadowing, the scale of significant variation is hundreds of wavelength, and the shadow effect is roughly constant over many tens of wavelengths. However, if we average the signal strength around a circular path centred on the based, including many shadowing occurrences, the familiar inverse cube or fourth power law reasserts itself.

The graph below shows that the shadowing produces fluctuations about an inverse third to fourth power path loss decrease. The fact that shadowing produces variations above and below, the path loss may be confusing, shadowing is an excess loss. The reason is simple; the path loss trend line is produced after the fact, as a best fit from measurements, so that the scatter is on both sides.

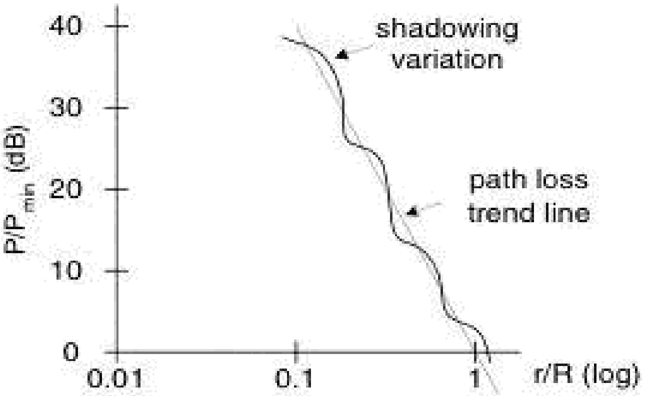

Figure 3.11: Shadowing vs Path Loss diagram[9]

Propagation studies usually conclude that shadowing loss is well described by a lognormal distribution: when expressed in dB, the mean is 0 dB and the standard deviation is typically 6 to 8 dB. There is a theoretical basis to the lognormal distribution in propagation studies: a typical signal has undergone several reflections or diffractions by the time it is received, each of which can be characterized by an attenuation, or multiplication. The result of these cascaded events is the sum of their in dB losses which, by the central limit theorem, tends to converge a normally distributed (Gaussian Distributed) random variable. In natural units (not dB's) this corresponds to a lognormal distribution. The probability density function (pdf) and the cumulative distribution function (cdf) are below respectively:

$$P_z\left(z\right) = \frac{1}{\sqrt{2 \cdot \pi}} \cdot e^{-\frac{z^2}{2}}$$

$$F_z(z) = \int_{-\infty}^{z} P_z(\gamma) \cdot d\gamma$$

Here we can see the plot of the PDF and CDF of the normal distribution for unit standard deviation.

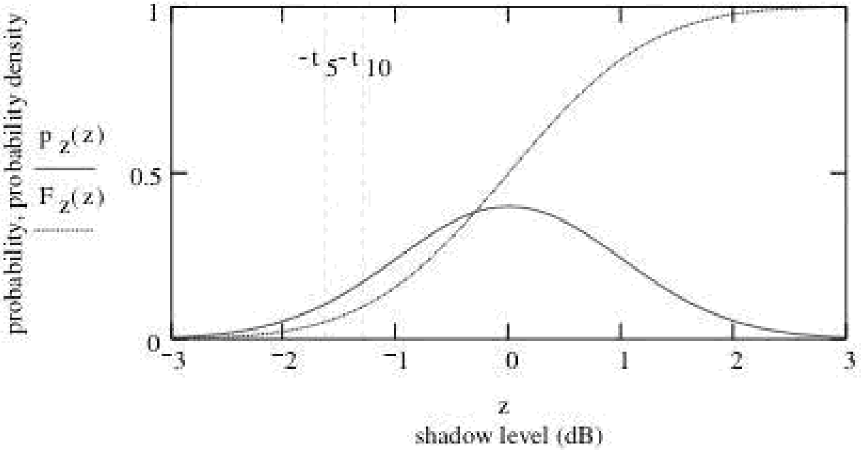

Figure 3.12: Probability, Probability density[9]

3.5.3 Multipath Fading/ Short term fading

3.5.3.1 Introduction

This kind of phenomenon appears in mobile communications, particularly in urban centers. The signal offered to the receiver, contains not only a direct line-of-sight radio wave, but also a large number of reflected radio waves. Even in some scenarios, like urban centers, line-of-sight is often blocked by obstacles, and a collection of differently waves is all what a mobile antennas receives.

These reflected waves interfere with the direct wave, which causes significant degradation of the performance of the link. If the antenna moves, the channel varies with location and time, because the relative phases of the reflected waves change. This is the meaning of fading: time variations of the received amplitude and phase.

In this case, short term fading, multipath fading or fast fading is related to the rate at which amplitude and phase fixed by the channel on the signal changes modifies.

Knowing all of this, it is possible to define fast fading like what occurs when the coherence time of the channel is small comparing it to the delay constraint of the channel. In this situation, the amplitude and phase change imposed by the channel varies considerably over the period of use.

In a fast fading channel is also possible to take advantage of the variations in the channel conditions, using time diversity to improve robustness of the channel in a temporary deep fade. Using an error-correcting code is recommended as well.

As the demand for mobile communications increases, basic models of fading had to be developed. In that way, Rayleigh or Rice distributions are used for modeling these effects, depending on the existence of a Line-of-Sight (LoS) component between the transmitter and the receiver. This approach is valid for narrow-band systems, whose bandwidth is much smaller, comparing it to the coherence bandwidth of the propagation channel.

3.5.3.2 Rayleigh Fading

The model that is considered in the System for modeling the Short term fading is the Rayleigh distribution.

The mobile antenna receives a large number of reflected and scattered waves. Because of wave cancellation effects, the instantaneous received power seen by a moving antenna becomes a random variable, dependent on the location of the antenna.

In this case, Rayleigh fading assumes that there is not line-of-sight amplitude. So many reflected and scattered waves can be a useful model in heavily built-up city centers, where there is no line-of-sight between the transmitter and receiver. Many buildings and other objects attenuate, reflect, refract and diffract the signal. Rayleigh distribution may also approximate tropospheric and ionospheric signal propagation.

Probability density function can be defined like this:

$$f\left(x;\sigma\right) = \frac{x}{\sigma^2}\cdot exp(\frac{-x^2}{2\cdot\sigma^2})$$

where $\sigma^2$is E(σ^2).

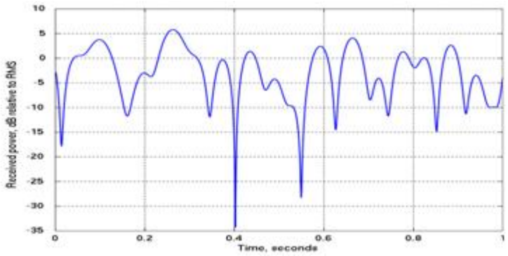

Figure 3.13: One second of Rayleigh fading with a maximum Doppler shift of 10 Hz

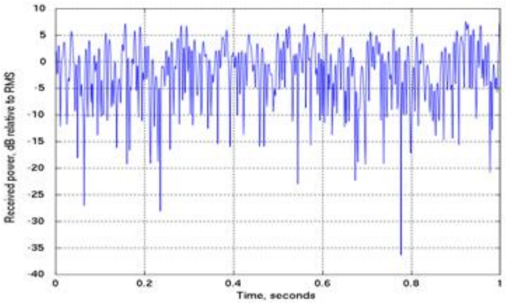

Figure 3.14: One second of Rayleigh fading with a maximum Doppler shift of 100 Hz

3.6 Methods

In this section, the different methods that the system uses and its functions are going to be explained.

3.6.1 The Arrival Process

The idea of the arrival process is to simulate a random arrival in the system to be transmitted.

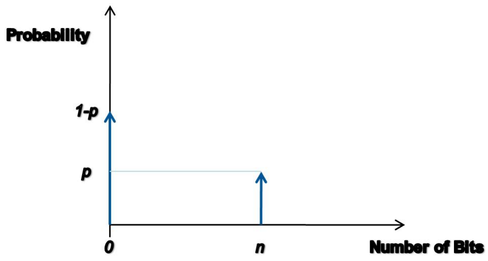

Figure 3.15: Bernoulli Distribution

The designed function has two different probabilities for arrival packets. Depending on the setting, the system will receive packets with a specific size (number of bits) or it will not receive any packets, as it can be seen in the figure. It has “n”, number of bits, and “p”, probability of arrival, as inputs.

3.6.2 Data Queue

The Data Queue is the transmit buffer for the Secondary Transmitter, and holds the size of the data queue at any given time. It has the arrival process Aq(t) as input, and depends on the transfer rate function r(t). The data queue‘s main purpose is to store the incoming data if it cannot be sent at that moment. The next value of the queue size is calculated with the following equation:

$$q(t+1) = \begin{cases} q(t) - r(t) + Aq(t) & if\, q(t) \geqq r(t) \\ Aq(t) & Otherwise \end{cases}$$

The queue would be stable,if and only if, the mean arrival is less or equal to the mean transmission data rate

3.6.3 Admission Protocol

An Admission Protocol is always needed in a Communication System, in order to maintain the correct behavior of the System. The admission Protocol that has been implemented is the “Dropping packets”, i.e. when the data queue is full no more packets are allowed to be stored, and these packets are lost.

3.6.4 The Interference Myaeasurement

The signal received at a general element is given by:

$$y(n) = c(n) \cdot x(n) + w(n)$$

Where:

- $c(n)$ is the channel state between the general element receiver and the transmitter.
- $x(n)$ is the transmitted signal.
- $w(n)$ is the AWGN noise, which is defined as

$$w \exists N(0, \sigma^2)$$

As known, the power of a signal x(n) is defined as:

$$P_x = \frac{1}{N} \cdot \sum_{n=1}^{N} |x(n)|^2$$

The signal power received at a general element, replacing (1) into (2), will be:

$$P_y = \frac{1}{N} \cdot \sum_{n=1}^{N} |y(n)|^2 = \frac{1}{N} \cdot \sum_{n=1}^{N} y(n) \cdot y^*(n) = c^2 \cdot \frac{1}{N} \cdot \sum_{n=1}^{N} x(n) \cdot x^*(n) + \sigma^2 = c^2 P_x + \sigma^2$$

Once the relationship between a signal and its power is known the interference measurement will be explained.

At the silent period, the sensor will only receive the contribution of the primary system, because the secondary system is not working at that moment. For that reason, the received signal at the sensor in the Silent Period is defined as:

$$y_{SP}(n) = e(n) \cdot x_{PU}(n) + w'(n)$$

Where:

- $e(n)$ is the cannel state between the primary transmitter and thwe sensor
- $X_{PU}(n)$ is the transmitted signal
- $w'(n)$ is AWGN, which is defined as

$$w \exists N(0, \sigma^2)$$

The receive power at the sensor, as shown previously, will be:

$$P_{SP} = \frac{1}{N} \cdot \sum_{n=1}^{N} |y_{SP}(n)|^2 = \frac{1}{N} \cdot \sum_{n=1}^{N} y_{SP}(n) \cdot y_{SP}^*(n)$$

$$= \frac{1}{N} \cdot \sum_{n=1}^{N} (e(n) \cdot x_{PU}(n) + w'(n)) + (e(n) \cdot x_{PU}(n) + w'(n))^*$$

$$= \frac{1}{N} \cdot \sum_{n=1}^{N} \left\{ (e(n) \cdot x_{PU}(n))^2 + 2 \cdot e(n) \cdot x_{PU}(n) + (w'(n))^2 \right\}$$

And the result is:

$$P_{SP} = e^2 P_{PU} + \sigma^2$$

Some assumptions have been considered like:

- $e(n)$ is constant during the whole sampling window.
- The second addition is close to zero, so it is possible to remove it

The received signal at the sensor in the Busy Period, where primary and secondary systems are working together, is defined as:

$$y_{BP}(n) = c(n) \cdot x_{SU}(n) + w''(n) + e(n) \cdot x_{PU}(n) \cdot e^{j\rho(\tau)}$$

In this case, note that the different signals are not in phase, so it is necessary to add a shift factor.

Applying the power equation to this new signal and taking the same assumptions into account , the following equation is obtained:

$$P_{BP} = c^2 P_{SU} + e^2 P_{PU} + \sigma^2 = c^2 P_{SU} + P_{SP}$$

Finally, the interference level denotes by I, can be obtained by the following subtraction:

$$I = c^2 P_{SU} \approxeq P_{BP} - P_{SP}$$

3.6.5 Interference Queue

The interference queue represents the cumulative deviation of the interference measurements in each sensor. The interference queue will be a vector of measurements where each element represents a sensor.

$$X(t+1) = \begin{cases} [X(t) - X_{av}]^{+} + I(t) & if\, X(t) > Xav \\ I(t) & if\, I(t) > Xmin\ \& X(t) < Xav \\ X_{min} & if\, X(t) < Xav \end{cases}$$

The interference queue´s next value is updated by every pair of a Silent and Busy Period, and depends on the interference measurement, I, and the average interferenceX_{av} . The average interference X_{av} is how much interference is allowed to be over an average. This value is an initial parameter, a high X_{av} allow a higher interference values, and make the secondary more interference at the receiver. A low X_{av} value allow be more carefully with the Primary System, i.e. be less interference because less power is allocated. The parameter X_{min}Xmin controls the maximal power allocated.

3.6.6 User Selection

From [8], the system is optimized using the Lyapunov technique. The equation that is used to select the best user at a any given time is,

$$J = argmax\left\{q^{T}\cdot r - X^{T}\cdot D\cdot p\right\}$$

where the notation is,

- $k,\, number\, of\, Secondary\, Transmitters$
- $j,\, number\, Sensors$
- $Data\, Queue,\ q(t) = [q_1(t),\, q_2(t), ...q_k(t)]$
- $Data\, Rate,\ r(t) = [r_1(t),\, r_2(t), ...r_k(t)]$
- $Power\, allocated,\ p(t) = [p_1(t),\, p_2(t), ...p_k(t)]^{T}$
- $[D(t)]_{j,k}$ $,\, path\, loss\, between\, secondary\, transmitters\, and\, sensors.$
- $Interference\, Queue,\ X(t) = [X_1(t),\, X_2(t), ...X_j(t)]^{T}$

For each user, the equation will be calculated, and it will be apparent which transmitter that produces the highest value.

The algorithm has two tuning parameters; the first parameter is the "$q^{T}\cdot r$" product, which takes into account the data stored at the data queue average with its data rate. It means that the user who has the largest data queue will have priority to send, because he has more data to transmit. Besides this parameter, is the “$X^T{\cdot}D{\cdot}p$” product. This product is like a penalty, and takes into account how interferent the user is. The user who maximizes the expression will be the selected user to transmit at that moment

It is worth pointing out that a tuning parameter has been included, the parameter “V”. This parameter is used to balance the equation, because the two factors of the equation have different orders of magnitude. So the equation changes to:

$$J = argmax\left\{q^T{\cdot}r - V{\cdot}X^T{\cdot}D{\cdot}p\right\}$$

As a result that the system works in densities of power, and do not use a particular frequency, the power values are very small, and the interference value is too small. So, when the algorithm calculates the allocated power, the values are extremely large, because the product “$X{\cdot}D$” appears at the denominator of the transmit power equation, as seen in the next point. The power constraint appears to control the allocated power, i.e. it reduces the calculate power. As a consequence, there is no adaptive system which optimizes the power, thus, an “on-off” allocation appears.

3.6.7 Transmit Power

The goal of the program is to obtain an adaptive System, where the transmit power allocation tries to transmit as much data as possible depending on the channel state and the system interference. So the transmit power allocation varies depending on the user that has to transmit.

The equation of the transmit power depends on the data queue state $q(t)$, "$V{\cdot}X^T{\cdot}D$" product and the SNR of each user. The same problem appears, as explained previously, when it is desirable to calculate the power.

$$p_k = min\left(Pmax, \left[\frac{q_k}{V{\cdot}X^T{\cdot}D} - \frac{No + Int}{c_k}\right]^+\right) = min\left(Pmax, \left[\frac{q_k}{V{\cdot}X^T{\cdot}D} - \frac{1}{SNR}\right]^+\right)$$

3.6.8 Data Rate

The purpose of the data rate function is to calculate how much data that can be transmitted over a given channel, and at a given power. According to Shannon´s capacity theorem, the data rate function is:

$$r_k = log_2(1 + \frac{p_k{\cdot}c_k}{No + Int})$$

Chapter 4

PERFORMANCE EVALUATIONS

While the previous chapter presented an approach based on sensing interference and data queue back-pressure for Cognitive Radio, this chapter examines the overall system performance.

In this chapter all the relevant simulator output is shown. The first subchapter explains the results that are obtained in the different scenarios. The second and third chapter will show the different scenarios, and the behavior of the system when the parameters change. There are 2 different models thatwill be study. The first one will be a simple model, where the basic performance is shown. The second one will be a real model, composed by a typical primary and secondary working system.

These thwo scenarios will show the different performances that can be obtained. They will also show which parameters that are the most relevant, and how the behavior of the system is affected.

4.1 Results

4.1.1 The arrival rate

Depending of the scenario under study, it will be shown that the most relevant parameter is the channel capacity (Shannon Capacity), i.e. the data rate that the transmitter can get.

For a particular packet length below to the capacity, the system will work correctly, depending on the arrival probability and how close it is to the limit. For a particular packet length above the channel capacity, the system can collapse, depending on how big the data queue is. As will be explained later, with a large data queue size, the system can become stable with a particular packet length above the channel capacity.

In addition, another relevant factor for the correct behavior of the system, is the arrival probability. The arrival probability is related to the packet length. With high arrival probability and values of packet length below the channel capacity, the system will be stable. However, with values of packet length above the channel capacity, the system will collapse. To see the effect of the different probabilities, several simulations have been done with probabilities between 0.1 and 1, with a constant packet length.

In systems with more than one user with different data rates, i.e. different channel capacities, finding the proper packet length with a particular arrival probability is a challenge. It will be show that depending on the data queue size, the system can be either stable or unstable.

"The System stability is related to the arrival probability, packet length and the data queue size for a desired data rate of the users."

4.1.2 Data Queue

An important parameter, as a fundamental parameter at the initial settings of the system, is the data queue size. Selecting a proper size of the queue is very important for the correct behavior of the system in terms of stability.

As said before, the System stability is related to the arrival probability, packet length and the data queue size. When can the data queue sizebe considered as a proper value?

The data queue size is considered as a proper value, when the system can stable. It is part of the "Water Filling solution"; the system will wait to send packets until it has a good channel to use. The system will wait by storing the packets at the data queue.

For small values of the data size, "V", the system will collapse quickly, depending on the arrival probability. If the packet size is close to the channel capacity limit. When it happens, it means that the system does not manage the amount of arrival packets and the system cannot be stable. As a result, packets will be lost and the dropping packets rates will increase, so the system will not be effective.

However, the data queue cannot be infinite, so the data queue size will be balanced, between the data rate that can be sent to the transmitters, the proper packet, length and the proper arrival probability.

An important metric used to evaluate the data queue size, and also the system, is the mean queue size. The mean queue size tells how long it is expected for data to stay in the queue before it is transmitted.

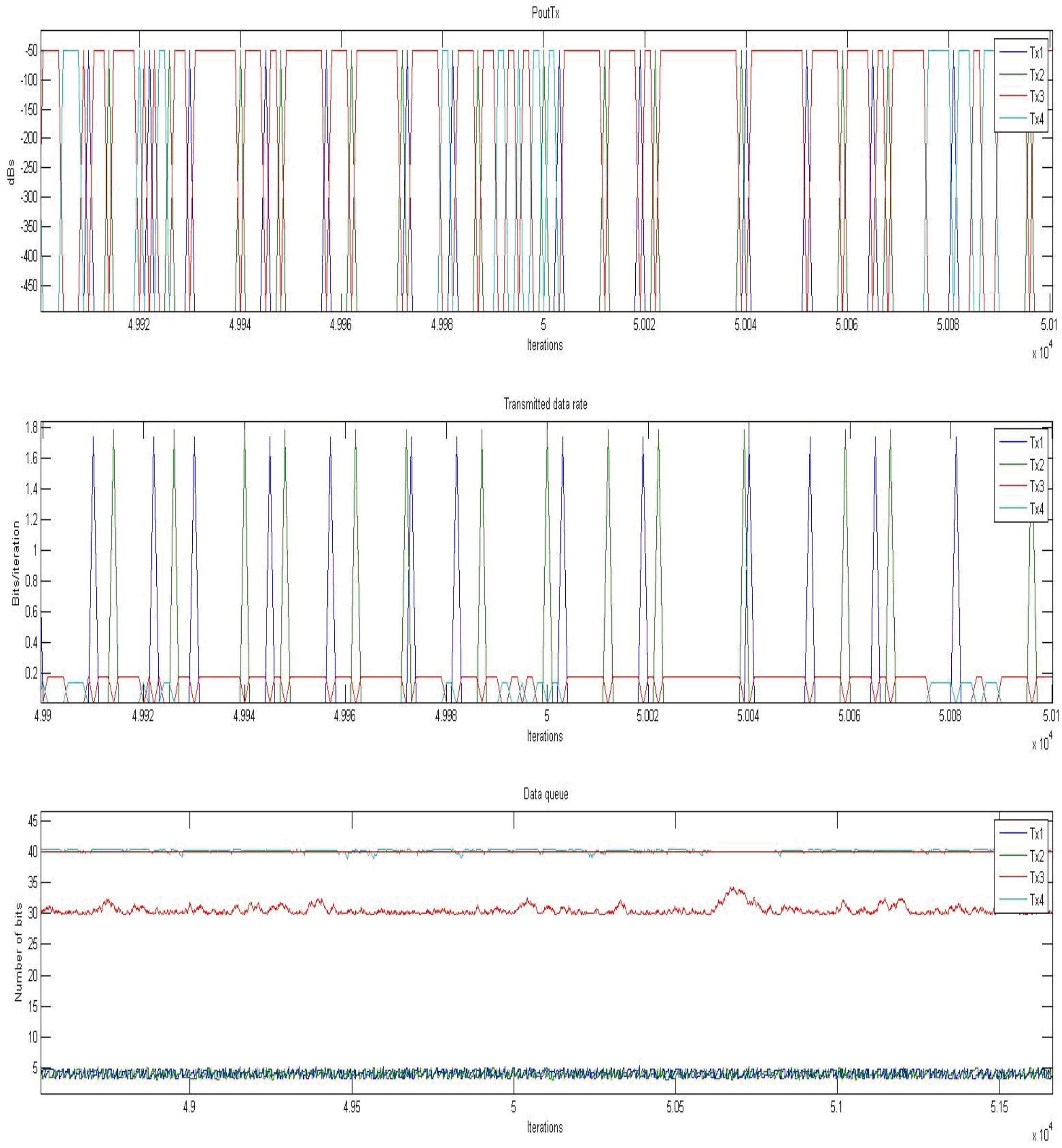

Figure 4.1: Data Queue effect

Figure 4.1, shows the different aspects that have been discussed earlier. The data packet that is considered is 0.4 bits, with an arrival probability, p=0.3. There are 4 transmitters, each one with different data rate, as shown at the figure. For users that have a higher data rate than packet length, there is no problems of saturation, and the mean queue sizes are 10 times the packet length (≊4.5 bits). For the other two transmitters, Tx 3 and Tx 4, the data rates are below the packet length. As seen, transmitter 3 can stabilize, as "water filling solutions" says, by storing at the data queue and sending when it is possible. The mean queue size is 75 times the packet size (≊30 bits). And finally, transmitter 4 cannot be stabilized with the set data queue length, so there are lost packets.

As a conclusion, it can be said that the packet size have to be at least the half of the data rate to get the system stabilized, and when it happens the data queue length has to be at least 100 times the data queue (for this particular example).

Figure 4.2 shows the same scenario as figure 4.1, but with a different packet size, packet=0.3 bits, and the same arrival probability, p=0.3. The packet size is less than the minimum data rate of the user, so the system is stabilized, as seen in the data queue graphics. The data queue maximum value is 1.2 bits, 4 times the packet size.

With figure 4.1, and figure 4.2, the different behavior of the data queue can be observed, depending on the different packet size at the same scenario.

In addition, the data queue size has been quantified in the system. It will be shown that the system behavior changes depending on the number of bits of quantification.

Depending on the data queue size, the number of bits of quantification is very important. The bigger data queue, the bigger steps of quantification, for particular bits of quantification. With small steps of quantification, the quantification measurement will be close to the real value of the data queue size.

It will be shown that, when the steps are big, the system behavior changes. As an example, one bit of quantification result is shown.

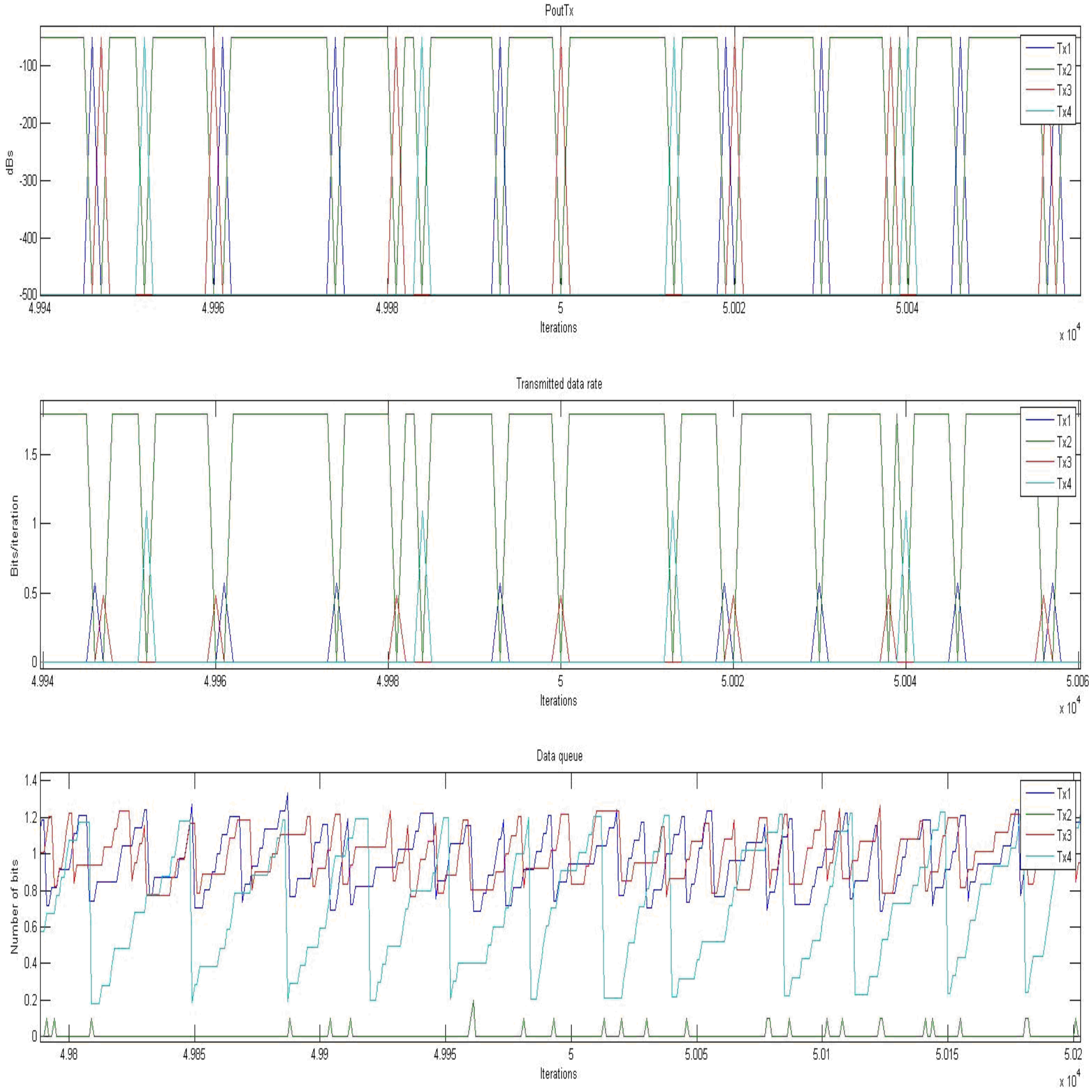

Figure 4.2: p=0.3, packet=0.3 bits

The following figure (4.3) shows the scenario that will be studied for the data queue effect.

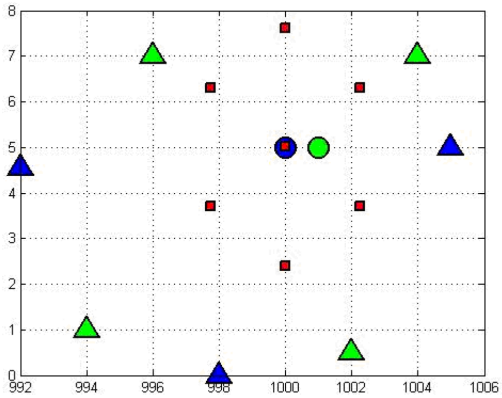

Figure 4.3: Scenario 3

Where,

- The Transmitter is represented by a pyramid.
- The Receiver is represented by a circle.
- The sensor is represented by a red square.
- Primary System in blue color.
- Secondary System in green color.

Figure 4.4 shows how the data queue is quantified, with one bit, for each user of the scenario being study.

As seen, the system has two models of function. The first one, until the users have their data queue half full, the system will only choose the user that has the best channel, because for the system the other users do not have packets to send. The second one, when all the users have a half full data queue, the system begins with the optimization, and will select the users depending on the "Best User Selection" algorithm. With only one bit, the system only will know if the users have packets to send or not , but for transmitting the users will have to have a half full data queue, so it is a bad performance of the system.

As a solution, if it is wanted to see the behavior of the system with only one bit of quantification, this delay time have to be deleted, or initializing the data queues of the users a half full queue size.

This is one example which permits to take into account the problems of the quantification in the system, which the proper number of quantification bits.

The following figures show how the system works for a different number of quantification bits, at the same scenario.

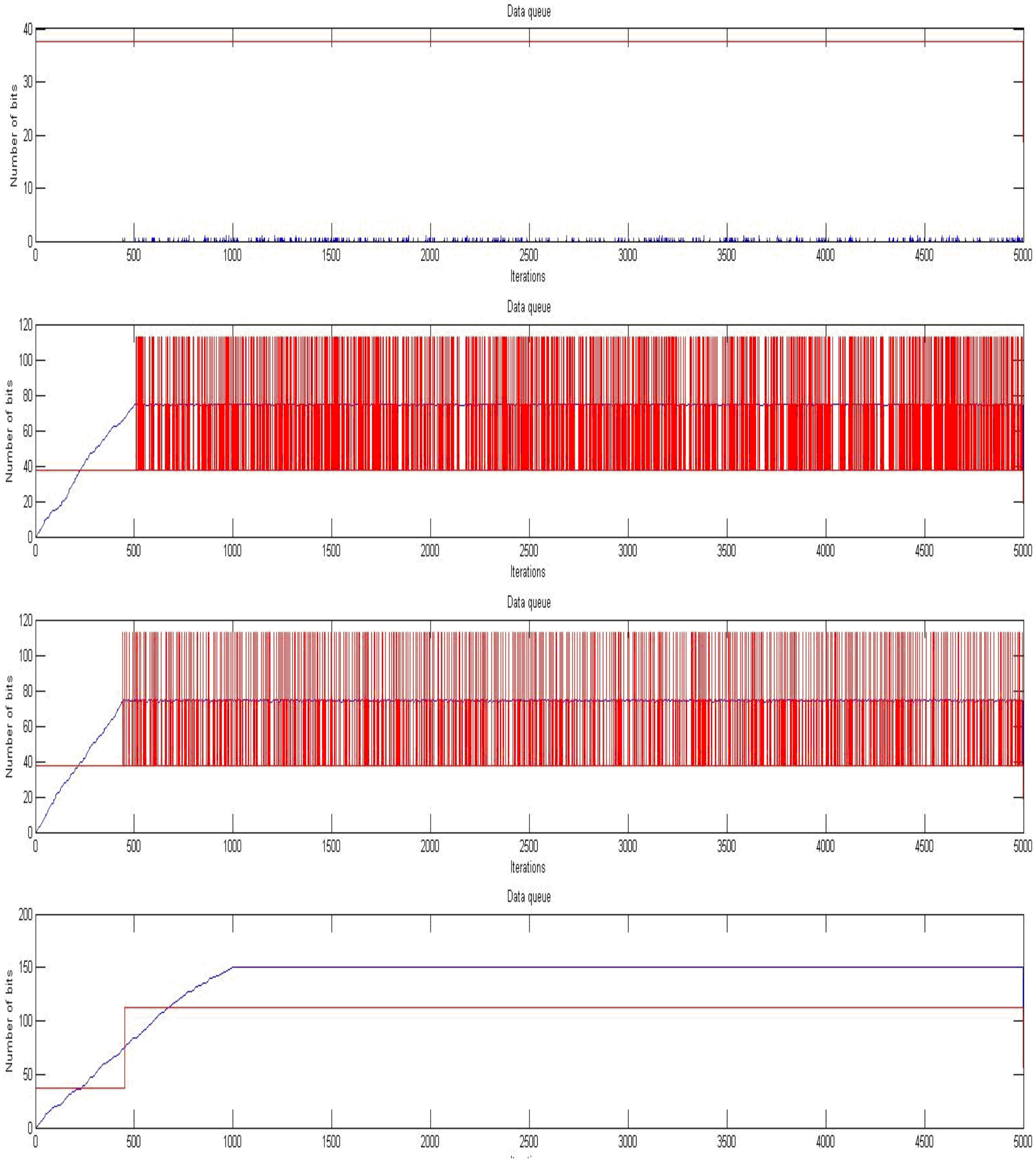

Figure 4.4: Quantified Data Queue with 1 bit

Figure 4.5 and 4.6 show how the system works with 3 bits of quantification. For figure 4.5, the power allocate can be seen,as well as the data rate and the real data queue for each user. Figure 4.6 shows how the data is quantified for each user, and how large the quantification step sizes are.

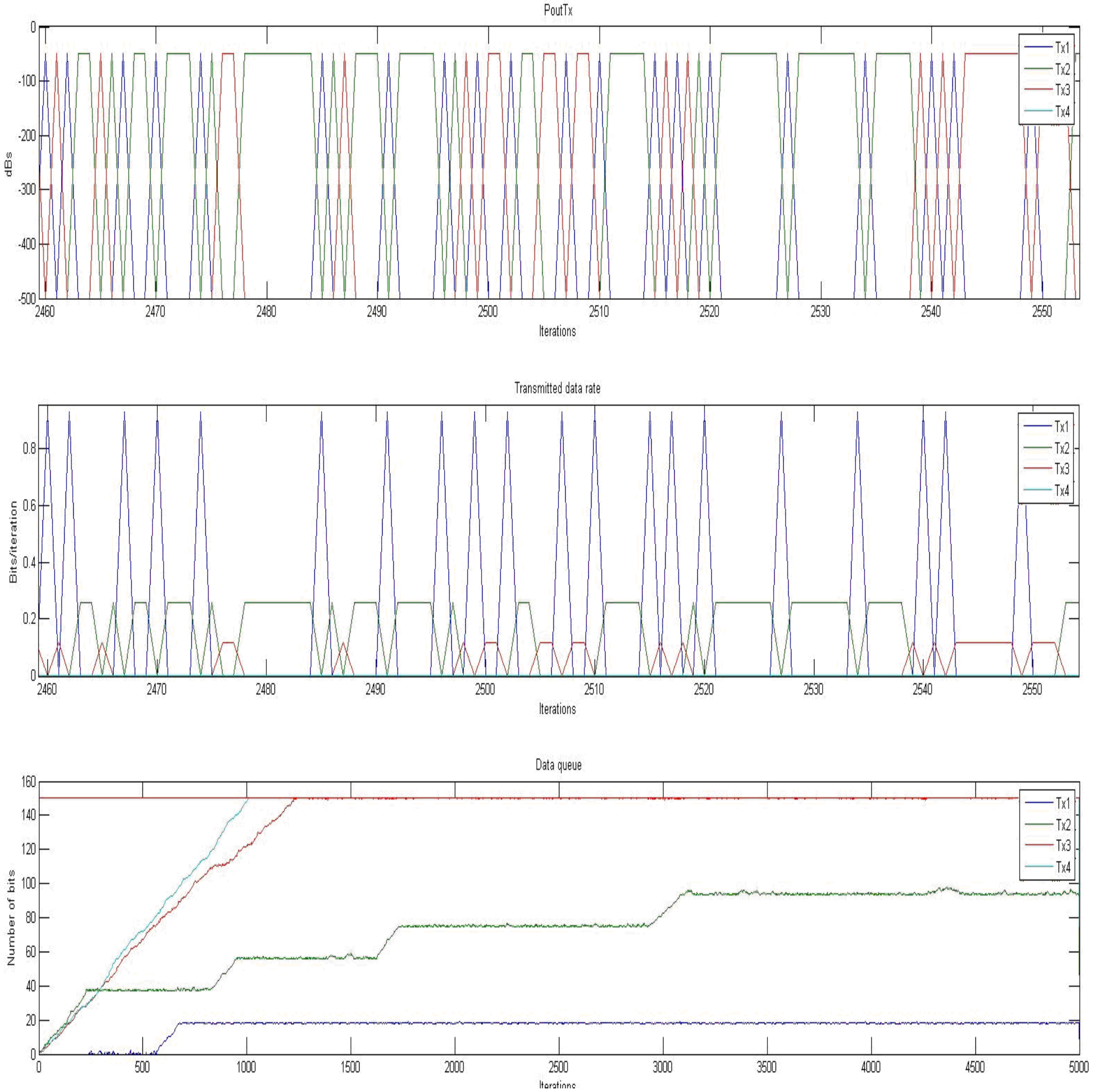

Figure 4.5: System with 3 bits of quantification

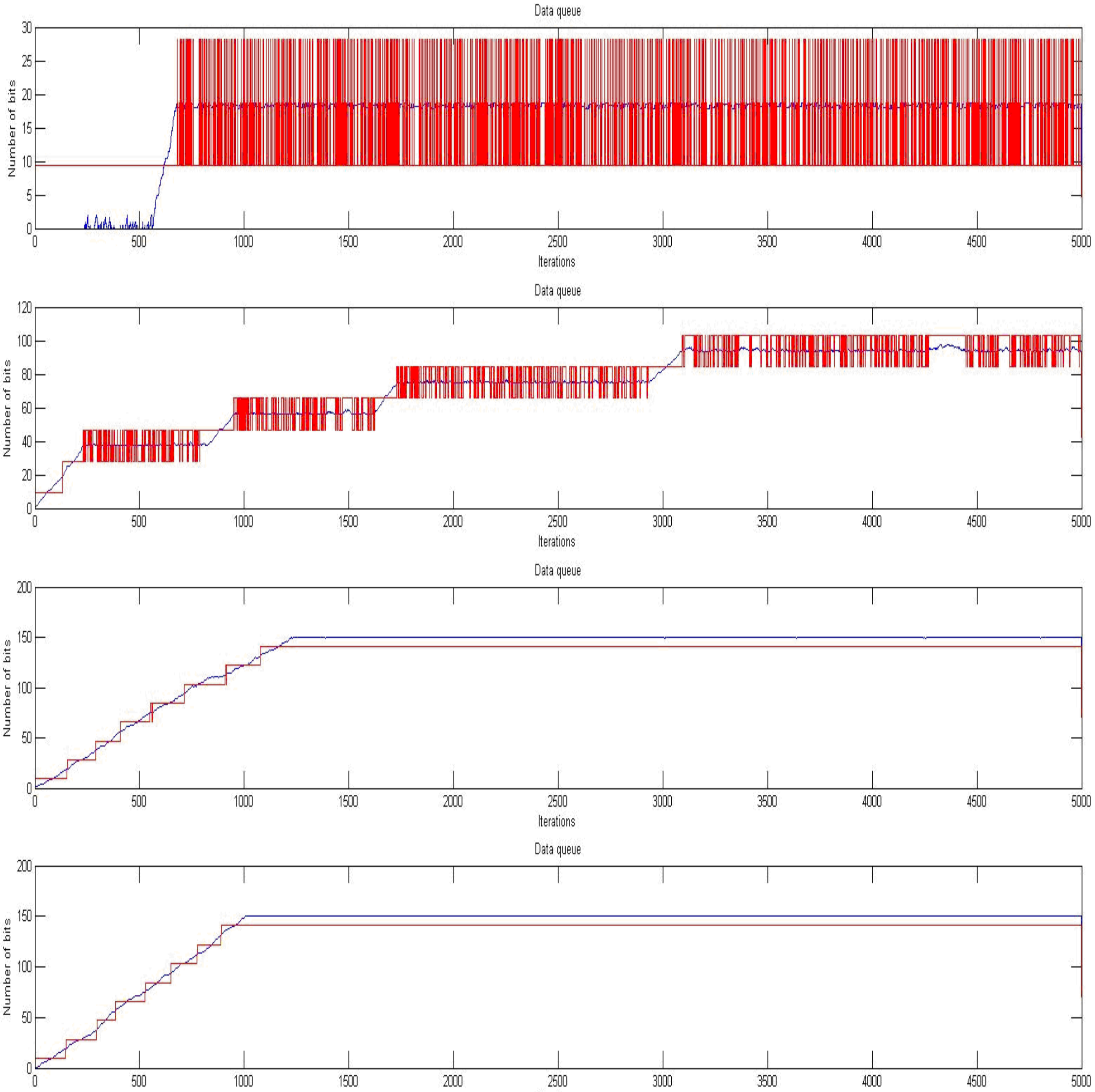

Figure 4.6: Quantified Data Queue with 3 bit

Figure 4.7 and 4.8 show how the system works with 5 bits of quantification.

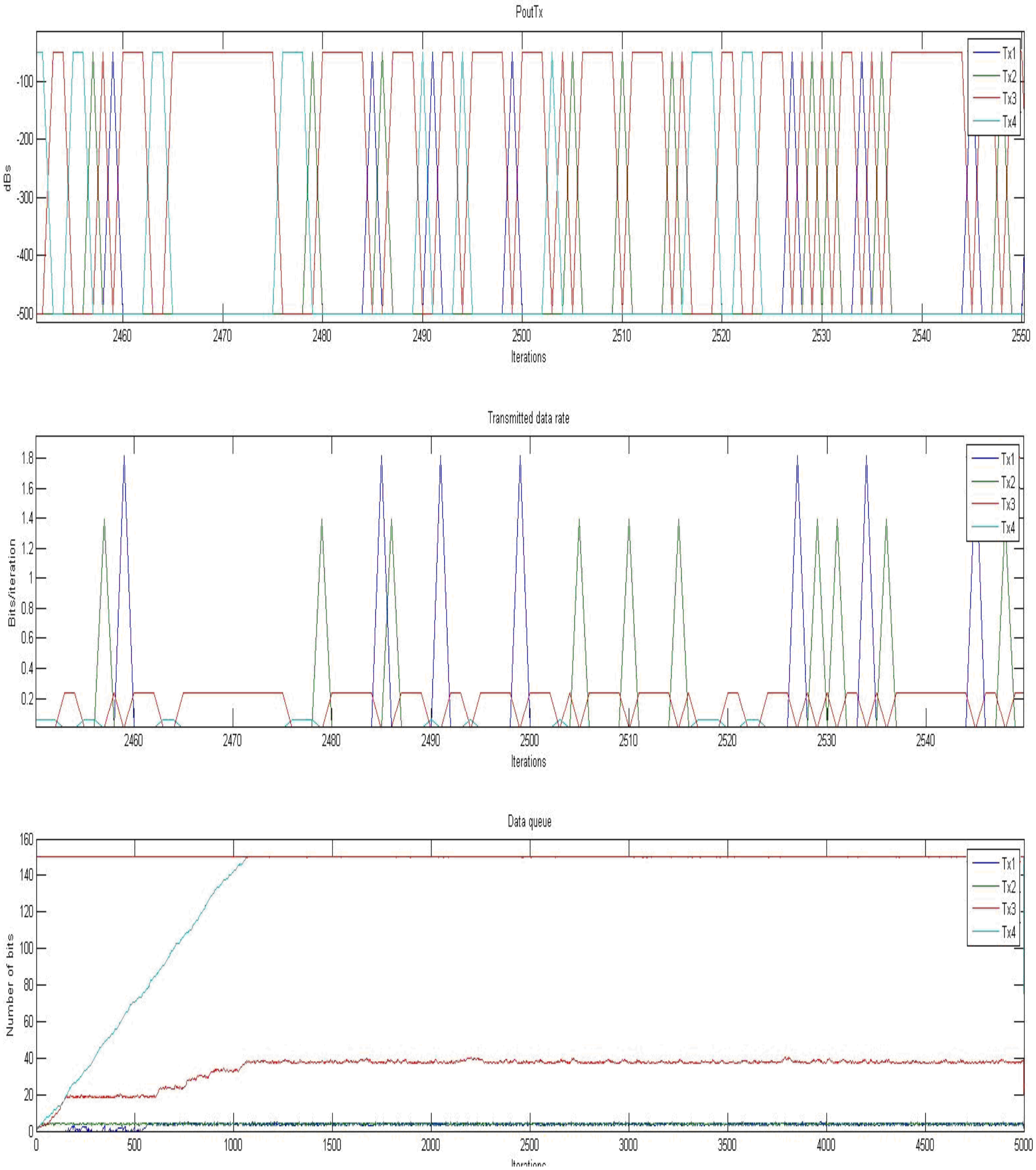

Figure 4.7: System with 5 bits of quantification

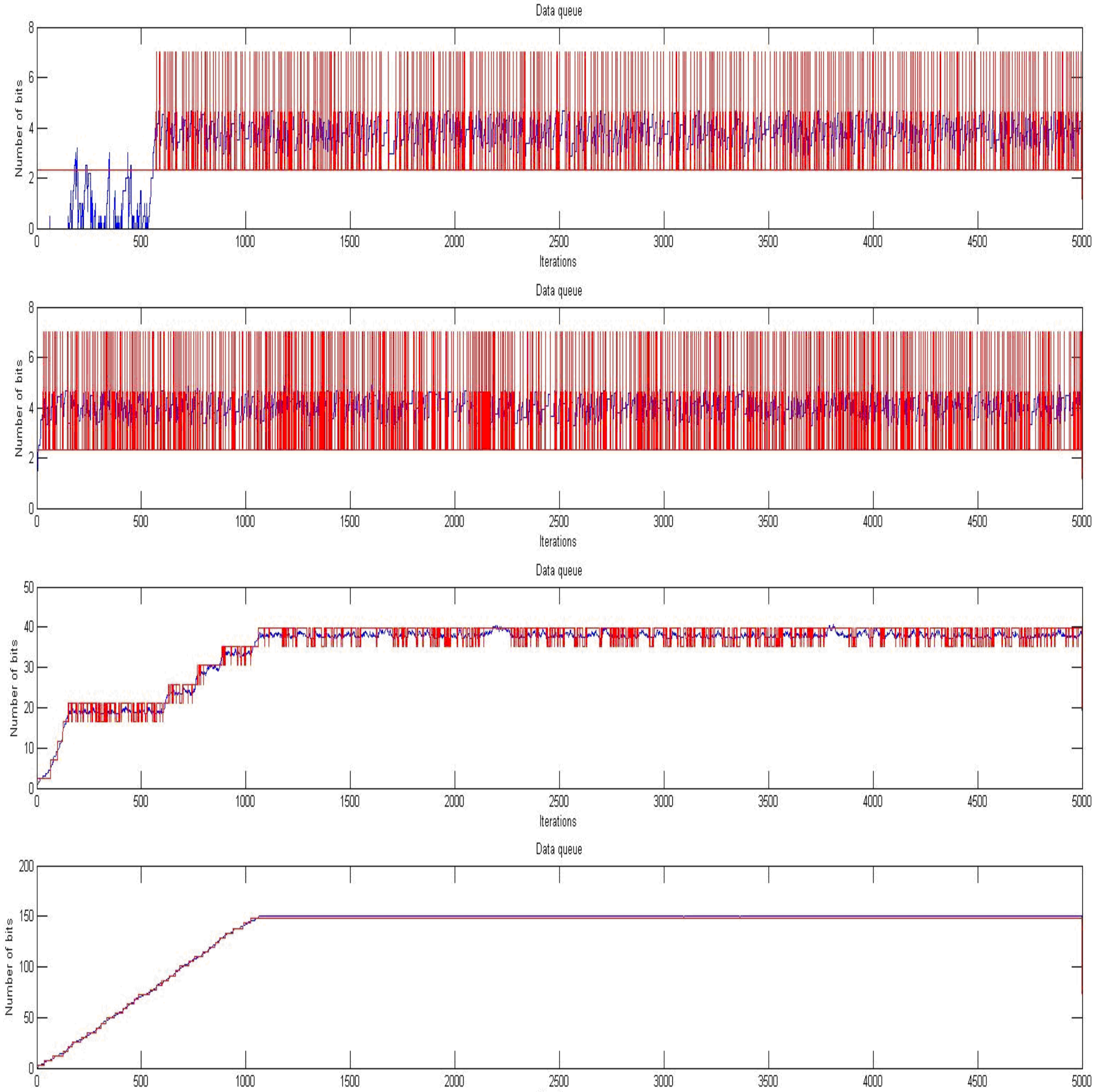

Figure 4.8: Quantified Data Queue with 5 bit

As a conclusion, it can be said that with more bits the system will work in a similar way, since no quantification exists in the system, because the quantification values are close enough to the real values. On the other hand, the more quantification bits, the more bits have to be sent by air. It has to be a balance between them.

4.1.3 Average received interference X_{av}

The average received interference, X_{av}, is a parameter related to the Sensor, and shows how much interference the sensor can tolerate.

Setting a high value of X_{av} means that a higher level of interference is allowed at the scenario. As a result, the Secondary System will be more interfered with Primary System, so the primary communication can be affected.

The value that has been chosen for the correct performance of the system is 5.0119e-017. This value have been chosen because for real systems, the level of interference permitted is -80dbm in a bandwidth B=200KHz. As the system works in densities of power, the value that is obtained to spread in frequency -80dBm is 5.0119e-017.

On the other hand, setting a small value of X_{av}, means to be more protective with the Primary System. Less interference values are permitted, and as a result, the Secondary System will have to reduce the allocated power.

The following figure (4.9) shows the scenario that is going to be studied for the Average received Interference effect parameter (X_{av}),

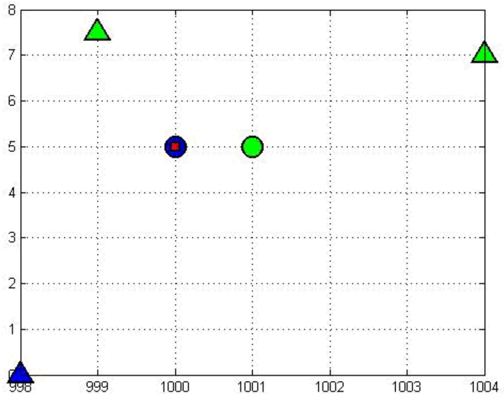

Figure 4.9: scenario 4

Where,

- The Transmitter is represented by a pyramid.
- The Receiver is represented by a circle.
- The sensor is represented by a red square.
- Primary System in blue color.
- Secondary System in green color.

For the three different graphics that will be shown, the system is stabilized. The differences between them is the value of Xav. The system will be more or less interfered, and the data queue will be with more packets stored or less depending on the value of X_{av}. If the system is more interferening with the other system them fewer packets are at the queue than if the system is more protective.

Figure 4.10, shows that the level of interference of the system is around -110 dB.

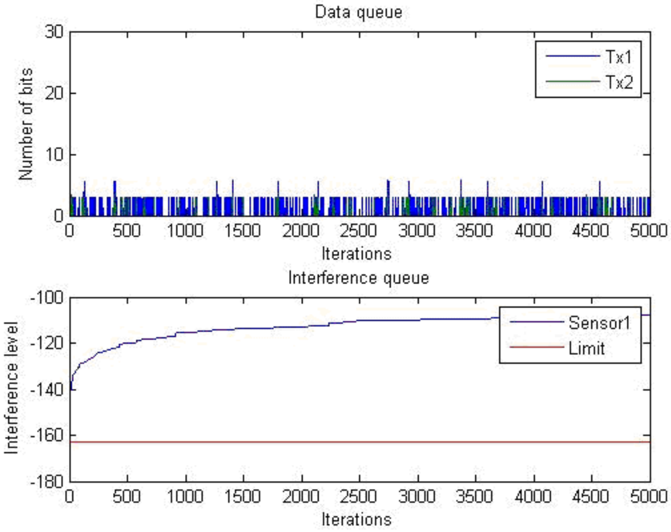

Figure 4.10: X_{av},=-110

Figure 4.11, shows that the level of interference of the system is around -100 dB.

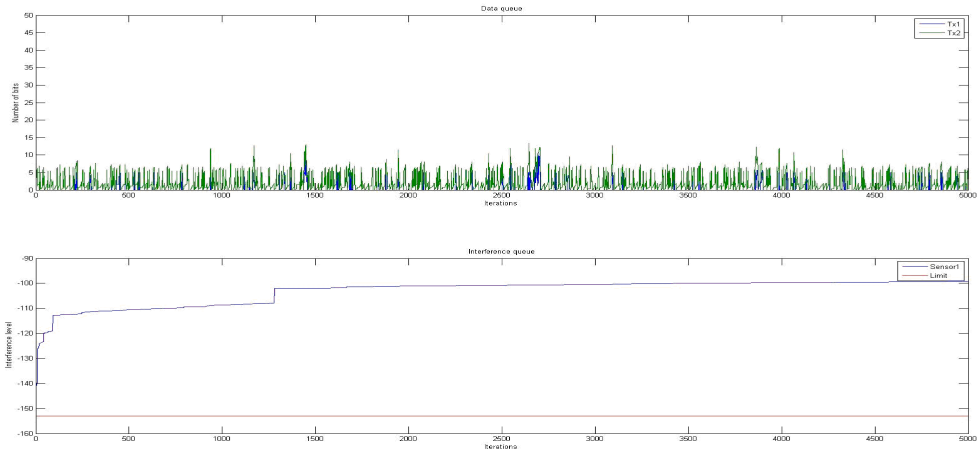

Figure 4.11: X_{av},=-100

Figure 4.12, shows that the level of interference of the system is around -120 dB.

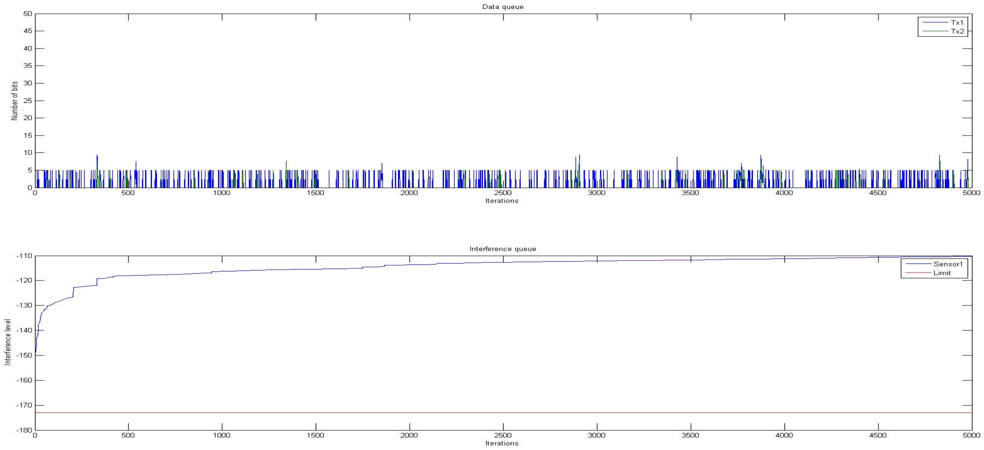

Figure 4.12: X_{av},=-120 dB's

4.1.4 Positions at the Scenario

The location of the elements at the scenario is an important factor when it is desirable to evaluate the system performance.

It will be seen that when the elements of the primary system are close to the elements of the secondary system, a higher level of interference will appear, i.e.

the secondary system will be more interfering. As a result, the allocated power will decrease,as well as the channel capacity, the data rates will decrease too.

In contrast, if the elements are spread at the cell, and if the secondary transmitters are far away from the primary receiver, better data will be obtained, because there will be less interference at the cell and between the elements, depending on the number of users that are set at the scenario.

In addition, there are four different ways to place the elements at the scenario:

1. Fix the elements in certain positions, with the "fixed_positions.txt" and "fixe_sensors.txt" for transmitters and sensors.
2. Place the transmitters around the receiver with a certain coverage radius that cannot go far away from them, i.e. tries to simulate a coverage radius.
3. Place the elements randomly at the scenario.
4. Place the elements as a cellular distribution, as sensors around the primary receiver.

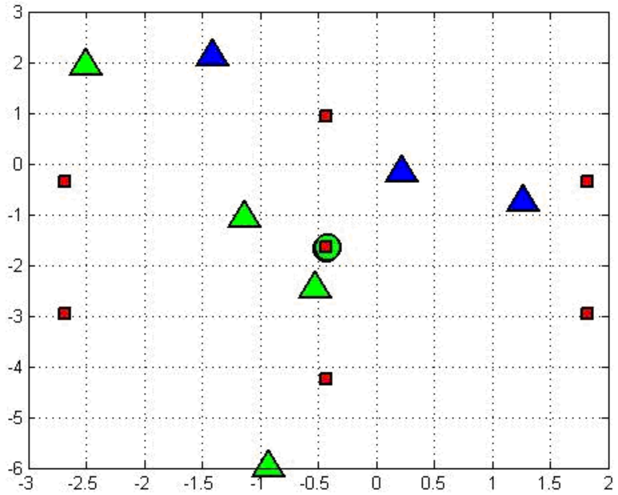

Figure 4.13: Different placements

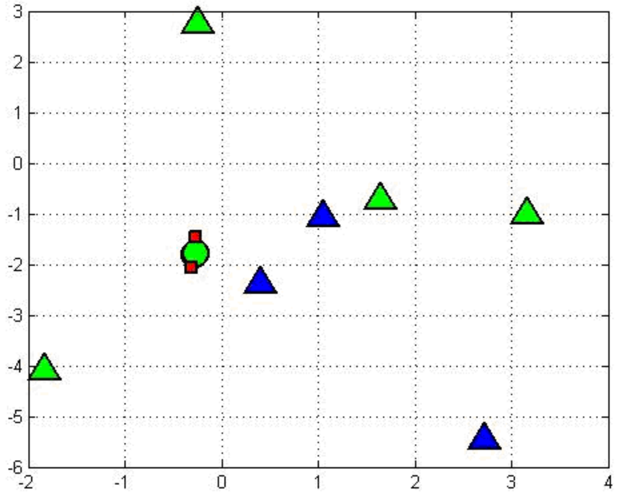

Figure 4.14: Different placement 2

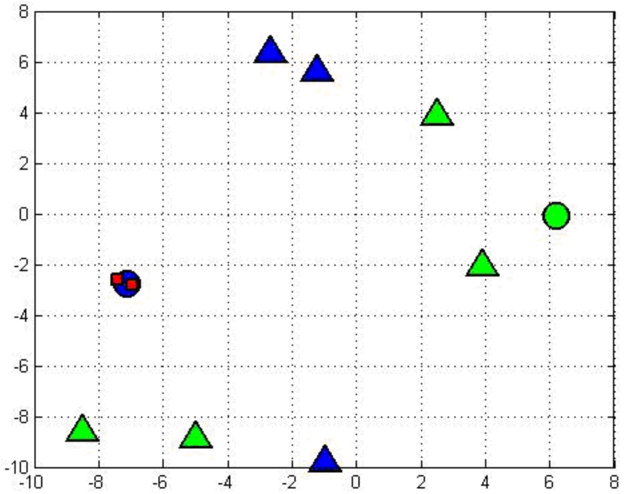

Figure 4.15: Different placement 3

4.1.5 Sensors

As will be shown in the different scenarios, the higher number of sensors set at a particular scenario, the more limitations will appear at the scenario. With more sensors, more interference values will be capture, so the allocated power will decrease to avoid the levels of interference.

For the different scenario simulations, it will be shown that the data rate will decrease depending on the number of sensors, and that the value of the interference measurement will increase. For a particular scenario, there will be used 1 sensor, 3 sensors, and 7 sensors, to study the system behavior.

The different locations of the sensor are shown in the following figures:

1. - One Sensor at the primary receiver .

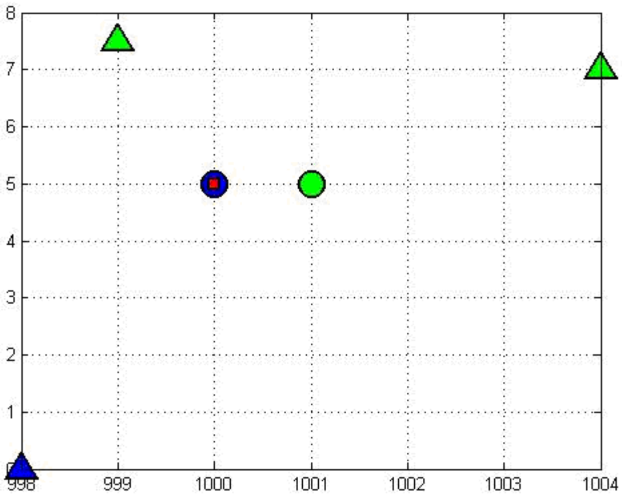

Figure 4.16: Scenario with 1 Sensor

2.- Three sensors located around the primary receiver.

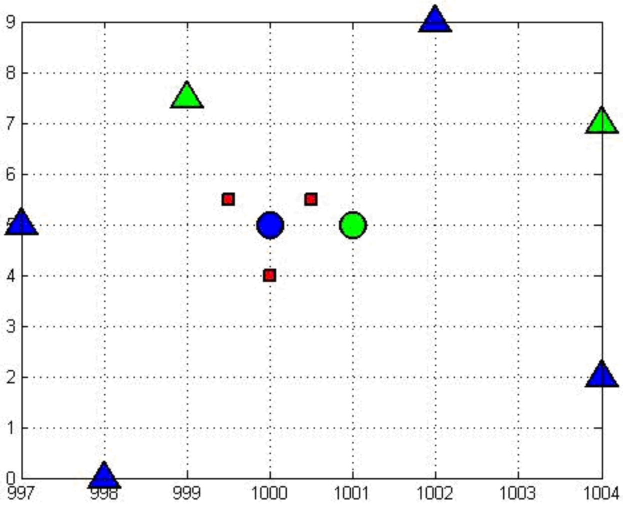

Figure 4.17: Scenario with 3 sensors

3.- Seven sensor as a cellular distribution.

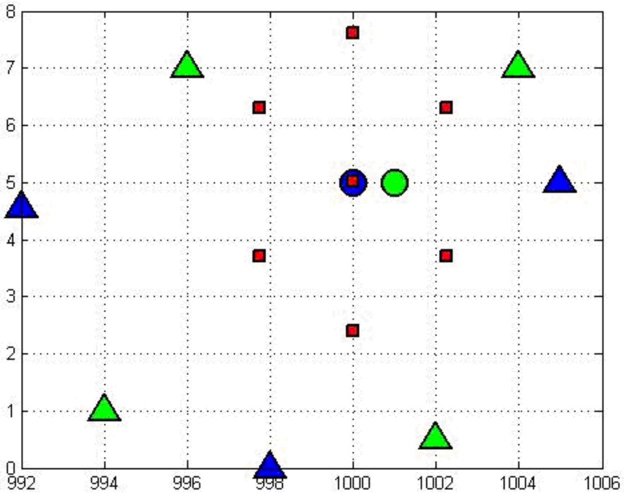

Figure 4.18: Secenario with 7 sensors

4.1.6 Power Allocation

An adaptive system varies its allocated power depending on the environment, i.e. it is less interferent with the Primary System. For that reason, the system uses a “Water Filling solution”, which means spending less power on bad channels and more power on good channels.

As will be seen, the allocated power will be so huge that the power peak constraint appears. The power constraint peak that is used is 1e-5 Watt, because a real system 2W over 200 kHz. Densities of power are wanted, the power must be divided by the bandwidth (2W/20000).

When this occurs, it means that there is a good channel and the SNR is good, so it can be allocated more power. Otherwise, when the SNR is not so good, the system begins to adapt the allocated power.

The different scenarios that are going to be studied for Power allocation are:

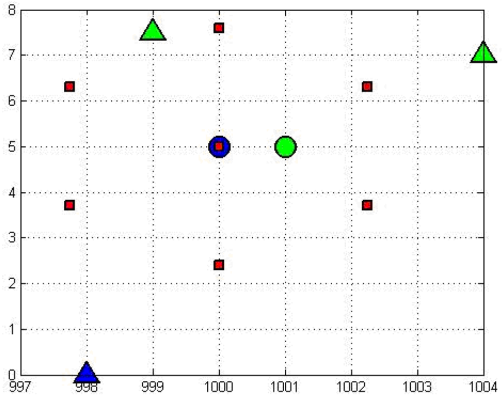

Figure 4.19: Scenario 5

Where,

- The Transmitter is represented by a pyramid.
- The Receiver is represented by a circle.
- The sensor is represented by a red square.
- Primary System in blue color.
- Secondary System in green color.

The following figures will show an adaptive system, where transmitter 2 sends less power than transmitter 1, because transmitter 2 is more interferent and it is close to the sensor. For that reason, transmitter 2 has to reduce its allocated power to fulfill the inference constraint.

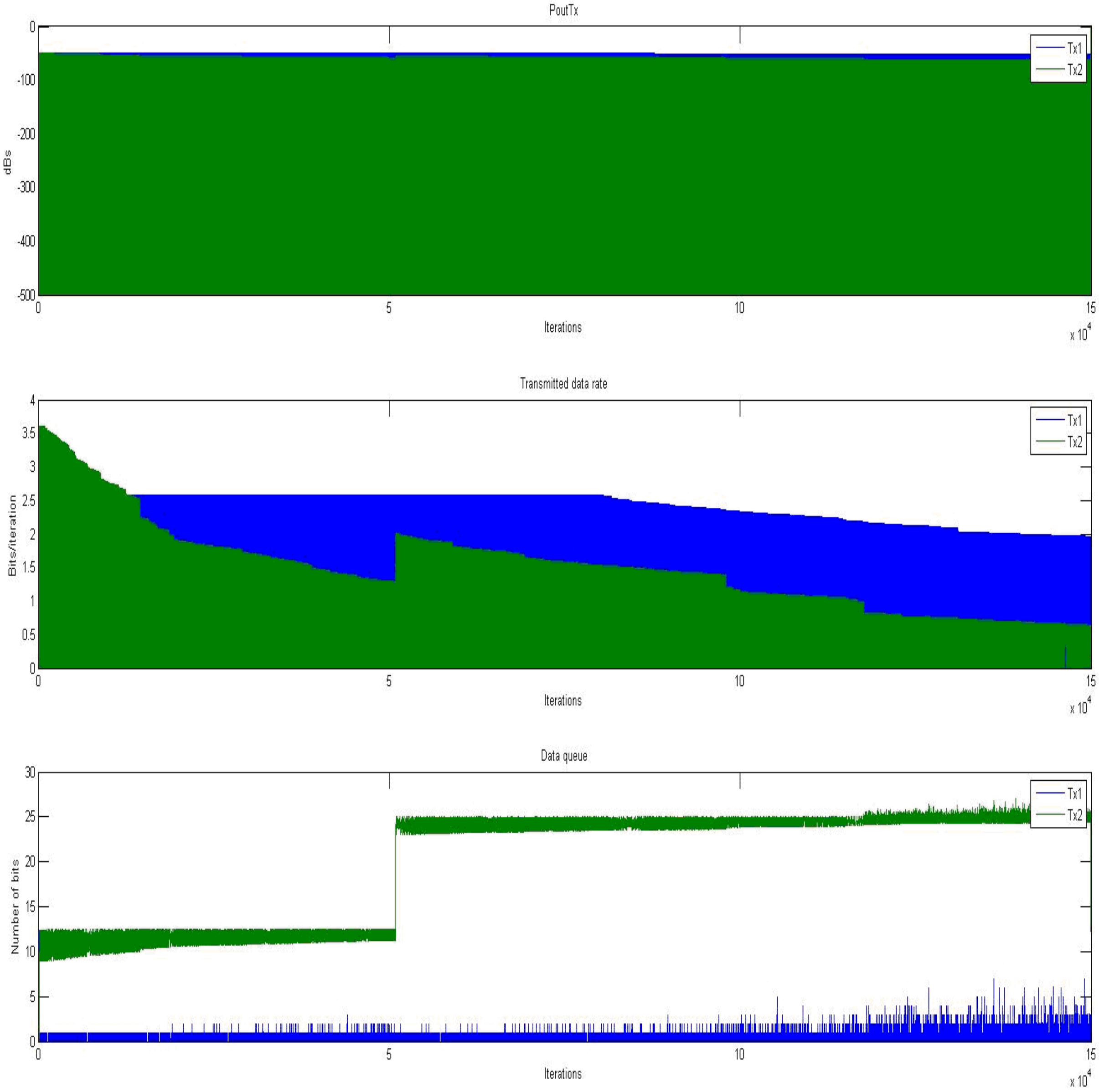

Figure 4.20: Power allocation

By zooming into figure 4.20, the figure 4.21 appears. It can be seen that transmitter 2 changes its power when its data increases, i.e. there are more packets at the data queue, so the transmitter needs to send more power in order to stabilize the system, but less power than transmitter 1 to fulfill the interference constraint.

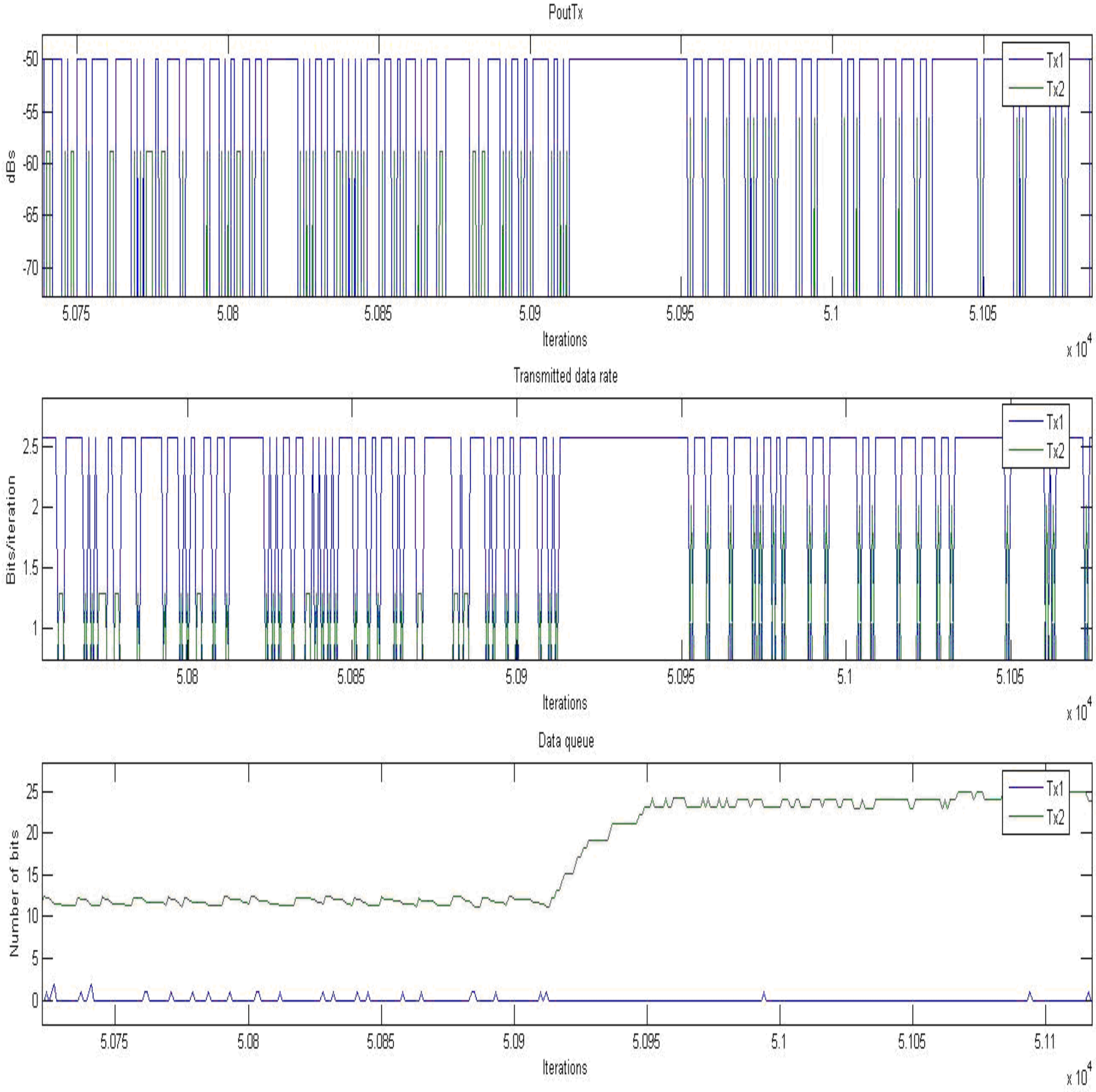

Figure 4.21: Power allocation

4.1.7 Frequencies

It will be shown that the use of several frequencies at the same time will help to improve the system performance. To see the differences between using 1 frequency or more, look at in the following figures.

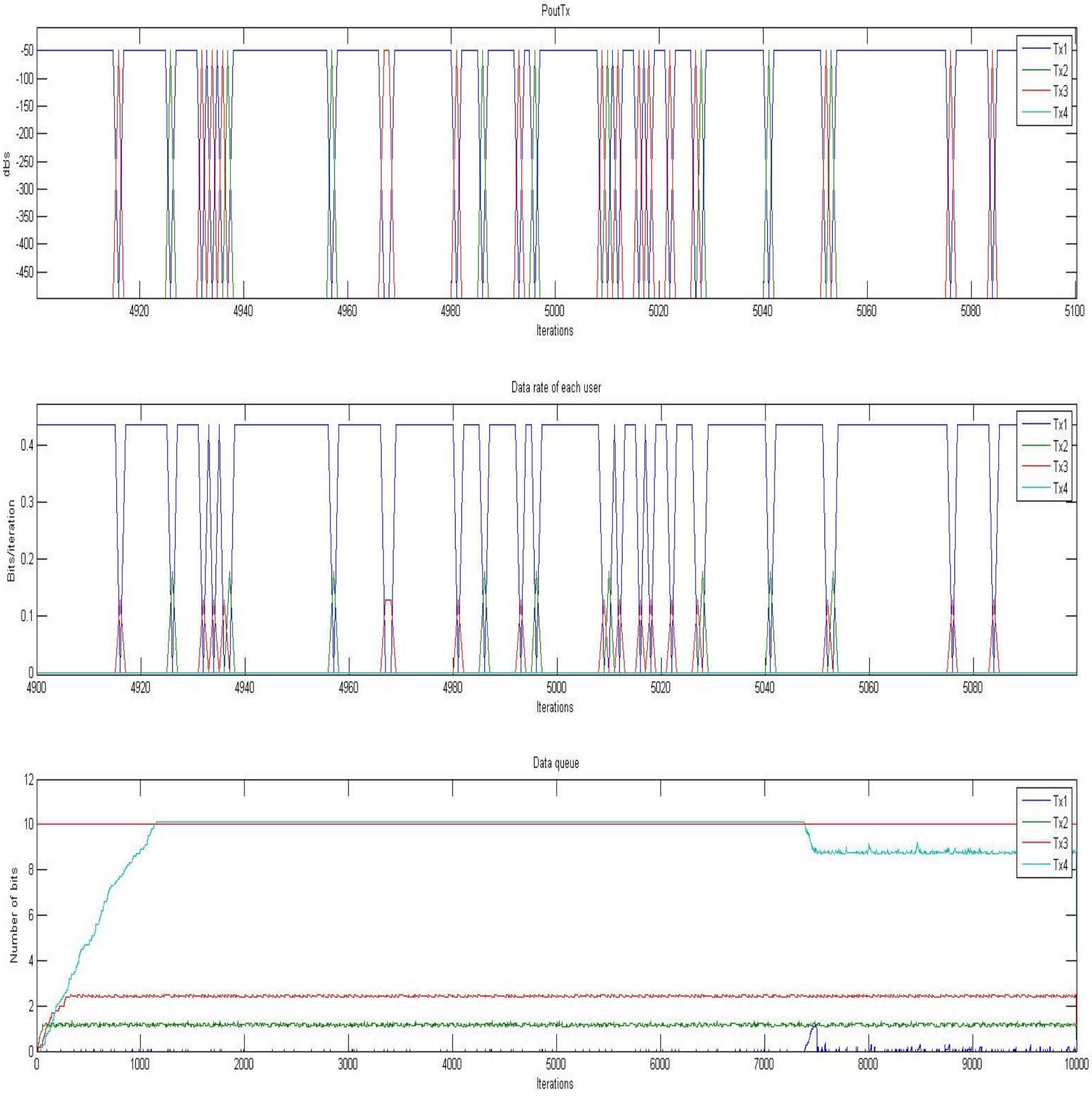

Figure 4.22: System with 1 frequency

Figure 4.22 shows a system that is working with one frequency. The system has 4 users, each one with different rates. For this example, the packet size is packet=3 bits, and the arrival probability p=0.3. The system changes the selection of the user between “Tx1”, “Tx2”, and “Tx3”, because they have a better channel than “Tx4”. The data of transmitter 4 is stored each time at the data queue, waiting for a good channel. But there are a lot packet losses, because its data queue its full.

Figure 4.23 corresponds to frequency A, and Figure 4.24 corresponds to frequency B at the same scenario as figure 4.22.

With 2 frequencies, the system can improve the performance of the system. The system will work as the same way as on frequency when it has to allocate a user, but now it has to allocate two different users in each frequency. As can be seen, the users twith a lower data rate, use one frequency to send their data. The other frequency will principally work with the other users.

With 2 channels of communication, the system works better than only one, because it can manage all the amount of incoming data, so there will not be packets lost for transmitter 4.

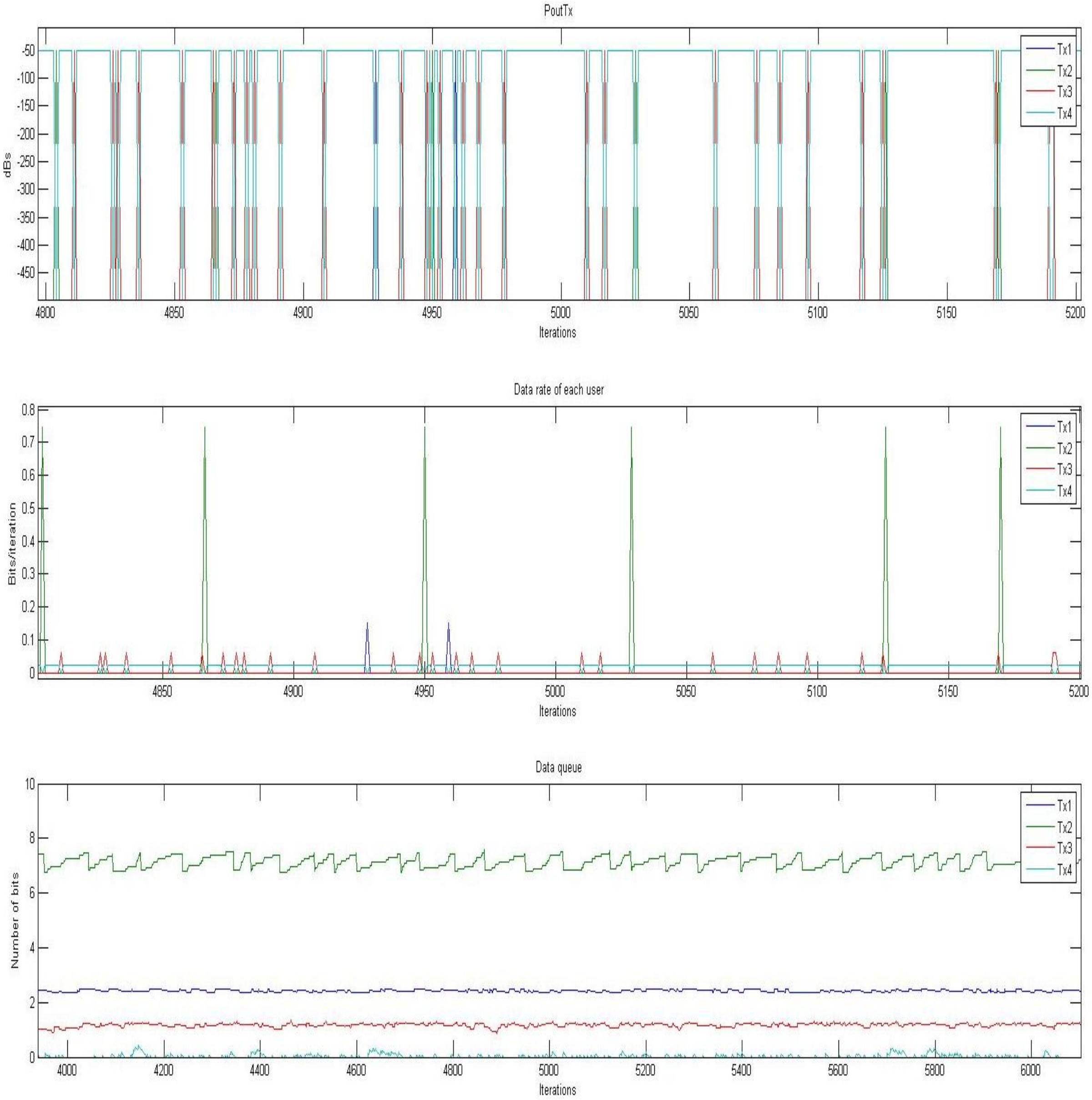

Figure 4.23: System with 2 frequencies, frequency A

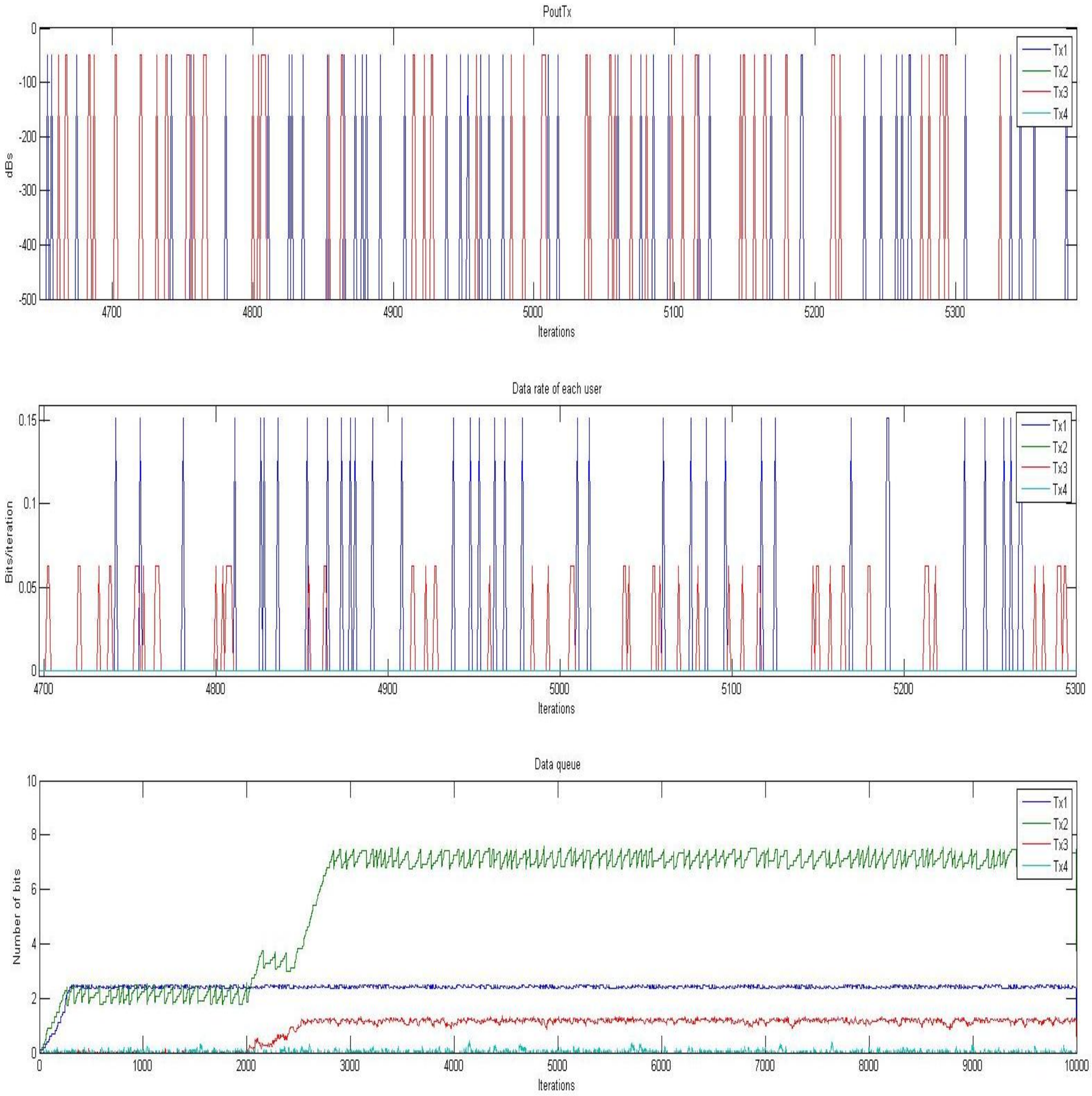

Figure 4.24: System with 2 frequencies, frequency B

4.2 Simple model

The first model that is shown is the Simple Model. It is composed by a Transmitter-Receiver pair of a Primary System, two Transmitters and One Receiver of a Secondary System. The system's behavior will be tested with different sensors placements. One Senor, two Sensors, and seven Sensors will be used. So, there will be three different scenarios of the Simple Model. These three scenario will be used to compare, and study the differences and similarity between them.

For that purpose, different packet lengths will be tested, with probabilities from 0.1 to 1. The measures will be performanced with 0.5 bits, 1 bit, 2 bit and 3 bits packet length. The results that will be taken into account are:

- Data Rate
- Queue Delay
- Allocated Power
- Dropping Packets
- Sending probability.

Graphics and tables will show the system behavior.

4.2.1 –1 Sensor-

The scenario that will be studied, is:

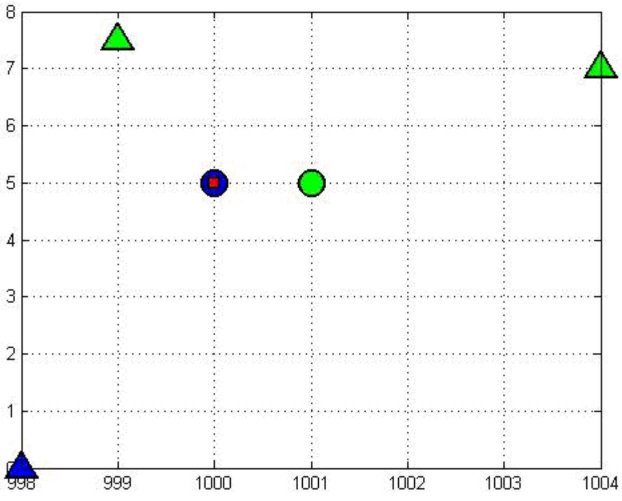

Figure 4.25: Simple Model, 1 Sensor

Where,

- The Transmitter is represented by a pyramid.
- The Receiver is represented by a circle.
- The sensor is represented by a red square.
- Primary System in blue color.
- Secondary System in green color.

Data Rate

	Number of Bits			
Transmitter	0.5	1	2	3
Tx 1	1.8950	1.880	1.875	1.883
Tx 2	2.8055	2.822	2.853	2.805

Mean Queue Delay

	Number of Bits			
Transmitter	0.5	1	2	3
Tx 1	5.2896	11.5	104.091	202.56
Tx 2	0.0502	0.2231	57.813	130

Allocated Power

	Number of Bits			
Transmitter	0.5	1	2	3
Tx 1	-50	-50	-50	-50
Tx 2	-50	-50	-50	-50

Sending Probability

	Number of Bits			
Transmitter	0.5	1	2	3
Tx 1	0.1441	0.2896	0.3752	0.2855
Tx 2	0.8557	0.7102	0.627	0.7143

Drop Packets

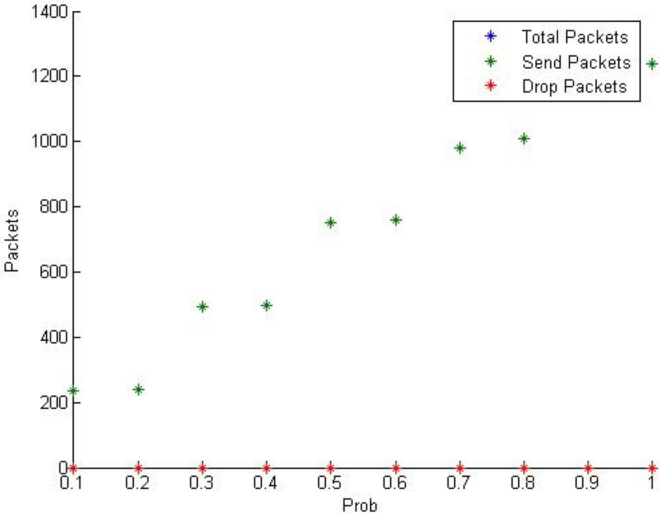

Figure 4.26: Sended Packets

System Interference

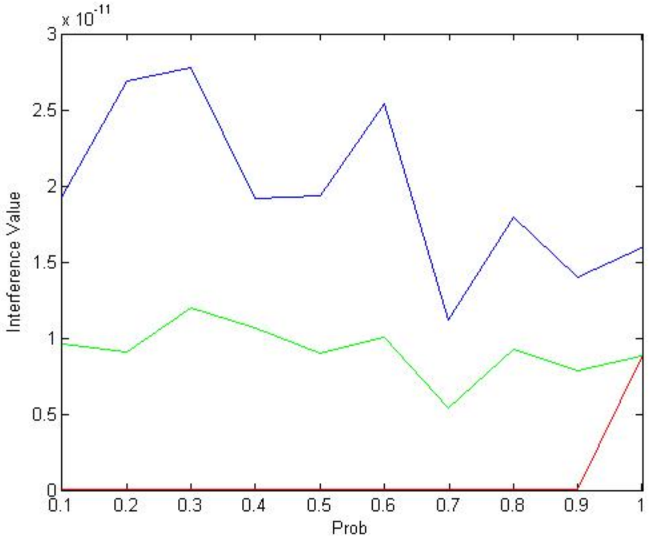

Figure 4.27: System Interference

4.2.2 - 3 Sensors -

The scenario that will be studied, is:

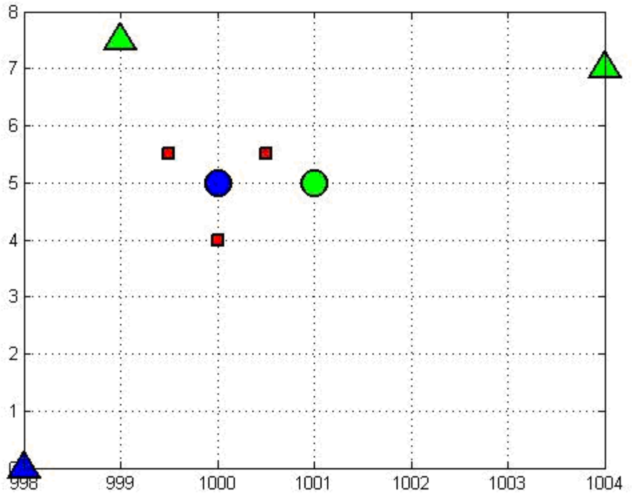

Figure 4.28: Simple Model, 3 Sensor

Where,

- The Transmitter is represented by a pyramid.
- The Receiver is represented by a circle.
- The sensor is represented by a red square.
- Primary System in blue color.
- Secondary System in green color.

Data Rate

	Number of Bits			
Transmitter	0.5	1	2	3
Tx 1	2.222	2.222	2.222	2.224
Tx 2	2.139	2.1373	2.133	2.10

Mean Queue Delay

	Number of Bits			
Transmitter	0.5	1	2	3
Tx 1	0.044	0.1710	82.354	104.15
Tx 2	5.155	11.38	106.43	208

Allocated Power

	Number of Bits			
Transmitter	0.5	1	2	3
Tx 1	-50	-50	-50	-50
Tx 2	-50	-50	-50	-50

Sending Probability

	Number of Bits			
Transmitter	0.5	1	2	3
Tx 1	0.8728	0.7494	0.749	0.7982
Tx 2	0.123	0.2504	0.2729	0.20

Drop Packets

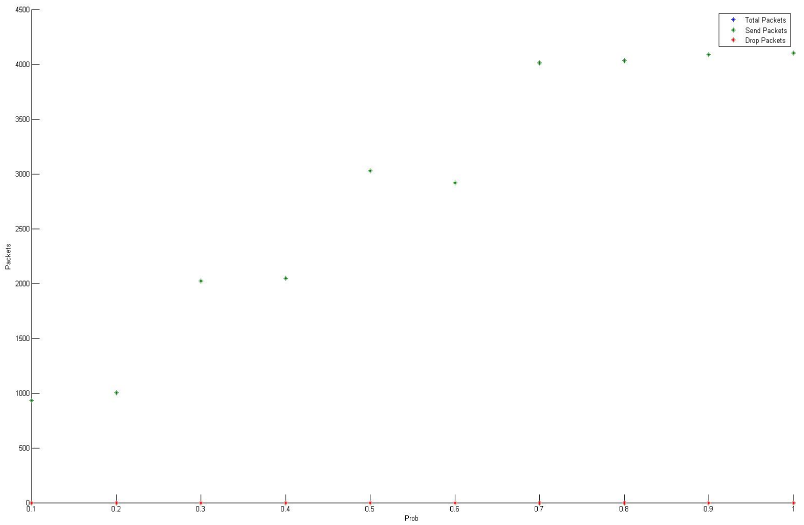

Figure 4.29: Drop Packets

Data queue

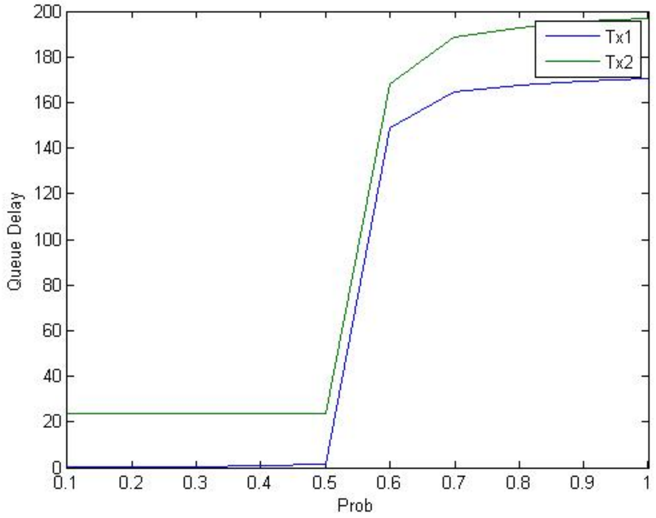

Figure 4.30: Queue Delay, packet=2

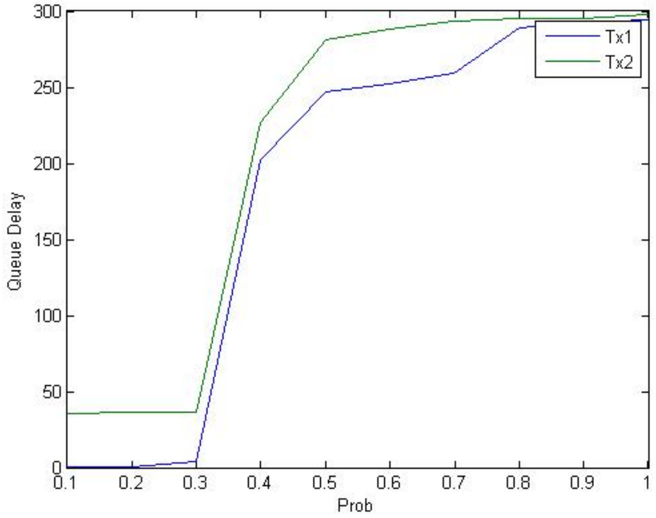

Figure 4.31: Queue Delay, packet=3

System Interference

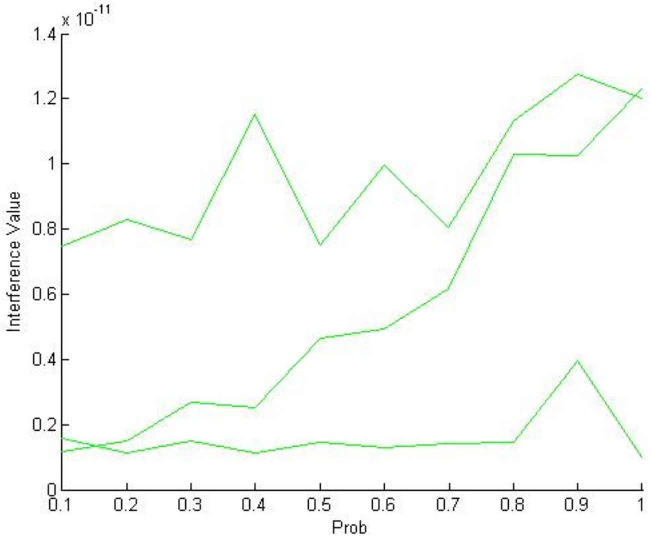

Figure 4.32: System Interference, packet=0.5 bits

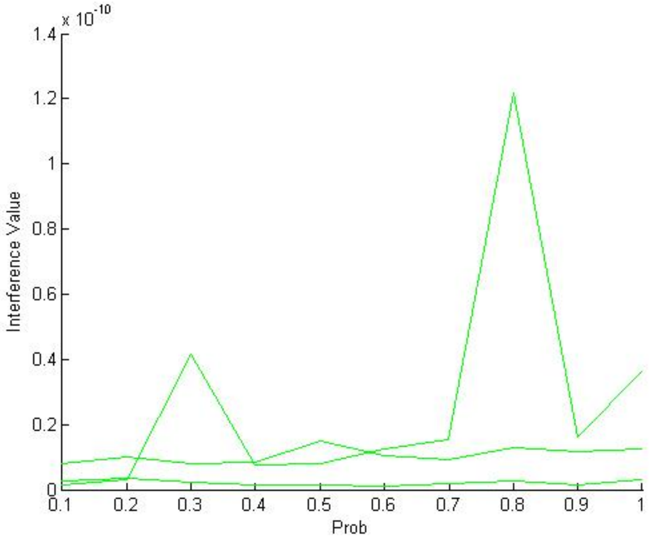

Figure 4.33: System Interference, packet=1 bit

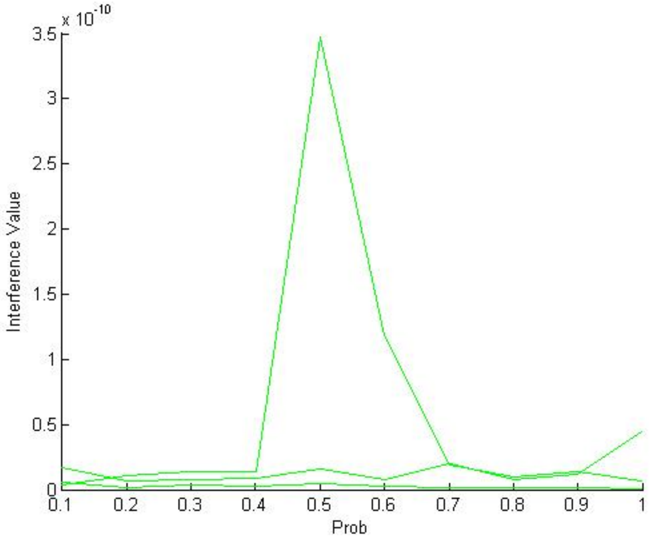

Figure 4.34: System Interference, packet=2 bits

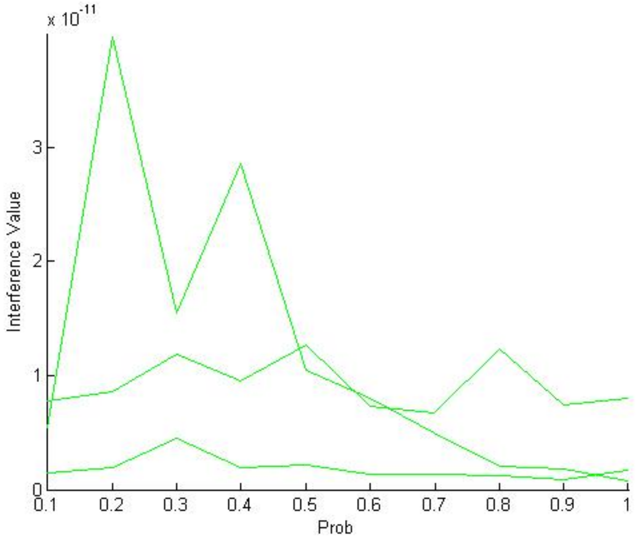

Figure 4.35: System Interference, packet=3 bits

4.2.3 7 Sensors -

The scenario that will be studied, is:

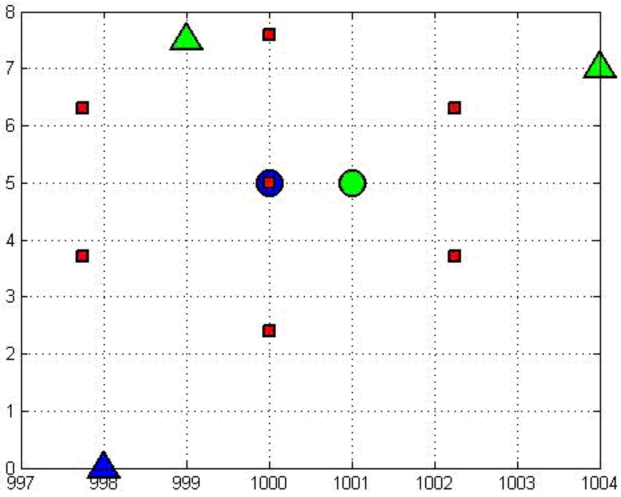

Figure 4.36: Simple Model, 1 Sensor

Where,

- The Transmitter is represented by a pyramid.
- The Receiver is represented by a circle.
- The sensor is represented by a red square.
- Primary System in blue color.
- Secondary System in green color.

Data Rate

	Number of Bits			
Transmitter	0.5	1	2	3
Tx 1	2.963	2.97	2.97	2.97
Tx 2	4.3854	4.63	4.72	4.78

Mean Queue Delay

	Number of Bits			
Transmitter	0.5	1	2	3
Tx 1	0.969	3.5	32.09	131.28
Tx 2	2.8949	6.4630	15.84	66.78

Allocated Power

	Number of Bits			
Transmitter	0.5	1	2	3
Tx 1	-50.10	-50	-50	-50
Tx 2	-54	-54.22	-53	-51

Sending Probability

	Number of Bits			
Transmitter	0.5	1	2	3
Tx 1	0.7558	0.6544	0.485	0.477
Tx 2	0.24	0.344	0.5144	0.522

Data queue

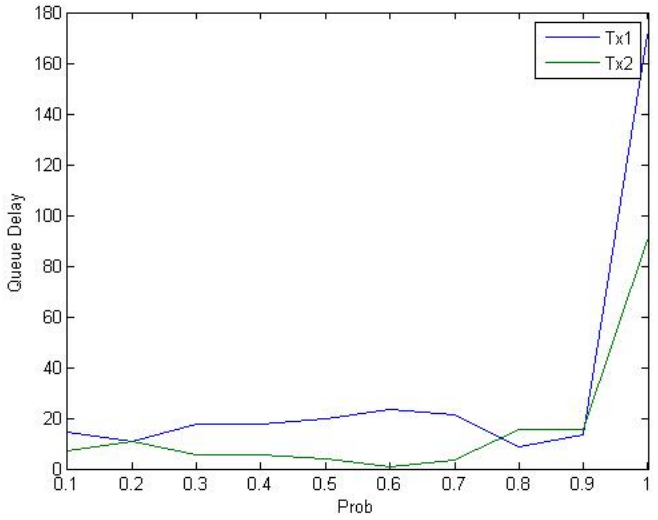

Figure 4.37: Queue Delay, packet=2

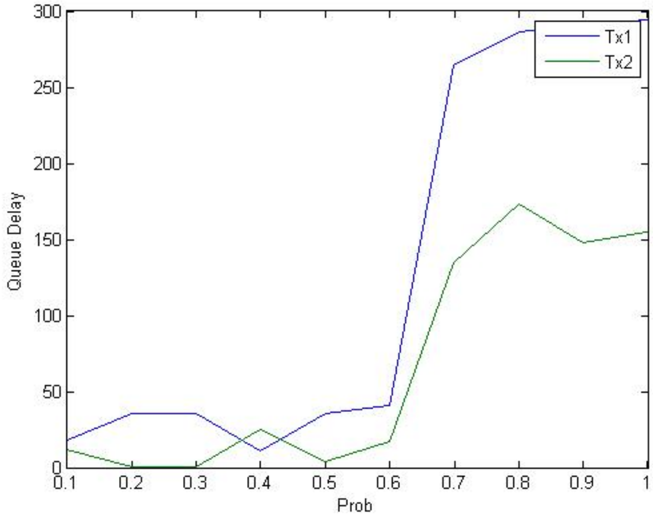

Figure 4.38: Queue Delay, packet=3

System Interference

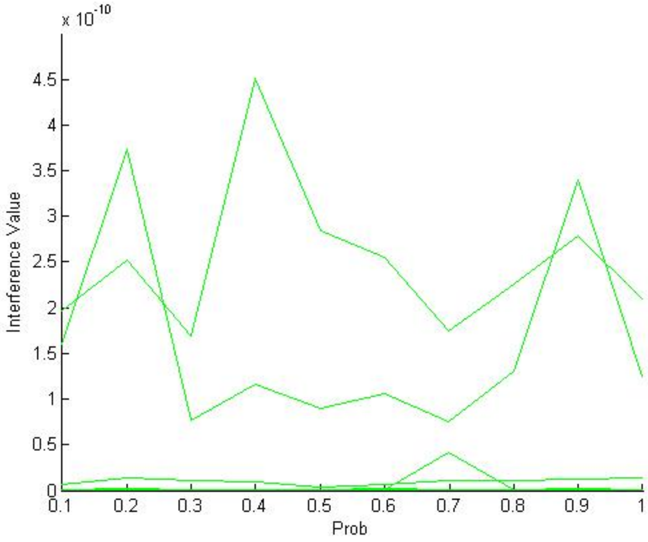

Figure 4.39: System Interference, packet=0.5 bits

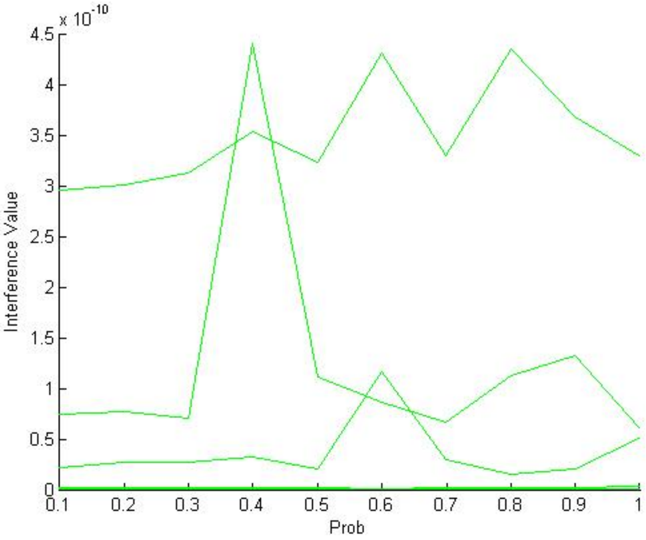

Figure 4.40: System Interference, packet=1bit

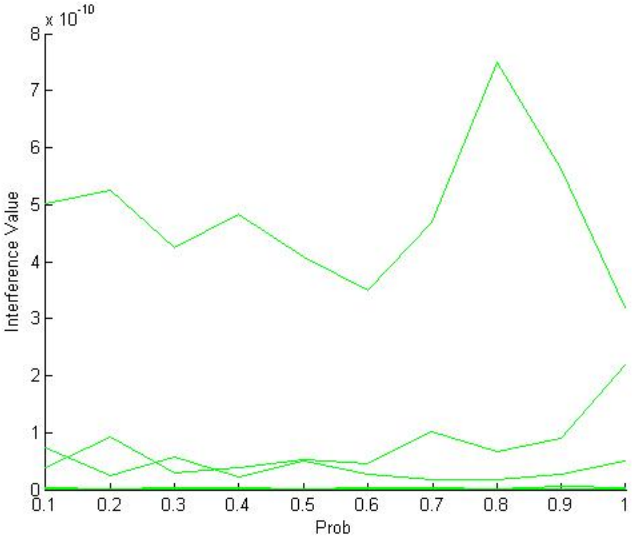

Figure 4.41: System Interference, packet=2 bits

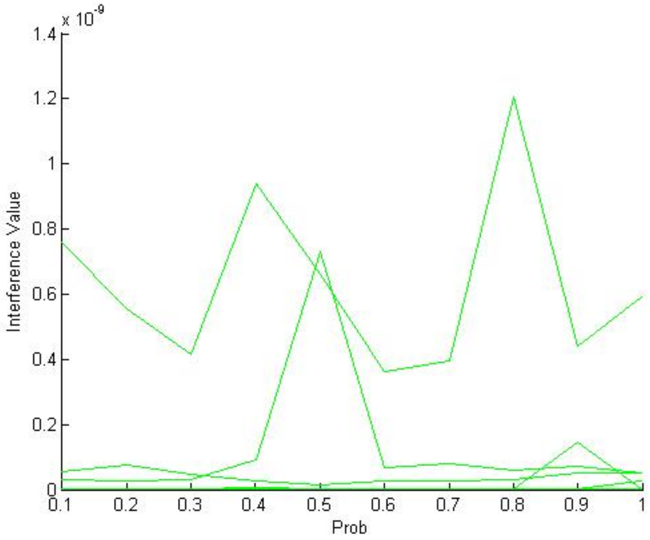

Figure 4.42: System Interference, packet=3 bits

Relevant Graphics

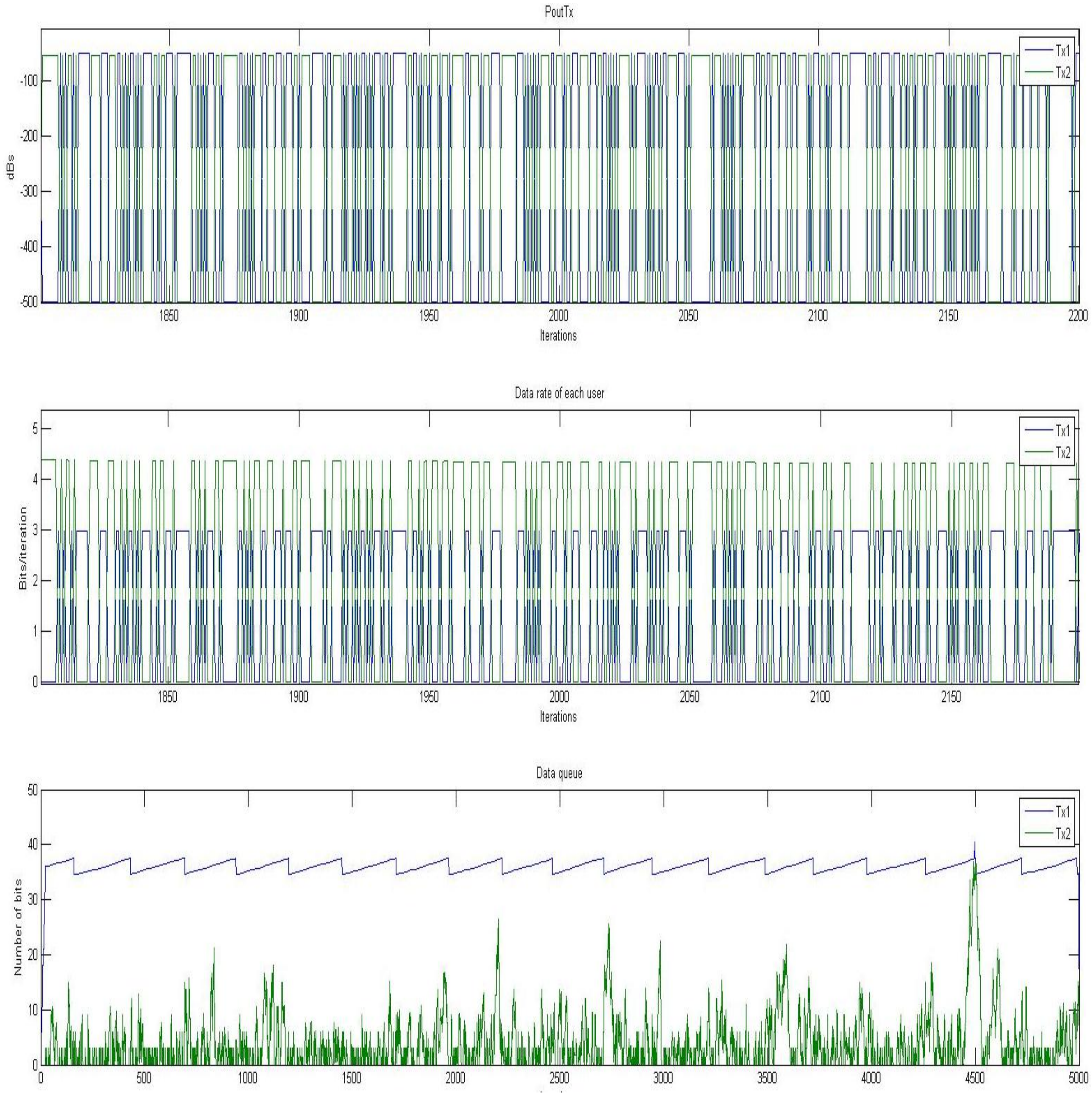

Figure 4.43: Scenario Relevant Graphics

4.3 General model

The second model that is shown is the General Model. It is composed by threeTransmitter and one Receiver Primary System, four Transmitters and One Receiver of a Secondary System. The system's behavior will be tested with different sensors placements. One Senor, two Sensors, and seven Sensors will be used. So, there will be three different scenarios of the General Model. These three scenario will be used to compare, and study the differences and similarity between them.

For that purpose, different packet lengths will be tested, with probabilities from 0.1 to 1. The measures will be performanced with 0.1 bits, 0.3 bits, and 0.5 bits bits packet length. The results that will be taken into account are:

- Data Rate
- Queue Delay
- Allocated Power
- Dropping Packets
- Sending probability.

Graphics and tables will show the system behavior.

4.3.1 -1 Sensors -

The scenario that will be studied, is:

Where,

- The Transmitter is represented by a pyramid.
- The Receiver is represented by a circle.
- The sensor is represented by a red square.
- Primary System in blue color.
- Secondary System in green color.

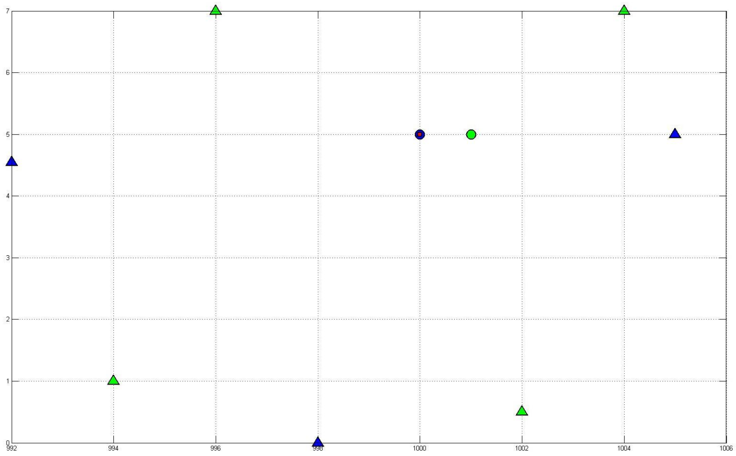

Figure 4.44: General Model, 1 Sensor

Data Rate

	Number of Bits		
Transmitter	0.1	0.2	0.3
Tx 1	1.21	1.20	1.22
Tx 2	0.40	0.41	0.405
Tx 3	0.2129	0.22	0.215
Tx 4	0.27	0.2717	0.272

Mean Queue Delay

	Number of Bits		
Transmitter	0.1	0.2	0.3
Tx 1	0.2	4.6	12.11
Tx 2	1.85	14.21	34.06
Tx 3	4.72	25.15	45.043
Tx 4	3.27	22.8	43.9

Allocated Power

	Number of Bits		
Transmitter	0.1	0.2	0.3
Tx 1	-50	-50	-50
Tx 2	-50	-50	-50
Tx 3	-50	-40	-35
Tx 4	-50	-50	-50

Sending Probability

	Number of Bits		
Transmitter	0.1	0.2	0.3
Tx 1	0.43	0.24	0.2759
Tx 2	0.133	0.398	0.5029
Tx 3	0.2359	0.09	0.06
Tx 4	0.20	0.26	0.16

Data Queue

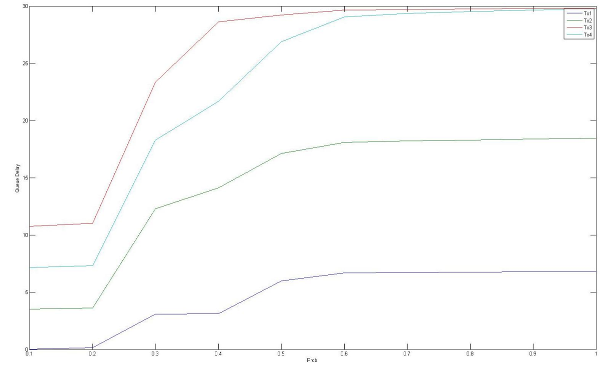

Figure 4.45: Data Queue, packet=0.3 bits

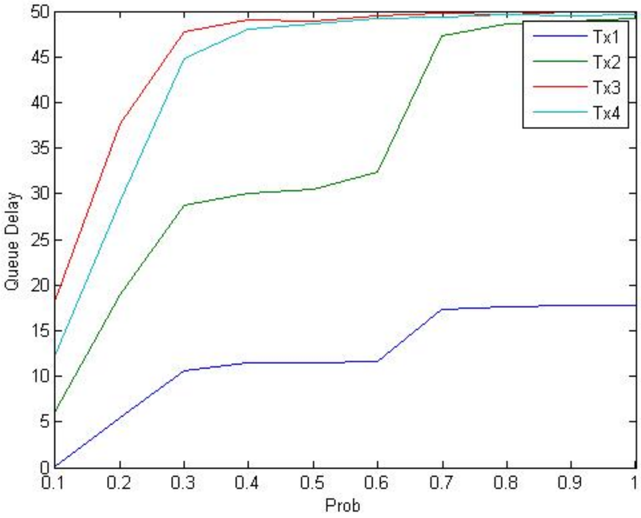

Figure 4.46: Data Queue, packet=0.5 bits

Drop Packets

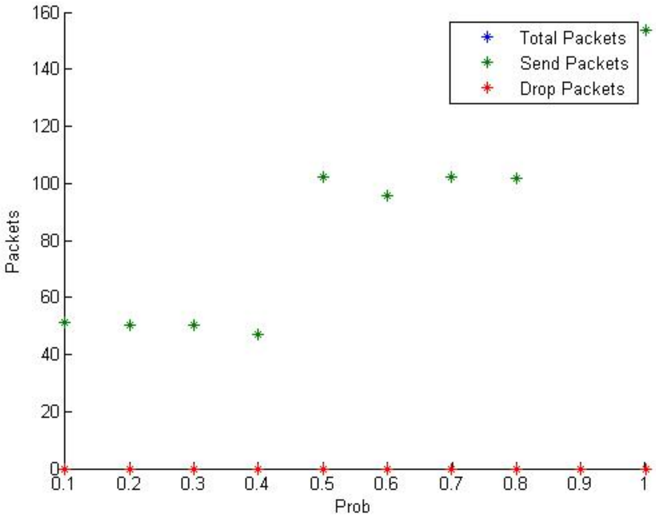

Figure 4.47: Drop Packets, packet=0.1 bits

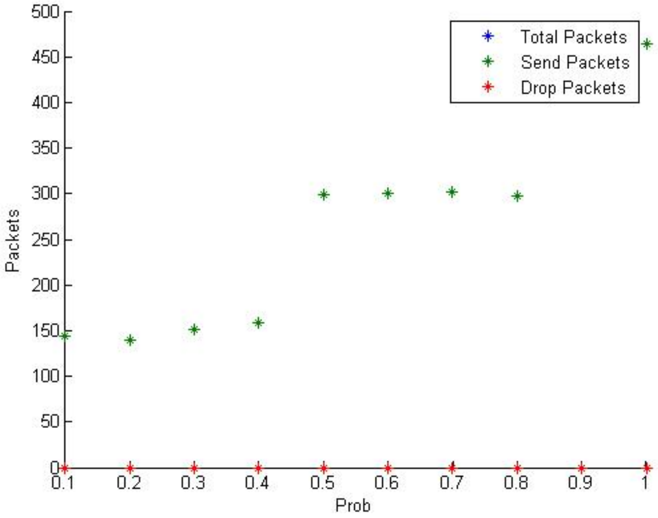

Figure 4.48: Drop Packets, packet=0.3 bits

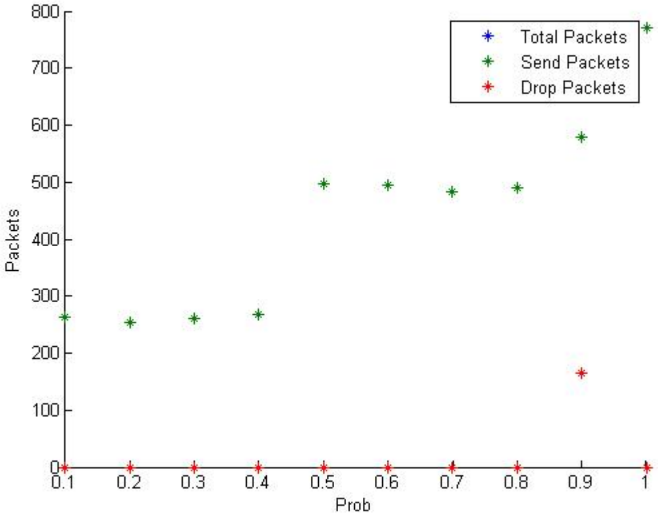

Figure 4.49: Drop Packets, packet=0.5 bits

System Interference

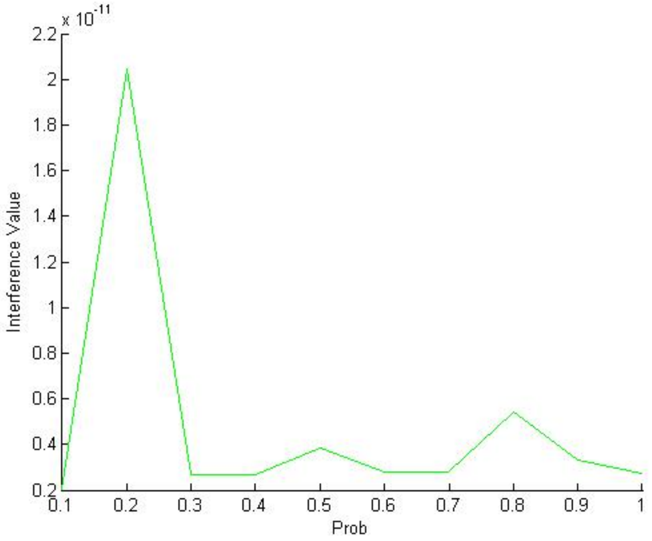

Figure 4.50: System Interference, packet=0.1 bits

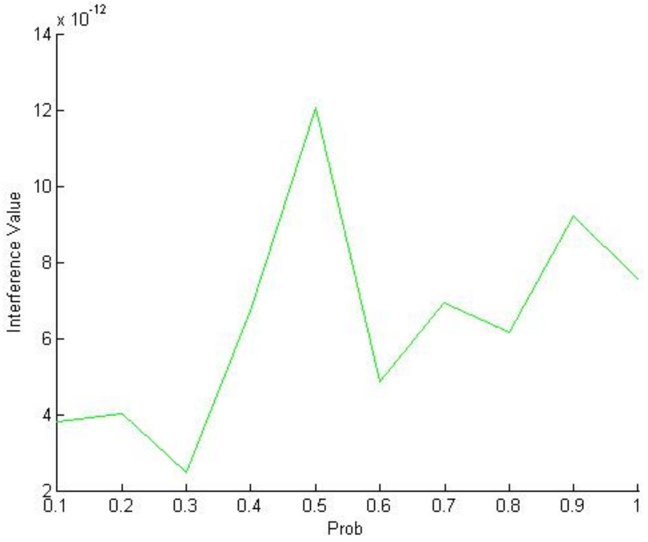

Figure 4.51: System Interference, packet=0.5 bits

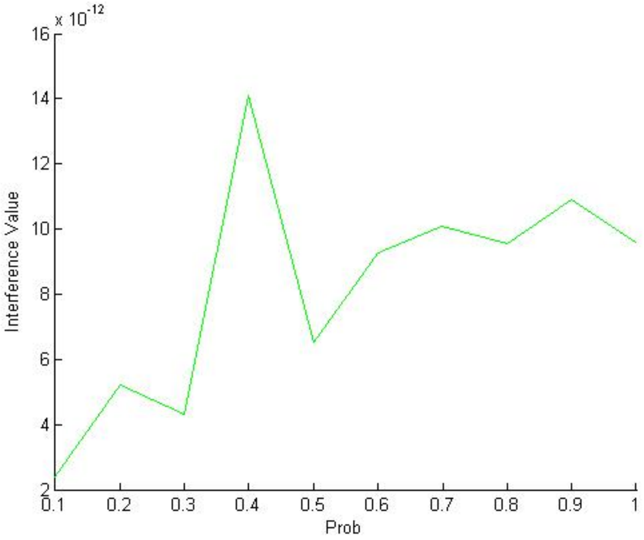

Figure 4.52: System Interference, packet=0.5 bits

Relevant Graphics

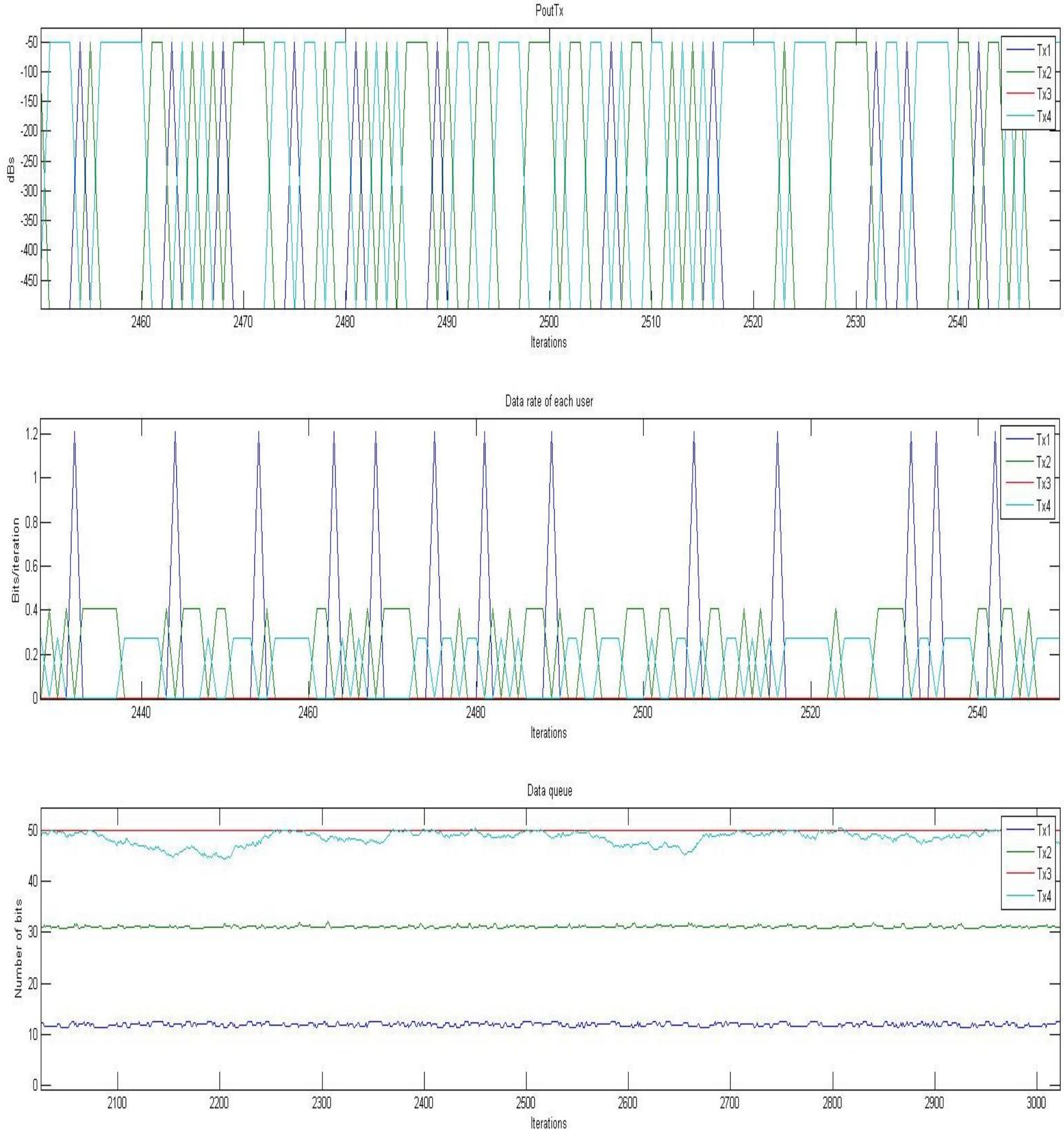

Figure 4.53: Relevant Graphics

4.3.2 -3 Sensors -

The scenario that will be studied, is:

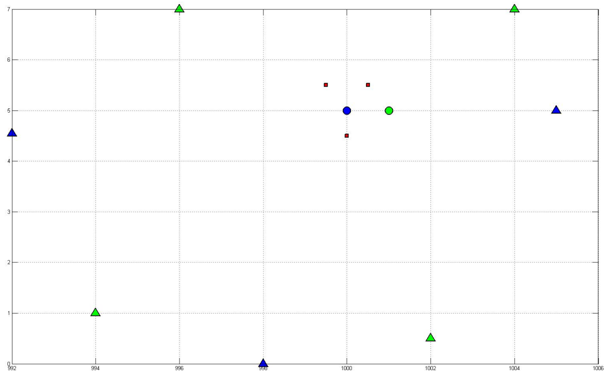

Figure 4.54: Simple Model, 1 Sensor

Where,

- The Transmitter is represented by a pyramid.
- The Receiver is represented by a circle.
- The sensor is represented by a red square.
- Primary System in blue color.
- Secondary System in green color.

Data Rate

	Number of Bits		
Transmitter	0.1	0.2	0.3
Tx 1	0.2521	0.2526	0.26
Tx 2	2.6431	2.6354	2.6451
Tx 3	1.944	1.988	1.962
Tx 4	0.3421	0.3256	0.3452

Mean Queue Delay

	Number of Bits		
Transmitter	0.1	0.2	0.3
Tx 1	6.03	24.95	45.197
Tx 2	0.059	1.6255	3.94
Tx 3	0.599	2.78	5.28
Tx 4	4.7675	20.38	40.29

Allocated Power

	Number of Bits		
Transmitter	0.1	0.2	0.3
Tx 1	-50	-50	-50
Tx 2	-50	-50	-50
Tx 3	-50	-50	-50
Tx 4	-50	-50	-50

Sending Probability

	Number of Bits		
Transmitter	0.1	0.2	0.3
Tx 1	0.2124	0.2191	0.1272
Tx 2	0.5885	0.2439	0.2061
Tx 3	0.042	0.084	0.1396
Tx 4	0.1566	0.45	0.526

Drop Packets

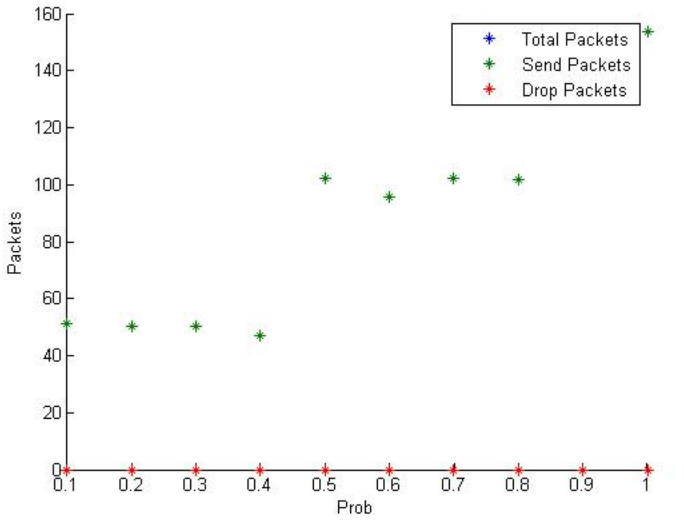

Figure 4.55: Drop Packets, packet=0.1 bits

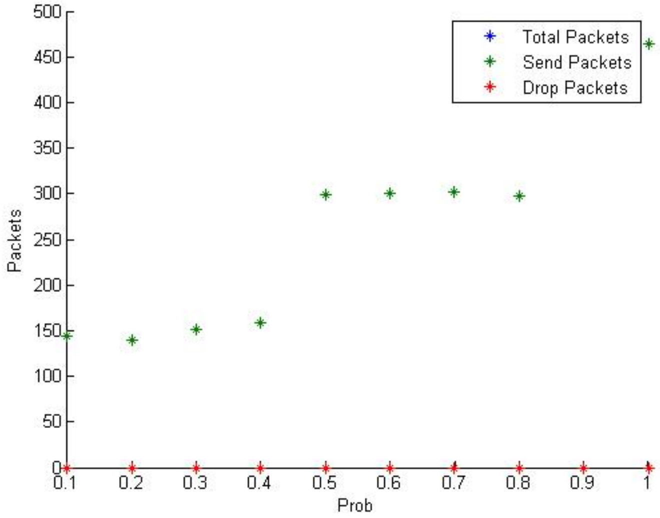

Figure 4.56: Drop Packets, packet=0.3 bits

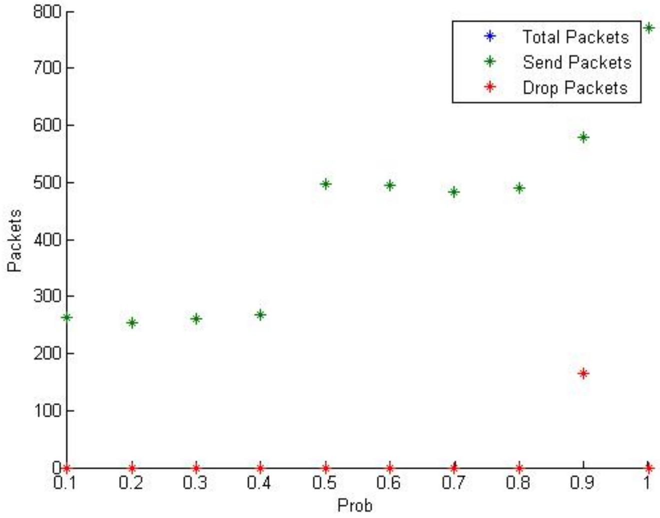

Figure 4.57: Drop Packets, packet=0.5 bits

System Interference

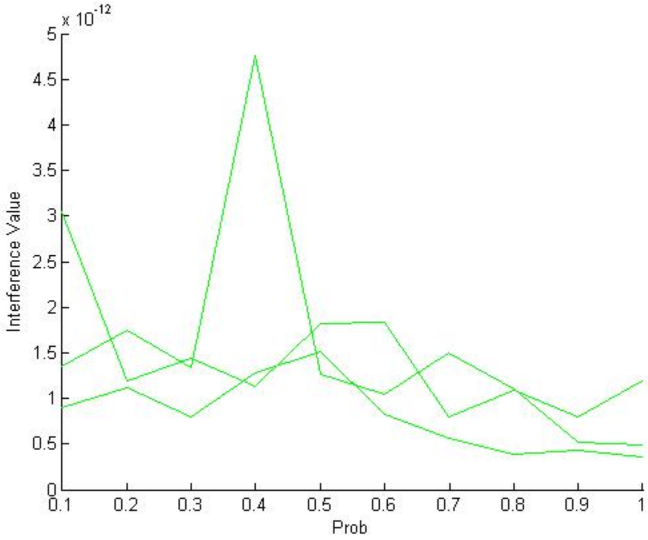

Figure 4.58: System Interference, packet=0.1 bits

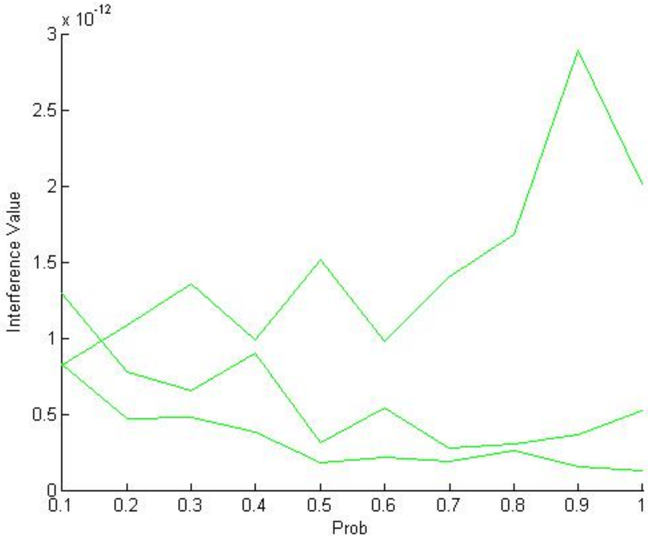

Figure 4.59: System Interference, packet=0.3 bits

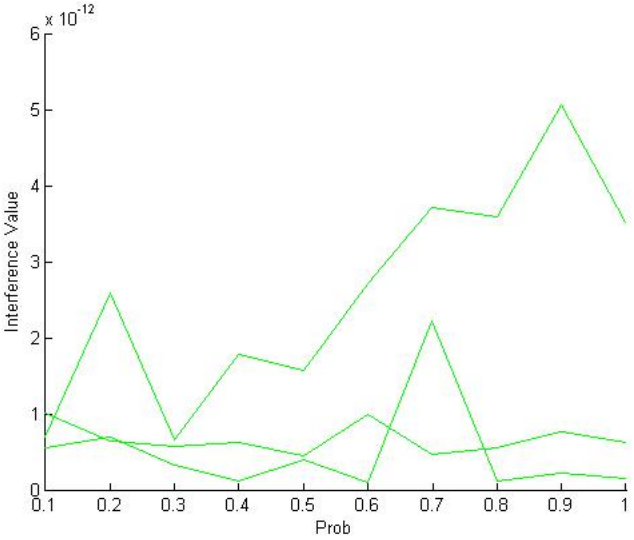

Figure 4.60: System Interference, packet=0.5 bits

Relevant Graphics

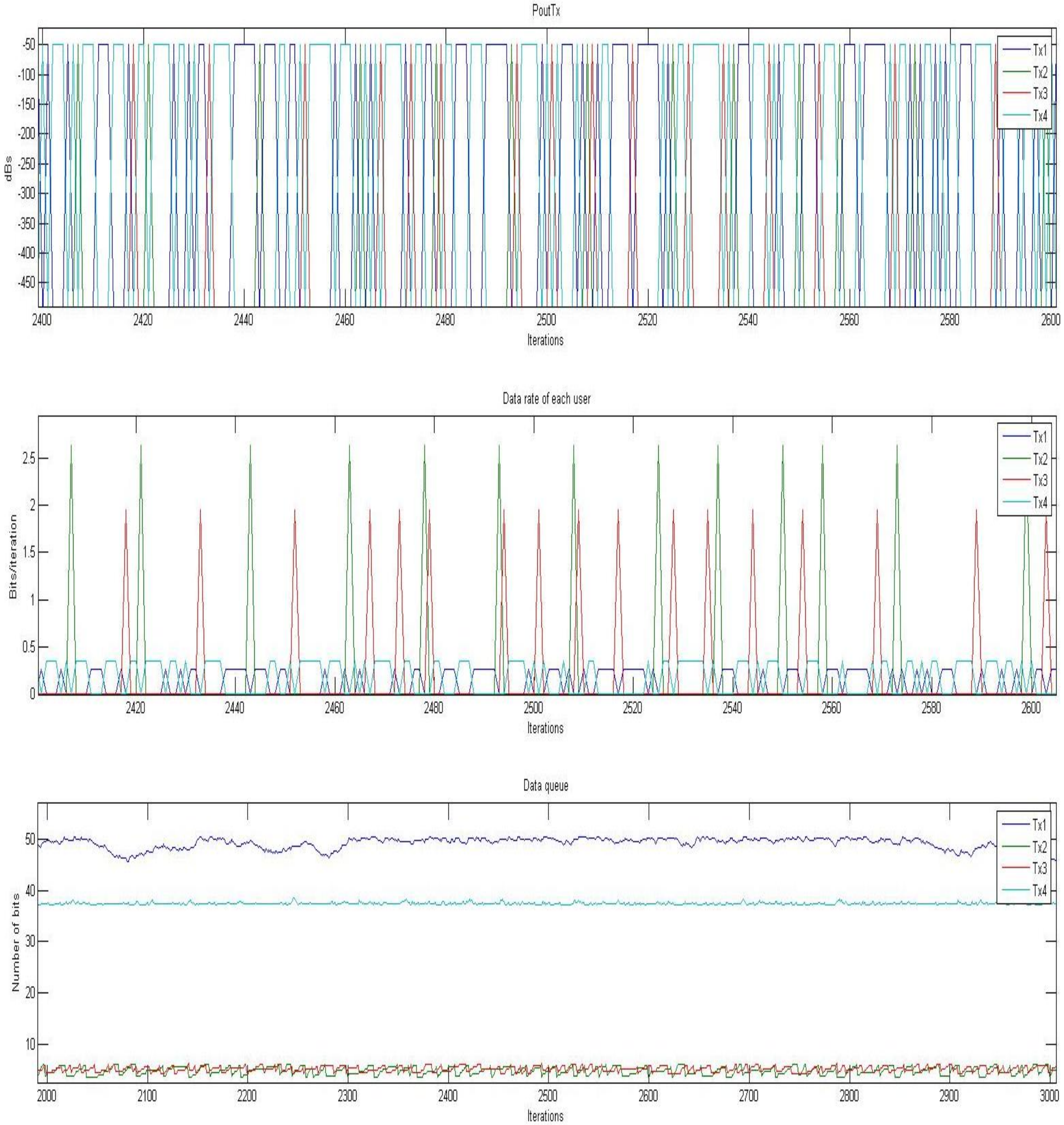

Figure 4.61: Relevant Grapics

4.3.3 -7 Sensors -

The scenario that will be studied, is:

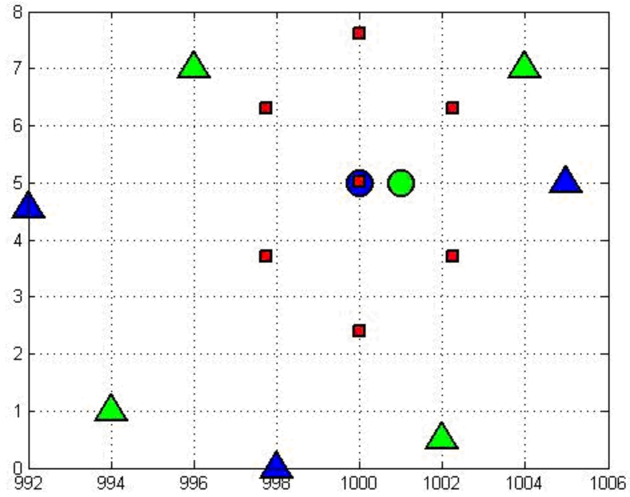

Figure 4.62: Simple Model, 1 Sensor

Where,

- The Transmitter is represented by a pyramid.
- The Receiver is represented by a circle.
- The sensor is represented by a red square.
- Primary System in blue color.
- Secondary System in green color.

Data Rate

	Number of Bits		
Transmitter	0.1	0.2	0.3
Tx 1	0.8986	0.8950	0.8947
Tx 2	0.4156	0.42	0.4198
Tx 3	0.206	0.25	0.24
Tx 4	0.2486	0.2546	0.2457

Mean Queue Delay

	Number of Bits		
Transmitter	0.1	0.2	0.3
Tx 1	0.506	5.89	13.47
Tx 2	1.774	14.48	33.77
Tx 3	3.935	24.7	44.98
Tx 4	3.32	23.29	43.5

Allocated Power

	Number of Bits		
Transmitter	0.1	0.2	0.3
Tx 1	-50	-50	-50
Tx 2	-50	-50	-50
Tx 3	-50	-50	-50
Tx 4	-50	-50	-50

Sending Probability

	Number of Bits		
Transmitter	0.1	0.2	0.3
Tx 1	0.42	0.28	0.3463
Tx 2	0.13	0.38	0.4521
Tx 3	0.23	0.085	0.05
Tx 4	0.21	0.246	

Data Queue

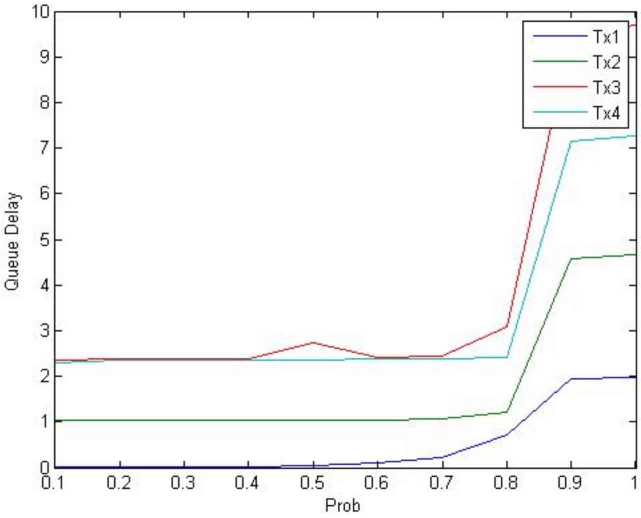

Figure 4.63: Data Queue, pacekt=0.1 bits

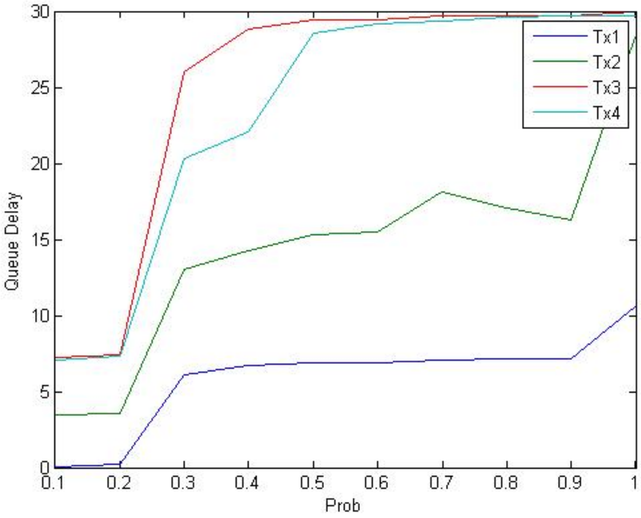

Figure 4.64: Data Queue, pacekt=0.3 bits

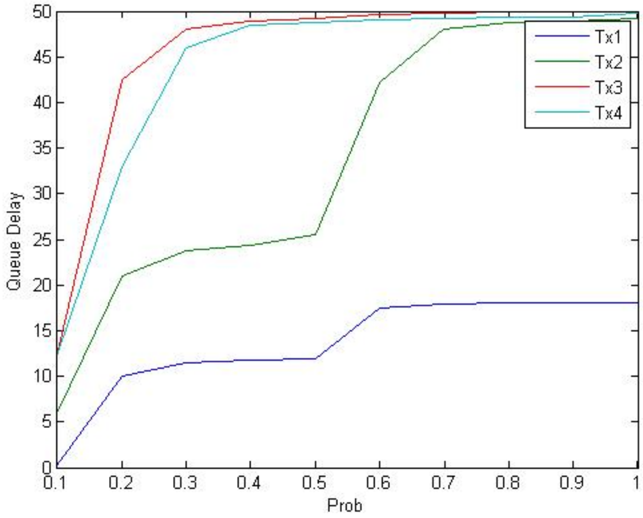

Figure 4.65: Data Queue, pacekt=0.5 bits

Drop Packets

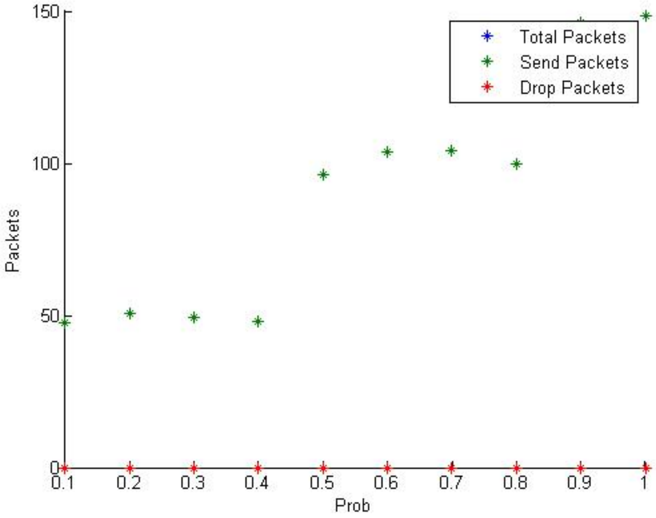

Figure 4.66: Drop Packets, packet=0.1 bits

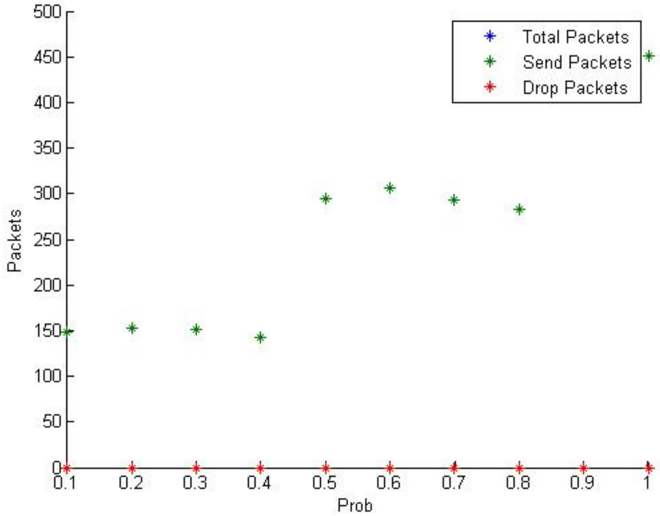

Figure 4.67: Drop Packets, packet=0.3 bits

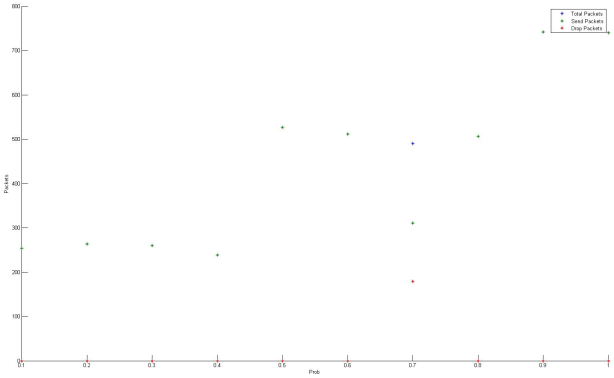

Figure 4.68:

System Interference

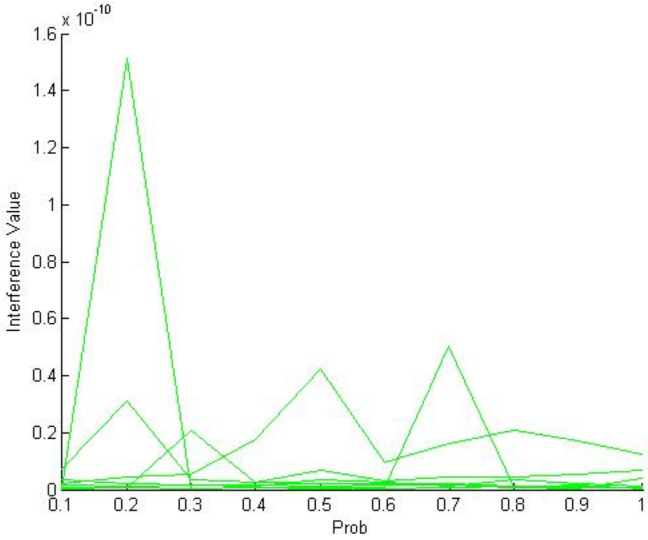

Figure 4.69: System Interference, packet=0.1 bits

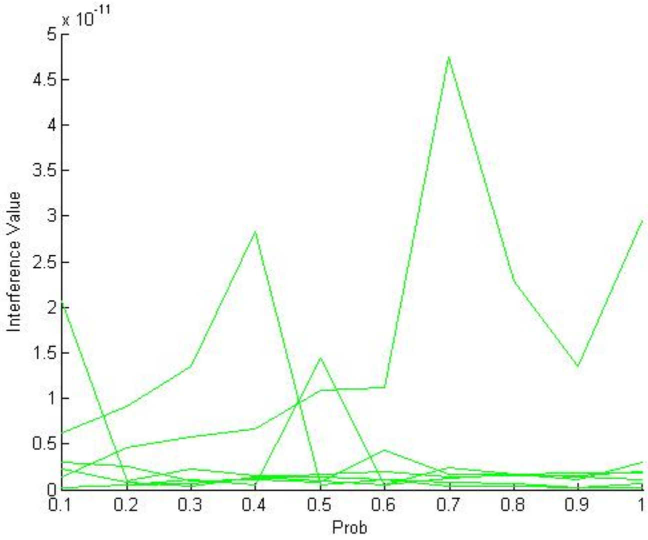

Figure 4.70: System Interference, packet=0.3 bits

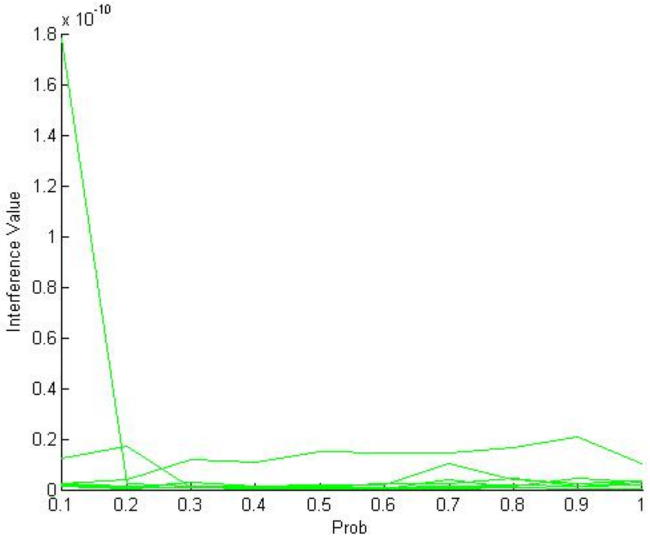

Figure 4.71: System Interference, packet=0.5 bits

Chapter 5

Conclusion and Discussion

By studying the results of the simulations of the two considered scenarios, the Simple Model and the General Model, some relevant conclusions can be made:

A relevant parameter of the scenarios that have been studied is the Channel Capacity of each transmitter, i.e. The data rate that they can be obtained. Depending on the data rate that they can achieve, the values of the arrival packets and the size of the data queue has to be taken into account.

As seen in the results, there are two types of behavior of the system; depending on the arrival packet length being below or above the channel capacity for each user.The system will manage the arrival packets of each user if his data rate is at least half of the considered packet length. If it is not, the data queue will be full, and no more packets will be admitted.

This happens because the system uses a"Water Filling solution". The system will wait to send packets until it has a good channel state to use. The system will wait by storing the packets at the data queue of the user. So the length of the data queue is another important parameter.

With an improper data queue size, the packets will not be stored, because admission protocols are implemented. So these packets will be lost, the communication will not be effective, and there will be loss of information.

By looking at the graphics, it can be seen that the arrival probability has to be in, the range 0.1-0.4 for a proper behavior of the system. With a higher arrival probability, the system cannot manage the amount of arrived packets, the data queue will be full, and the stability of the system will be lost.

Another remarkable point is the interference limitations imposed by the sensors. It can be seen from the results, that depending on the number of sensors there will be more constraints at the system, or not. The transmitters will have to adapt their allocated power, creating an adaptive system.

In addition, the position of the transmitters at the scenario is relevant, depending on how close they are to the sensort. With transmitters close to the sensor their power will be more limited than the others, because they will cause more interference than the others (that are far away from the sensors).

Moreover, the allocated power of each user will change, if they have good channel to use or not. If the transmitters have good channel to send, the system will allocate more power to them, so the limit power constraint appears to limit the power. If there are good channels, the allocated power will be "On-Off". With a bad channel, the allocate power is less than the other allocated power. It can be said that the system uses a "Water Filling Solution".

There are a lot of users in the cell with only one channel of communication. The allocated power will be the highest allocated power, to transmit as much rate as possible.

With more than one frequency, the performance of the system improves a lot. The system will allocate one channel for those users that have a lower data rate to transmit, and the other channel for the rest of the transmitters. If all users have the same data rate, there will be no distinctions between using one frequency or the other.

By looking the dropping packets rates it can be observed if the system needs more channels of communication for the amount of users at the cell. This is the parameter that has to be taken into account to add more frequencies to the system.

And finally, the system behavior changes a lot depending on the bits of quantification that have been used, and the size of the data queue. For the simulations done, the number of bits of quantification have been changed, and getting for 3 bits a good energy per bit rate.

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Appendix A

Matlab Code

To see the details of the developed Matlab program, please take a look at the contents of the attached ZIP file, “PROJECT_THESIS.ZIP”.

A.1 Main Program

```
function [Posout,Pout,rout,Xout,Aqout,qout,qQout,SNRout,TotalPack,DropPack]=simple_model()


%-------------------------------------------------------------------
%Inicialization
[names,data]=textread('parameters.txt','%s%f','commentstyle','matlab');
[x,y]=textread('fixed_positions.txt','%f%f','commentstyle','matlab');
[xs,ys]=textread('fixed_Sensors.txt','%f%f','commentstyle','matlab');

global numTxPU numRxPU numTxSU numRxSU numSensors N0 PtxPU TotalPack DropPack
global Pmax controlqueue  bits
global celularBase Rbase celularSens  Rsens numfrec numbits

close all

numTxPU=data(1);
numRxPU=1;
numTxSU=data(3);
numRxSU=1;
numSensors=data(5);
scale=data(6);
sigmaS=data(7);
hb=data(8);
hm=data(9);
celularBase=data(10);
```

```
Rbase=data(11);
celularSens=data(12);
Rsens=data(13);
prob=data(14);
bits=data(15);
controlqueue=data(16);
PtxPU=data(17); %db
PtxSU=data(18); %db
Pmax=data(19);
Xav=data(20);
Xmin=data(21);
work=data(22);
numfrec=data(23);
numbits=data(24);
load_data=data(25);

Pb=[x,y]';
Ps=[xs,ys]';
cont=1;
%------------------------------------------------------------------


%----------------------------MAIN PROGRAM---------------------------



%----------------- CREATE ENVIROMENT -------------------------------


       [Cavg,Intavg,Esavg,Dsavg]=CreateEnviroment(Pb,Ps,scale,hb,hm,sigmaS);

       if load_data==1

        load('load_data_file')
        Cavg=CavgSave;
        Intavg=IntavgSave;
        Esavg=EsavgSave;
        Dsavg=DsavgSave;


       end



%---Output Inicialization---
```

```
        Posout=zeros(numfrec,work);
        Pout=zeros(numfrec,numTxSU,work);
        rout=zeros(numfrec,numTxSU,work);

        Xout=zeros(numfrec,numSensors,work);
        Aqout=zeros(numTxSU,work);
        qout=zeros(numTxSU,work);

        qQout=zeros(numTxSU,work);

        SNRout=zeros(numfrec,numTxSU,work);


        cout=zeros(numfrec,numTxSU,work);
        intout=zeros(numfrec,numTxPU,work);
        esout=zeros(numSensors,numTxPU,numfrec,work);
        dsout=zeros(numSensors,numTxSU,numfrec,work);


        TotalPack=zeros(1,numTxSU);
        DropPack=zeros(1,numTxSU);

%-----------------------------

        X0=Xmin*ones(numfrec,numSensors);
        q=zeros(1,numTxSU);

        SP=0.1*ones(1,numSensors)';
        BP=0.1*ones(1,numSensors)';

while work>cont


        %------------- NOISE ------------------------------
        kb=1.3806e-23; %Boltzmann constant
        T=300;
        N0=randn(1)*kb*T;


        %------------- CONTROL PERIOD -------------------------------

        %-------- Tx Users ------------------------
        [Aqout0,qQ,q1,SNR]=Transmittersfunction(prob,bits,Cavg,Intavg,q) ;
        %-----------------------------------------

        %--------FUNCION CENTER -------------------
```

```
[p,X,posTx,Po,q,r]=FunsionCenter(X0,Xav,Xmin,BP,SP,qQ,q1,SNR,Dsavg);
%-----------------------------------------

%----------------------------------------------------------


%------ SILENT PERIOD and BUSY PERIOD  ---------------------


%--------- UPDATE CHANNEL ----
[C,Int,Es,Ds]=CalulateFastFading(Cavg,Intavg,Esavg,Dsavg);
%-----------------------------

PtxSU=10*log10(p);
[SP,BP]=Sensorfunct(PtxPU,PtxSU,Es,Ds,posTx);
%---------------------------------------------------------



%-----  OUTPUT ------
     Posout(:,cont)=posTx;
     Pout(:,:,cont)=PtxSU;
     SNRout(:,:,cont)=SNR;

     for i=1:numfrec
         raux=zeros(1,numTxSU);
         raux(posTx(i))=r(i,posTx(i));
         rout(i,:,cont)=raux;
     end


     Xout(:,:,cont)=X;
     Aqout(:,cont)=Aqout0;
     qout(:,cont)=q;

    V=controlqueue*bits;


    for i=1:numTxSU

         Vunq=data_queue_unquant(qQ(i*numbits-(numbits-1):i*numbits),numbits,V);
         qQout(i,cont)=Vunq;

     end

     cout(:,:,cont)=C;
```

```
             intout(:,:,cont)=Int;
             esout(:,:,:,cont)=Es;
             dsout(:,:,:,cont)=Ds;
        %-------------



    %----------UPDATE VECTORS------------------
            cont=cont+1;
            X0=X;
     %---------------------------
end

%----------SAVE DATA------------------

if load_data==0

            CavgSave=Cavg;
           IntavgSave=Intavg;
           EsavgSave=Esavg;
           DsavgSave=Dsavg;

           save('load_data_file','CavgSave','IntavgSave','EsavgSave','DsavgSave')
end



%----------REPRESENTATION------------------
Xavgout=Xav*ones(work,1);




for i=1:numfrec

figure
subplot(3,1,1)

aux1=Pout(i,:,:);
aux2=reshape(aux1,numTxSU,work);
plot(aux2');
title('PoutTx')
ylabel('dBs')
xlabel('Iterations')
legend('Tx1','Tx2','Tx3','Tx4');
```

```
subplot(3,1,2)
aux1=rout(i,:,:);
aux2=reshape(aux1,numTxSU,work);

plot(aux2')
title('Data rate of each user')
ylabel('Bits/iteration')
xlabel('Iterations')
legend('Tx1','Tx2','Tx3','Tx4');

subplot(3,1,3)
qoutlimit=(controlqueue*bits)*ones(work,1);

subplot(3,1,3)
plot(qout')
hold on
plot(qoutlimit,'r');
hold off
title('Data queue')
ylabel('Number of bits')
xlabel('Iterations')
legend('Tx1','Tx2','Tx3','Tx4');


figure
subplot(3,1,1)

aux1=Pout(i,:,:);
aux2=reshape(aux1,numTxSU,work);
plot(aux2');
title('PoutTx')
ylabel('dBs')
xlabel('Iterations')
legend('Tx1','Tx2','Tx3','Tx4');

subplot(3,1,2)
plot(Aqout');
title('Arrival data')
ylabel('Number of bits')
xlabel('Iterations')
legend('Tx1','Tx2','Tx3','Tx4');

subplot(3,1,3)
aux1=rout(i,:,:);
aux2=reshape(aux1,numTxSU,work);
```

```
plot(aux2’)
title(’Data rate of each user’)
ylabel(’Bits/iteration’)
xlabel(’Iterations’)
legend(’Tx1’,’Tx2’,’Tx3’,’Tx4’);

figure
subplot(3,1,1)
aux1=rout(i,:,:);
aux2=reshape(aux1,numTxSU,work);

plot(aux2’);
title(’Transmitted data rate’)
ylabel(’Bits/iteration’)
xlabel(’Iterations’)
legend(’Tx1’,’Tx2’,’Tx3’,’Tx4’);

subplot(3,1,2)
aux1=Xout(i,:,:);
aux2=reshape(aux1,numSensors,work);

plot(10*log10(aux2’),’b’);
hold on
plot(10*log10(Xavgout’),’r’);
hold off
title(’Interference queue’)
ylabel(’Interference level’)
xlabel(’Iterations’)

qoutlimit=(controlqueue*bits)*ones(work,1);

subplot(3,1,3)
plot(qout’)
hold on
plot(qoutlimit,’r’);
hold off
title(’Data queue’)
ylabel(’Number of bits’)
xlabel(’Iterations’)
legend(’Tx1’,’Tx2’,’Tx3’,’Tx4’);

%----------Channel state------------------

figure
subplot(4,1,1)
```

```
aux1=cout(i,:,:);
aux2=reshape(aux1,numTxSU,work);

plot(-1*aux2');
title('TxSU-RxSU (c) Channel state')
ylabel('dBs')
xlabel('Iterations')

subplot(4,1,2)

aux1=intout(i,:,:);
aux2=reshape(aux1,numTxPU,work);

plot(-1*aux2');
title('TxPU-RxSU (int) Channel state')
ylabel('dBs')
xlabel('Iterations')

subplot(4,1,3)

aux1=esout(:,1,i,:);
aux2=reshape(aux1,numSensors,work);

plot(-1*aux2')
title('TxPU-RxPU (es) Channel state')
ylabel('dBs')
xlabel('Iterations')

subplot(4,1,4)

aux1=dsout(:,1,i,:);
aux2=reshape(aux1,numSensors,work);

plot(-1*aux2')
title('TxSU-RxPU (ds) Channel state')
ylabel('dBs')
xlabel('Iterations')

end
%----------Packect state------------------


figure

subplot(3,1,1)
bar(TotalPack);
```

```
title('Total Packets')
ylabel('Packets Number')
xlabel('TxSU Users')


SendPack=TotalPack-DropPack;

subplot(3,1,2)
bar(SendPack);
title('Send Packets')
ylabel('Packets Number')
xlabel('TxSU Users')

subplot(3,1,3)
bar(DropPack);
title('Drop Packets')
ylabel('Packets Number')
xlabel('TxSU Users')

figure
plot(1:numTxSU,TotalPack)
hold on
plot(1:numTxSU,SendPack,'g')
plot(1:numTxSU,DropPack,'r')
hold off

%------ data queue --------------


figure

for i=1:numTxSU

    subplot(numTxSU,1,i)
    plot(qout(i,:));
    hold on
    plot(qQout(i,:),'r');
    hold off

    title('Data queue')
    %ylabel('Number of bits')
    xlabel('Iterations')
end
```

A.2 Fusion Center

```
function [p,X,posTx,Popt,q,r]=FunsionCenter(X0,Xav,Xmin,BP,SP,qQ,q1,SNR,Ds)

global numTxSU Pmax numfrec numbits controlqueue bits


%lineal
ds=10.^((-1*Ds)/10);


%--------- UPDATING INTEFERENCE QUEUE--------

I=BP-SP;
I=I';
X=interferqueue(X0,Xav,Xmin,I);


%--------- CONTROL PROCESSING --------------


V=controlqueue*bits;
q0=zeros(1,numTxSU);


for i=0:numTxSU-1

a=i*numbits+1;
b=(i*numbits+1)+numbits-1;
qaux2=qQ(a:b);
q0(i+1)=data_queue_unquant(qaux2,numbits,V);

end


    %----- UPDATING BEST TX USER-------------
     [posTx,r]=first_transmitter(X,q0,SNR,ds);
     V=1e25;
     %V=1;
     Popt=zeros(1,numfrec);
```

```
     for i=1:numfrec
        potaux=(q0(posTx(i))/(V*(X(i,:)*ds(:,posTx(i),i)))-(1/SNR(i,posTx(i))));

       if potaux>=Pmax
           Popt(i)=Pmax;
       elseif potaux<=1e-50
           Popt(i)=1e-50;
       else
           Popt(i)=potaux;
       end

     end

%--------- POWER ALLOCATION ------------

p=zeros(numfrec,numTxSU);

for i=1:numfrec


    aux=1e-50*ones(1,numTxSU);
    Palloc=min(Pmax,Popt(i));
    aux(posTx(i))=Palloc;

    p(i,:)=aux;

end



%--------- UPDATE DATAQUEUE ----------------
 q=dataqueue2(q1,r,0,posTx);
```

A.3 User Selection

```
function [posTx,r]=first_transmitter(X,q,SNR,ds)


global numTxSU numfrec Pmax
```

```
 r=zeros(numfrec,numTxSU);
 posTx=zeros(1,numfrec);
 user=ones(1,numTxSU);

for j=1:numfrec

    %We can not select the same user for different frequencies
    J=zeros(1,numTxSU);
    i=1;
        while i<=numTxSU

            if user(i)==0 %tenemos que ver que no lo hemos seleccionado ya
                J(i)=-1;
                i=i+1;

            else
               V=1e25;

               %V=1;
               a=(q(i)/(V*(X(j,:)*ds(:,i,j))));
               b=(1/SNR(j,i));
               potaux=((q(i)/(V*(X(j,:)*ds(:,i,j))))-(1/SNR(j,i)));

               if potaux>=Pmax
                   pk=Pmax;
               elseif potaux<=1e-50
                   pk=1e-50;
               else
                   pk=potaux;
               end
                pk;

               r(j,i)=log2(1+pk*SNR(j,i));
               J(i)=(q(i)*r(i))-(V*(X(j,:)*ds(:,i,j))*pk);

               i=i+1;
            end

        end

        [y,posTx0]=max(J);
        posTx(j)=posTx0;
        user(posTx0)=0;
end
```

A.4 Transmitter Function

```
function [Aqout0,qQ,q0,SNR]=Transmittersfunction(prob,bits,C,Int,q)


   global PtxPU  controlqueue  N0 numfrec numTxSU numbits

    %-------- ARRIVALS ------------------------
    [Aqout0,q0]=ArrivalProcess(q,prob,bits,controlqueue);


    V=controlqueue*bits;
    qQ='0';

    for i=1:numTxSU

        qaux1=data_queue_quant(q0(i),numbits,V);
        qQ=[qQ,qaux1];
    end
    qQ=qQ(2:end);




    %---------- SNR--------------------
     c=10.^((-1*C)/10);
     Pint=10.^((PtxPU-Int)/10);
     SNR=zeros(numfrec,numTxSU);

    for i=1:numfrec
        SNR(i,:)=c(i,:)./(N0+sum(Pint(i,:)));
    end
```

A.5 Sensor Function

```
function [SP,BP]=Sensorfunct(PtxPU,PtxSU,Es,Ds,posTx)

global N0 numfrec numSensors

SP=zeros(numSensors,numfrec);
BP=zeros(numSensors,numfrec);
```

```
for i=1:numfrec

   %--- Silent Period -----
            y=PtxPU-Es(:,:,i); %db
            ySP=sum((10.^(y/10))')'+N0; %lineal

            SP(:,i)=ySP;


   %--- Busy Periods ----
            y=(PtxSU(i,posTx(i))-Ds(:,posTx(i),i));
            y1=10.^(y/10);
            yBP=y1+ySP; %lineal

            BP(:,i)=yBP;
end
```